Concentrated Solar Power Plant (CSP)

Molten Salt Tower with Thermal Storage
Midelt, Morocco

Group 6

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MJ2412 Advanced Renewable Energy Technology

March 2017

EXECUTIVE SUMMARY

After the successful execution of the $NOOR_0$ projects, a feasibility study for the next phase, $NOOR_1$I, was conducted. With an already existing knowledge of DNI potential in the Midelt area and a familiarity with CSP technology, a feasibility study including a proposal detailing plant configuration, estimated annual performance, estimated costs, and expected base price for eventual power purchase agreements was performed.

This report details results from the aforementioned proposal to build a CSP plant with molten salt storage in Midelt, Morocco. Using June 21st as a reference day, a CSP plant was proposed which would have one receiver on a 185-m tower, 18,125 dual-axis tracking heliostats, and 2 thermal fluid storage tanks. The proposed plant would require 1350 hectares of land. The electricity supply schedule and thermal output was based on a combination of the given tariff multiplier of 4 and a solar multiple of 2 which was determined from calculations.

The plant would provide an annual electricity production of 495.6 GWh/year with a solar energy to electricity efficiency of 15% and a receiver efficiency of 85%. A power block consisting of a 2-stage SST-700 turbine, generator, and boiler were suggested.

The CSP plant is anticipated to operate for 4434 hours annually. Of these, 2755 hours would be operations directly to the grid whereas the remaining 1679 hours would come from storage. The CSP plant has been designed with an anticipated plant life of 30 years with a capacity factor of 56%. The plant would provide electricity to the grid between 05:00 – 22:00, with 17:00 – 21:00 considered peak operation time with an increased tariff. The thermal capacity of the storage, 3870 MW_{th}, provides 10 hours of storage for the production of 150 MW_e. Storage hours were determined based on transients in irradiation as well as expected start-up transients. The storage system would maintain power output especially during peak hours to ensure maximum profitability of the plant. Energy from storage utilized for start-up and shut-down was accounted for as parasitic losses. 40,000 tonnes of molten salt would be utilized as the heat transfer fluid. The CSP plant would be expected to be operational for 330 days in a typical year with the rest designated for scheduled maintenance.

Based on the design parameters suggested, the economic analysis was performed and results show that for such a plant, \$546 million capital would be required for investment. The primary expense would be the equipment costs, taking up approximately 74% of the investment. The total operation and maintenance cost was estimated at \$6.99 million per year. With a given IRR of 10%, the levelized cost of electricity was calculated as \$140.48/MWh during the 25 years of operation. The base tariff was calculated at \$65/MWh.

To keep the CSP plant environmentally friendly, dry cooling offered a better alternative due to reduced consumption of water. Furthermore, in comparison to coal power plants, the proposed CSP plant provides a better alternative as it emits far less carbon dioxide. Additionally, the existence of such a plant in Midelt has a positive socio-economic impact as jobs are created and Morocco becomes less dependent of fossil fuels from other nations.

Nomenclature

Symbol	Description
CO_2-eq	Carbon Dioxide Equivalent
MW_{th}	Megawatts Thermal
MW_e	Megawatts of electricity
MWh	Megawatts Hour

Abbreviations

CSP	Concentrated Solar Power
CAPEX	Capital Expenditure
C_{inv}	Investment Costs
C_{eqn}	Equipment Costs
C_{inst}	Installation Costs
C_{eng}	Engineering Costs
C_{land}	Land Costs
C_{tax}	Taxes
DNI	Direct Normal Irradiance
HTF	High Temperature Fluid
GHG	Greenhouse Gas
IRR	Internal Rate of Return
NPV	Net Present Value
OPEX	Operational Expenditure
O&M	Operation and Maintenance
SM	Solar Multiple
TES	Thermal Energy Storage
Q_{SF}	Thermal Power of Solar Field
PB	Power Block
X	Base PPA Tariff
LCOE	Levelized Cost of Electricity

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1 INTRODUCTION

This section gives the reader an introduction to the country and the techniques used.

1.1 Country Overview

Morocco is a country situated on the north-western coast of Africa. The topography is diverse with a fertile coastline, rich plateaus, lowlands, and semiarid area in the south which merges into the Sahara Desert. In general, great solar resources are applicable to the country as a whole. In 2015, Morocco suffered a big drought which was the start of several conserving activities to cope with the threat of climate change. But since the country is a big energy importer with 97% of its energy imported 2015, solutions for energy independence were sought even earlier [1]. Morocco aims to generate 52% of its electricity from renewable sources by 2030. In recent years, Morocco has invested in solar and wind power and has plans to expand these electricity sources further.

The world’s biggest CSP plants are under construction in the country and with great solar resources, the ability to export electricity to neighbouring countries and Europe is large [2]. The return on such investments for the country and its inhabitants are improved energy security, creating a cleaner environment, and promoting new industries and job opportunities [3].

1.2 Concentrated Solar Power (CSP) Plant

Concentrated solar power (CSP) is a technology that utilizes the sun’s radiation to create electricity. Mirrors concentrate the sunbeams to a receiver that reaches high temperatures. A circulating fluid heats up while passing through the receiver and ultimately a generator is driven through a heat engine. The mirrors cover a large area and the configuration is preferably placed in sun-rich desert landscape. CSP plants are not as common as PVs but the number of plants are growing and there is large potential in the technique [4].

To better meet the electricity demand and to secure electricity production, energy storage in the plant is desirable. This is most commonly done with thermal storage or a steam accumulator.

CSP is available in different configurations, such as parabolic trough, enclosed trough, power tower, Fresnel reflectors, and dish Stirling. All of them have drawbacks and benefits and different commercial availability.

An example of a CSP tower configuration can be seen in Figure 1. Thousands of heliostats (two-axis tracking mirrors) concentrate the sunbeams to a certain area on a central tower. The high temperature fluid (HTF) is pumped across this heated area to transfer energy to the power block [5]. This configuration reaches higher operating temperatures than other configurations and that is part of the reason why the efficiency is better [6].

Another major advantage is that many components to the plant can be produced locally, stimulating the local economy [7].

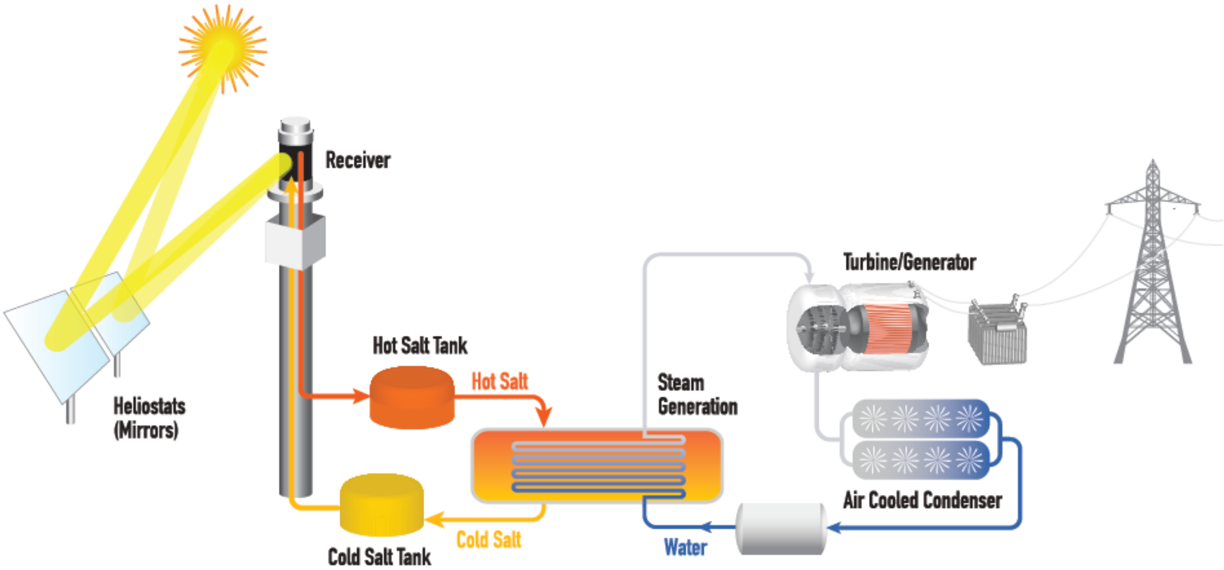

Figure 1. Schematic figure of the tower configuration [8]

In this section power plant configuration, technical performance and economic performance are described. The process from site selection, dimensioning of solar field, storage, and power block, as well as annual performance are disclosed with assumptions made along the way.

2.1 Power Plant Configuration Design

Meteorological data, plant design, and storage calculations constitute the foundation of the plant. The procedure to determine these components are described below.

2.1.1 Location of the Project Site

The Moroccan Agency for Solar Energy (MASEN) has done a comprehensive site investigation for solar plant development in the Midelt area. Since this agency has great knowledge as well as resources for the investigation, this feasibility project will follow their results. Their site investigation resulted in a promising area north of Midelt. The suggested site is shown in Figure 2 where access to water, national roads, and grid connections are taken into account as well as solar irradiation and topography.

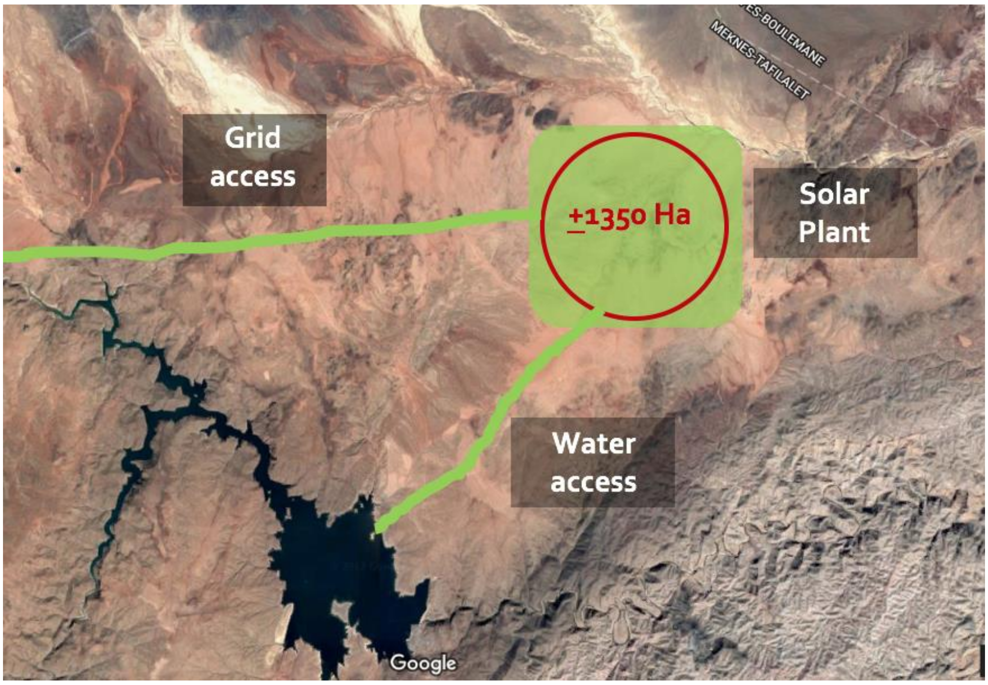

Figure 2. Suggested location for the CSP plant

The site has been selected due to good solar potential, nearby transmission lines, and a reservoir 11 km away with easy accessibility. The land is mostly flat with no residents occupying the area in question. Furthermore, the area is not protected nor used for livestock [9]. In Table 1, the position of the site can be seen.

Table 1. Latitude and longitude for the selected site

Latitude	Longitude
32.8542° (North)	-4.7571° (West)

2.1.2 Meteorological Conditions of the Site

For the meteorological data of Midelt, the initial data used was historical data from SoDa-IS, a website that shows solar radiation data over the years [10]. Upon choosing a location at a latitude of 32.8542°N and a longitude of -4.7571°W, data was extracted for 2005 at an hourly time step.

The limitations encountered with this data collection were that there were errors in methodology where 0 or -99 was the returned irradiance. In this case, an average irradiance was calculated using data provided for irradiance from the hours before and after. The cause of the error in the returned data was stated to be meteorological, i.e. unclear or cloudy sky.

Another error which could possibly impact the results presented is that the irradiance data used was over a period of 1 year. This could be improved if data with many more years was taken into account in the case that 2005 was usual year.

To even out the fluctuations of the irradiance from day to day an "average day" for each month was calculated and the results are shown in Figure 3. The highest irradiance in 2005 was measured in May and the lowest in December. The data provides a good estimation of the monthly variation of irradiance in Midelt.

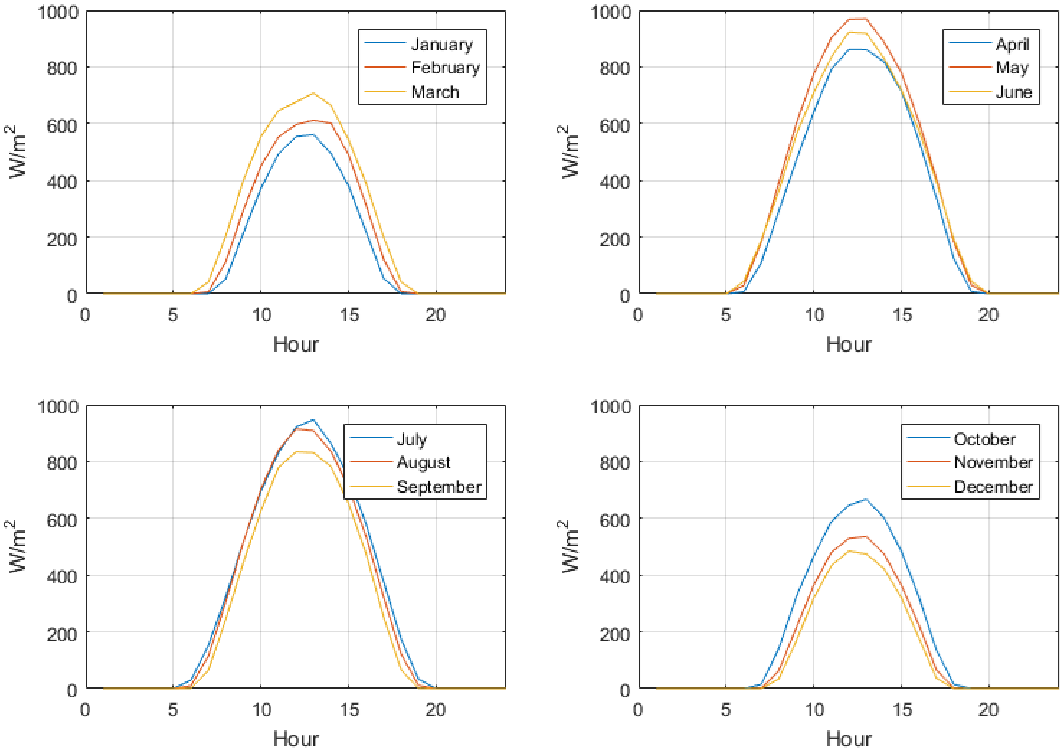

Figure 3. Solar irradiance [W/m^2] in Midelt for an average day every month of the year 2005

2.1.3 Designing of CSP Plant

This part contains the procedure and algorithm used to design to the CSP plant.

