

Integrated Master in Environmental Engineering

Concentrating Solar Power Technologies using Molten Salts for Storage and Production of Energy

Master Thesis

Francelim Rodrigues Cardozo

Dissertation submitted for the degree of
Master in Environmental Engineering - Management Field

Jury President: António Manuel Antunes Fiúza

(University Professor of the Mining Engineering Department at the Faculty of Engineering,
University of Porto - FEUP)

Academic Coordinator: Luis Miguel Palma Madeira

(Associate Professor of the Chemical Engineering Department at the Faculty of Engineering,
University of Porto - FEUP)

Company Coordinator: Jose Luis Romeral Martínez

(Director of Energy Area at Fundació CTM Centre Tecnològic - CTM;
Director of MCIA Center at Catalonia Polytechnic University - UPC)

Performed in



Fundació CTM Centre Tecnològic



Universidade do Porto
Faculdade de Engenharia

FEUP

Department of Environmental Engineering

July 2012

Acknowledgements

The first words of this thesis are dedicated for the people who helped me in many ways for making this work. I would like, sincerely, to thanks to:

Prof. Luis Madeira from Portugal who gave me a crucial orientation during my stay in the company even being far away and helped me to get this internship abroad.

Dr. Luis Romeral from *CTM* for the opportunity given in developing my master thesis under a professional experience in his Area of Energy, more specifically, renewable energy and for the support provided during the internship.

Eng^a. Tamara Tolon for all the orientation and help provided during my stay in *CTM* and time spent in meetings regarding my work since the beginning till the end. It was a pleasure to work with such a good professional.

Eng. Jordi Macia for all the Matlab help and all the new features of this software that I've learned thanks to him and also his time spent.

Eng. Aleix Badia for his help in my integration in the city of Manresa and also specifically the help supplied in Matlab coding.

Eng. Marc Castellà for the Simulink help given during the last part of this work, namely developing the model, and also for the mornings and afternoons of work.

Eng. Joan Junyent for the relaxed and funny moments provided during those five months in the company and also for some tips to get information about molten salts properties.

Eng. Mario Heredero for the help provided in the electrical generation system of the thermo solar plant.

Eng^a. Isabel Rojo for the information provided about residual salt mining operations.

All my family and for their support provided during these five months even far away from them. Thank you dad, mom and brother, without you, it would be impossible to have such a good experience like I had and pass through everything like I did.

All my friends, specially Albino, Costa, Joel, Jorge, Nuno, Sophie, Roby and Pedro, who gave me an important support during this experience and never let me down along these years of friendship.

Abstract

The developed work approaches a connection between concentrating solar power (CSP) technologies and an innovative storage system with molten salts. An evaluation of salt mining is done in order to better understand if the residual salt of mines can be used as heat transfer fluid and storage media in CSP, due to the existence of those mines in Catalonia, Spain. It is stated that cooperation between the mining sector and CSP plants doesn't exist and it could be a great idea for re-using these residual salts. A state of the art of CSP technologies is made and the main conclusions of previous works are presented, as also descriptions of energy storage technologies, heat transfer fluids (HTF) used and main design requirements and operation parameters for an optimization of energetic performance.

A model of a CSP plant based on central tower receiver (CTR) technology is implemented on Matlab© using molten salts as heat transfer fluid (HTF) and storage media, where the solar position and radiation are also developed and simulated. Once developed the model implemented in Matlab©, an analysis and control of the simulation results is done. The defined parameters, such as operation temperatures between 290 °C and 565 °C, and the solar thermal power reached by the tower receiver, exhibits a coherent behavior, having peak values between 12h00 and 14h00 along a day and different values between summer and winter seasons; so, the thermal power is higher along the summer and lower along the winter followed by the solar radiation. The effect of raising the mass of molten salt in each tank provokes different performances of the CSP plant, such as a higher autonomy between 2.6 and 3.6 hours depending on year season, winter and summer, respectively. This plant is defined for particular design and key operation requirements but the molten salt can be adaptable to different parameters/conditions of the plant, to different power demand or even the selected CSP technology.

Keywords: Concentrating Solar Power, renewable energy, thermal energy storage, design, analysis and control of CSP operation, molten salts.

Declaration

I declare, under honor commitment, that this work is original and all non-original contributions were properly referred with sources identifications.

Signature: _____

Contents

Contents	i
Abbreviations and symbols list	iv
<i>Abbreviations</i>	iv
<i>Variables and Units used</i>	v
<i>Greek letters</i>	vi
<i>Glossary</i>	viii
Illustrations and Tables list	xi
1. Introduction.....	1
1.1 Background and project presentation	1
1.2 Company Presentation	1
1.3 Work contribution	1
1.4 Organization of the Thesis	2
2. State of the art.....	3
2.1 Energy characterization of the mining sector.....	3
2.1.1 Mining sector in Catalonia, Spain	4
2.2 Characterization of residual salts available in mines	6
2.3 CSP energy production technologies	9
2.3.1 Parabolic Trough Collectors.....	10
2.3.2 Linear Fresnel Reflectors	12
2.3.3 Parabolic Dish Collector (Stirling engine).....	13
2.3.4 Central Tower Receiver	14
2.4 World current status of CSP market.....	16
2.5 Characterization of heat transfer media and storage fluids.....	18
2.5.1 Types and properties of heat transfer media and storage fluids	18
2.5.2 Composition of heat transfer and storage fluids	19
2.5.3 Thermal energy storage (TES) media	22
2.6 Energy storage technologies	23

2.6.1	Active storage systems	24
2.6.2	Passive storage systems	26
2.7	Identification of design requirements, key operation parameters and criteria for optimizing energetic performance	27
2.7.1	Design requirements.....	27
2.7.2	Key operation parameters	29
2.7.3	Criteria.....	30
3.	Technical description	31
3.1	Development of a CSP plant model.....	31
3.1.1	The thermal solar energy generation system	32
3.1.2	The storage and electric generation systems	44
3.2	Simulation Results	54
3.2.1	Effect of mass of molten salt	60
4.	Conclusions	67
4.1	Objectives accomplished	68
4.2	Limitations and future work	68
4.3	Final presentation	69
5.	Bibliography.....	70
6.	Annex I: Energy efficiency solutions	75
7.	Annex II: Matlab code (script) for solar position angles and solar radiation.....	78
7.1	Variables days and hours of a year	78
7.2	Geographic location	79
7.3	Declination of north pole (degrees)	80
7.4	Equation of time	80
7.5	Solar hour angle.....	80
7.6	Solar elevation angle	80
7.7	Solar zenith angle.....	80
7.8	Solar azimuth factor.....	80
7.9	Solar azimuth angle	80

7.10	Surface azimuth angle	80
7.11	Tower receiver parameters (constants)	81
7.12	Receiving angle of reflected rays on tower receiver (degrees).....	81
7.13	Angle between reflected ray and vertical direction (degrees).....	81
7.14	Tilt angle of the aperture plane to the vertical direction (degrees).....	81
7.15	Azimuth angle of each heliostat during a year	82
7.16	Inclination angle of each heliostat during a year	82
7.17	Solar incidence angle.....	82
7.18	Cosine efficiency	83
7.19	Atmospheric attenuation Efficiency.....	83
7.20	Heliostat reflectivity efficiency	83
7.21	Optical efficiency	83
7.22	Extraterrestrial irradiance	83
7.23	Beam irradiation	84
7.24	Total incident beam irradiation on tower receiver for a year	85
8.	Annex III: Plot Digitizer v. 2.5.0	86

Abbreviations and symbols list

Abbreviations

CSP	Concentrating Solar Power
CTM	Fundació CTM Centre Tecnològic
CTR	Central Tower Receiver
DHW	Domestic Hot Water
DNI	Direct Normal Irradiation
HiTec	High Technology
HTF	Heat Transfer Fluid
INETI	Instituto Nacional de Engenharia, Tecnologia e Inovação (National Engineering, Technology and Innovation Institute)
kW, MW, GW	Units of power. The basic unit is watt = 1 Joule flowing per second. kW is the symbol for a thousand watts, MW the symbol for a million watts, and GW the symbol for a billion watts.
kWh, MWh, GWh	Measures of energy corresponding to the measures of power listed above. So, for example, 1 kWh is the amount of energy resulting from the flow of a kW of power for an hour.
LFR	Linear Fresnel Reflector
MENA	Middle East and North Africa countries.
MS	Multiple Factor
Mt	Metric Tons
MW _e	Megawatt Electrical Power
MW _{th}	Megawatt Thermal Power
PCM	Phase Change Materials
PDC	Parabolic Dish Collectors
PSA	Plataforma Solar Almería (Solar Platform of Almeria)
PS10	Planta Solar 10 (Solar Plant 10)
PTC	Parabolic Trough Collectors
R&D	Research and Development
SEGS	Solar Electric Generating System
SOP	Sulfate of potash
SOPM	Sulfate of potash magnesia
STP	Standard Temperature and Pressure
TES	Thermal Energy Storage

Variables and Units used

T	Temperature	°C, K
$\dot{m}$	Mass flow rate	kg/h
C_p	Heat Capacity	kJ/kg.K
M	Mass	kg
Q, P	Power	MW, W
V	Volume	m ³
VHC	Volume specific heat capacity	kWh/m ³
ΔH_f	Enthalpy of formation	kJ/mol
d_{tb}	Distance from each heliostat to the tower base	
d_{sp}	Diameter of the reflected spot of heliostat field	
S_0	Distance from each heliostat to the tower receiver	m
L	diameter of the absorbing aperture	
l	distance between receiver aperture and the absorbing aperture	
G_0	Extraterrestrial radiation	
G_{sc}	Solar constant	W/m ²
B_{ic}	Solar beam irradiation on inclined surface	
B_{0c}	Solar beam irradiation normal to the solar beam	
dr_m	Rayleigh optical thickness at air mass m_{opt}	dimensionless
m_{opt}	Relative optical air mass	dimensionless
N	Number of days during the year 2012 starting at the 1 st January	dimensionless
Tlk	Air mass linke atmospheric turbidity factor	dimensionless

Greek letters

ρ	Density	kg/m^3
λ	Thermal Conductivity	W/m.K
φ_s	Solar azimuth angle	
α_s	Solar altitude angle	
h_s	Solar hour angle	
θ_s	Incidence angle	
θ_z	Solar zenith angle	
Φ_{lat}	Latitude	
Φ_{lon}	Longitude	
δ_s	Solar declination	
λ_s	Angle between reflected rays and vertical direction	Degrees
α_{tr}	Solar altitude angle of the tower receiver relative with each heliostat position on the solar field	
β_{hs}	Slope of each heliostat during a year relative to the tower receiver	
δ_{tr}	Tilt angle of the aperture plane to the vertical direction	
θ_{tr}	Receiving angle of reflected rays on tower receiver	
φ_{surf}	Surface azimuth angle	
φ_{hs}	Solar azimuth angle of each heliostat during a year relative to the tower receiver	
φ_{tr}	Solar azimuth angle of the tower receiver	
η_{cosine}	Cosine efficiency	
η_{at}	Attenuation efficiency	
η_{ref}	Mirror reflectivity efficiency	%
η_{opt}	Optical efficiency	
η_{tr}	Tower receiver efficiency	

Subscripts

incd	incident
+	next iteration
1	flow from hot tank to cold tank
2	flow from the cold tank, passing through tower receiver and ending in hot tank
a	ambient
at	attenuation
c	cold tank
cosine	cosine
dem	demand
e	electrical
f	formation
h	hot tank
hs	heliostat
i	inner or inlet
ini	initial
ms	molten salts
o	outer or outlet
opt	optical
ref	reflectivity
s	solar
sc	solar constant
sp	reflected spot
surf	surface
tb	tower base
th	thermal
tr	tower receiver
turb	turbine

Glossary

Air mass: the ratio of mass of atmosphere through which beam radiation passes to the mass if the sun was at the zenith.

Alkynes: hydrocarbons that have a triple bond between two carbon atoms, with the formula C_nH_{2n-2} .

Angle of incidence: the angle between the beam radiation on a surface and the normal to that surface ($0^\circ \leq \theta \leq 180^\circ$).

Atmospheric attenuation: is related to radiation losses in the distance (d) between a heliostat and the receiver, assuming a visibly distance of about 40 km.

Beam radiation: the solar radiation received from the sun without having been scattered by the atmosphere (is often referred to as direct solar radiation).

Brayton cycle: the thermodynamic cycle converting heat into power using gas turbines.

Chemical reactivity: the rate at which a chemical substance tends to undergo a chemical reaction.

Concentration ratio: describes the amount of sunlight energy concentration achieved by a given collector, reflector, solar tower receiver or parabolic dish (depending on CSP technology). Usually there are two different concentration ratios, optical and geometric.

Cosine Efficiency: related to cosine incidence angle (θ) relative to each heliostat geometric center.

Declination: the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive ($-23.45^\circ \leq \delta \leq 23.45^\circ$).

Direct normal irradiation/ insulation: direct irradiance on an area perpendicular to the sun rays.

Eutectic: in chemistry is a mixture of two substances having a distinct melting point which is lower than the melting points of the separate constituents, so easily melting.

Extraterrestrial irradiation: the incident radiation outside the earth's atmosphere.

Focal distance: or focal length of an optical system is a measure of how strongly the system converges or diverges light.

Heat capacity: amount of heat required to change the temperature of the whole system by one degree.

Hi-Tech Salt: commercial salt constituted of 48 % of calcium nitrate and 45% of potassium nitrate.

Hour angle: the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour ($-180^\circ \leq h \leq 180^\circ$).

Irradiance: the rate at which radiant energy is incident on a surface per unit area of a surface.

Irradiation: the incident energy per unit area on a surface, found by integration of irradiance over an hour or a day.

Latitude: the angular location north or south of the equator, north positive ($-90^\circ \leq \phi \leq 90^\circ$).

Longitude: the angular location, measured east or west from the prime meridian at Greenwich, England, to the meridian passing through a position.

Marine Salt: salt obtained through evaporation of seawater.

Metric tons: metric ton is a unit of measurement based on the metric system, rather than the standard system used in the United States. A metric ton is equivalent to 1000 kilograms.

Multiple Factor (or solar multiple): relation between useful thermal power provided by solar receiver and the thermal power which the cycle power requires in design conditions.

Nominal power: power output under design point conditions.

Optical efficiency: amount of energy that is transferred through an optical system.

Plaster: is a building material used for coating walls and ceilings. There are three types of plaster: gypsum, lime and cement.

Polyalphaolefin: polymer produced from a simple alpha-olefin (family of organic compounds which are olefins or alkenes).

Polydimethylsiloxane: belongs to a group of polymeric organosilicon compounds that are commonly referred to as silicones.

Potash: common name for various mined and manufactured potassium salts.

Rankine cycle: the thermodynamic cycle converting heat into power using steam turbines.

Reflectivity efficiency: related to the mirror reflectivity of each heliostat and how much quantity of incident radiation it reflects.

Rock Salt: or mineral salt is the salt extracted from salt landmines from a rock named halite, consisting of sodium chloride crystals.

Siloxanes: any chemical compound composed of units of the form R_2SiO , where R is a hydrogen atom or a hydrocarbon group.

Slope: the angle between the plane of the surface in question and the horizontal ($0^\circ \leq \beta \leq 180^\circ$).

Solar altitude angle: the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle ($0^\circ \leq \alpha \leq 180^\circ$).

Solar azimuth angle: the angular displacement from south of the projection of beam radiation on a horizontal plane ($0^\circ \leq \varphi \leq 360^\circ$).

Solar constant: the energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the radiation at mean earth-sun distance outside the atmosphere ($G_{sc} = 1367 \text{ W/m}^2$).

Solar time: time based on the apparent angular motion of the sun across the sky, with solar noon the time the sun crosses the meridian of the observer.

Solar to electricity efficiency: fraction of electric energy produced by a solar system to the solar radiation energy collected by the optical aperture of the system.

Specific heat capacity: amount of heat required to change a unit mass of a substance by one degree in temperature.

Spring Salt: or source salt obtained by evaporation processes produced in mountains.

Stirling cycle: is the reversible thermodynamic cycle, driven by an external heat source, used in Stirling engines.

Surface azimuth angle: the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive ($-180^\circ \leq \varphi_s \leq 180^\circ$).

Thermal conductivity: quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient under steady state conditions.

Thermocline: is a thin but distinct layer in a large body of a fluid in which temperature changes more rapidly with depth than it does in layers above or below.

Volume specific heat capacity: measure of the change in internal energy at a particular temperature and constant volume.

Zenith angle: the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface ($0^\circ \leq \theta_z \leq 180^\circ$).

Snell's law: determine the angle at which a beam irradiation bends, according to the initial angle and the index of refraction of the two materials.

Illustrations and Tables list

Illustrations list

Figure 2.1 World mine production of potash during 2010 and 2011. Source: adapted from (U.S. Department of the Interior, 2011).	3
Figure 2.2. Primary reason for mines closure from 1985 till 2005. Source: (Laurence D.C., 2006).	5
Figure 2.3 Components and sub-systems of a CSP plant. Source: (EASAC, 2011)	9
Figure 2.4 Different types of CSP technology. Source: (Gharbi N. et al., 2011).....	10
Figure 2.5 Collectors Field of a thermo solar plant with parabolic trough collectors in California (SEGS). Source: (NextEra Energy, Inc., 2012)	11
Figure 2.6 Linear Fresnel demo reflector erected on the Plataforma Solar de Almería (PSA). Source: (Plataforma Solar de Almería, 2008-2009)	12
Figure 2.7 EuroDISH from back and front view. Source: (PSA, 2012)	13
Figure 2.8 Gemasolar Solar Thermal plant using CTR technology with molten salts storage system. Source: (Torresol Energy Investments, S.A., 2011)	15
Figure 2.9 Direct normal irradiation potential for Southern Europe and Mediterranean regions. Source: (GeoModel Solar s. r. o., 2010).....	16
Figure 2.10 Worldwide distribution of operational, under construction and planned CSP plants. Source: (EASAC, 2011)	17
Figure 2.11 Classification of thermal storage concept systems in CSP plants. Source: (Gil A., Medrano M., et al, 2010)	23
Figure 2.12 Scheme of installation of a center tower receiver power plant, with direct two-tanks based on molten salts. Source: (Gil A., Medrano M., et al, 2010)	24
Figure 2.13 Scheme of installation of a parabolic trough power plant with indirect system, with two-tank storage system using oil (PT-Oil) and molten salts. Source: (Herrmann U., et al, 2002).....	25
Figure 2.14 Scheme of installation of a parabolic trough power plant, with single-tank storage system using oil (PT-Oil) and molten salts. Source: (Herrmann U., et al, 2002)	26
Figure 2.15 Scheme of a parabolic trough power plant, with passive storage concept using concrete or castable ceramics as storage system. Source: (Herrmann U., et al, 2002)	27
Figure 3.1 CSP plant scheme with the main systems for modeling and simulation with Matlab.	31
Figure 3.2 Slope, surface azimuth angle, solar azimuth angle and zenith angle for a tilted heliostat surface (left). Plan view showing solar azimuth angle (right). Source: Duffie J.A. and Beckman W.A, 2006.	32

Figure 3.3 Solar declination angle for the year of 2012 and for the latitude and longitude proposed.	33
Figure 3.4 Plotting the solar altitude angle over the year 2012.....	34
Figure 3.5 Plotting the solar altitude angle over one day of the year 2012 which is the day number 174 (22 nd of June).....	34
Figure 3.6 Slope of each heliostat during the total hours of the year (B_{hs}) and the azimuth angle relative the tower receiver for each heliostat during the year (φ_{hs}). Source: adapted from (Shen C., et al, 2008).....	36
Figure 3.7 Proposed PS10 field layout with the tower receiver on position. Source: (Wei X., et al, 2010).....	36
Figure 3.8 Solar azimuth angle of each heliostat (φ_{tr}) relative to the tower receiver (x_{hs} , y_{hs}).....	37
Figure 3.9 Solar altitude angle of the tower receiver relative to each heliostat position on the solar field.	37
Figure 3.10 Definition of the tower receiver characteristics and θ_{tr} . Source: adapted from (Wei X., et al, 2010).....	39
Figure 3.11 Solar thermal power on the tower receiver (Q_{tr}) in each hour of the year 2012.....	43
Figure 3.12 Thermal power on the tower receiver along one of the hottest days during the year of 2012 (17 th of June).	44
Figure 3.13 Simulink model of the CSP plant with storage system.	46
Figure 3.14 Tower receiver subsystem for outlet temperature modeling.	49
Figure 3.15 Hot tank subsystem designed with Simulink.....	51
Figure 3.16 Electric generation subsystem designed with Simulink.	52
Figure 3.17 Simulink equation model for calculation $P_{turb,o}$ in function of bypass, mass flow and P_{dem} and under control conditions.	52
Figure 3.18 Cold tank subsystem designed with Simulink.	53
Figure 3.19 Cold and hot tank masses and their variation during the 1 st day of January in 2012.....	54
Figure 3.20 Mass simulation of cold tank and hot tank (M_c and M_h) along the 27th of June in 2012. ..	55
Figure 3.21 Temperatures of cold and hot tank along each hour the year of 2012	56
Figure 3.22 Turbine power output ($P_{turb,o}$) and tower receiver solar thermal power (Q_{tr}) along the year of 2012.....	57
Figure 3.23 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during four days in the Summer (27 th , 28 th , 29 th , 30 th of June)	57
Figure 3.24 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the Summer (29 th of June)	58

Figure 3.25 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during four days in the winter (19 th , 20 th , 21 th , 22 th)	59
Figure 3.26 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the winter (22 th of December)	59
Figure 3.27 Turbine power output ($P_{turb,o}$) and tower receiver solar thermal power (Q_{tr}) along the year of 2012.....	60
Figure 3.28 Turbine power output ($P_{turb,o}$) and tower receiver solar power (Q_{tr}) along the first six days of January in 2012.....	61
Figure 3.29 Turbine power output ($P_{turb,o}$) and tower receiver solar power (Q_{tr}) along four days of June in 2012.....	62
Figure 3.30 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the Summer (29 th of June)	62
Figure 3.31 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one part of the 29 th of June .	63
Figure 3.32 Turbine power output ($P_{turb,o}$) and tower receiver solar power (Q_{tr}) along four days of December in 2012.	64
Figure 3.33 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the Winter (22 nd of December)	64
Figure 3.34 Solar power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one part of the 22 nd of December	65
Figure 6.1. Basic scheme of three heat pumps with intermediate heating storage and DHW storage. Source: (Palacio J.S., 2010)	76
Figure 6.2 Basic scheme of heat pump with water from the mine and storage system (cold and hot). Source: (Palacio J.S., 2010)	77

Tables list

<i>Table 2.1</i> Salt production evolution in Spain (units in tons). Source: adapted from (Federación Minerometalúrgica de Comisiones Obreras , 2005)	4
<i>Table 2.2</i> Chloride eutectic salts compositions. Source: Kenisarin M. M., 2010.....	7
<i>Table 2.3</i> Chloride eutectic salts compositions (continuation). Source: Kenisarin M. M., 2010.	7
<i>Table 2.4</i> Hydroxides and nitrates salt compositions. Source: Kenisarin M. M., 2010.....	8
<i>Table 2.5</i> Carbonates and some other salts compositions. Source: Kenisarin M. M., 2010.	8
<i>Table 2.6</i> Description and specifications of CSP technologies. Source: adapted from (Barlev D. et al, 2011)	10
<i>Table 2.7</i> Technical options regarding the use of heat transfer fluids / storage fluids for each CSP technology family. Source: adapted from (EASAC, 2011).....	19
<i>Table 2.8</i> Thermal storage oils and their properties. Source: adapted from (Barlev D. et al, 2011) ..	20
<i>Table 2.9</i> Thermal storage salts and their properties. Source: adapted from (Barlev D. et al, 2011).	21
<i>Table 2.10</i> Thermal Energy options according to the heat storage media and heat transfer fluid (adapted). Source: (Gil A., Medrano M., Martorell I., Lázaro A., Dolado P., Zalba B., Cabeza L., 2010)	22
<i>Table 2.11</i> Typical values of plant capacity factor as a function of the combination of MS-h in thermo solar plants. Source: (García C.X., 2001)	28
<i>Table 2.12</i> Current performance of CSP technologies. Source: adapted from (IEA, 2010)	29
<i>Table 3.1</i> Heliostat and tower receiver parameters. Source: adapted from (Noone C. J., Torrilhon M., Mitsos A., 2012).....	40
<i>Table 3.2</i> The linke turbidity factor under typical atmospheric conditions. Source: (Bason F., 2012)	42
<i>Table 3.3</i> Resuming table with the most relevant variables.	45
<i>Table 3.4</i> Control conditions for each operation state of the CSP plant.	49

1. Introduction

1.1 Background and project presentation

The framework of the project is the connection of a Concentrating Solar Power (CSP) plant to salt mining activities, regarding the existence of these mines in Catalonia, analyzing the use of molten salts as a heat transfer fluid and storage media.

The technical aims of the project are:

- State of the art of the mining sector;
- State of the art of the CSP technologies, the heat transfer fluids (HTF) and the storage system;
- Design of a CSP plant based on Central tower receiver (CTR) technology;
- Development of a model implemented on Matlab®;
- Simulation, analysis and control of the CSP plant operation.

1.2 Company Presentation

Fundació CTM Centre Tecnològic aim is to efficiently contribute for the improvement of competitiveness and for the technological development of companies by providing specialized services and carrying out R+D+IT projects.