The CSP plant for this feasibility study is mainly divided into three major categories, which consist of the power block part, thermal energy storage, and the solar field (including the tower and heliostats). The major components and specs of each category will affect the design of others; thus, it requires a consecutive sequence of designing the proposed CSP plant in order to accomplish the most robust and reliable configuration. Three categories which are designed are (in chronological order):

- Power Block : Turbines, Boiler, Condenser, FWT, Pumps, Auxiliaries
- Solar Field : Tower, Heliostats
- Thermal Energy Storage : 2-Tanks with Molten Salt

With the above mentioned main categories, the method and algorithm to design the proposed CSP plant in Midelt is described in Figure 4.

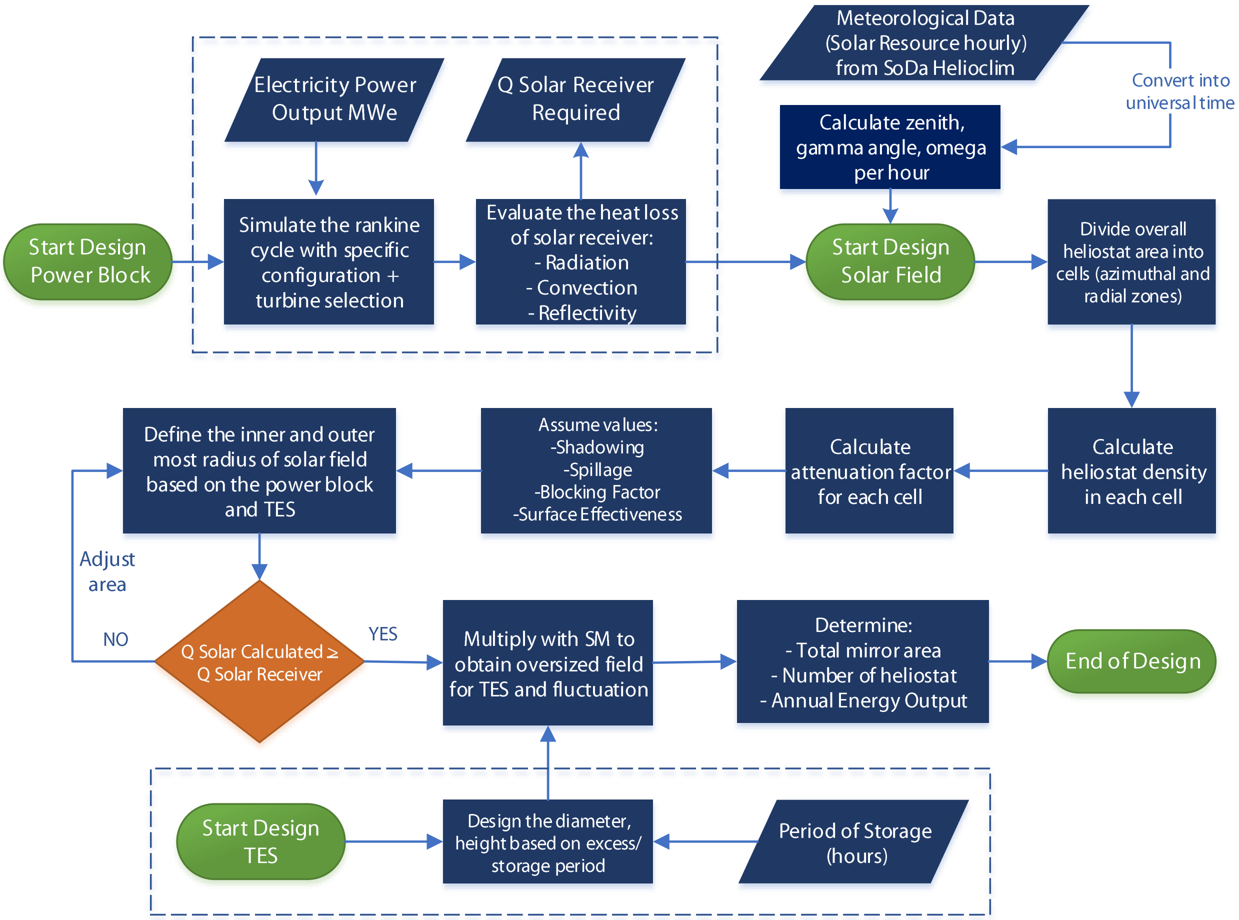

Figure 4. Schematic illustration of the procedure to design the main components of the plant

As shown in Figure 4 above the design process includes several iterative moments. From the Figure 4, it can be seen that the process started with the desirable power output where power block simulations followed. Together with meteorological data and the process explained above, the solar field calculation started. When the area of the solar field and the number of heliostats was determined, incorporating the concept of thermal storage and solar multiple were considered to define the appropriate design for the CSP plant.

2.1.4 Nominal Plant Design

This part contains dimensioning of the solar field, determination of the solar multiple, losses, and the designing of the power block. Only the main equations are shown in this section. For the complete set of equations used please see the Appendix A-D.

- **Electric Power**

The first step in designing the CSP plant involves defining the electricity output that the plant provides to the grid. Based on the project requirement, MASEN has stated that the maximum electricity to be supplied is 300 MW_e with stable electricity output each hour. According to the pricing scenario, the CSP plant in optimum performance must be able to feed 17 hours of operation, with 4 hours of peak demand between 17:00 – 21:00. Thus, in order to maximize the profitability of the plant and further introduce enticing price for the grid, the following electricity power output in Table 2 has been decided for the designed CSP plant.

Table 2. Time and electricity output for of the plant

Clock Time	Electricity Ouput (MWe)	Duration (hours)
00:00 - 05:00	0	5
05:00 - 17:00	100	12
17:00 - 21:00	150	4
21:00 - 22:00	100	1
22:00 - 24:00	0	2

- **Power block**

Since the electrical power output is known, the thermal output from the receiver can be calculated. The power block consists of a high pressure and a low-pressure turbine with temperature and pressure levels corresponding to information given by the manufacturer. There are two preheaters connected to each of the turbines. The high-pressure preheater is fed with steam at 40 bar and the low-pressure preheater is fed with steam at 2 bar. The feed water from the condenser is heated by the two preheaters and the temperature is increasing before it enters the boiler, thereby increasing the efficiency of the steam cycle. However, it should be elaborated that the efficiency of power block gained from this configuration could only achieve a level of 34%, due to the minimum limit of pressure at the air condenser (set at 0.15 bar). If the pressure can be reduced even lower to a near vacuum state, it will indeed raise the efficiency to around 38-40%, yet this has the consequence of not being able to utilize air as the cooling medium. Since the temperature of air in Midelt varies from around 20-30°C, a pressure level of 0.15 bar was set to obtain a 54°C outlet temperature of the condenser which leads to the main condenser pump. In Figure 5, the complete setup of the power block can be seen.

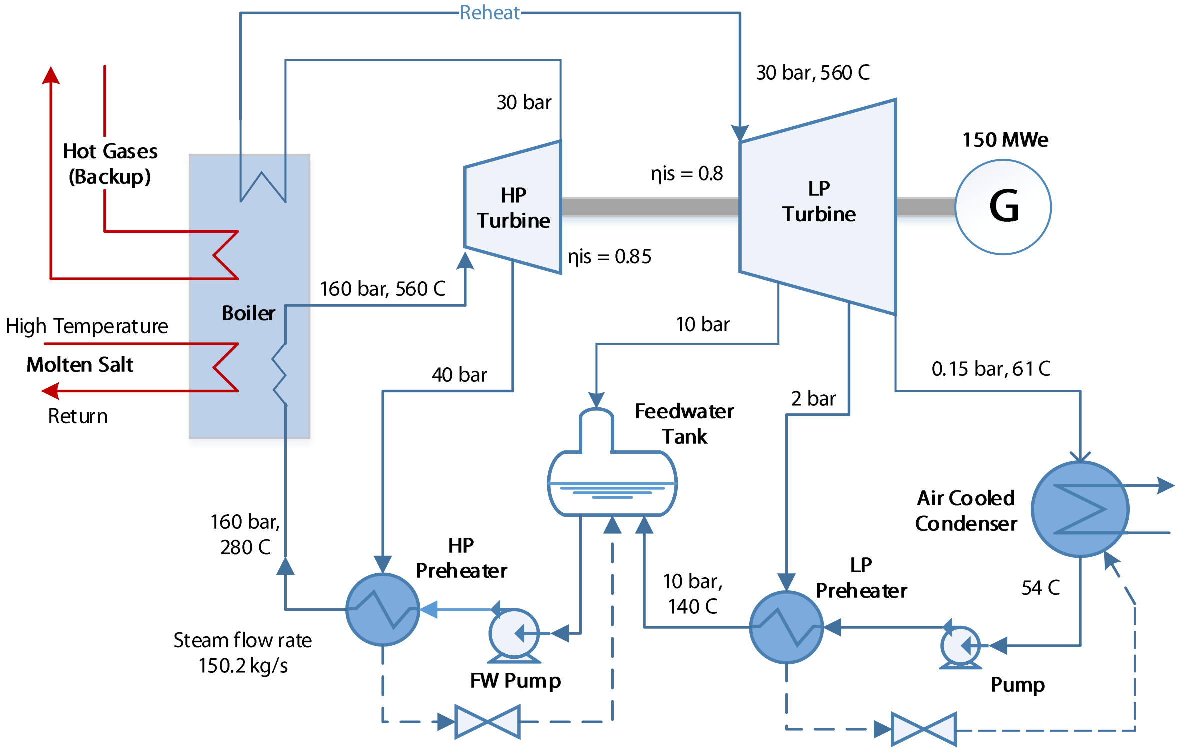

Figure 5. The power block used in the plant

In Table 3, the operating conditions of the power block can be seen. The inlet conditions for the high and low pressure turbine have been provided by the manufacturer. The efficiency of the generator and the shaft has been assumed to have the typical value of 98%. The parasitic losses factor corresponding to pumping water, internal consumption, etc. has been assumed to be 0.05 [11]. The boiler efficiency has been assumed by a similar project [12].

Table 3. Technical data for operating the power block

Power Block Operating Condition	
Turbine Type	SST-700 with Steam Extraction
Inlet HP Turbine (Pressure, Temperature)	160 bar, 560 °C
Efficiency of HP, LP Turbine	85%, 80%
Total Steam Mass Flow (kg/s)	98 - 150
Thermal Efficiency	33.67%
Condenser Type	Air-cooled
Condenser (Pressure, Temperature)	0.15 bar, 53 °C
Boiler Efficiency	90%
Efficiency (Generator, Shaft)	98%, 98%
Parasitic Losses	5%
Electricity Output	
Normal Hours	100 MWe
Peak Hours	150 MWe

- **Heliostat field**

An essential step before starting the design of the solar field is choosing a specific day as a reference for the calculations. For designing purposes, the summer solstice (21st June) was selected. Additionally, for oversizing (solar multiple), choosing the summer solstice is also relevant as it avoids the excess thermal power dissipation (energy dumping) in the summer.

The main equations and procedure of calculating the solar field will be shown in the following part. Primarily, the heliostat field was divided into 144 cells (12 x 12) as shown in Figure 6.

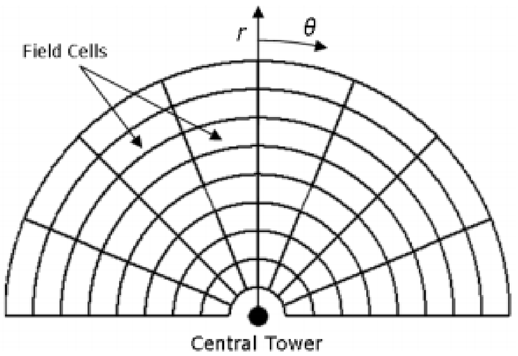

Figure 6. The solar field and the discretization made for the calculations

The position of each cell is described by its radial and azimuthal position, using the tower as a point of reference. The ratio of the mirror area and the land area (called density) of each cell is calculated with the equation below

$$\rho_f = 0.721 \cdot exp \cdot \left(-0.29 \cdot \frac{r_h}{h_T}\right) + 0.03,$$

where r_h is the radial position of the heliostat and h_T is the height of the tower. The power output of each cell was then calculated using

$$\dot{Q}_h = A_h \cdot I_o \cdot \varepsilon_{surf} \cdot \varepsilon_{cos} \cdot (1 - f_{shad}) \cdot (1 - f_{block}) \cdot (1 - f_{att}) \cdot (1 - f_{spill}),$$

where A_h is the heliostat area, I_o is the incident beam radiation, ε is the surface and cosine effectiveness, and the f-values are the losses corresponding to shadowing, blocking, spillage, and attenuation. The different effectiveness and loss factors can be seen in Table 4.

Table 4. Effectiveness and loss factors used in the power output calculation

Technical Data	
ε_{surf}	0.848
ε_{cos}	$\varepsilon_{cos} = \overrightarrow{v_t} * \overrightarrow{n_h}$
f_{shad}	0.05
f_{block}	0.05
f_{att}	$f_{att} = 0.1 d_r / 1000$
f_{spill}	0.05

The attenuation factor is a function of the heliostat's distance from the top of the tower and the cosine effectiveness is a function of sun direction and the normal of the heliostat [13]. The thermal power to the receiver is then calculated by adding all the cells together with

$$\dot{Q}_f = \sum_{cells} \rho_f \cdot \frac{A_{cells}}{A_h} \cdot \dot{Q}_h$$

These are the main equations used to calculate the thermal output of the solar field. For the complete set of equations please go to Appendix C. In Table 5 the result of the calculations is shown.

Table 5. Data for tower, receiver and heliostat field

Tower and Receiver Design	
Tower Height (m)	185
Receiver Height (m)	20
Receiver Diameter (m)	16
Thermal Power Output (MW_{th})	1200 (max)
Efficiency Receiver due to Thermal Losses	85% (explained below)
Outlet, Inlet Temperature	565 °C, 290 °C
Expected # of Operating Years	25
Heliostat and Field Design	
Mirror Area (m^2)	2175000
Total Land Requirement (ha)	1350
Inner Ring Diameter (m)	100
Outer Ring Diameter (m)	2065
Tracking	Dual-Axis Tracking
Azimuthal Zones	12
Radial Zones	12
Total Number of Cells	144
Number of Heliostats	18125
Aperture Area of Heliostat (m^2)	120
Dimension of Heliostat (m^2)	12 x 10
Number of Small Mirrors/Facets	30
Dimension of Small Mirrors (m^2)	2 x 2
Design Reference Date	Summer Solstice (21st June)
Solar Irradiance (W/m^2)	925

It should be mentioned that the efficiency of receiver has been assumed the same for the proposed CSP plant design. Even though the value (85%) is based on the calculation of thermal losses incorporated at the solar receiver (as in the next section), the losses might change over time due to different thermal loads and solar irradiance. The efficiency fluctuations (power block and solar thermal receiver) are discussed thoroughly in the solar multiple section.

- ## Thermal Losses of CSP Plant

At the receiver, three losses will be predominant: reflection, radiation and convection. All of them are described below.

1. *Radiation*

   Since the area of the receiver has a higher temperature during operation than the surroundings it will emit radiation heat. The equation for radiation loss is

$$Q_{loss,rad} = A_{rec}\varepsilon\sigma(T_{rec}^4 - T_{amb}^4)$$

where epsilon was given in the project description. Sigma is Stefan Boltzmann's constant and the receiver temperature is the average value of the inlet and outlet temperature.

2. *Convection*

   As the receiver is exposed to the wind it will lose some of its heat due to convection. The equation used for convection is

$$Q_{loss,conv} = A_{rec}h_{conv\_tot}(T_{rec} - T_{amb})$$

where h_{conv_tot} is a function of the natural convection and the forced convection.

The forced convection is a function of the Reynolds number, the Prandtl number, the Nusselt number, as well as the estimated average wind speed at the location which was provided by the project description.

3. *Reflection*

   The receiver is not a blackbody and will thereby reflect an amount of the incoming radiation. The equation used to estimate the reflectivity is

$$Q_{loss,ref} = (1 - \alpha) * F_r * Q_{inc}$$

where Q_{inc} is the incoming radiation. The α value was given in the project description and F_r is a factor which is estimated by looking into similar projects [14].

The total heat losses from the receiver are a summation of the above described losses

$$Q_{loss\_tot} = Q_{loss,rad} + Q_{loss,conv} + Q_{loss,ref}$$

- ## Solar Multiple (SM) for Proposed CSP Plant

Since there is a high demand of electricity, especially during the evening time after sunset, the concept of a solar multiple becomes essential as it gives a possibility of increasing solar thermal output. The excess of thermal energy that is produced during the day can be used either in the morning time (for starting up) and evening (after sunset). The following equation gives a better relation between SM and thermal output from the solar field.

$$Solar\ Multiple\ (SM) = \frac{Q_{SF}\ nominal}{Q_{SF} min}$$

To obtain a reasonable value of SM, particularly to identify the right amount of excess thermal power generated during the day, the following sensitivity analysis is performed. This provides different performance evaluations based on the impact of SM. Afterwards, the right value of SM is chosen when the excess thermal power from storage could be discharged sufficiently both for morning and evening time. Figure 8 gives an illustration on how the plant operates per different SM values.

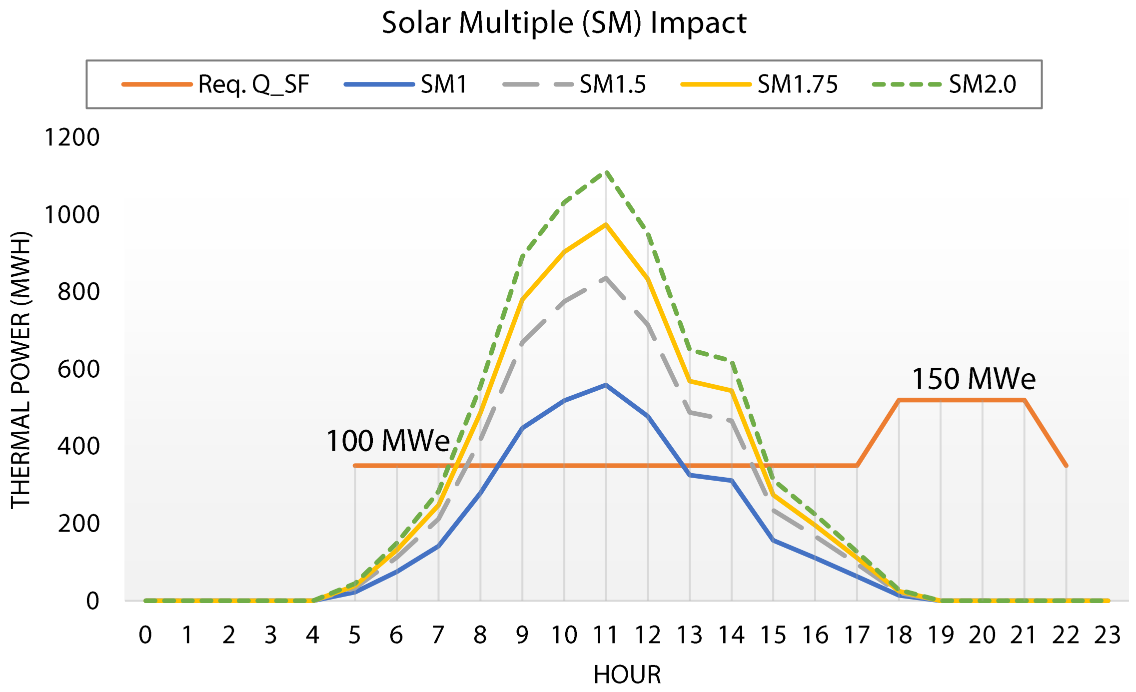

Figure 8. The thermal power for different SM over the hours of the day

It can be clearly seen that the power generated from the solar receiver rises following the increase in SM. It should also be mentioned that the orange stable line represents the required solar thermal power from the plant in order to provide enough power to the power block during the normal operating hours and peak hours. Table 6 demonstrates the impact of SM on the generated solar receiver thermal power that is supplied to power block.

Based on Table 6, solar multiple (SM) of 2 is selected as the value for the proposed CSP plant since it balances the excess power during the day (charging period) and morning/evening time (discharging period) with a little amount of available thermal power.

Table 6. Different solar multiple for different required thermal power

Period	Required Thermal Power (MWh)	Generated Power from Receiver (MWh)			
		SM1	SM1.5	SM1.75	SM2
00:00 - 05:00	0.0	0.0	0.0	0.0	0.0
05:00 - 17:00	4 550,0	3 488,2	5221.2	6 088,8	6956.4
17:00 - 21:00	2 080,0	13.9	20.9	24.5	28.1
21:00 - 22:00	350,0	0.0	0.0	0.0	0.0
22:00 - 05:00	0.0	0.0	0.0	0.0	0.0
Total Energy	6 980,0	3 502,0	5 242,1	6 113,3	6 984,5
Surplus/ Deficit		-3478.0	-1737.9	-866.7	4.5

For this proposed CSP plant design, fluctuation in efficiencies (solar thermal receiver and power block) have been omitted. It has been assumed that both maintain the same performance regardless of its load. When these changes and impact of load are considered in the design, the direct implication would be oversizing the plant which is translated as higher SM (> 2).

- ## Thermal Storage calculations and considerations

As stated, the plant consists of 2 molten salt storage tanks. The cold tank is installed between the outlet of the power block and the inlet to the receiver. The hot tank is installed between the outlet of the receiver and the inlet to the power block. The maximum storage temperature is estimated at 560°C based on the estimated temperature of the solar receiver of 580°C. There is a need to keep molten salts from solidifying and as such the temperature of the molten salts is monitored using electric thermal resistors and maintained using immersed electric heaters in the storage tank. The cold tank is controlled above 260°C to maintain the molten salts above the melting temperature (237°C). [15]

In estimating the dimensions of the storage tanks 2 methods were compared:

1. Method 1

Base dimensions on the given reference material for a molten salt tower CSP plant. In this case scaling up from 4 hours of storage to 8 hours of storage per day both the cold and hot tanks are calculated at diameter of 60.14 m and height of 21.06 m.

2. Method 2

First, it was required to find how much molten salt is needed to heat the steam from which the power is being extracted. To produce 150 MW_e, the thermal power needed was calculated to be 445.5 MW_{th}. This result took into consideration the LP and HP efficiencies of 80% and 85% respectively, a mechanical efficiency of 98%, a generator efficiency of 98%, a boiler efficiency of 90%, and losses of 4%. With the thermal power required, the mass of the molten salt was calculated based on the number of storage hours needed. Considerations for storage hours are shown below. The mass of molten salts required was calculated at approximately 40,000 tons to provide 3870 MWh thermal capacity in order to deliver 150MW_e. These molten salts would be stored a tank 30 m in height and 30 m and diameter with a volume of 21,206 m^3.

Based on the tariffs provided, between 05:00 and 17:00 and between 21:00 and 22:00, supplying to the grid would only yield the plant base price. It would be most profitable to supply the grid between 17:00 and 21:00 since there is a higher tariff. Even on the chosen design day June 21, the CSP plant does not produce power throughout all the 17 hours of required production. There is a need to extract energy from storage when the solar radiation is not enough (before sunrise and after sunset) to capitalize on the CSP tariffs. Between 5:00 and 7:00, and between 15:00 and 22:00, solar radiation is not sufficient, and energy to the grid must be supplied from storage. This is a total of 9 hours, additionally; 1 hour of energy is extracted from storage to account for a daily hot start-up. A total of 10 hours of storage is needed to provide thermal energy in order to supply electricity at the profitable times.

2.1.5 Operating Strategies

The key transients in the projected CSP plant are the transients associated with solar irradiation especially in accounting for storage, as well as transients associated with startups and shut downs.

The transients related to solar irradiation are typically more difficult to design around since they are weather dependent. As is noted in the impact of transient section, different days and different seasons in the year will have different solar irradiation. This results in variations in power output and in some seasons producing more than we can sell and other seasons producing less than is demanded. Also on a typical day cloud cover could cause variations in production. This type of transient leaves uncertainties. The storage was designed to provide a substitute.

In the case of CSP plants the most intricate transients are associated with fast startups. How quickly and safely the plant can start up is important because it affects how quickly energy can be delivered. The transients associated with startup and shut down were much easier to consider in design since they are scheduled

The start-up would include feeding the power block with molten salts from the hot salt storage tank. The energy for daily start-up was accounted for in storage calculations. The turbine would cycle throughout the period when the plant is shut down that is between 22:00hrs and 05:00hrs.

For the projected plant design the shutdown times are very short for the turbine to fully cool down. In this case, this works to our advantage as lower heat losses are anticipated in the system and as such the startups are assumed hot.

2.1.6 Impacts of Transients

Transient operations can be subdivided in scheduled transients or forced transients. The scheduled transients are what could be considered intentional whereas the forced are not foreseen or could be emergencies.

In the proposed design the scheduled transients include the start-ups, load variations and shut-downs. The start-up and shut-downs are operational based on demand and economics. These impact the storage in which the energy for start-ups is accounted for.

Throughout the year the variation in irradiation impacts the thermal energy production. In Midelt, it was identified that in the Winter Solstice there is approximately 3-4 hours of thermal energy production whereas during the Spring Equinox, Summer Solstice and Fall Equinox approximately 8 hours of thermal energy production could be obtained, see summation in Table 7.

Table 7. Impacts on transients during different seasons

Season	Type of Start-up	Number of Thermal Energy Hours
Winter Solstice	Cold Start	3 hrs
Spring Equinox	Warm Start	8 hrs
Summer Solstice	Hot Start	8 hrs
Fall Equinox	Warm Start	8 hrs

- **Number of starts /year and turbine Impact to lifetime**

For the projected CSP plant the SST-700 turbine was considered. The Maximum output for SST-700 is approximately 175MW which covers the range of output needed for the proposed plant. The turbine is projected to start daily and the operational days per year are 330days. This implies that the number of turbine starts per year is estimated to be 330. Due to the transients as shown in the figure above, these starts could be cold, warm or hot depending on the season. The SST-700 (chosen turbine type) has optional start times at the expense of the turbine lifetime shown in a summarized table below.

Table 8. Lifetime of the turbine as effect on starting time and temperature

	Option A			Option B		
Turbine lifetime	3 000 Cycles to failure			30 000 cycles to failure		
Start type	Hot	Warm	Cold	Hot	Warm	Cold
Start time (Minutes)	7	13	30	14	25	57

Based on the demand and location of the CSP plant proposed which affect operational hours, there was no need for faster startups since the plant would not be in production every night. This nightly plant down-times provided for sufficient time to start the turbine daily without jeopardizing the turbine lifetime to the multiple of 10 and as such option B (from table above) was chosen. Since the SST -700 at these start times has 30000 cycles to failure, the proposed plant turbines would have approximately 90 years' lifetime.

2.1.7 Plant Operation Strategy

Since the proposed power plant is required to run for 17 hours daily from 5 a.m. to 22 p.m. with peak hours between 17 p.m. and 21.00 p.m. Besides that, electricity is sold during peak hours at a price four times higher the normal price.

In order to make use of the revenue generated only during peak hours, it has been decided to ensure the full operation of the plant during peak hours by running the power plant at partial load where the turbine would supply 100 MW between 5 a.m. and 17 p.m. and from 21 p.m. to 22 p.m. Whereas the plant will run at full load to supply 150 MW between 17 p.m. and 21 p.m.