CTM's team works for companies, organizations and institutions in the fields of materials technology, environmental technology, innovation support, energy, simulations and innovative design and other processes.

When carrying out projects together with companies, *Fundació CTM Centre Tecnològic* also searches, in a parallel and active manner, for different financing ways for the projects at an autonomic, state, or European level, and orientates customers in the different tax reductions related to R+D/IT projects which can be applied.

1.3 Work contribution

Following a project in course of CTM with a mining company, are accomplished some of the goals of this project which are the implementation of molten salts obtained from mining salt activities of this company as a heat transfer fluid and storage media in a CSP plant.

This work presents an innovative type of thermal energy storage for concentrating solar power (CSP) plants, where the only one and unique commercial plant built worldwide is located in Seville, Spain, regarding this type of storage system.

This innovative thermal energy storage is based on molten salts and became a totally different storage media, independent of fossil fuels (generally oils, the most common used as

thermal energy storage media in CSP plants) and much more environmental friendly, which allows a CSP plant working up to 15 hours per day without its natural source of energy, the sunlight.

1.4 Organization of the Thesis

This thesis is constituted mainly by 4 chapters, such as, Introduction, State of the art, Technical description and Conclusions.

On the Introduction (Chapter 1) are presented, in a general point of view, the main objectives of the developed work and also in which type of institution the work was performed and its contribution.

The Chapter 2, State of the art, describes a global review study in many topics related to this work and is in general divided as follows. On the subchapter of energy characterization of the mining sector are addressed the worldwide potash mining production, the active potash mining, an overview about previous experiences using mining facilities for production of energy and a possible chemical constitution of residual salts which can be recovered from mines. On the subchapter related with CSP energy production technologies, available and more developed technologies are described concerning their main characteristics. Regarding world market current status subchapter, a review about main CSP plants installed for commercial scale in the world, potential regions where it can be more developed and emergent markets are presented. On the subchapter of characterization of heat transfer media and storage fluids, an approach about most used HTF in CSP plants, their main thermo physical properties and different types of thermal energy storage media is described. The next subchapter is energy storage technologies where many type of storage systems are presented according to the type of HTF used and energy storage needing. The last subchapter identifies design requirements, key operation parameters and criteria for optimizing energetic performance based on previous experiences.

On the Technical Description Chapter 3 a design of a CSP plant based on central tower receiver (CTR) technology is made, the development of a simulation model based on Matlab and the analysis and the control of the CSP plant operation. This chapter is divided in three parts which are; the solar energy generation design consisted by modeling the solar position and the solar radiation, the heliostats solar field and the tower receiver system; the heat transfer fluid and storage system consisted by the cold tank and hot tank using molten salts; and the electric generation system consisted by the steam turbine.

In Conclusions (Chapter 4), a general overview is made about all the phases of the developed work where the most important aspects are referred and on the same chapter a proposal about a future work is presented as well some limitations of this work.

2. State of the art

2.1 Energy characterization of the mining sector

The first production of potassium was in former URSS, which is divided today by Belarus and Russia. Together they produced 10 of 28 Mt per year of K_2O that was ascending the world's potassium production (Consejo Superior de Colegios de Ingenieros de Minas de España, 1996) which nowadays is similar to these quantities.

A serious problem of European potassium productions is the dumping that those two countries made, so the necessity of facing it from European Union. The decreasing use of potassium by Russian and Belarus agriculture resulted in an excess of this mineral in Europe.

Nowadays, the first world potassium producer is Canada, followed by Russia and Belarus, with an annual production between 5 and 8 Mt of potash (U.S. Department of Energy, 2007). Canada has an important installed quantity, and thus can respond quickly to world's variations potassium demand. In **Figure 2.1** is listed potash world mine production, during the years of 2010 and 2011.

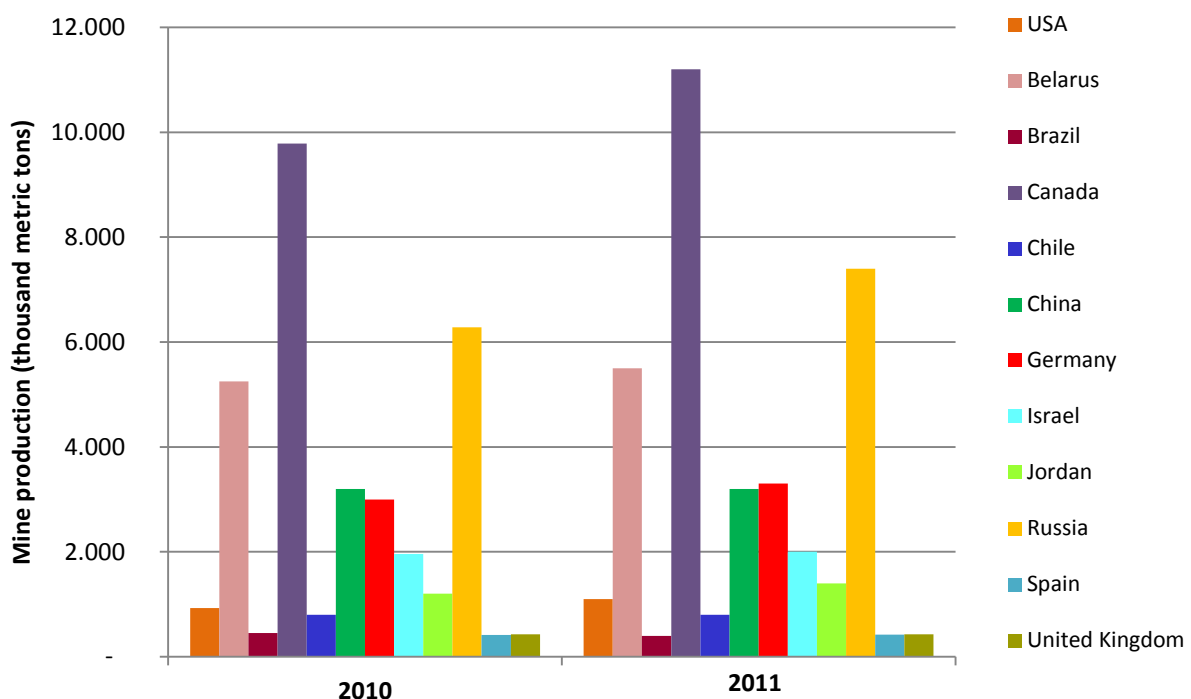


Figure 2.1 World mine production of potash during 2010 and 2011. Source: adapted from (U.S. Department of the Interior, 2011).

Analyzing this chart (**Figure 2.1**) is notably seen that Canada is still leading the world's production of potash which is one of the most consumed manufactured salts by the human population.

Potash is used primarily as an agricultural fertilizer because it's a source for dissolved potassium and has a wide variety of mined and manufactured salts, all containing the element potassium in water-soluble form. Therefore, Potash, can have many different compositions, such as, potassium chloride (KCl), or muriate of potash (MOP), potassium sulfate (K_2SO_4), sulfate of potash (SOP), potassium/magnesium sulfate ($K_2SO_4 + MgSO_4$) as known as sulfate of potash magnesia (SOPM), potassium nitrate (KNO_3) and mixed sodium/potassium nitrate ($NaNO_3 + KNO_3$). The term potash was originally applied to potassium carbonate/potassium hydroxide crystals that were recovered in iron "pots" from leaching wood "ashes" with water (U.S. Department of the Interior, 1997).

Along this study the most important form of Potash will be considered to be potassium chloride, potassium sulphate and potassium nitrate, as they are the most common potassium salts used as heat transfer fluid (HTF) or thermal energy storage (TES) materials for CSP plants.

2.1.1 Mining sector in Catalonia, Spain

The beginning of the mining activity in Catalonia is connected to ancient times. Mining has always been present, on a more or less intense way, and contributes significantly for the development of Spain's society.

The exploitation and production of potassium salts in one of the most important mining activities of Catalonia and Spain, and is presented in **Table 2.1** for the period 1998-2001.

Table 2.1 Salt production evolution in Spain (units in tons). Source: adapted from (Federación Minerometalúrgica de Comisiones Obreras , 2005)

Years	1998	1999	2000	2001
Salt Mining	2 062345	2 109150	2 068760	2 100000
Potash Mining	223885	316188	259704	219800
Total (Rock Salt)	2 286230	2 425338	2 328469	2 319800
Marine Salt	1 321059	1 400152	1 436345	1 420000
Spring Salt	92408	95346	105187	100000
Total (Marine and Spring)	3 699697	3 920836	3 869996	3 839800

Salt production has suffered a negative evolution between 1999 and 2000, and in 2001 a decrease on production is still observed, but not so significant according to the Mining Spanish Statistics (Federación Minerometalúrgica de Comisiones Obreras , 2005).

The potassium Catalanian basin, which extends through Barcelona and Lerida provinces, is among the most important of the world, containing large mineral reserves economically viable and is strategically located near Barcelona's port with direct access to the important French market and other European markets through the Mediterranean Sea. This basin, on the beginning, was exploited through four subterranean mines: Suria; Cardona; Sallent; and Balsareny (all of them located on Barcelona's Province).

The last two have been unified in the 70's to become *Potasas Del Llobregat* mine. Meanwhile Cardona was closed facing the depletion of mineral reserves economically exploitable. So, until 1996 there were only two remaining in activity: *Potasas Del Llobregat* and *Suria* (Consejo Superior de Colegios de Ingenieros de Minas de España, 1996) and nowadays there's just one potash mine in activity in *Suria*, because meanwhile *Potasas Del Llobregat* was closed facing also depletion of resources. During an International Seminar about mine closures, the main reasons for these closures were listed (**Figure 2.2**). The main reason for a mine closure was concluded to be depletion of mineral resource, as expected in mining sector during operation for several years, but also an important factor was observed to be related with high costs and low prices, respectively on the minerals extracted and produced for industrial sale.

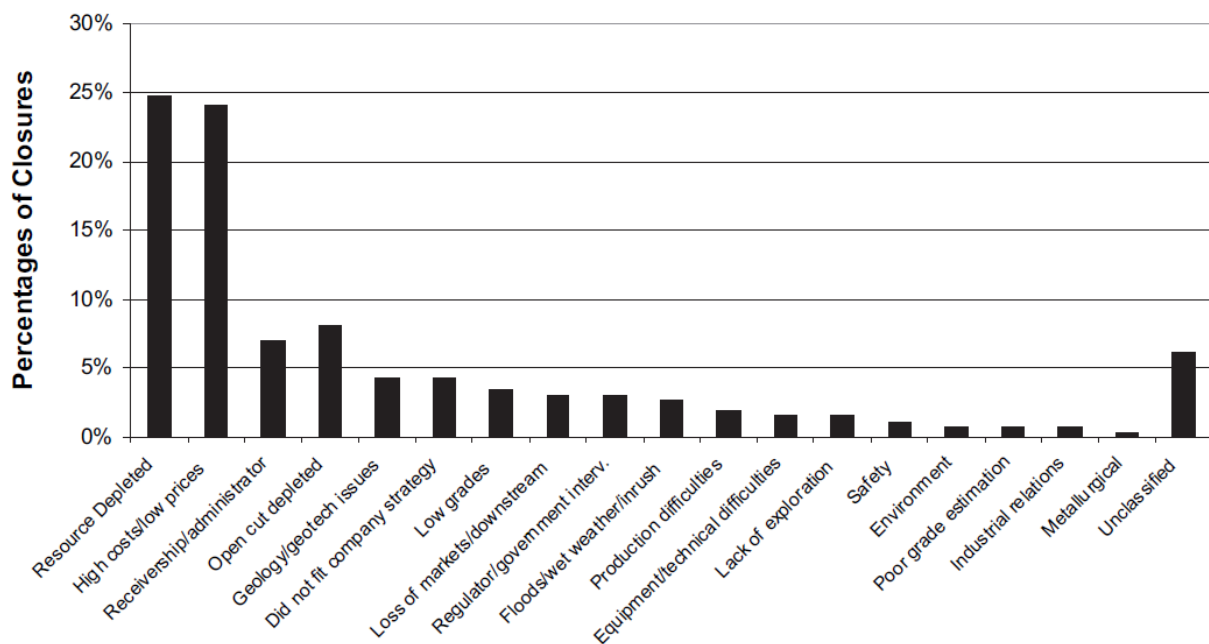


Figure 2.2. Primary reason for mines closure from 1985 till 2005. Source: (Laurence D.C., 2006).

The sodium salts produced in Catalonia are divided in marine salt, sub product exploitation salt from potassium salt mines and rock salt directly coming from mining exploitation (table 2.1). One part of the sodium salt that is obtained as sub product of potassium production is commercialized as industrial salt for the production of Chlorine and Soda in electrolytic processes. The quantity of sub product exceeds the market capacity, so residual salt is deposited in salt tailings next to potassium mines.