The main difference between solar power and fossil fuel is the fluctuation in solar irradiance that leads to variation in the thermal energy supply to the receiver. The irradiance varies not only by month and season but also from one hour to another daily. The operation of the CSP power plant will be affected by the amount of thermal energy (Q_{SF}) reaching the receiver. Consequently, the operation strategies will vary all over the year.
Therefore, a two-tank thermal storage system use two reservoirs, a hot tank and cold tank, was designed to store excess thermal energy and use it to feed the steam generator during peak hours with no sun.
The system was designed to the chosen reference day, the summer solstice on the 21st of June and with a solar multiple of 2 to reach the objective. However, three other days in the year; winter solstice, spring equinox, and the fall equinox were considered to build an overall idea about the impact of solar field energy variation on the power plant operation throughout the year. Figure 7 shows the hourly variation of the solar field thermal energy and power output on the four different days and hours for each season.

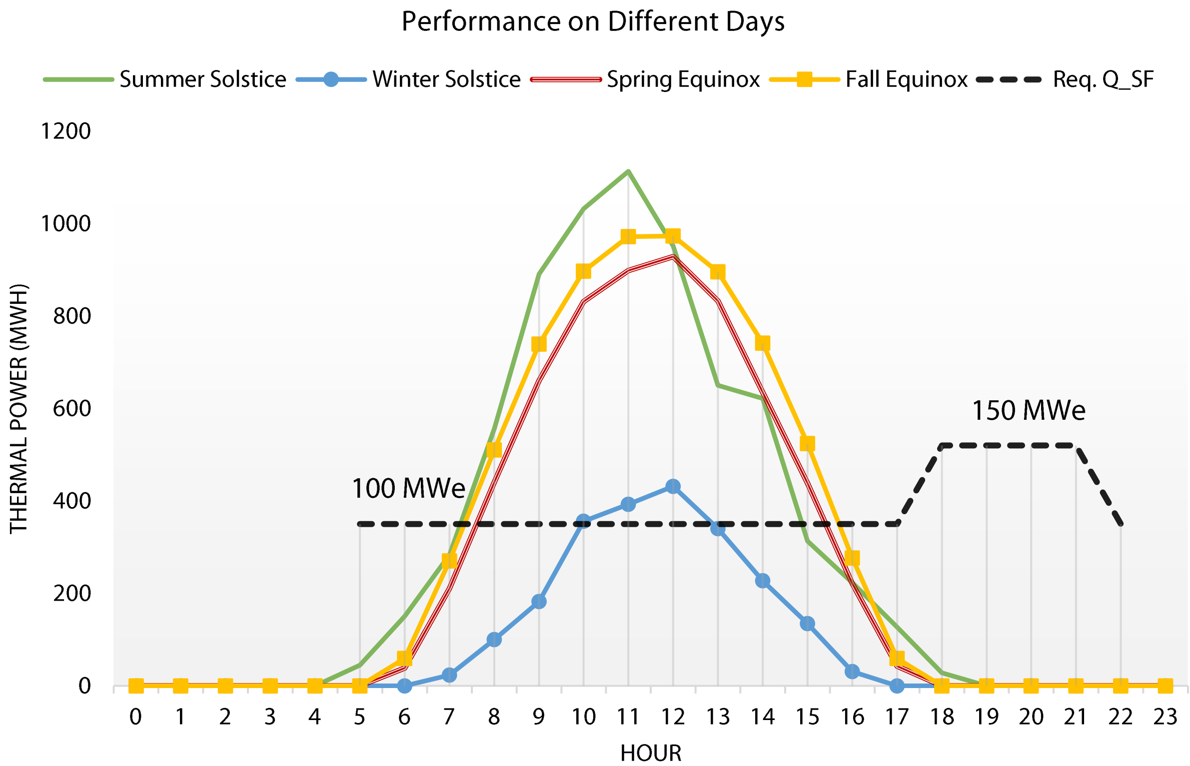

Figure 7. Hourly variation of solar thermal energy, thermal energy storage in MWh. The corresponding power output at design conditions are 100 MWe and 150 MWe

In the context of our research, it was found that the power block requires a thermal energy ($Q_{SF, DP}$) of 520 MWh to run at one-hour full turbine load and 350 MWh to run at partial load during summer. See calculations (Appendix D)

Having known the required thermal energy for one full or partial load hour at the designed point ($Q_{PB,\ DP}$), together with the hourly variation solar field energy (Q_{SF}) and the time at which sun rises and sets each day, the number of hours when the available energy from the solar field will be sufficient to directly feed the power block and produce electricity. During these hours, the solar field produces excess energy more than the energy directly connected to the power block and that's when the excess energy is dispatched to the TES. Then when the Q_{SF} becomes insufficient, the TES will feed the power block and prolong the electricity generation for several hours.

- **Dispatch Conditions**

The total thermal energy available from the solar field (Q_{SF}) can either be partially or completely dispatched to directly feed the PB, to the TES, or from TES to PB. The conditions for dispatch are as follow [16]:

a) Thermal energy dispatched directly to PB (QSF to PB), if QSF ≤ QPB, DP, then
b) QSF = QSF to PB. Else QPB, DP = QSF to PB. Where QPB, DP is the thermal energy required to operate the power block at the design point.
c) Thermal energy to TES (QSF TO TES), if QSF > QPB, DP, then QSF - QPB, DP = QSF TO TES.
d) Thermal energy from TES to PB (QTES to PB), if QSF < QPB, DP due to shadowing and low irradiance days or QSF = 0 during nights. Then QTES to PB = QPB, DP - QSF, for shadowing and QTES to PB = QTES, stored . Where, QTES, stored is the accumulated stored energy in the thermal storage tank.

Calculations were done depending the explained method, dispatch conditions, and solar resource data and result for the four different days are displayed in Table 9 below.

Table 9. Data for the CSP plant operation for 4 different days in the year.

Day of the year	Sun rise to Sun Set	Q_{SF} (MWh)	$Q_{SF\ to\ PB}$ (MWh)	$Q_{SF\ TO\ TES}$ (MWh)	Charging / Direct feeding hours	Normal operation hours	Peak operation hours
Summer Solstice (21st of June) Reference day	13 hours from 5-18	6984.5	2450	3365	6 hours from 8-14	7 hours from 5-8, 14-17 & 21-22	4 hours from 17-21
Winter Solstice (21st of December)	9 hours from 7-16	1180	-	2219.2	-	-	4 hours from 17-21
Fall Equinox (22nd of September)	11 hours from 6-17	6178.28	2800	3452.6	7 hours from 8-15	6 hours from 5-8, 15-17 & 21-22	4 hours from 17-21
Spring Equinox (20th of March)	11 hours from 6-17	6917.24	2800	2865.4	7 hours from 8-15	3 hours from 15-17 & 21-22	4 hours from 17-21

Results from the table shows that,

- During the summer months, the proposed power plant with thermal storage capacity about 3870 MWh will be able to operate for 17 hours by directly feeding QSF to the steam generator for 6 hours and 3356 MWh excess heat will be stored and will be sufficient to cover energy needed for the remaining 11 hours of operation. The plant will provide 150 MW during peak hours and only 100 MW during normal hours as proposed. On days of total available energy from the solar field exceeding 6985 MWh, excess thermal energy will be dumped and the plant cannot make use of it due to limitations in the maximum power that could be received at the tower.
- During spring and autumn months, the available thermal energy from the solar field will be high enough to cover 15-17 hours of operation. So 150 MW of electricity will be provided during the 4 peak hours and 100 MW of electricity will be provided for the rest of the hours. Shortages of thermal energy from the solar field can be provided by supplementary firing.
- During the winter months, the available thermal energy from the solar field will be low, around 1180 MWh due to low irradiance. Then the power block would only operate for a few hours (from 10 a.m. till noon) when directly fed from the Q_{SF} and for only one more hour depending on the TES. Consequently, the plant cannot operate at the proposed strategy.

  Since the revenue is generated during peak hours, so it was suggested to store the total available thermal energy from the solar field during hours between sunrise and sunset then the stored energy, $Q_{TES, stored}$, would be sufficient for the operation of the plant during peak hours. For the remaining 13 hours, supplementary firing should be provided.

2.1.8 Daily Operation on the chosen Reference day

On the summer solstice, the plant is expected to operate on solar energy for 17 hours a day. During Peak Hours (high electricity demand with conditions of low or no solar radiation) an energy storage system consisting of two molten salt tanks will be used to generate steam for the turbines. Figure 8 shows an hourly operation on the 21st of June, the reference day.

During the daily operation, four operation modes can be distinguished: preheating and starting up mode, normal operation mode, operation on cloudy days or night and shutting down mode [17].

1- Preheating and start-up mode

In the initial state or after a long stop of the proposed CSP plant, main equipment, the power block, the heliostats, the receiver and tower, is stopped and they are at the ambient temperature. Salt is emptied from the tower and receiver and collected in the cold salt tank, while salt at the hot salt tank is maintained at 260°C by electric heaters to avoid solidification of the salts.

The start-up mode begins several hours before the normal operation where the entire electrical tracing system is activated. The circulation pump in the cold salt tank is started up and salt is circulated passing through the pipes, pipe accessories and receiver to heat them up till 260°C and then pumped back to the cold storage tank. The receiver bypasses the salt back and there is no connection with the hot storage tank.

To start-up the turbine, salt is pumped from the hot storage to the steam generator to start up the turbine which is decoupled with the generator at this stage. Cold salts are then pumped back to the cold storage tank. This process lasts for a maximum of 57 minutes and this is in the case of cold starts in winter. For the reference day, a hot start will take about 14 minutes. The heliostats are also transferred to the standby position.

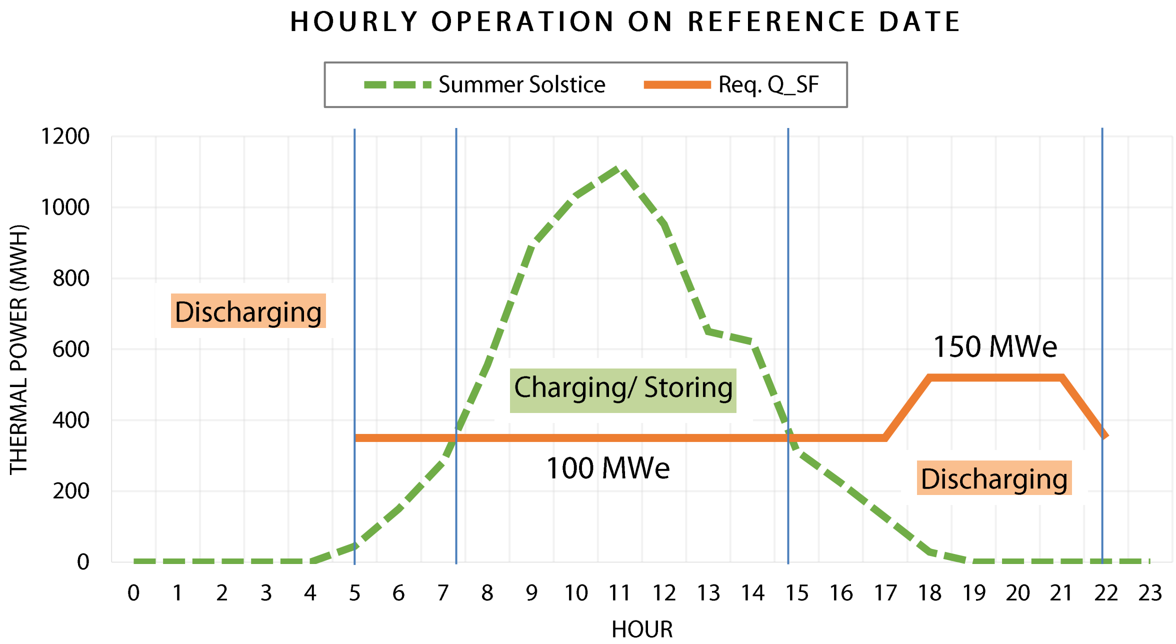

Figure 8. The charging and discharging of the storage throughout the day

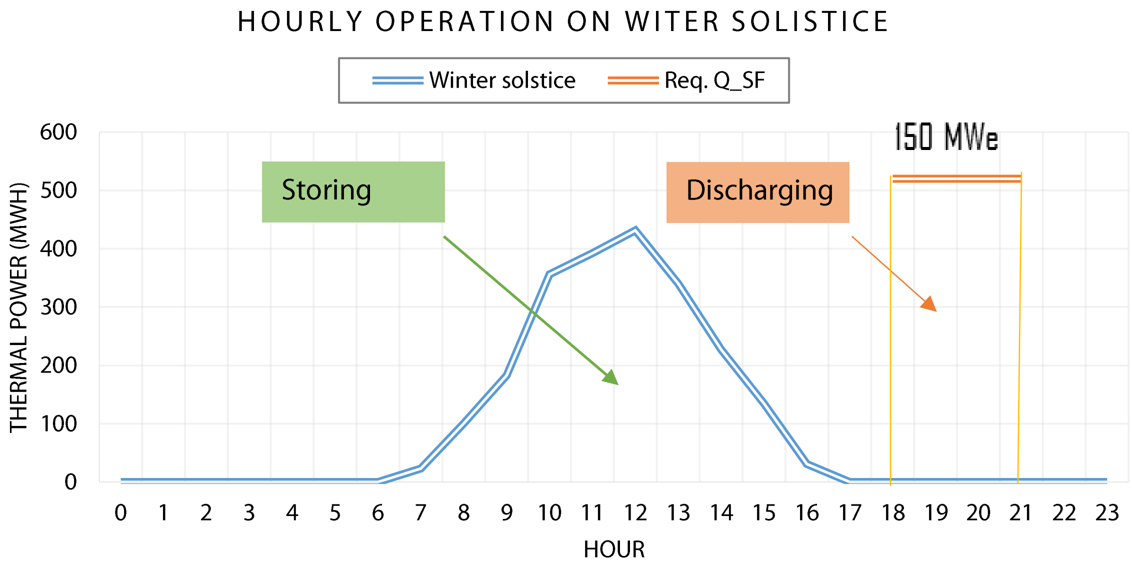

Figure 9. The charging and discharging of the storage throughout the day during winter

To better demonstrate how the plant operates in winter time, Figure 10 shows that the solar thermal power is mostly stored during the day for later usage during peak demand (150 MWe).