Sodium salts, for the abundant existing reserves in Catalonia, are being exploited under an inferior level they actually should be, but not only in this region, sodium salts are very abundant around all Spanish territory (Consejo Superior de Colegios de Ingenieros de Minas de España, 1996).

Indeed, Catalanian mining of sodium and potassium resources is not making enough efforts for salt revalorization, which is mostly intended to industrial uses for chlorine and soda production by electrolysis, as above-mentioned, when there's a real possibility of producing salt for human consumption or for implementation to CSP plants.

The use of residual salts of mines as a heat transfer fluid and/or storage system has never been tested before and needs experience from the mining sector to prove its potential use on concentrating solar power plants as TES medium.

2.2 Characterization of residual salts available in mines

Salts can be classified in many different types with various chemical compositions, melting and freezing points and thermo-physical properties. The most common anions presented are chloride, fluoride, sulphate, nitrate and carbonate. Combining those salt based compositions with their characteristic minerals containing sodium, potassium, magnesium and calcium, the most usual and extracted salts from salt mining industries are obtained. Salts have indeed a variety of compositions, but the most frequent on salt mining industries are: *chloride*-based salts, such as sodium chloride (NaCl), potassium chloride (KCl), magnesium chloride (MgCl_2) and calcium chloride (CaCl_2); *sulphate* based salts, including sodium sulphate (Na_2SO_4) and calcium sulphate (CaSO_4); and *carbonate* based salts as calcium carbonate (CaCO_3).

From the point of view of residual salt availability of one mine in Catalonia, the higher quantities observed are CaSO_4 , NaCl , KCl and MgCl_2 , so these are potential residual salts to be used as HTF and TES, according to real data from residual salts in one Catalanian mine, provided by CTM.

Concretely, CaSO_4 is coming mostly from residual *Plaster* which is a mineral formed by $[\text{CaSO}_4 + 2\text{H}_2\text{O}]$. In addition, MgCl_2 is appearing also from a mineral but called *Carnallite*, which is formed by $[\text{MgCl}_2 + \text{KCl} + 6\text{H}_2\text{O}]$.

Comparing these compositions and reviewing the literature of high-temperature phase change and heat storage materials for thermal energy storage proposed by Kenisarin M. M. (2010), some salts are found along with their usual composition as heat storage and phase change materials compatible with the most common salts extracted.

Table 2.2 and Table 2.3 present several chloride salt compositions and the different melting temperatures of those compositions.

Table 2.2 Chloride eutectic salts compositions. Source: (Kenisarin M. M., 2010)

Salt composition (mol.%)	$T_m, ^\circ\text{C}$	$\Delta H_f, \text{J/g}$
BaCl ₂ (13.1)–16.9CaCl ₂ – 47.3KCl–22.7NaCl	478	208
BaCl ₂ (9.3)–22.2CaCl ₂ – 42.7KCl–25.8NaCl	479	217
LiCl(69.5)–26.5LiF–4MgF ₂	484	157
CaCl ₂ (50)–1.5CaF ₂ –48.5NaF	490	264
CaCl ₂ (52.3–55)–(45–47.2) NaCl	490–500	233–239
CaCl ₂ (52.8)–47.2NaCl	500	239
NaCl(33)–67 CaCl ₂ ^a	500	281
MgCl ₂ (37)–63 SrCl ₂ ^a	535	239
KCl(25)–27 CaCl ₂ –48 MgCl ₂ ^a	487	342
CaCl ₂ (66)–5KCl–29NaCl ^a	504	279
SrCl ₂ (68)–13KCl–19NaCl ^a	504	223
KCl(21)–17NaF–62K ₂ CO ₃ ^a	520	274
NaCl(5)–40NaBr–55Na ₂ MoO ₄	524	215
KCl(40)–23KF–37K ₂ CO ₃ ^a	528	283
KCl(28)–19NaCl–53BaCl ₂ ^a	542	221
KCl(24)–47BaCl ₂ –29CaCl ₂ ^a	551	219
NaCl(952)–48NiCl ₂	573	558
LiCl(94.5)–5.5MgF ₂	573	131
KCl(45)–55KF	605	407
NaCl(38.5)–23NaBr–38.5Na ₂ MoO ₄	612	168
CaCl(38.5)–11CaSO ₄ –4CaMoO ₄	673	224

Table 2.3 Chloride eutectic salts compositions (continuation). Source: (Kenisarin M. M., 2010)

Salt composition (mol.%)	$T_m, ^\circ\text{C}$	$\Delta H_f, \text{J/g}$	Salt composition (mol.%)	$T_m, ^\circ\text{C}$	$\Delta H_f, \text{J/g}$
LiCl(28.5–28.9)–(43.5–44.5)CsCl– (13.7–14.1)KCl–(13.3–13.5)RbCl	256 ± 2.5	375–380	KCl(22)–51MgCl ₂ –27NaCl	396	290
LiCl(59.15)–40.85Ca(NO ₃) ₂	270	167	KCl(37.7)–37.3MnCl ₂ –25NaCl	400	235
NaCl(7.8)–85.8NaOH–6.4NaCO ₃	282	316	LiCl(51.5)–16.2LiF– 16.2Li ₂ SO ₄ –16.2Li ₂ MoO ₄	402	291
NaCl(8)–5NaF–87NaNO ₃	288	224	NaCl(56)–44MgCl ₂	430	320
LiCl(54.2)–6.4BaCl ₂ –39.4KCl	320	170	KCl(54)–46ZnCl ₂ ^a	432	218
LiCl(41.5,0)–16.4LiVO ₃ –7.0LiF– 11.6Li ₂ SO ₄ –35.1Li ₂ CrO ₄	340	177	KCl(61)–39MgCl ₂ ^a	435	351
LiCl(47.4–47.7)–(46.8–47.0)KCl– (3.2–3.4)LiCO ₃ –(2.1–2.4)LiF ^a	340–343	375–380	NaCl(56.2)–43.8MgCl ₂	442	325
LiCl(58)–42KCl	348	170	LiCl(58.5)–23.6Li ₂ SO ₄ –17.9Li ₂ MoO ₄	445	327
KCl(28.7)–45MnCl ₂ –26.3NaCl	350	215	KCl(36)–64MnCl ₂	448	236
KCl(45.5)–34.5MnCl ₂ –20NaCl	390	230	LiCl(49.0)–12.75Li ₂ SO ₄ –38.25LiVO ₃	449	450
LiCl(23.4–24.2)–(24.8–25.3) LiVO ₃ –(27.1–27.6)Li ₂ MoO ₄ – (17.3–17.8)Li ₂ SO ₄ –(6.1–6.2)LiF ^a	360–363	278–284	KCl(35)–65MnCl ₂	450	237
LiCl(42.0)–17.4LiVO ₃ –17.4LiF– 11.6Li ₂ SO ₄ –11.6Li ₂ MO ₄	363	284 ± 7	NaCl(60)–40MgCl ₂	450	328
NaCl(22.5–26.5)–(18.5–22.5) KCl–(57.0–53.0) MgCl ₂ ^a	385–393	405–410	NaCl(48)–52MgCl ₂ ^a	450	430
KCl(21.6)–45.4MgCl ₂ –33.0NaCl	385	284	CaCl ₂ (47.6)–8.1KCl– 41.3NaCl–2.9NaF	460	231
KCl(20)–50MgCl ₂ –30NaCl	396	291	CaCl ₂ (41.6)–2.2KCl– 8.8MgCl ₂ –47.4NaCl	460	245
			CaCl ₂ (50)–7.25KCl–42.75NaCl	465	245
			KCl(36)–64MgCl ₂ ^a	470	388
			BaCl ₂ (8.7)–52.3KCl– 18.2MgCl ₂ –20.7NaCl	475	248

Some examples of chloride salts are $[\text{NaCl} + \text{KCl} + \text{MgCl}_2]$, $[\text{KCl} + \text{MgCl}_2 + \text{NaCl}]$, $[\text{MgCl}_2 + \text{NaCl}]$, $[\text{KCl} + \text{MgCl}_2]$, $[\text{CaCl}_2 + \text{KCl} + \text{MgCl}_2 + \text{NaCl}]$ among many others.

In addition, hydroxide, nitrate and carbonate salts are found in Table 2.4 and Table 2.5, below.

Table 2.4 Hydroxides and nitrates salt compositions. Source: (Kenisarin M. M., 2010)

Salt composition (mol.%)	$T_m, ^\circ\text{C}$	$\Delta H_f, \text{J/g}$	Salt composition (mol.%)	$T_m, ^\circ\text{C}$	$\Delta H_f, \text{J/g}$
Hydroxides			Nitrates		
NaOH(50)–50KOH	169–171	202–213	LiNO ₃ (29)–17NaNO ₃ –49.4KNO ₃ –4.6Sr(NO ₃) ₂ ^a	105	110
LiOH(30)–70NaOH	210–216	278–329	LiNO ₃ (33)–67KNO ₃ ^a	133	170
NaOH(20)–80NaNO ₂	230–232	206–252	LiNO ₃ (31.7)–68.3KNO ₃ ^a	135	136
NaOH(73)–27NaNO ₂	237–238	249–295	KNO ₃ (53)–40NaNO ₂ –7NaNO ₃ ^a	142	80
NaOH(78.1)–3.6NaCl–18.3NaNO ₃	242	242	LiNO ₃ (55.4)–4.5NaNO ₃ –40.1KCl ^a	160	266
NaOH(28)–72NaNO ₃	246–247	182–257	LiNO ₃ (58.1)–41.9KCl ^a	166	272
NaOH(55.6)–4.2NaCl–40.2NaNO ₃	247	213	LiNO ₃ (47.9)–1.4LiCl–50.7NaNO ₃ ^a	180	265
LiOH(63)–37LiCl	264	437	LiNO ₃ (57)–43NaNO ₃ ^a	193	248
NaOH(59)–41NaNO ₃	266	278	LiNO ₃ (49)–51NaNO ₃ ^a	194	265
LiOH(65.5)–34.5LiCl	274	339	LiNO ₃ (45)–47NaNO ₃ –8Sr(NO ₃) ₂ ^a	200	199
LiOH(62)–36.5LiCl–1.5KCl	282	300	LiNO ₃ (87)–13NaCl ^a	208	369
NaOH(81.5)–18.5NaNO ₃	256–258	251–292	KNO ₃ (54)–46NaNO ₃ ^a	222	100
NaOH(59)–41NaNO ₃	266	221	NaNO ₃ (54)–46KNO ₃	222	117
NaOH(85.8)–7.8NaCl–6.4Na ₂ CO ₃	282	316	NaNO ₃ (18.3)–3.6NaCl–78.1NaOH	242	242
NaOH(88.3)–5.3NaCl–6.4Na ₂ CO ₃	282	279	NaNO ₃ (40.2)–4.2NaCl–55.6NaOH	247	213
NaOH(87.3)–6.1NaCl–6.6Na ₂ CO ₃	291	283	NaNO ₃ (70)–30NaOH	247	158
NaOH(85.8)–7.8NaCl–6.4Na ₂ CO ₃	298	286	LiNO ₃ (97.4)–2.6Ba(NO ₃) ₂	253	368
NaOH(77.2)–16.2NaCl–6.6Na ₂ CO ₃	318	290	LiNO ₃ (93.6)–6.4NaCl ^a	255	354
LiOH(80)–20LiF	427	1163	Ca(NO ₃) ₂ (40.85)–59.15LiCl	270	167
			NaNO ₃ (86.3)–8.4NaCl–5.3Na ₂ SO ₄	287	177

Table 2.5 Carbonates and some other salts compositions. Source: (Kenisarin M. M., 2010)

Salt composition (wt.%)	$T_m, ^\circ\text{C}$	$\Delta H_f, \text{J/g}$
Na ₂ CO ₃ (6.4)–85.8NaOH–7.8NaCl	282	316
Li ₂ CO ₃ (32.1)–34.5K ₂ CO ₃ –33.4Na ₂ CO ₃	397	276
Li ₂ CO ₃ (47)–53K ₂ CO ₃	488	342
Li ₂ CO ₃ (47)–53K ₂ CO ₃	491	321
Li ₂ CO ₃ (46.6)–53.4K ₂ CO ₃	488	391
Li ₂ CO ₃ (44)–56Na ₂ CO ₃	496	370
Li ₂ CO ₃ (28)–72K ₂ CO ₃	498	263
Li ₂ CO ₃ (28.5)–71.5K ₂ CO ₃	498	316
Li ₂ CO ₃ (44.3)–55.7Na ₂ CO ₃	498	393
Li ₂ CO ₃ (35)–65K ₂ CO ₃	505	344
Li ₂ CO ₃ (32)–35K ₂ CO ₃ –33Na ₂ CO ₃	397	276
K ₂ CO ₃ (62)–17NaF–21KCl	520	274
K ₂ CO ₃ (37)–40KCl–23KF	528	283
Li ₂ CO ₃ (20)–60Na ₂ CO ₃ –20K ₂ CO ₃	550	283
Li ₂ CO ₃ (22)–16Na ₂ CO ₃ –62K ₂ CO ₃	550	288
K ₂ CO ₃ (47.8)–52.2K ₂ CO ₃	710	176
K ₂ CO ₃ (50)–50Na ₂ CO ₃	710	163
K ₂ CO ₃ (51)–49Na ₂ CO ₃	710	163
NaBr(43)–2NaF–55Na ₂ MoO ₄ ^a	506	241
Li ₂ SO ₄ (59.8)–36.7Li ₂ MoO ₄ –3.5CaMoO ₄ ^a	538	406
KBr(60)–40KF ^a	576	315
KBr(65)–35K ₂ MoO ₄ ^a	625	90.5
Li ₂ SO ₄ (82)–11.44CaSO ₄ –6.56CaMoO ₄ ^a	680	207

In those tables it's observed the many different salts compositions and their melting temperatures, which are very important regarding the range of temperatures of a CSP plant.