2- Normal operation

Once the receiver has reached a sufficient temperature and the whole system is heated up the receiver is bypass is stopped so the receiver will be loaded with salt and the system is ready for normal operation. See Figure 11.

At 5 a.m., the heliostat field focuses on the receiver to transmit the thermal power from the solar irradiance to the salt circulating at the receiver. Salt is heated up till 580°C then pumped to the hot storage tank. Then the circulation pump pumps the required hot salt to the steam generator and while the remaining unrequired salt remain at the storage tank to be used for hours with less radiation. In the steam generator, salt is cooled by means of heat exchanger and cold salt is pumped back to the cold storage tank again and the circulation goes on till sunsets.

3- Operation on cloudy days, hours of low radiation and at after sunset

During unfavorable weather conditions, the heliostats stay pointed at the receiver while the hot storage circulation pumped is controlled so it pumps and compensates the deficient flow that should occur when the solar radiation is at normal conditions. thanks to the capacity of the hot
Same happens a, from 5 to 7 a.m. and from 15 to 18 p.m. when the solar energy is insufficient to keep the receiver system in operation, the hot storage tank maintains the circulation for power production.

From 18 to 22 p.m. when there is no more radiation, salt will be completely emptied from the receiver and stored in the cold tank, the tracing system in the tower will be shut until the next start-up mode.

The heliostats will be unfocused and set to the standby mode while the steam generator will continue to operate, thanks to the capacity of the hot storage tank.

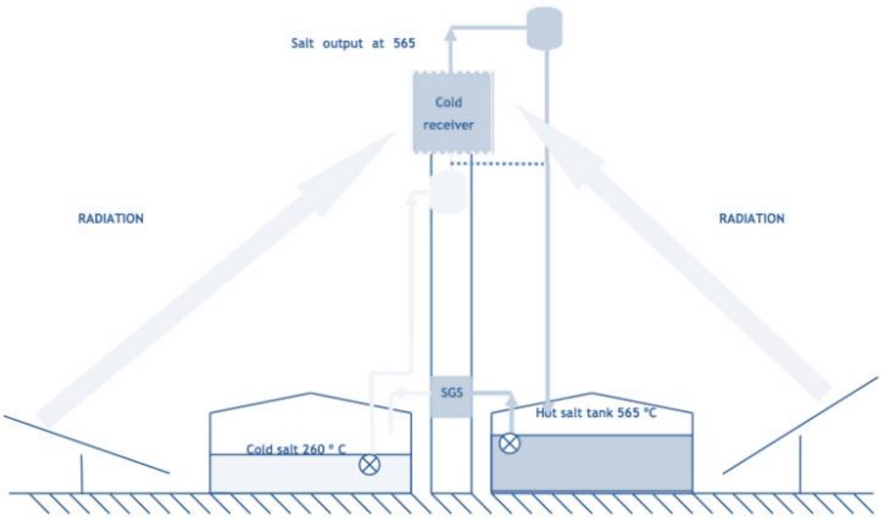

Figure 11. Illustration of Normal Operation

4- Shutting down mode

After 22 p.m., the whole tracing system, circulation pumps and the steam generator will be shut down for an extended time till the next day. Only the electric heaters immersed in the cold storage tanks are on to maintain the temperature at 260°C till the next operation mood that starts a few hours before normal operation around 3 a.m. For the different seasonal operation modes please see Figure 7.

2.2 Power Plant Technical Performance Estimation

In this section, the performance of the plant in operation is shown

2.2.1 Annual Performance

Figure 12 shows the annual performance of the plant with all losses the operation is associated with. Most of the incoming energy from the incident solar energy is lost on the way to the energy output. Most part of the energy is lost due to solar filed losses like reflectivity, spillage etc. A large fraction of the original energy is lost due to the heat losses in the receiver at which the radiation losses are the largest. Since the bower block has an overall efficiency of 33.67% a big amount of the energy is lost in the steam cycle. Some of the energy must be dumped due to the limitations of the capacity in the storage tanks. Comparing the incident solar energy of 3513.2 GWh with the electrical energy of 496.5 GWh one can see that the overall efficiency around 15 %.

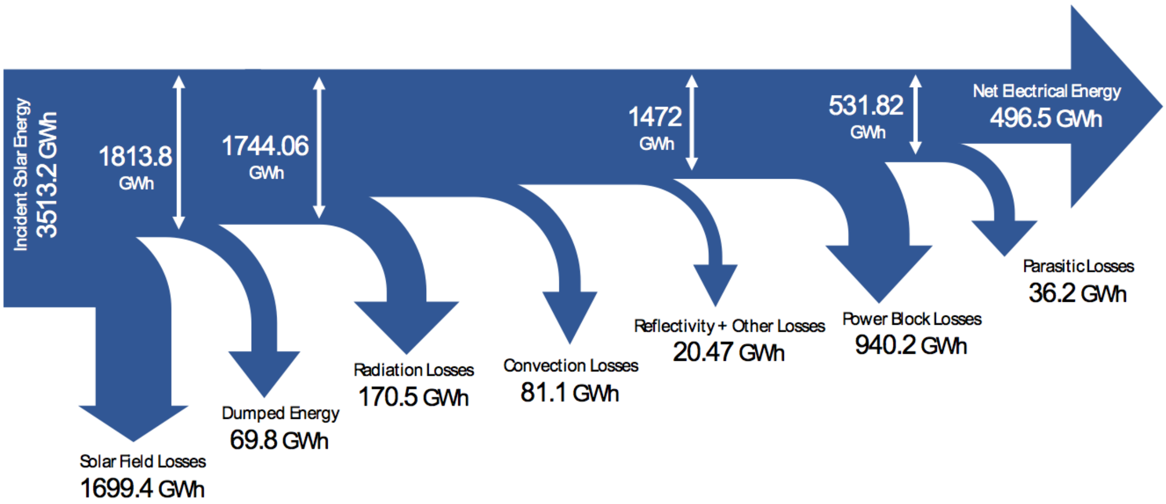

Figure 12. Overall performance in a year in GWh

2.2.2 Capacity factor

In Table 10, the annual performance regarding operating hours and efficiencies are shown. The capacity factor of the plant is 56 %. For annual DNI and thermal power for Midelt see Appendix E.

Table 10. Annual performance of the plant

Annual Performance	
Total Operating Hours	4434
- Operating hours Direct from Receiver	2755
- Operating hours from Storage	1679
Capacity Factor	56%
Receiver to Electricity Efficiency	29%
Incident Solar to Electricity Efficiency	15%

2.3 Power Plant Economic Performance

Specific factors and other variables required for calculating the economic indicators are tabulated in the Appendix F-G. Such values were determined through calculation and others were estimated from the reference values provided in the course material [18]. For example, certain components of the labour costs were scaled with the size of the plant, such as mirror cleaning, while others, such as electrical technicians, were scaled with annual production of the plant. The scaling factor used was one, which means linear extrapolated values. Often the scaling coefficient used is separated from one but this value was chosen as simplification [19]. In general, while the solar field costs scale with size, the power station costs benefit from economies of scale [20].

2.3.1 Capital Expenditure (CAPEX)

The dominant costs of the CSP plant are the investment costs, or the CAPEX. The estimated CAPEX for the proposed plant is $546 million. This indicator is calculated with the following equation:

$$C_{inv} = C_{eqp} + C_{inst} + C_{eng} + C_{cont} + C_{land} + C_{tax}$$

Input values were entered for the final calculation of the CAPEX. The determination of each term is summarized in Table 11 below.

Table 11. CAPEX Terms & Calculation

Cost	Calculation	Currency	Value (Million)
$\boldsymbol{C_{eqp}}$	see appendix	$	401.89
$\boldsymbol{C_{inst}}$	$= C_{epq} \cdot f_{inst}$	$	23.24
$\boldsymbol{C_{eng}}$	$= C_{plant} \cdot f_{eng}$	$	63.55
$\boldsymbol{C_{cont}}$	$= C_{plant} \cdot f_{cont}$	$	14.68
$\boldsymbol{C_{land}}$	$= A_{plant} \cdot c_{land}$	$	2.53
$\boldsymbol{C_{tax}}$	$= tax\ rate \cdot costs$	$	40.47
$\boldsymbol{C_{inv}}$	**Total**	**$**	**546.4**

The components of the CAPEX are also summarized in the Figure 13 below.

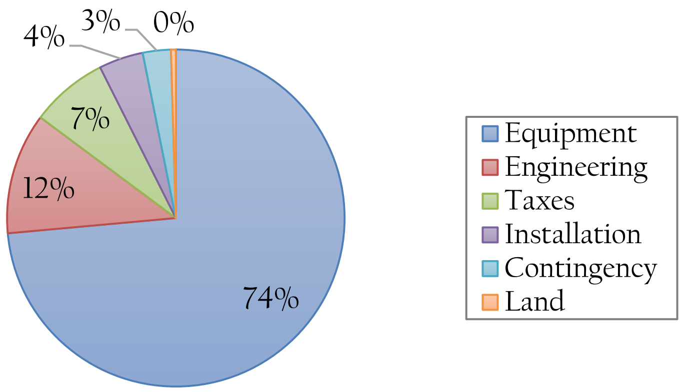

Figure 13. CAPEX Breakdown

2.3.2 Operational Expenditure (OPEX)

Another significant set of costs are the operation and maintenance (O&M) costs, or the OPEX. The estimated OPEX for the proposed plant is $6.99 million. For our purposes, labor and fuel costs are included in the calculation of the OPEX. Consequently, this indicator is calculated in the following manner:

$$C_{OPEX} = C_{O\&M} + C_{fuel} + C_{labor}$$

Input values were entered for the final calculation of the OPEX. The determination of each term is summarized in Table 12.

Table 12. OPEX Terms & Calculation

Cost	Calculation	Currency	Value (Million)
$\boldsymbol{C_{O\&M}}$	$= C_{epq} \cdot f_{O\&M}$	$	5.91
$\boldsymbol{C_{fuel}}$	$= m \cdot c_{fuel}$	$	0.05
$\boldsymbol{C_{labor}}$	scaled from reference	$	1.02
$\boldsymbol{C_{OPEX}}$	**Total**	**$**	**6.99**

The components of the OPEX are also summarized in Figure 14.

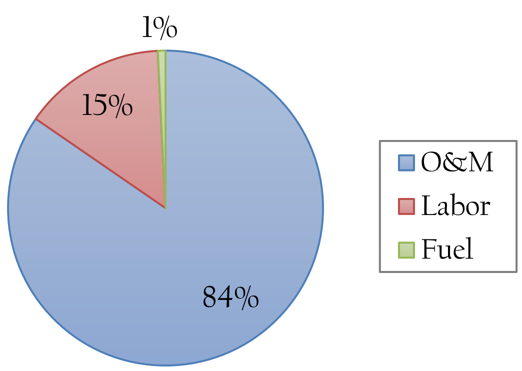

Figure 14. OPEX breakdown

2.3.3 Levelized Cost of Electricity (LCOE)

The levelized cost of electricity, or LCOE, provides a price for electricity that would exactly cover all costs throughout the lifetime of the power plant. The estimated LCOE for the proposed plant is 140.48 \$/MWh. It is calculated as:

$$LCOE = \frac{\alpha \cdot C_{inv} + C_{fuel} + C_{O\&M} + \beta \cdot C_{dec}}{E_{net}}$$

Once again, input values were entered into Excel for the final calculation of the LCOE. It is important to note that all costs are annualized. The determination of each term is summarized in Table 13.

Table 13. LCOE Terms & Calculations

Cost	Calculation	Currency	Value (Million)
$\boldsymbol{C_{inv}}$	calculated previously	\$	546.4
$\boldsymbol{C_{fuel}}$	$= m \cdot c_{fuel}$	\$	0.1
$\boldsymbol{C_{O\&M}}$	$= C_{epq} \cdot f_{O\&M}$	\$	5.9
$\boldsymbol{C_{dec}}$	$= C_{plant} \cdot f_{dec}$	\$	25.5
$\boldsymbol{E_{net}}$	calculated previously		495600 MWh
LCOE			**140.48 \$/MWh**

This indicator provides a starting point for determining the base tariff, but other factors must be taken into account as well. First, real debt interest can be a problem to determine because of the lifetime of a CSP in addition to the fact that a country like Morocco will have more volatility in inflation. Second, additional earnings are not taken into consideration as a result of electricity price variations.

Using LCOE to compare CSP to other renewable energy sources is misleading. It does little to quantify the stability and lifetime of a CSP plant. Other metrics such as capacity factor should be taken into account. For the values for each category see Appendix F.

2.3.4 Base Tariff (X)

A base tariff of 65 \$/MWh is suggested. The tariff during hours of peak demand is 260 \$/MWh due to the peak multiplier factor of 4. This value was obtained by assuming a single-owner financial model and an internal rate of return of 10%. Excel was used to find a base price that set the net present value of all cash flows over the lifetime of the plant equal to zero, as written in the equation below.

$$\mathrm{NPV} = -\sum_{t=0}^{n_{con}-1} \frac{CAPEX}{n_{con} * (1+IRR)^t} + \sum_{t=n_{con}}^{n_{con}+n_{op}-1} \frac{\sum_{h=1}^{8760} E_{net},h - OPEX}{(1+IRR)^t} - \sum_{t=n_{con}+n_{op}}^{n_{con}+n_{op}+n_{dec}-1} \frac{C_{dec}}{n_{dec} * (1+IRR)^t} = 0$$

The suggested base tariff scheme is given in Table 14 below:

Table 14. Hourly Tariff Scheme

Clock Time	CSP Tariff ($/MWh)
00:00 – 05:00	0
05:00 – 17:00	65.00
17:00 – 21:00	4× 65.00 = 260.00
21:00 – 22:00	65.00
22:00 – 24:00	0

2.3.5 Economic Analysis (Cashflow and NPV)

To further evaluate the profitability of the plant, cashflow projection is conducted to analyze the economic indicators in an annual basis. For this study, two main indicators are included which are internal rate of return (IRR) and Net present value (NPV). From the problem statement, it was given that IRR = 10%, thus resulting on electricity price tariff (X) = 65 USD/ MWh. It should be noted that the PPA agreement for this power plant configuration would last for 25 years, which culminating the NPV = 0 at the year 27. Table 15 summarizes the values of important economic parameters used in the study.