2.3 CSP energy production technologies

The solar irradiation arriving at the Earth's surface is an important renewable energy source. In a general point of view, solar irradiation, which is contained by photons, can be converted into electricity through Photovoltaic Systems or Concentrating Solar Power (CSP) systems. Along this thesis only CSP technologies are focused, which use mirrors or optical lenses and concentrate the sunlight to create a high energy density and temperature level. These types of systems can only work with direct solar irradiation, so they are more likely to be used in areas where there are few clouds because otherwise photovoltaic technologies would fit better (Barlev D. et al, 2011). A CSP plant is consisted by four main sub-systems including a concentrating system, a solar receiver, storage and/or supplementary firing (as a back-up system) and a power block. These sub-systems are linked together by transferring a suitable fluid or radiation. The function of the solar receiver is to absorb the concentrating solar energy and transfer it to the heat transfer fluid (HTF). The power block receives a high temperature heat from the heat transfer fluid and the storage tank stores solar heat coming from the transfer fluid. A scheme of the sub-systems of a CSP plant is shown in **Figure 2.3**:

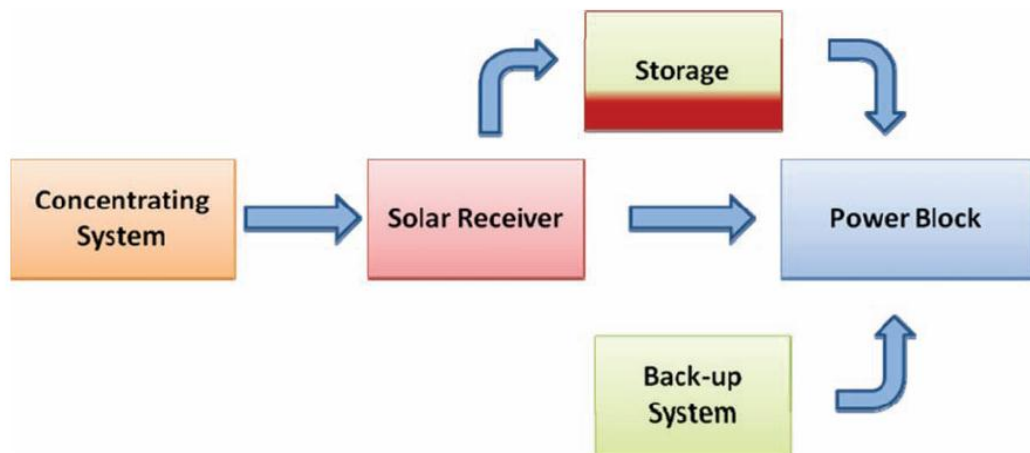


Figure 2.3 Components and sub-systems of a CSP plant. Source: (EASAC, 2011)

Among the four existing technologies of Concentrating Solar Power (CSP) used to concentrate and collect sunlight in order to turn it into heat, these CSP technologies are divided in two groups: the ones that focus the sun rays to a line and the one that focus the sun rays to a point, as shown in **Figure 2.4**.

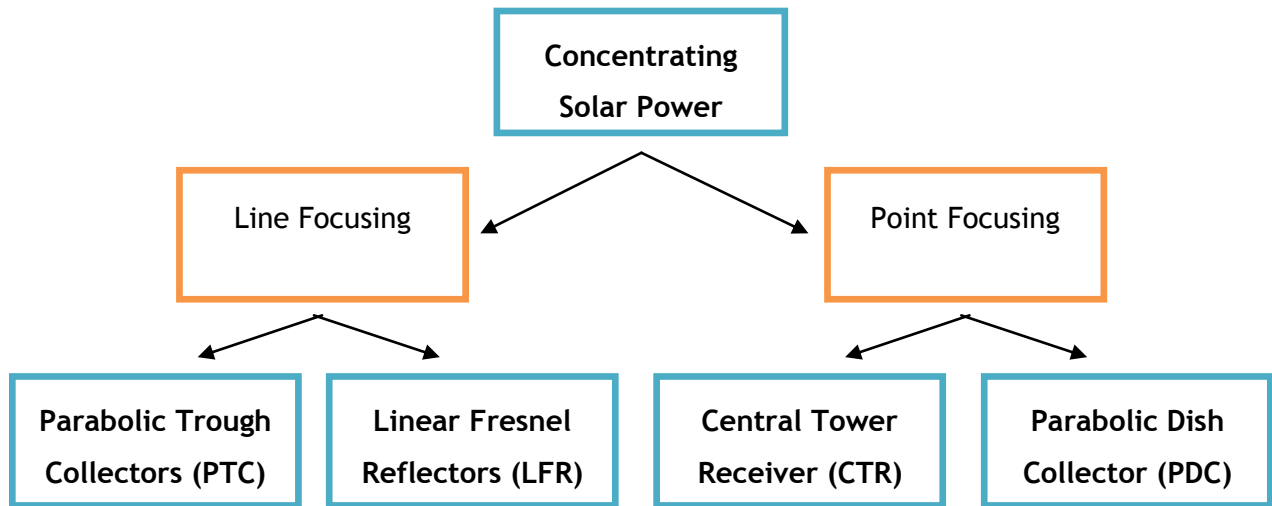


Figure 2.4 Different types of CSP technology. Source: (Gharbi N. et al., 2011)

A description of the main specifications of the four CSP technologies described in **Figure 2.4** is made in **Table 2.6**, to better clarify and highlight the main differences of operating temperatures range of each technology and the current relative costs, maturity level and concentration ratios.

Table 2.6 Description and specifications of CSP technologies. Source: adapted from (Barlev D. et al, 2011)

Technology	Operating temp. range (°C)	Relative cost	Concentration ratio	Technology maturity
PTC	50-400	Low	15-45	Very mature
LFR	50-300	Very low	10-40	Mature
CTR	300-2000	High	150-1500	Most recent
PDC	150-1500	Very high	100-1000	Recent

2.3.1 Parabolic Trough Collectors

The parabolic trough collectors (PTCs) became the most implemented concentrating solar power technology nowadays. Since the 70's this technology has been installed in solar central facilities for generating electricity and providing thermal energy at an average temperature appropriate for industrial processes. On the second half of the 80's nine thermo solar centrals were built in California, with a total installed power of 354 MW_e, based on parabolic trough collector's technology; they worked satisfactorily during 15 years (Cohen G.E., 1994) and continue working without major technical problems. These thermo solar plants comprehend a storage system, usually with oil. In **Figure 2.5** is shown the collector field of one SEGS (Solar

Electric Generating System) in California (NextEra Energy, Inc., 2012). Analyzing the picture beneath, is possible to see the constitution and structure components of a PTC: an absorber tube, a curved mirror, and pipes containing the HTF.



Figure 2.5 Collectors Field of a thermo solar plant with parabolic trough collectors in California (SEGS). Source: (NextEra Energy, Inc., 2012)

After 15 years of operation of these thermo solar plants, i.e., around the 90's, it was a starting point to implement these technologies in other parts of the world. The operation and maintenance costs have been continuously reducing and the annual production of electricity has been increasing while earning experience in operation of this type of thermo solar plants (Cohen G.E., 1994; Kearney D.W., Cohen G.E., 1996; Cohen G.E., et al, 1998). Until today, most of the PTC fields installed for commercial applications are using thermal oil as a working fluid of the solar field. Besides having a considerable cost, this oil has a serious limitation over the efficiency of the thermo solar plant. In fact, the used oil is degraded when it reaches high temperatures, and so it's not possible to operate over 390 °C with these collectors, which limits the maximum temperature of the turbine vapor cycle to 370 °C.

On the other hand, the restrictions of transfer processes in heat exchangers and thermo physical properties of the heat transfer fluid makes the pumping bomb, which carries about the distribution of oil in the solar field, to have also a considerable energetic consumption and a reduced efficiency due to the high average temperatures of the oil.

Parabolic trough collectors are a technology which has reached its level of maturity in prototype applications and an excellent performance in commercial power plants for energy production, with very positive results. However, and so far, there are three other concentrating solar power technologies using the same energy source (the sunlight) with

other characteristics, using different transfer and storage fluids, different storage technologies and having also different characteristics, costs and efficiencies. They will be described in the following sections.

2.3.2 Linear Fresnel Reflectors

Linear Fresnel Reflectors are quite similar to PTCs technology because they are characterized by a linear receptor in which the incident radiation is concentrated (line focusing - **Figure 2.4**). LFR incorporates however long arrays of flat mirrors that concentrate the light onto a linear receiver, which is mounted on a tower suspended above and along reflector arrays (**Figure 2.6**). A disadvantage of LFR technology is the fact of being more recent when compared to the PTC historical record, but analyzing studies and prototypes meanwhile developed, puts into evidence that there are many advantages when compared to PTC.

In fact, the design of a LFR is cheaper than a PTC due to the flat and elastic nature of the mirrors used. Not considering it as a disadvantage, but a challenge, the light blocking between adjacent reflectors needs a solution as it requires more space between mirrors, which occupies more land, as well as the tower receiver height needs to be increased, causing additional costs.

One of the first prototypes of a LFR demonstration was implemented on the Plataforma Solar de Almeria (PSA), in Spain, where it took its first steps (Plataforma Solar de Almería, 2008-2009). As demonstrated below, a prototype of a LFR in PSA is composed by curved mirrors, absorber tube and re-concentrator.



Figure 2.6 Linear Fresnel demo reflector erected on the Plataforma Solar de Almería (PSA). Source: (Plataforma Solar de Almería, 2008-2009)

Concluding, LFR technology has many advantages when compared to PTCs concerning the lower investment, maintenance and operation costs required, the inexistence of metal-glass welds at the ends of each receiver tube module for maintaining vacuum within the outermost tube, and do not uses rotating joints (Häberle A., et al, 2002). Admitting the lack of commercial and experimental applications with LFR, PTC technology has a big advantage of being already validated. Despite of these aspects and analyzing previous studies, LFR can also be easily coupled to direct steam generation as well as to molten salts for thermal energy storage and HTF.

This is the reason why the next step for LFR technology should be a pilot plant under real commercial operation conditions because previous studies and experiences have demonstrated a wide potential on LFR technology and results for reaching a higher level of efficiency than any other CSP technology.

2.3.3 Parabolic Dish Collector (Stirling engine)

A Parabolic Dish Collector (PDC) consists on a parabolic mirror of big diameter with an external combustion Stirling engine located at its focal area. The parabolic mirror (dish) does a continuous solar tracing, and the sun's rays are reflected at its focal plan.

The Stirling engine is an external combustion engine which also uses a Stirling thermodynamic cycle and has two aspects that makes it more adequate for this application: i) energy intake can be done through collected sunlight from the parabolic dish and concentrated at its focal area and ii) very high efficient thermodynamic cycle.

The well-known PSA has contributed in a very positive manner for this type of technology with three projects, namely: Distal I, Distal II and EuroDISH (Plataforma Solar de Almería, 2008-2009). In **Figure 2.7** is shown the result of the EuroDISH project where Spain and Germany were involved to develop new prototypes of PDCs with a Stirling engine.



Figure 2.7 EuroDISH from back and front view. Source: (PSA, 2012)

The heat loss of these systems is a highly important and incompletely solved issue and, for the moment, only few literature studies report trials to work through the convection heat loss mechanisms of cavity receivers with no-wind conditions (Leibfried U., Ortjohann J., 1995; Taumoefolau T., Lovegrove K., 2002; Paitoonsurikarn S., Lovegrove K., 2006) and free-forced convection heat loss mechanisms under wind conditions. Four types of receivers shaped in cubical, rectangular, cylindrical, and hemispherical forms have been investigated, both experimentally and numerically. Numerous studies have been published on square and rectangular open cavities due to their wide applications in various engineering systems, in addition to those in solar thermal receivers. On the contrary, fewer studies of predicting convection heat loss for cylindrical and hemispherical cavity receivers have been undertaken (Prakash M., et al, 2009).