Table 15. Summary of important economical parameters

Investment (2 years)	540.4 Million USD
NPV Max. (Year 27)	25.5
PPA Agreement	25 years + 5 years after PPA
Decommissioning Period	1 year after full operation
IRR	10%
Electricity Base Price (USD/ MWh)	65
Price Multiplier during Peak	4x

To better understand the cashflow in every year, starting from year 1 until year 33 (decommissioning of CSP plant), Figure 15 exhibits the trend of CSP plant's cash flow which also can be referred as NPV. A notable period here is in the year 27 (the power plant begins to operate in year 3), the investment (CAPEX) of the plant has been paid back, which is equivalent to breakeven point. It can also be inferred from this result that the chosen PPA agreements is within the range of common CSP plant in the world (15-30 years) [26] [27].

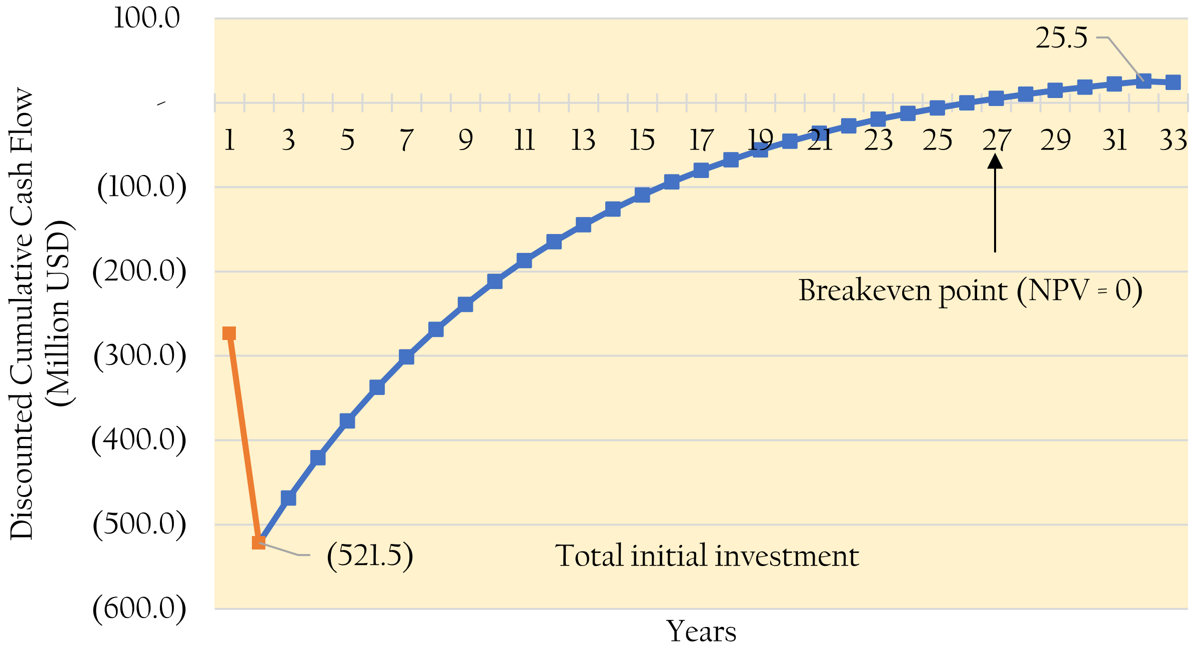

Figure 15. Cash Flow of CSP Project Along the Year

Above cashflow and NPV economic parameters are based on the model of "Single entity Owner" which is similar to the given project case. Still, the current model of CSP plant funding nowadays require additional grant from different sources, for instance banks, stocks, etc. These funding can be represented as Debt percentage (Debt%) which consists of certain percentage from total investement required for constructing the proposed CSP plant.

$$WACC = Eq\%\ x\ IRR_{eq} + Debt\%\ x\ i_{debt}\ x\ (1 - Tax_{corporate})$$

As further evaluation to examine the impact of borrowing the money from the "Bank of Morocco" for this proposed CSP plant design, following Table 16 summarizes parameters/ values used on the new weighted PPA price.

Table 17. Economic Analysis when WACC = 10% for the Proposed CSP Plant

Equity%	60%
Debt%	40%
Corporate Tax in Morocco	30% [27]
i_{debt}	2.25% [27]
IRR_{eq}	15.6%
Weighted Average Cost of Capital - WACC	10% (Set)
Impact on the new PPA price	
IRR (10%) – Single Entity	WACC (10%) – Additional Investment Source
65 USD/ MWh	**94 USD/ MWh**

*Note: * Data was gathered from Morocco Trading Economics 2017*

According to Table 18, if the owner decides to receive financial support from additional source (for this case: Bank), it requires higher PPA price to the grid as the implication since the plant needs to clear the debt payment to the bank in the beginning. This price could even rise higher supposing the percentage of money borrowed from the bank increases from 40% up to certain portion.

2.4 Environmental Performance

The power plant has an impact on the environment where of the different categories are described below.

2.4.1 Water consumption

The power cycle needs to be cooled and there are three different commercial available techniques; water cooling, dry cooling and hybrid cooling. Water cooling is the most frequently occurring technique and further the cheapest one allowing for highest power production. The second technique is dry cooling which is used in the proposed plant. This is due to 90 % water reduction which is desirable in semiarid areas like Midelt but the tradeoff is higher investment cost and 6 % loss in production [21]. Hybrid cooling is another alternative which combines the two techniques also with a performance in-between when it comes to water usage, cost and production.

Neglecting the water use during constructing, since it’s a single event, the steam cycle and mirror washing consume water.

Taking the assumption that the tower configuration consumes the same amount of water as a parabolic trough leads to 0.2 – 0.4 m^3/MWh which results in 100 000 – 200 000 m^3 water yearly [22]. This is in comparison to other power generating technologies low and the nearby water reservoir will cover the demand hith the Hassan ll dam having a storage capacity of 400 million m^3 [23]. Water saving with the proposed cooling technique can be seen in Table 19.

Table 19. Water consumption for wet and dry cooling

Type of Cooling	Annual Water Requirement (thousand m^3/ year)
Wet Cooling	1,090.4
Proposed CSP Plant (Dry Cooling)	123.9
Reduced Consumption Amount	966.5

2.4.2 CO_2 Emission

Although the power plant is operated by a clean source certain emissions is vitiated with the plant looking at the entire lifecycle. Having the cradle to grave perspective includes material extraction, transport, construction, manufacturing, operation, and waste disposal. Comparing LCA done on CSP towers results in an average CO_2-eq of 30 g/kWh. This can be compared to the value of a coal fired plant where 400 – 1000 CO_2-eq / kWh [24]. As seen in Figure 16 hundreds of thousands of tons CO_2 emission can be avoided with the CSP plant compared to coal plant and gas turbine cycles [25] [26].

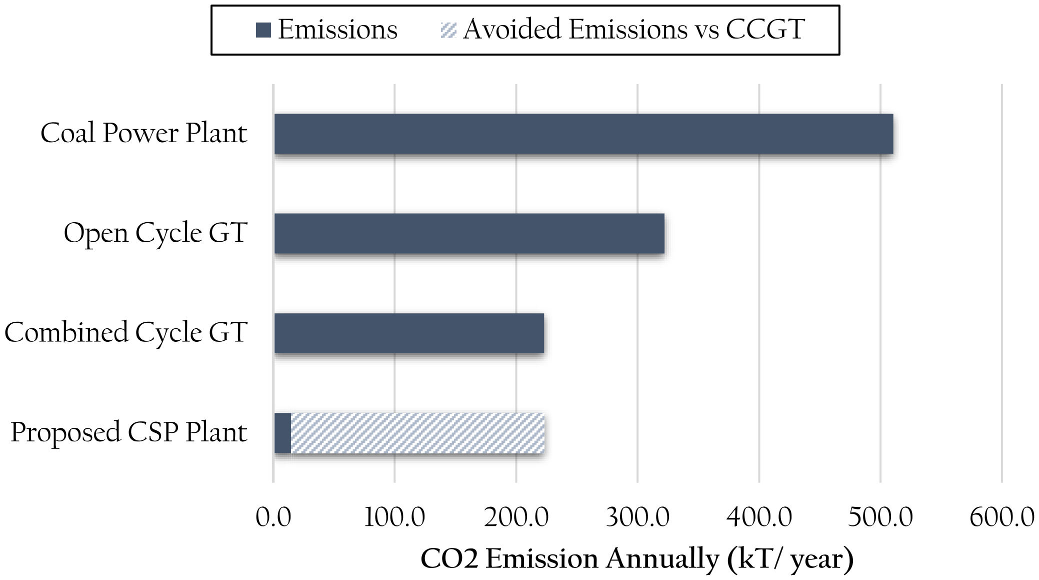

Figure 16. Annually avoided CO_2 emission compared to coal plant and gas turbine

The numbers related to the graph above can be seen in Table 20 below

Table 20. Carbone dioxide emission from different power generating technologies and their yearly emission for generating the same amount of electricity.

Plant Comparison	Annual CO_2 Emission (t CO_2/ year)	CO_2 Avoided (t CO_2/ year)
Proposed CSP Plant	14868.5	-
Combined Cycle GT	223027.9	208159.4
Open Cycle GT	322151.4	307282.9
Coal Power Plant	510486.1	495617.6

2.4.3 Socio – Economic

In general, for Morocco having solar power plants leads to energy security since they can rely on their own production, getting less dependent on international relations. Increasing their share of renewable, fossil independence increase as well contributing to the Moroccan goal of generating 52 % its electricity demand from renewable sources 2030.

The CSP plant contributes to local job opportunities and a cleaner environment for the inhabitants. The tower configuration particularly stimulates the local economy since many of the components can be constructed in the area with locally available material [7].

Effects on flora and fauna are considered. Birds and insects can fly into the tower or top mirrors especially when these are poorly illuminated at night. Insects can also confuse the mirrors with water and get burned. After all, these effects are small compared to the environmental effects of fossil fuel affecting flora and fauna to a large extent [24].

3 CONCLUSIONS AND FUTURE WORK

A discussion of the results and the conclusions that the authors have drawn during the project proposal are presented in this chapter.

3.1 Conclusions

- A thorough feasibility analysis for a CSP plant project in Midelt was conducted and the following are the summarized findings on estimated annual performance, costs, expected base price, environmental and social-economic impact

- The proposed CSP plant would produce between 100-150MWe electricity output with an annual electricity production of 495.6GWh/year. The efficiency of the plant (Solar to electricity output) is 15%.

- The limiting factor for the electricity output was the receivers which are designed for 1200MW thermal hence 150MWe electricity output. The proposed receiver design parameters are tower height -185m, receiver height – 20m, receiver diameter – 16m, which provides thermal power output 1200MW thermal, at a receiver efficiency of 85%. The thermal fluid temperature conditions in and out of the receiver are 290°C and 565°C respectively.

- To obtain the maximum amount of energy from the receiver, 18125 Heliostats were used considering a solar multiple of 2. Dual axis tracking, single mirror heliostats are proposed with an aperture area of 120sqm. The total land requirement to accommodate the plant was estimated at 1350 hectares.

- For electricity generation, a 2-pressure level SST-700 turbine would be used with a reheat thermal efficiency 33.67%. For condenser cooling, dry cooling is proposed using a condenser. Boiler would be used for steam generation and equipment efficiencies and losses considered were boiler efficiency 90%, parasitic losses 5%, mechanical efficiency 98%, isentropic efficiency 85% and 80% for high pressure and low pressure respectively.

- To reduce impact of transients, 2 tank storage system was designed each dimensioned at 30m X 30m, providing 10hrs of thermal fluid storage. The proposed thermal fluid would be 40 000 tons of molten salts providing 3870MWh thermal capacity.

- Due to meteorological conditions of Midelt, the CSP plant would be operating for 4 434hrs over 330 days/ year. Operation wise winter solstice would have the shortest operation hours approximately 3hrs. The plant would operate for17hrs/day in the rest of the seasons. Trade-offs would be dumping the power in the days when it is higher which 1 month (July) and 3 months of low production time during winter solstice.

- While comparing with other technologies, the CSP plant would yield the best environmental impacts, 495 kilotons of CO_2 emission would be avoided compared to coal power plant. Compared to open cycle gas turbine 307 kilotons and 208 Kiloton combined cycle gas turbine. The plant was estimated to consume approximately 124m³ of water per year using dry cooling method.

- Furthermore, this CSP plant would have a social-economic impact on Midelt by improving energy security, creating jobs and reducing fossil fuel independence.

- The estimated CAPEX required for the project was $USD546M with OPEX of $USD7M. The estimated LCOE was $141USD/MWh and the base Tariff X of $65USD/MWh based on an IRR of 10%.

3.2 Future work

For the process to become better a few future recommendations would have to be considered. These include but are not limited to:

- Use of a wider range of data, for this above proposed CSP plant, an analysis on 2005 irradiation data was used. However, in the future with more time and detailed engineering more years of historical irradiation could be taken into account. This would eliminate the possibility of working with data that might have been of an outlier year.
- For expansion purposes, a second tower could be added to this CSP plant and the comparison based on production vs. economic investment and profit could be carried out with regards to one tower vs. having two towers.
- The optimization of heliostat field arrangements could be assessed for the future work, instead of designing as fully circular shape.
- The incorporation of load vs efficiencies impact on the power produced annually to get more accurate output of the plant.
- The possibility of supplementary firing could also be analyzed. A comparison on cost of using energy directly from the plant (parasitic losses) vs. incorporating supplementary firing. This could help improve or streamline the proposed CSP plant.