The innovation in PDC technology has promoted this highly efficient but expensive technology to become reasonably affordable. However, PDCs are heavy and expensive structures that must track the sun very accurately to fulfill their maximum potential. The use of heat engines and high energy conversion cycles makes their energy production very efficient and compensatory because they do not require the use of any heat transfer media.

Apart from all these positive aspects there's a crucial negative one: PDCs cannot be easily linked with thermal storage media, especially when the concern is to implement them in large solar power energy production plants for commercial scale, so maybe this option would fit better at a smaller scale production and instantaneous consumptions.

2.3.4 Central Tower Receiver

The development of thermo solar plants with Central Tower Receivers (CTRs) has started around the 70's, as well as PTCs, and during 25 years they were implemented and tested as demonstration models in many countries around the world, particularly in the USA, Spain and Israel (Radosevich L.G., 1988; DeLaquil P., et al, 1991; Avellaner J., et al, 1985).

The first experiences of CTRs were focused on building and operating centrals of 10 MW_e connected to the electric network in the California, USA, named as Solar One and Solar Two. The Solar One central was in operation from 1982 till 1988 and was formed with an exterior receptor that used water vapor, which could be directly addressed to a turbine vapor cycle or through numerous heat exchangers, TES with oil, sand and gravel for its later use in the power cycle. Another project, more recent, was Solar Two, which was operating from 1996 till 1999. This thermo solar plant was a reconversion of the Solar One to work with molten salts as HTF.

However, these thermo solar plants of CTR didn't have the chance of experimenting themselves in commercial applications as the PTC in California did.

After those projects, Solar Tres was developed between 2002 and 2008, based on Solar Two experience, but with the goal of building a demonstration plant at commercial scale, able to produce 17 MW of nominal power from solar energy with a TES with molten salts (Plataforma Solar de Almería, 2008-2009). Solar Tres was used mainly to innovate and validate some technological options and to boost the most recent project, Gemasolar, considered to be the first commercial plant in the world with heliostats, central tower and molten salts receiver and storage fluid with a nominal power of 20 MW. It was inaugurated on October of 2011 in Seville, Spain (Torresol Energy Investments, S.A., 2011), and is illustrated in **Figure 2.8**.



Figure 2.8 Gemasolar Solar Thermal plant using CTR technology with molten salts storage system.

Source: (Torresol Energy Investments, S.A., 2011)

Amongst all of the advances achieved, the most significant of Gemasolar are the capability to store energy (and so to have it available when users need it) and the capacity to operate at very high temperatures, achieving greater energy efficiency than any other conventional system. This system allows a continuous production of electricity up to 15 hours in absence of sunlight, guaranteeing the supply of electricity for around 6600 hours per year, which can still be adapted to user consumption demand.

The operation process consists in capturing sunlight by heliostats and reflecting it towards the receiver. In the receiver salts heat up and descend to the hot salt storage tank where they are stored at up to 500 °C. From the hot salts tank, salts are transferred to heat exchangers through pipes and when they lose their heat they yield a steam that will move a turbine for the coupled generator, producing electrical energy (Torresol Energy Investments, S.A., 2011). Central Tower Receiver technology has greatly improved over the last few decades, and continues to draw much attention as suitable scheme for large solar thermal plants. The exceeding high temperatures at which they operate guarantees to CTR plants excellent

energy efficiencies. The only obstacle for this technology is the high initial investment necessary for construction and maintenance costs, so further technological advancements in efficiencies must be followed by low cost materials and storage schemes for this CSP system becoming less expensive, more competitive and mature compared with PTC (the most mature technology nowadays).

2.4 World current status of CSP market

From a European and Mediterranean perspective and analyzing direct normal irradiation (DNI) potential, two promise countries are easily identified in Europe for the development of thermal solar energy plants, namely as Spain and Portugal. In North Africa region there's Morocco, Algeria, Libya and Egypt and in the Middle-East there's Saudi Arabia, Israel and Jordan as potential countries to install these solar-based systems (**Figure 2.9**). Among all these countries, Spain is the number one in CSP plant investment and solar energy production, and unfortunately Portugal, despite of its potential, has almost not invested in CSP technology. For political and economic reasons, many Middle East and North Africa (MENA) countries are far behind Spain, which is, as mentioned, the leader solar thermal energy world producer and pioneer in Europe and Mediterranean regions. On the other hand, USA is the world leader due its strong investments in CSP technology and other new projects.

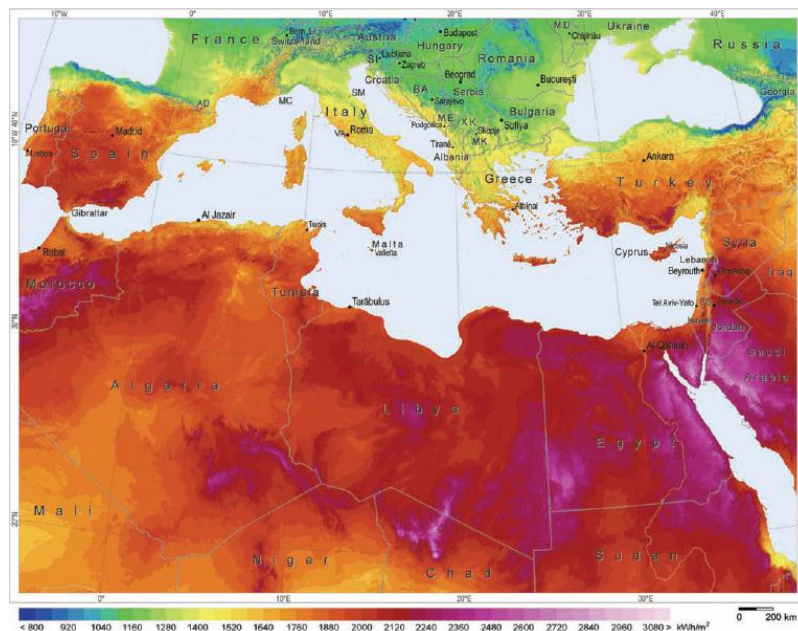


Figure 2.9 Direct normal irradiation potential for Southern Europe and Mediterranean regions.

Source: (GeoModel Solar s. r. o., 2010)

There's a long challenge on developing CSP technology in MENA countries, where the DNI available becomes an important waste regarding all the thermal energy possible to convert in

electricity from its high levels of irradiation. But the most important for these populations is certainly not developing and investing in CSP plants at this moment, and especially during all the conflicts happening in Libya and Egypt, and so political issues and economic instability of those countries are thus a priority.

A global view of CSP plant planned, operating and under constructing is shown in **Figure 2.10** where it can be seen the higher power capacity operating CSP plants in Spain, with two times the power capacity of the USA. However, due to the investments made in the USA and the current construction of new CSP plants, they will quickly produce more power than any other country in the world. But in Europe and as a consequence of the DNI potential in Iberian Peninsula, Spain has invested significantly in thermal energy production during last year's. So, this country became revolutionary using a brand new system employing only molten salts as TES media applied to CTR technology for commercial electricity production; as previously referred, it is noteworthy the Gemasolar Plant project inaugurated last year located in Seville. Today, Spain is the world leader in installed power and technological capacity, and companies of the solar thermo electrical sector are starting to participate in ambitious projects in many regions of the world (USA, North Africa, Middle-East, China, India and Australia). Besides the ones which are operative, 60 new plants are expected to be in operation, which together will sum up around 2500 MW_e of installed power in Spain according to Protermosolar informations available online (Protermosolar, 2011). Lamentably, Portugal doesn't have any CSP plant in commercial scale production and since 2007 is making efforts for developing a CSP pilot-plant demonstration based in LFR technology in Southern Portugal (Tavira, Algarve), developed by Algarve University and INETI (Silva A., 2010).

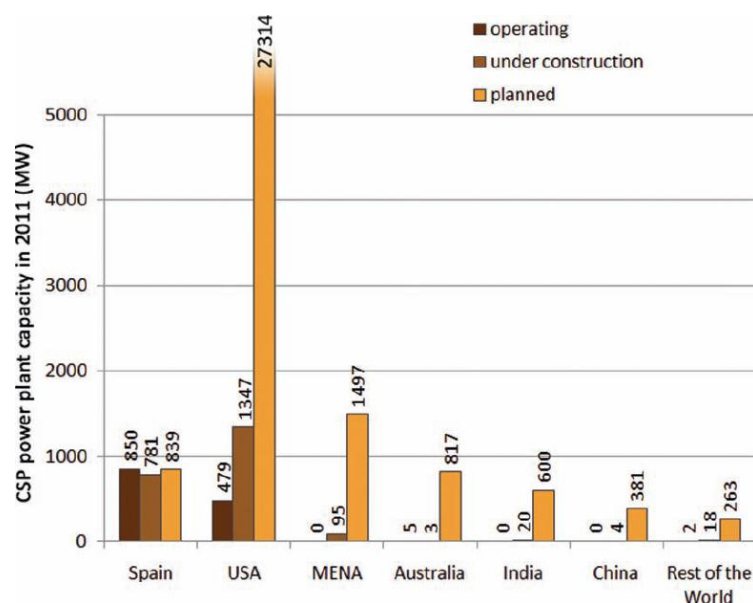


Figure 2.10 Worldwide distribution of operational, under construction and planned CSP plants.

Source: (EASAC, 2011)

In MENA countries, projects and investments in many different CSP plants are proposed, but just a few are under construction. It is desirable that they start operation as soon as possible because MENA countries are the regions that have more DNI and land for construction available. Thereby, there is a long path for innovation and improvements, but the four important areas where it should be focused are energy efficiency, supply capacity, cost reductions of construction and materials used and environmental sustainability.

2.5 Characterization of heat transfer media and storage fluids

2.5.1 Types and properties of heat transfer media and storage fluids

There are many existing options of heat transfer fluids and thermodynamic cycles. The most used as heat transfer fluids are synthetic oil and saturated steam in commercial plants, while molten salts and superheated steam are coming to the market. Use of air (at ambient pressure or pressurized) and other pressurized gases (for example, CO₂ and N₂) are under development, while helium or hydrogen are exclusively used in Stirling engines with parabolic dish systems (EASAC, 2011). Molten salts are the only commercial option nowadays for storing during extended periods of time (between 8 and 15 hours), allowing electricity production to better match demand, while steam is more appropriate for short time (less than 1 hour) storage. Thermodynamic cycles are currently steam Rankine cycles, and Stirling cycles for parabolic dish collectors. Brayton cycles are under development, where a gas turbine is driven by pressurized gas heated by the solar collector. The combination of Brayton cycle that supplies its waste heat to a bottoming Rankine cycle promises the best efficiency and thus the highest electrical output per square meter of collector field (EASAC, 2011).

Meanwhile, the four CSP technology systems and technical options (mainly differing according to the heat transfer fluid used) are listed in **Table 2.7**. For parabolic troughs collectors, an emergent additional option is the use of compressed gas as the heat transfer fluid and molten salt for storage. However, this option is at a very early stage of development and efficiency data are not yet available. Nevertheless, the use of molten salt as a HTF and storage system is yielding excellent results, as provided by Gemasolar plant system based only on molten salts. The big call of TES using molten salts is to improve their capacity for storage during more than 15 hours according to different weather conditions along the year, so that CSP can be implemented in many other countries where the level of DNI is not that high as in MENA countries. The most common salt based compositions are chloride, fluoride, sulphate, nitrate and carbonate. Combining those salt based compositions with their characteristic minerals containing sodium, potassium, magnesium and calcium, the most usual and extracted salts from salt mining industries are obtained.

An engineering study was carried out to evaluate a concept, where another (less expensive) liquid medium, such as molten salt, is used as storage medium rather than the HTF itself. Detailed performance and cost analyses were conducted to evaluate the economic value of this concept. Since the salt storage was operated successfully in the Solar Two project in California and Solar Tres in Spain, no major barriers were identified to realize this concept in the first commercial parabolic trough power plant (Herrmann U., et al, 2004).

If molten salts can be more and more applied to Parabolic Trough Collectors and Central Tower Receivers, it could be a huge step for becoming a revolutionary storage system, because PTC and CTR are the most mature technologies at commercial scale production. So far there are many prototypes using molten salts as HTF and storage system, but just a few are effectively being applied commercially. Even so, molten salts provides numerous advantages when compared to other storage and HTF concerning specially their costs and the fact that a residual salt provided by the mining sector can be employed, which can be reused in thermo electrical solar plants to fill a storage tank and/or as a heat transfer fluid.