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Appendix A. Power Block and Heat Losses Calculation Script (EES)

"---Power Block Calculation START---------------------------------
------------Raka----"

"Turbine performance"
eta_is_HP=0.85 "from manufacturer"
eta_is_LP=0.8
eta_mechanical=0.98 "typical value"

eta_generator=0.98
Parasitic_loss=0.06 "Losses due to pumping water, molten salt, and internal consumption, source: http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1225&context=coolingpubs"

"Boiler Part"
Cp_water=4.18 [kJ/kg] "assumed constant"
"mass of steam is presented in parametric table"
T_after_closedpreheater_LP=140 [C]
T_after_closedpreheater_HP=280 [C]
eta_boiler=0.9 "source: https://esc.fsu.edu/documents/DascombJThesis.pdf"

"HP Turbine Part"
"Pressure & Temperature (P_1, T_1) in Parametric Table,
P_1=160, T_1=560 for SST 900 Siemens" "before entering HP Turbine"
"source for HP and LP: http://datasheets.globalspec.com/ps/5244/SiemensEnergySector"

P_2=30 [bar]
P_x=40 [bar] "steam extraction to HP preheater"

"LP Turbine Part"
P_3=30 [bar] "before entering LP Turbine"
T_3=T_1
P_4=0.15 [bar] "To ensure that air cooler condenser can work at this pressure level"

P_y=10 [bar] "2 stream extractions"
P_z=2 [bar]

```
"Condenser Part"
P_condenser=P_4                                "dry cooling with 60 C condensing
temperature"
P_11=P_z

"LP Preheater"
T_7=140 [C]

"Feedwater Tank"
P_8=P_y

"HP Preheater"
T_9= 280 [C]
P_10=P_x

"State Points of Enthalphy"
h_1=enthalpy(Steam,T=T_1,P=P_1)
s_1=entropy(Steam,T=T_1,P=P_1)
s_2_is=s_1
h_2_is=enthalpy(Steam,s=s_2_is,P=P_2)
eta_is_HP=(h_1-h_2_real)/(h_1-h_2_is)          "energy from HP Turbine"

h_x_is=enthalpy(Steam,s=s_2_is,P=P_x)          "bleeding to HP preheater"
eta_is_HP=(h_1-h_x_real)/(h_1-h_x_is)

h_3=enthalpy(Steam,T=T_3,P=P_3)
s_3=entropy(Steam,T=T_3,P=P_3)
s_4_is=s_3
h_4_is=enthalpy(Steam,s=s_4_is,P=P_4)
eta_is_LP=(h_3-h_4_real)/(h_3-h_4_is)          "energy from LP Turbine"

h_y_is=enthalpy(Steam,s=s_4_is,P=P_y)          "bleeding to FW tank"
eta_is_LP=(h_3-h_y_real)/(h_3-h_y_is)

h_z_is=enthalpy(Steam,s=s_4_is,P=P_z)          "bleeding to LP preheater"
eta_is_LP=(h_3-h_z_real)/(h_3-h_z_is)

h_5=enthalpy(Steam,x=0,P=P_condenser)          "condenser, saturated liquid condition"
h_6=h_5                                        "assumed that pump adds negligible
enthalpy"
h_7=Cp_water*T_7
h_8=enthalpy(Steam,x=0,P=P_8)                  "FW Tank fluid goes to HP Preheater"
h_9=Cp_water*T_9
h_10=enthalpy(Steam,x=0,P=P_10)                "1st extraction to FW tank"
h_11=enthalpy(Steam,x=0,P=P_11)                "extraction to condenser"
```

```
"Mass and Energy Balance HP Preheater"
m_steam_total*(h_9-h_8)=m_x*(h_x_real-h_10)     "To find mx steam extraction"

"Mass and Energy Balance Feedwater Tank"
m_steam_total*h_8=m_y*h_y_real+m_x*h_10+(m_steam_total-m_x-m_y)*h_7
    "To find my steam extraction"

"Mass and Energy Balance LP Preheater"
(m_steam_total-m_y-m_x)*(h_7-h_6)=m_z*(h_z_real-h_11)
    "To find mz steam extraction"

"Turbine Power Output"
P_gross_HP=m_steam_total*(h_1-h_x_real)+(m_steam_total-m_x)*(h_x_real-h_2_real)
P_gross_HP_megawatt=P_gross_HP/1000

P_gross_LP=(m_steam_total-m_x)*(h_3-h_y_real)+(m_steam_total-m_x-m_y)*(h_y_real-
h_z_real)+(m_steam_total-m_x-m_y-m_z)*(h_z_real-h_4_real)
P_gross_LP_megawatt=P_gross_LP/1000
P_gross_total_MW=P_gross_HP_megawatt+P_gross_LP_megawatt

"Net Electrical Output Total"
P_net_total_MW=P_gross_total_MW*eta_mechanical*eta_generator*(1-Parasitic_loss)
    "including generator, mechanical, parasitic losses"

"Thermal Power Input to Boiler"
P_thermal=(m_steam_total*(h_1-h_9)+(m_steam_total-m_x)*(h_3-h_2_real))/eta_boiler
P_thermal_input_MW=P_thermal/1000
                                                "Thermal Power from the Molten Salt"

eta_overall_cycle=P_net_total_MW/P_thermal_input_MW
                                                "Overall rankine efficiency"

"-----------------------------------------Power Block Calculation END----------------------------------Raka-------------"


"---------------------Receiver Thermal Loss, Receiver Efficiency Calculation START-----------Raka------------"

"Receiver Data"
I_o=925 [W/m2]                                  "Source: Solar Data Midelt at summer
solstice noon"
epsilon_ave=0.88                                "Source: Project Description"
alfa=0.94                                       "same source as above"
sigma_stefan=5.67*1e-8                          "Stefan Boltzman Constant"
T_HTF_inlet=565 [C]
T_HTF_outlet=290 [C]
T_receiver=(T_HTF_inlet+T_HTF_outlet)/2         "average of temperature"
```

```
"H_receiver=24[m]"                          "Source:
https://www.gerenewableenergy.com/content/dam/gepower-
renewables/global/en_US/documents/csp-
solar/GEA32276%20MSCR_Product_Sheet_VDEF.pdf"
"D_receiver=20[m]"                          "different for varyring power output same
source"

"Heliostat Data"
A_heliostat=115 [m2]                        "source: project description"

"Air Property surrounding Receiver"
T_ambient=21.5[C]                           "Source:
https://www.worldweatheronline.com/midelt-weather-averages/ma.aspx"
V_wind=3 [m/s]                              "Source: Project description"
rho_air=1.2 [kg/m3]                         "Source:
http://www.peacesoftware.de/einigewerte/calc_luft.php5"
miu_dynamic=18.306*1e-6 [Pa.s]
Cp_air=1006 [J/kgK]
k_air=25.797*1e-3 [W/mK]

"Radiation Losses"
A_receiver_envelope=0.25*pi*D_receiver^2*H_receiver
Q_loss_rad=A_receiver_envelope*epsilon_ave*sigma_stefan*((T_receiver+273)^4-
(T_ambient+273)^4)
Q_loss_rad_MW=Q_loss_rad/1e6

"Reflectivity Losses"
FR=0.18                                     "Source: Heliostat Field Layout Design for
Solar Tower Power Plant Based on GPU - Paper Zhejiang University"
Q_loss_reflectivity=(1-alfa)*FR*Q_SF
Q_loss_ref_MW=Q_loss_reflectivity

"Convection Losses"
h_natural=0.81*(T_receiver+T_ambient+273)^0.426
    "free convection"
Re_air=(rho_air*V_wind*D_receiver)/miu_dynamic
    "Reynold numbers"
Pr_air=(Cp_air*miu_dynamic)/k_air           "Prandtl numbers"
Nu_f=0.0287*Re_air^0.8*Pr_air^0.333         "Nusselt"
h_forced=(Nu_f*k_air)/H_receiver            "forced convection"
h_conv_total=(h_forced^3+h_natural^3)^(1/3)  "total convection"

Q_loss_conv=A_receiver_envelope*h_conv_total*(T_receiver-T_ambient)
Q_loss_conv_MW=Q_loss_conv/1e6

"Total Heat Losses"
```

```
Q_losses=Q_loss_rad_MW+Q_loss_conv_MW+Q_loss_ref_MW
Q_SF=P_thermal_input_MW+Q_losses
eta_STE=P_net_total_MW/Q_SF
eta_receiver=(Q_SF-Q_losses)/Q_SF

"---------------------Receiver Thermal Loss, Receiver Efficiency Calculation END-----------Raka-
-----------"


"------------Preliminary Calculation of Solar Field Mirrors START-------------------------------
Raka------------"

"Resource Data of Midelt"
Latitude=(32.7/180)*pi                      "Source: http://www.soda-pro.com/web-
services/radiation/helioclim-3-for-free"
Longitude=(-4.73/180)*pi
I_beam=925 [W/m2]                           "Source: Solar Data summer solstice at
noon"
t_s=12
omega=(pi/12)*(t_s-12)
n=31+28+31+30
delta=arcsin(0.39795*cos(2*pi*(n-173)/365))
N_daylength=(24/pi)*arccos(-tan(Latitude)*tan(delta))
   "Length of Day Calculation"

theta_z=arccos(cos(Latitude)*cos(delta)*cos(omega)+sin(Latitude)*sin(delta))
theta_z_degree=(theta_z/pi)*180
theta_s_degree=90-theta_z_degree            "Solar Elevation Angle"
gamma_s=sign(omega)*abs(arccos((cos(theta_z)*sin(Latitude)-
sin(delta))/(sin(theta_z)*cos(Latitude))))

"Number of Mirrors Required"
eta_field_Helio=0.75                        "Gathered from Lecture Slides"
Q_SF*1e6=I_beam*A_heliostat*N_heliostat*eta_field_Helio "Calculate number of heliostats in
the field"
A_mirror_total=A_heliostat*N_heliostat

"The number of mirrors will be calculated in detail using MATLAB for more robust results"

"------------Preliminary Calculation of Solar Field Mirrors END-------------------------------Raka--
----------"
```

Parametric Table

Sensitivity Analysis | Preliminary Solar Part

1..7	$P_{net,total,MW}$	$D_{receiver}$ [m]	$H_{receiver}$ [m]	P_1 [bar]	T_1 [C]	$m_{steam,total}$ [kg/s]	$P_{thermal,input,MW}$	$\eta_{overall,cycle}$	$Q_{loss,rad,MW}$	$Q_{loss,conv,MW}$	$Q_{loss,ref,MW}$	Q_{SF}	η_{STE}	$\eta_{receiver}$
Run 1	100	15	16	160	560	98.05	297	0.3367	32.91	15.85	3.775	349.5	0.2861	0.8497
Run 2	125	15	18	160	560	122.6	371.2	0.3367	37.02	17.66	4.65	430.6	0.2903	0.8622
Run 3	150	16	20	160	560	147.1	445.5	0.3367	46.8	22.26	5.618	520.2	0.2884	0.8564
Run 4	175	16	22	160	560	171.6	519.7	0.3367	51.48	24.37	6.503	602.1	0.2906	0.8632
Run 5	200	18	22	160	560	196.1	594	0.3367	65.16	30.99	7.535	697.7	0.2867	0.8514
Run 6	250	20	24	160	560	245.1	742.5	0.3367	87.76	41.72	9.52	881.5	0.2836	0.8423
Run 7	300	22	24	160	560	294.1	891	0.3367	106.2	50.73	11.44	1059	0.2832	0.8411

Appendix B. Solar Field Calculation Script (MATLAB)

- Hourly Irradiation

```
clc;
clear all;
close all;
format long g;


[Year] = xlsread('SolarData','Worksheet','E1:E8760');
January = zeros(24,1);
February = zeros(24,1);
March = zeros(24,1);
April = zeros(24,1);
May = zeros(24,1);
June = zeros(24,1);
July = zeros(24,1);
August = zeros(24,1);
September = zeros(24,1);
October = zeros(24,1);
November = zeros(24,1);
December = zeros(24,1);

hour=transpose(1:24);

for k=1:1:24


for i=k:24:744

January(k) = January(k)+ Year(i);

end

for i=744+k:24:1416

February(k) = February(k)+ Year(i);

end
for i=1416+k:24:2160

March(k) = March(k)+ Year(i);

end
for i=2160+k:24:2856
```

```
April(k) = April(k)+ Year(i);
end
for i=2856+k:24:3624
May(k) = May(k)+ Year(i);
end
for i=3624+k:24:4344
June(k) = June(k)+ Year(i);
end
for i=4344+k:24:5088
July(k) = July(k)+ Year(i);
end
for i=5088+k:24:5832
August(k) = August(k)+ Year(i);
end
for i=5832+k:24:6552
September(k) = September(k)+ Year(i);
end
for i=6552+k:24:7296
October(k) = October(k)+ Year(i);
end
for i=7296+k:24:8016
November(k) = November(k)+ Year(i);
end
for i=8016+k:24:8760
December(k) = December(k)+ Year(i);
end
end
January=January./31;
February=February./28;
```

```
March=March./31;
April=April./30;
May=May./31;
June=June./30;
July=July./31;
August=August./31;
September=September./30;
October=October./31;
November=November./30;
December=December./31;

figure; hold on;
x=subplot(2,2,1);
plot(hour,January, hour, February, hour, March);
legend('January','February','March')
axis([0 24 0 1000])
grid on


x2=subplot(2,2,2);
plot(hour, April,hour, May, hour, June);
legend('April','May','June')
axis([0 24 0 1000])
grid on

x3=subplot(2,2,3);
plot(hour,July, hour, August, hour, September);
legend('July','August','September')
axis([0 24 0 1000])
grid on

x4=subplot(2,2,4);
plot(hour, October, hour, November, hour, December);
legend('October','November','December')
axis([0 24 0 1000])
grid on
```