Table 2.7 Technical options regarding the use of heat transfer fluids / storage fluids for each CSP technology family. Source: adapted from (EASAC, 2011)

CSP technology	Technical options
Parabolic Trough Collector (PTC)	PTC-oil: oil as HTF and molten salt storage
	PTC-SHS: superheated steam as HTF
	PTC-MS: molten salt as HTF and storage
Linear Fresnel Reflector (LFR)	Fresnel SaS: saturated steam as HTF
	Fresnel SHS: superheated steam as HTF
Central Tower Receiver (CTR)	CTR-SaS: saturated steam as HTF
	CTR-SHS: superheated steam as HTF
	CTR-MS: molten salt as HTF and storage
	CTR-AR: ambient pressure air as HTF and Rankine cycle
	CTR-GT: pressurized air as HTF and Brayton cycle
	CTR-SC: supercritical cycle
Parabolic Dish Collector (PDC)	CTR-CC: pressurized air as HTF and combined cycle
	PDC: helium or hydrogen Stirling cycle

2.5.2 Composition of heat transfer and storage fluids

There are many types of thermal energy fluids used such as oils, salts, helium, hydrogen and steam that can be used as a HTF or storage system depending on which CSP technology is to be implemented and storage system required, as detailed in the previous section.

The composition of oils can be divided in three types: mineral, synthetic and silicone oil. Mineral oil is any of various colorless, odorless, light mixtures of alkynes from a non-vegetable source, particularly a distillate of petroleum (Erhan S. Z., et al, 2005). Synthetic oil is a lubricant consisting of chemical compounds that are artificially made such as polyalphaolefin (Jantzen E., 1996). Silicone oil is any polymerized siloxanes with organic side chains such as polydimethylsiloxane (Miyahara H., et al, 2006).

Salt is a mineral mainly consisted of sodium chloride, but it may include other anions such as nitrates, chlorides, carbonates and sulphates, while molten salt is the salt in its liquid state considered to as class of ionic liquid.

Steam is water vapor in its technical mean and represents the gaseous state of water, which is produced when the water reaches its boiling point. Detailed characteristics and properties of some of those fluids are given in **Table 2.8** and **Table 2.9**, where are particularly considered the cold and hot temperatures, the average density, the average thermal conductivity, the average heat capacity and the volume specific heat capacity, because these are the most important thermo-dynamic properties of interested for the designed applications.

Table 2.8 Thermal storage oils and their properties. Source: adapted from (Barlev D. et al, 2011)

Storage Medium	Mineral Oil	Synthetic Oil	Silicone Oil
Cold temperature (°C)	200	250	300
Hot temperature (°C)	300	350	400
Average Density (kg/m ³)	770	900	900
Average thermal conductivity (W/m.K)	0.12	0.11	0.10
Average heat capacity (kJ/kg.K)	2.6	2.3	2.1
Volume specific heat capacity (kWh/m ³)	55	57	52

Table 2.9 Thermal storage salts and their properties. Source: adapted from (Barlev D. et al, 2011)

Storage Medium	HiTec Solar Salt	Nitrite salts	Nitrate salts	Carbonate salts	Liquid Sodium	NaCl (solid)
Cold temperature (°C)	120	250	265	450	270	200
Hot Temperature (°C)	133	450	565	850	530	300
Average Density (kg/m ³)	n/a	1825	1870	2100	850	1700
Average thermal conductivity (W/m.K)	n/a	0.57	0.52	2.0	71.0	1.0
Average heat capacity (kJ/kg.K)	n/a	1.5	1.6	1.8	1.3	1.30
Volume specific heat capacity (kWh/m ³)	n/a	152	250	430	80	60

The desired characteristics for molten salts are low vapor pressure, high density, low chemical reactivity, moderate specific heat and low cost. A negative aspect of different salts is that they are usually quite pricey (Barlev D. et al, 2011) when obtained directly from industrial production. The properties of the three oils referred are similar between them, however, analyzing their temperatures and comparing to salts it's easily identified a limitation of oils for having much lower temperatures than salts, which stand only between 200 and 400 °C. Salts vary more their values in the cold and hot temperatures, thermal conductivity and volumetric heat capacity, which allows a wider use with different temperatures range depending on the solar field size, demands and power output required of a given CSP plant.

Globally, the properties of salts can fit better in different situations of applications and their average thermal conductivity is considerably higher than that of the oils, as is also their volumetric heat capacity, so it means they are more able to conduct heat and accumulate it in higher quantities, which are very important properties for a heat transfer and/or storage fluid being used in CSP plants.

2.5.3 Thermal energy storage (TES) media

TES is the heat transferred to storage media during the charging period and released during the discharging step, to be usefully applied. The goal of storing heat is to have a CSP working even when the sun is not shining anymore, through TES storage technologies (media). TES media is divided in three types: thermal storage as sensible heat, as latent heat and as thermo-chemical heat. These storage options are presented according to the heat transfer fluid in **Table 2.10**.

Table 2.10 Thermal Energy options according to the heat storage media and heat transfer fluid (adapted). Source: (Gil A., Medrano M., et al, 2010)

Heat storage media	Heat transfer fluid
Sensible heat storage	Mineral oil
	Molten Salts
	Steam
	Gas (CO ₂ , air helium, etc.)
Latent Heat Storage	Steam (Phase change materials)
Chemical Storage	Various (Ammonia, Hydroxides, Calcium carbonate, metals, Iron carbonate, etc.)

Sensible heat is the energy released or absorbed by a material as its temperature is reduced or increased, respectively. The storing system consists in a storage medium, a tank and input/output equipment. Tanks must both retain the storage material and prevent losses of thermal energy. This system can work with solid or liquid media but in this work it will be addressed only liquid media, such as molten salts.

Latent heat is the energy required to convert a solid into a liquid or a liquid into a gas, for instance. The capacity of energy storage is higher when latent heat storage complements sensible heat storage. Nowadays, mainly the solid-liquid transition is used and substances used under this technology are called phase change materials (Gil A., Medrano M., et al, 2010). The third and less developed type of heat storage is the thermo-chemical heat storage involved in reversible endothermic/exothermic reactions. Since sensible and latent thermal energy schemes can only retain their energy efficiently for long periods, thermo-chemical storage processes can make it possible for short-periods. Despite its high energy density, thermo-chemical heat storage is an expensive alternative and is at a very early stage of development; as this study is focused on sensible and latent heat storage, it will not be considered as an important TES media.

2.6 Energy storage technologies

The possibility of incorporating thermal storage systems into CSP plants allows increasing the energy efficiency of the system, correcting the deviations between energetic production and consumption, improving energy release of these types of plants and making the electric network integration easier.

Deciding and defining the design and type of the thermal energy storage system is a hard task that has to consider many facts where the most important is the thermal capacity of the material used, which should be compatible with a cost-effective system design.

Several additional factors and requirements need to be considered, and from the technical point of view, the most important are: high density in the storage material (storage capacity); good heat transfer between the HTF and the storage medium (efficiency); mechanical and chemical stability of the storage material (must support several charging/discharging cycles); compatibility between HTF, heat exchanger and/or storage medium (safety); complete reversibility and stability in a number of charging/discharging cycles (lifetime); low thermal losses; and easy of control. And, from the point of view of technology, the most important requirements are: operation strategy; adequate maximum load; appropriate nominal temperature and specific enthalpy drops in load; and integration into the power plant (Zalba B., et al., 2003).

In what concerns the nature of the thermal storage process, there are active systems and passive systems. An active system is based on thermal transfer through forced convection in the storage material, while a passive system is based in solid materials through which the heat transfer fluid circulates in charging and discharging thermal cycles. Active systems are subdivided into direct and indirect systems. In direct systems, the heat transfer fluid is used also as storage media and on indirect systems a second storage medium is used for storing the heat. A classification of the storage concept is illustrated in **Figure 2.11**.

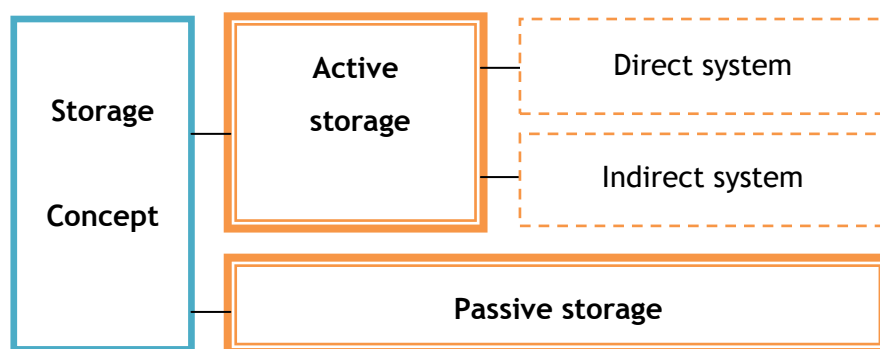


Figure 2.11 Classification of thermal storage concept systems in CSP plants. Source: (Gil A., Medrano M., et al, 2010)

2.6.1 Active storage systems

An example of a direct active system is a two-tank system, in which the HTF is stored in a hot tank, allowing its use during the night or cloudy days. The other tank is cold, and the cooled HTF is pumped for being heated in continuous cycles (Herrmann U., et al, 2004). In **Figure 2.12** is presented the system of Solar Tres project with a central tower receiver located near Seville, Spain, which was built during 2008 using a molten nitrate salts (NaNO_3 and KNO_3) storage two-tank system (Plataforma Solar de Almería, 2008-2009).

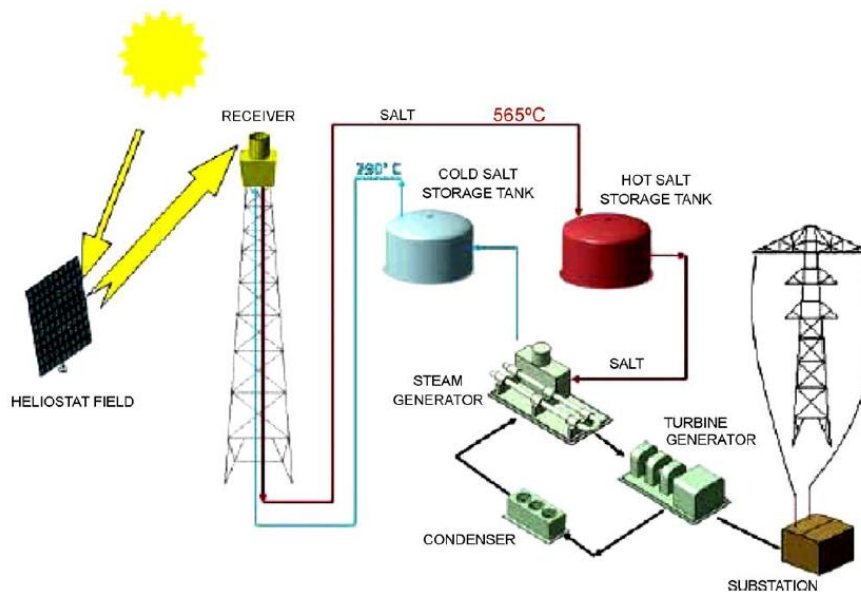


Figure 2.12 Scheme of installation of a center tower receiver power plant, with direct two-tanks based on molten salts. Source: (Gil A., Medrano M., et al, 2010)

The main advantages of a two-tank system are the fact of storing the materials separately, there's a low risk investment, the possibility to raise the solar field output temperature to 500 °C and also to increase Rankine cycle efficiency of the power block steam turbine.

Some negative aspects are the high cost materials used as HTF and storage, the high cost of heat exchangers due to the use of two-tanks instead of one, the difference between the fluid in cold and hot tank is relatively small and the high risk of solidification of storage fluid due to its high freezing point. The lowest cost electricity is not justifying the lowest cost of TES design and operation.

The other type of active storage system is called an indirect system, because the heat transfer fluid which is circulating in the solar field is different from the fluid contained in the storage tanks. This type of system was developed recently during the last years and is constituted by two tanks (hot and cold) where the energy is stored not directly by the HTF but by a second heat fluid (usually oil), making the use of a heat exchanger.

The “connection” between oil and salt occurs when heat from the HTF is absorbed by the oil and after transferred to the salt on the heat exchanger, as illustrated in **Figure 2.13**.