Appendix C. Solar Field Cells (MATLAB)

```
%-------------------------Solar Field Calculation Start ----------raka-------%
clc;
format long;

%% Given Data Based in Midelt Area
%Raka

%data_solar_per_hour Source: Solar Data Online 2005
%theta_z=0.3247; %all angle in radians
%gamma_s=0;      %solar azimuth angle %these 3 variables change with day and time
%I_o=925;        %Irradiance DNI in Midelt Area
I_o=xlsread('Matlab Midelt.xlsx','Sheet1', 'A2:A8761') ;   %Irradiance DNI in midelt Area
theta_z=xlsread('Matlab Midelt.xlsx','Sheet1', 'B2:B8761');
gamma_s=xlsread('Matlab Midelt.xlsx','Sheet1', 'C2:C8761');

N=12;           %Zones Discretization, both for radial and azimuthal

h_tower=165;    %height of tower
h_helio=12;     %height of heliostats
A_helio=115;    %Area of one heliostat, similar to project description data

TES_diameter=30.07;  %diameter of TES
D_receiver=16;       %Receiver diameter
A_total=9.3*1e6 ;    %This v"
A_TES=2*0.25*pi*TES_diameter^2;  %Area for 2 TES tanks
A_Powerblock=A_TES;           %assumed to be the same
A_Tower=0.25*pi*D_receiver^2 ;    %land area for tower in m2
A_inner=(A_TES+A_Powerblock+A_Tower)*3;  %Source from real layout
r_h_inner=sqrt((A_inner/pi)) ;   %radius of inner heliostat
A_solarField=A_total-A_inner;
r_h_outer=sqrt((A_total/pi));   %radius of outermost heliostat

theta_h = linspace(0, 2*pi, N); %azimuthal angle from 0-2pi, with N discrete
R = linspace(r_h_inner,r_h_outer , N);          %radius of cell from tower (m)
Rho_f = zeros(N);                    %density of heliostats in a given cell

cosine_eff = zeros(N);              %cosine effectiveness
Q_h = zeros(12,12,8760);                   %Qthermal of solar for each cell
f_att = zeros (N);                %attenuation loss cell
f_spill = zeros(N);               %spillage loss cell

for k=1:8760 %Calculating annual power from solar receiver

  for i=1:N
  for j=1:N
```

```
        Rho_f(i,j) = 0.721 * exp(-0.29 * R(i)/h_tower) + 0.03;  % Calculation of single heliostat density

        theta_T=atan((h_tower-h_helio)/R(i));      %tower angle
        v_s= [-sin(theta_z(k))*cos(gamma_s(k)); -sin(theta_z(k))*sin(gamma_s(k)); cos(theta_z(k))]; %vector of v_s calculation
        v_t= [sin(theta_h(j))*cos(theta_T); -cos(theta_h(j))*cos(theta_T); sin(theta_T)]; %vector of v_t

        n_h=(v_s+v_t)/abs(norm(v_s+v_t));

        cosine_eff(i,j)=dot(v_t,n_h);     %cosine effectiveness value for single cell
        d_r = sqrt(R(i).^2+(h_tower-h_helio).^2);
        f_att(i,j) = 0.1*(d_r)/1000;          %attenuation loss due to distance from tower
        e_surface=0.93*0.95*0.96;              %average value from the lecture slide
        f_spill=0.05;                       %assumed to be 5% losses of power
        f_shadow=0.05;                       %assumed to be 5% losses of power
        f_block=0.05;                          %assumed to be 5% losses of power

        Q_h(i,j,k) = A_helio*I_o(k)*e_surface*cosine_eff(i, j)*(1-f_shadow)*(1-f_block)*(1-f_att(i,j))*(1- f_spill);
    end
    end
end

%% Accumulating all Qh & Mirror Area in the field

A_cell= zeros(N);   %zero matrix for single cell area

A_total_mirror=0;   %initial value for mirror area, before summing all heliostats

for k=1:8760
    Q_field=0      ;  %initial value
    for i=1:N-1
    for j=1:N
        A_cell = pi*(R(i+1).^2 - R(i).^2) / N;
        Q_field = Q_field + Rho_f(i,j) * (A_cell / A_helio) * Q_h(i,j,k);
        A_total_mirror=A_total_mirror+A_cell*Rho_f(i,j);
        Q_hourly(k) = Q_field*1e-6;
    end
end
end

N_heliostat=A_total_mirror/A_helio;

Q_perhour=transpose(Q_hourly(1:8760));
xlswrite('Matlab Midelt.xlsx',Q_perhour,'Sheet1', 'E2');
```

```
%--------------------------Solar Field Calculation End ----------raka-------%
```

Appendix D. Solar Hourly Thermal Power Calculation

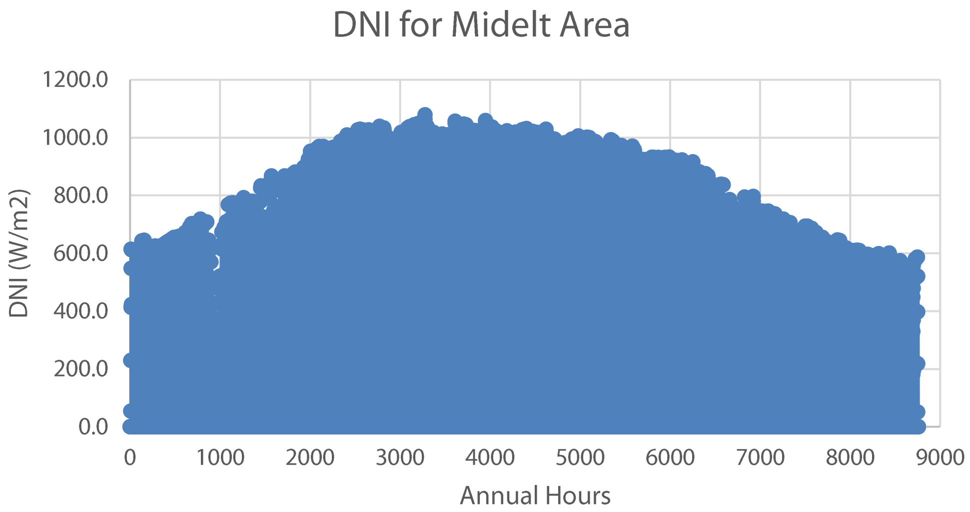
```
%--------------------------Solar Field Calculation Start ----------raka-------%
clc;
format long;

%% Given Data Based in Midelt Area
%Raka

%data_solar_per_hour Source: Solar Data Online 2005
%theta_z=0.3247; %all angle in radians
%gamma_s=0;      %solar azimuth angle %these 3 variables change with day and time
%I_o=925;        %Irradiance DNI in Midelt Area

I_o=xlsread('Matlab Midelt.xlsx','Sheet1', 'A2:A8761') ;  %Irradiance DNI in midelt Area
theta_z=xlsread('Matlab Midelt.xlsx','Sheet1', 'B2:B8761');
gamma_s=xlsread('Matlab Midelt.xlsx','Sheet1', 'C2:C8761');

N=12;          %Zones Discretization, both for radial and azimuthal

h_tower=185;    %height of tower
h_helio=12;     %height of heliostats
A_helio=115;    %Area of one heliostat, similar to project description data

TES_diameter=30.07;  %diameter of TES
D_receiver=16;       %Receiver diameter
A_total=13.4*1e6 ;    %This v"
A_TES=2*0.25*pi*TES_diameter^2;  %Area for 2 TES tanks
A_Powerblock=A_TES;            %assumed to be the same
A_Tower=0.25*pi*D_receiver^2 ;    %land area for tower in m2
A_inner=(A_TES+A_Powerblock+A_Tower)*3;   %Source from real layout
r_h_inner=sqrt((A_inner/pi)) ;   %radius of inner heliostat
A_solarField=A_total-A_inner;
r_h_outer=sqrt((A_total/pi));   %radius of outermost heliostat

theta_h = linspace(0, 2*pi, N); %azimuthal angle from 0-2pi, with N discrete
R = linspace(r_h_inner,r_h_outer , N);          %radius of cell from tower (m)
Rho_f = zeros(N);                   %density of heliostats in a given cell

cosine_eff = zeros(N);              %cosine effectiveness
Q_h = zeros(12,12,8760);                  %Qthermal of solar for each cell
f_att = zeros (N);               %attenuation loss cell
f_spill = zeros(N);              %spillage loss cell

for k=1:8760 %Calculating annual power from solar receiver

    for i=1:N
```

```
        for j=1:N

            Rho_f(i,j) = 0.721 * exp(-0.29 * R(i)/h_tower) + 0.03;  % Calculation of single heliostat density

            theta_T=atan((h_tower-h_helio)/R(i));       %tower angle
            v_s= [-sin(theta_z(k))*cos(gamma_s(k)); -sin(theta_z(k))*sin(gamma_s(k)); cos(theta_z(k))]; %vector of v_s calculation
            v_t= [sin(theta_h(j))*cos(theta_T); -cos(theta_h(j))*cos(theta_T); sin(theta_T)]; %vector of v_t

            n_h=(v_s+v_t)/abs(norm(v_s+v_t));

            cosine_eff(i,j)=dot(v_t,n_h);     %cosine effectiveness value for single cell
            d_r = sqrt(R(i).^2+(h_tower-h_helio).^2);
            f_att(i,j) = 0.1*(d_r)/1000;          %attenuation loss due to distance from tower
            e_surface=0.93*0.95*0.96;             %average value from the lecture slide
            f_spill=0.05;                     %assumed to be 5% losses of power
            f_shadow=0.05;                    %assumed to be 5% losses of power
            f_block=0.05;                     %assumed to be 5% losses of power

            Q_h(i,j,k) = A_helio*I_o(k)*e_surface*cosine_eff(i, j)*(1-f_shadow)*(1-f_block)*(1-f_att(i,j))*(1- f_spill);
        end
        end
    end

    %% Accumulating all Qh & Mirror Area in the field

    A_cell= zeros(N);   %zero matrix for single cell area

    A_total_mirror=0;   %initial value for mirror area, before summing all heliostats

    for k=1:8760
        Q_field=0      ;   %initial value
        for i=1:N-1
        for j=1:N
            A_cell = pi*(R(i+1).^2 - R(i).^2) / N;
            Q_field = Q_field + Rho_f(i,j) * (A_cell / A_helio) * Q_h(i,j,k);
            A_total_mirror=A_total_mirror+A_cell*Rho_f(i,j);
            Q_hourly(k) = Q_field*1e-6;
        end
    end
    end

    %N_heliostat=A_total_mirror/A_helio;

    Q_perhour=transpose(Q_hourly(1:8760));
```

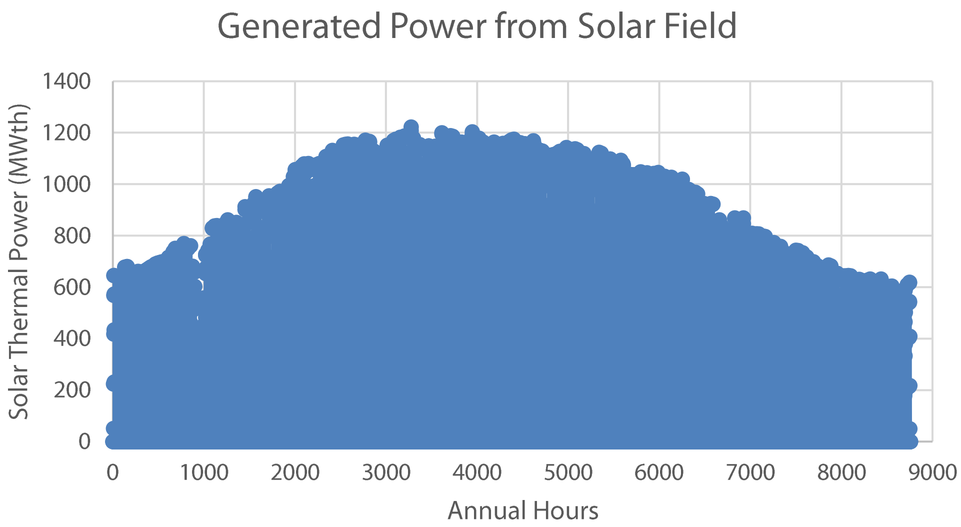
```
xlswrite('Matlab Midelt.xlsx',Q_perhour,'Sheet1', 'E2');

%-------------------------Solar Field Calculation End ----------raka-------%
```

Appendix E. Annual DNI (SoDA) and Thermal Power for Midelt Area

- Solar Irradiance from SoDa Site Helioclim



- Solar Field Thermal Power in a Year



Appendix F. Equipment cost and economical fractions

Description	Variable	Value	Unit
Installation Fraction	f_{inst}	15	%
Engineering Fraction	f_{eng}	6	%
Contingencies Fraction	f_{cont}	12.5	%
O&M Fraction	$f_{O\&M}$	5.5	%
Decommissioning Fraction	f_{dec}	6	%
Annualization Factor	α	11.3	%
Discount Factor	β	7.5	%

Description		Value
Solar Field	$	160126606.61
Power Block Island	$	53330419.54
Balance of Plant	$	15156881.06
Solar Receiver & Steam Generator	$	78112413.84
Thermal Energy Storage	$	39627739.20
Civil Works	$	55532207.46
Equipment Costs	**$**	**401886267.72**

Appendix G. **Cumulative cash flow**

- CSP Plant Cash Flow Table (IRR = 10%)

Note: Number in bracket is negative value

Time	0	1	2	3	4	5	6	7	8	9	10
Year	1	2	3	4	5	6	7	8	9	10	11
Revenue	-	-	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8
Operating Expense	-	-	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)
Investment	(273.2)	(273.2)	-	-	-	-	-	-	-	-	-
Decommissioning Cost	-	-	-	-	-	-	-	-	-	-	-
Cash Flow	(273.2)	(273.2)	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8
Discounted Cash Flow	(273.2)	(248.3)	52.8	48.0	43.6	39.6	36.0	32.8	29.8	27.1	24.6
Cumulative Cash Flow	(273.2)	(521.5)	(468.8)	(420.8)	(377.2)	(337.6)	(301.6)	(268.8)	(239.0)	(211.9)	(187.3)

Time	11	12	13	14	15	16	17	18	19	20	21
Year	12	13	14	15	16	17	18	19	20	21	22
Revenue	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8
Operating Expense	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)
Investment	-	-	-	-	-	-	-	-	-	-	-
Decommissioning Cost	-	-	-	-	-	-	-	-	-	-	-
Cash Flow	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8
Discounted Cash Flow	22.4	20.3	18.5	16.8	15.3	13.9	12.6	11.5	10.4	9.5	8.6
Cumulative Cash Flow	(165.0)	(144.6)	(126.1)	(109.3)	(94.0)	(80.1)	(67.5)	(56.0)	(45.6)	(36.1)	(27.5)

Time	22	23	24	25	26	27	28	29	30	31	32
Year	23	24	25	26	27	28	29	30	31	32	33
Revenue	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	70.8	-
Operating Expense	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(7.0)	(25.5)
Investment	-	-	-	-	-	-	-	-	-	-	-
Decommissioning Cost	-	-	-	-	-	-	-	-	-	-	-
Cash Flow	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	63.8	(25.5)
Discounted Cash Flow	7.8	7.1	6.5	5.9	5.4	4.9	4.4	4.0	3.7	3.3	(1.2)
Cumulative Cash Flow	(19.6)	(12.5)	(6.0)	(0.1)	5.2	10.1	14.5	18.5	22.2	25.5	24.3