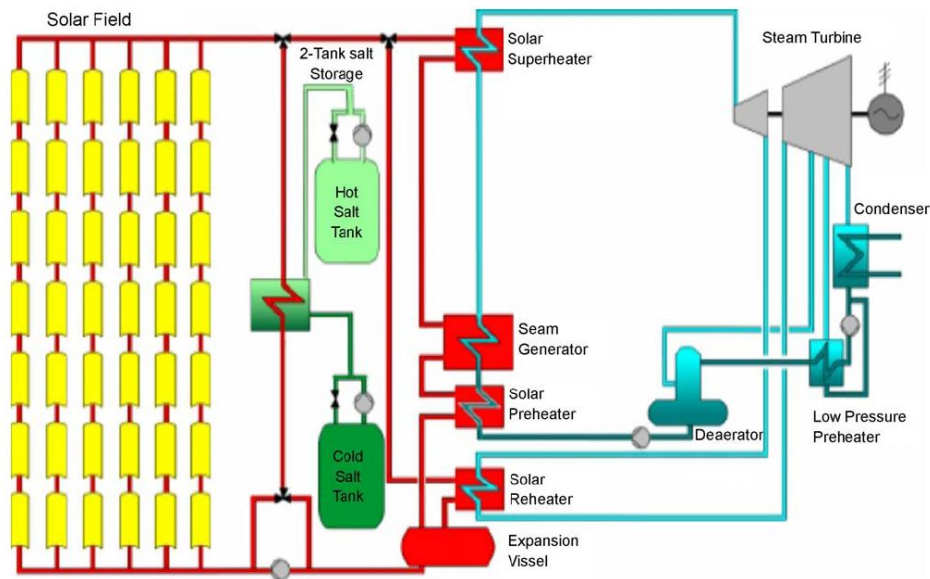


Figure 2.13 Scheme of installation of a parabolic trough power plant with indirect system, with two-tank storage system using oil (PT-Oil) and molten salts. Source: (Herrmann U., et al, 2002)

During the increasing energy demand and heating, when the oil is circulating in the solar collector field it is directed to the heat exchanger where it connects with the salt and cools from 391 °C to 298 °C. The other fluid, usually nitrate salt, flows in a different direction inside the heat exchanger (counter-currently) from the cold storage tank and is finally heated from 291 °C to 384 °C and then stored in the hot storage tank (Herrmann U., et al, 2002). On the other hand, along the decreasing of energy demand and solar radiation (cloudy periods or night) a reversed flow paths is occurring in the heat exchanger and the heat is transferred from the salt to the oil, providing thermal energy to steam turbine for generating electricity continuously. Once this indirect system is very similar to the previous two-tank system, its advantages and disadvantages are respectively similar to those of the two-tank direct systems.

There's another indirect active storage system but with one single tank where cold and hot fluids are both stored, i.e. in the same tank (**Figure 2.14**). The main advantage of this system would be reducing costs of a two-tank storage system. The single tank is called thermocline storage tank because it can storage hot and cold fluids inside the same space, the fluids being separated by stratification where the zone between them (hot and cold) is forming a label called thermocline. The disposal is very simple, where hot fluid is disposed on the top and the cold on the bottom, according to their densities. The HTF arriving from the solar field is

passing through a heat exchanger, heating the salts (as a thermal storage media), and both will be stored in a single tank. Usually, a filler material is used to help thermocline effect and according to previous experiences quartzite rock and silica sands are adapted and it was demonstrated that both materials are able to resist to molten salt environments with no deterioration (Brosseau D., et al., 2004).

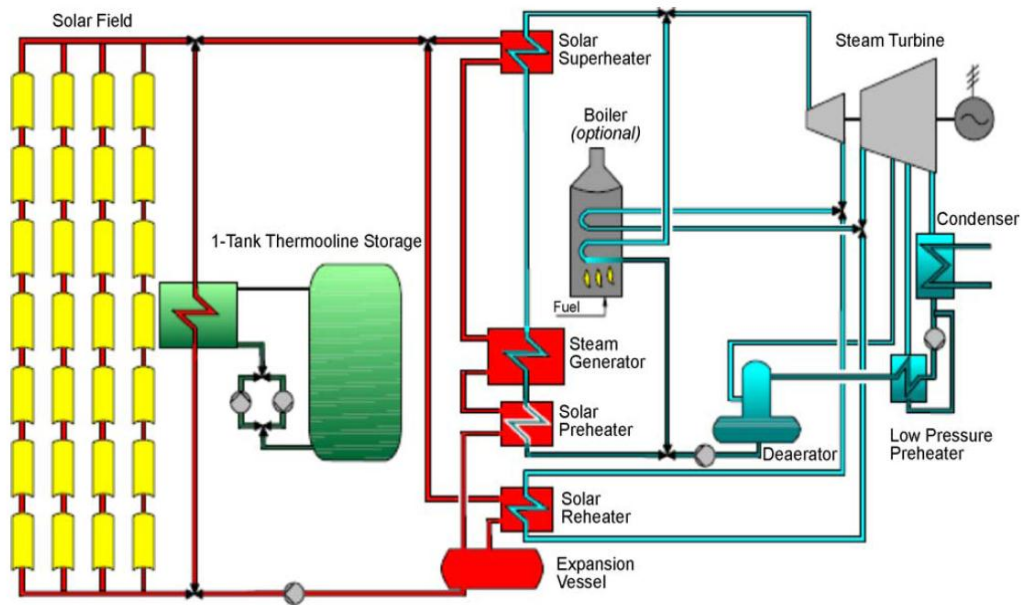


Figure 2.14 Scheme of installation of a parabolic trough power plant, with single-tank storage system using oil (PT-Oil) and molten salts. Source: (Herrmann U., et al, 2002)

The main economic advantages are the low costs of filler materials such as quartzite rock and sand that can replace most of HTF and the reduced costs of one single storage tank system. Thermocline effect needs a controlled charge and discharge of the HTF cycles and weather conditions are not constant, driving the storage design tank to a complex issue and of inefficiency of the thermo electrical plant.

2.6.2 Passive storage systems

These systems use solid storage systems, usually concrete, castable materials and phase change materials. In the case presented in **Figure 2.15**, a concrete storage material is used where solar thermal energy provided by solar field is transferred from HTF to concrete. A tubular system is incorporated in the storage material to transfer the thermal energy from

the HTF to the storage material. This plant was developed in the project “Midterm Storage Concepts” between 2001 and 2003 (Tamme R., et al, 2002) where the development of an efficient and low cost storage solid media was tested.

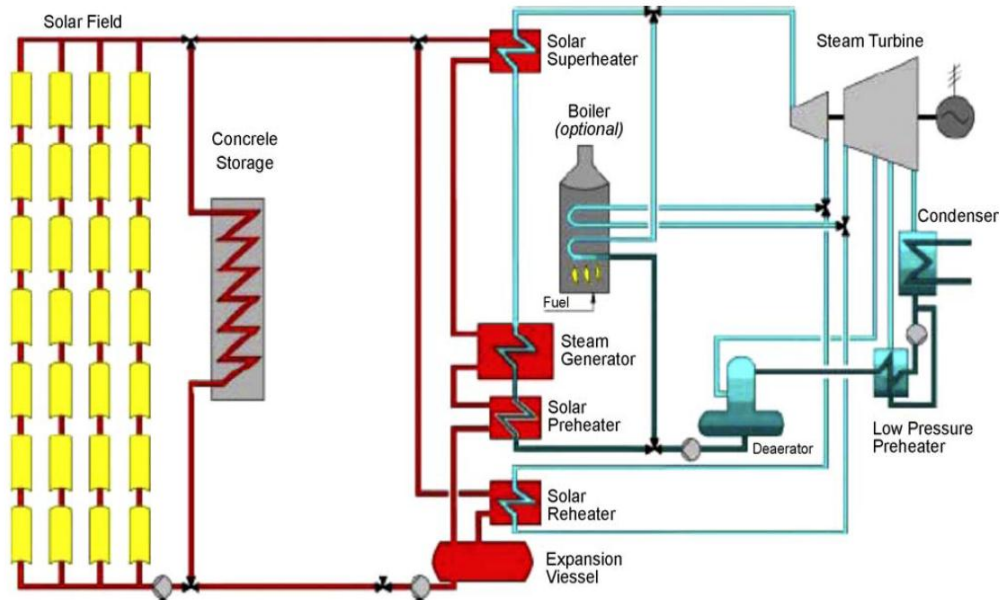


Figure 2.15 Scheme of a parabolic trough power plant, with passive storage concept using concrete or castable ceramics as storage system. Source: (Herrmann U., et al, 2002)

Clearly, the main advantage is the evident low cost of the material used as TES due to its big offer and availability in the markets, and also the good heat transfer between the concrete and the HTF. Indeed, this storage system can be very competitive with other storage systems as a consequence of its extremely low cost and significant market offers on the material used.

2.7 Identification of design requirements, key operation parameters and criteria for optimizing energetic performance

2.7.1 Design requirements

The components of a CSP plant should have an optimized design to better fit with HTF, TES system and parameters of solar field, meteorology, storage and power block. Previously, it was shown in **Figure 2.3** the main sub-systems of a CSP plant: concentrating system, solar receiver, back-up system, storage system and power block.

From a technical point of view, design requirements are the solar multiple factor, capacity factor and storage system capacity.

An optimized design of the CSP plant is based on electing the best configuration for the plant and each dimension of its containing sub-system, so optimizing the multiple factor (MS) with the storage system capacity.

Combining these factors it's obtained a capacity factor (CF) which is the relation between the annual energy generated by the CSP plant that would produce, if working during 8760 hours per year, at its nominal power. On **Table 2.11** are presented the orders of magnitude of CF's reached by a thermo solar plant as a function of its MS factor and storage capacity:

Table 2.11 Typical values of plant capacity factor as a function of the combination of MS-h in thermo solar plants. Source: (García C.X., 2001)

MS	Storage capacity (h)	CF
1	0	17 %
1.2	0	28 %
1.4	1.5	33 %
1.6	3	38 %
2	4.5	46 %

The considered factors are design requirements for having an evaluation of the storage capacity and energy generation of a thermal solar power plant.

From a structural point of view, the solar field parameters are its size, architecture (includes the number of heliostats for CTR, parabolic dish concentrators with Stirling engines for PDC, flat mirrors for LFR or parabolic curved mirrors for PTC needed according to CSP technology used), collector parameters (focal length and length, orientation and tilt angle, aperture), receiver parameters (type, coating and tilt angle), mirror reflectivity, each heliostat size, tube diameters, shading factor, cloudy factor and soiling factor according to each CSP technology used.

Meteorology parameters are location (latitude and longitude), total DNI, meteorological data (provided by typical meteorological year, representative of chosen location) and annual average wind speed.

The piping system and electrical components parameters are important design issues to follow the solar field area concerning the availability of land area and sunlight in the region where a CSP plant construction is planned.

The main electrical components are integrated in the power block: a steam turbine which will be linked to a generator and an electrical transformer to convert the electricity produced directly into the network (transmission and distribution).

2.7.2 Key operation parameters

The operation parameters of a CSP plant consist in the properties of the HTF used, but especially on the range of temperatures at which the HTF is able to operate, its mass flow rate and also the operating temperatures of each CSP technology.

Besides these parameters it's important to evaluate the efficiency of mechanical to electricity conversion, the efficiency of solar to electric conversion and annual electric energy production of a CSP plant, as well solar irradiance.

Operation temperatures of HTF are listed in the previous **Table 2.8** and **Table 2.9**, and resuming it, all different types of oils that can be used are operating between 200 °C (minimum) and 400 °C (maximum) and most of salts are operating between 250 °C (minimum) and 850 °C (maximum), which allows more temperature operation flexibility of the HTF when molten salts are used. Other temperatures to be considered are the range of temperatures of each CSP technology system as presented in **Table 2.6**. It was concluded that the technologies that present more flexibility are CTR and PDC, operating between 150 °C and 2000 °C. On the other hand, PTC and LFR are operating on much lower temperatures and lower range, between 50 °C and 400 °C. Previous studies have reported some data performances regarding the four CSP technologies cited in this study using oil or steam as heat transfer fluids and are listed on **Table 2.12** below.

Table 2.12 Current performance of CSP technologies. Source: adapted from (IEA, 2010)

CSP technology	Peak solar to electricity conversion efficiency (%)	Annual solar-to-electricity efficiency (%)
Parabolic trough collector	23-27	15-16
Linear Fresnel Reflector	18-22	8-10
Central Receiver Tower	20-27	15-17
Parabolic Dish Collector	20-30	20-25

Comparing the four technologies it is observed that PTCs have the higher peak solar to electricity conversion efficiency, but looking at the annual solar to electricity efficiency PDCs perform better. As expected, LFR is a technology under development, so it doesn't have high values of annual efficiencies when compared to other CSP technologies. The importance of solar irradiance resides on predicting solar beam irradiance in the direction of rays (as also

known by DNI), the amount of radiation incident on the reflector surface, the cloud factor and optical efficiency (function of absorptivity of the absorber pipes or mirror reflectivity).

2.7.3 Criteria

The criteria for optimizing energetic performance is based on minimizing maintenance, operation and investments costs for projects, construction, materials and fluids used, and maximizing and optimizing crucial design requirements and key operation parameters, contributing for a further CSP optimization and reducing limitations of these systems.

Reviewing design requirements and key operation parameters, is necessary to adjust them between different configurations and technologies used, for an optimization of energetic performance, and for having a greater efficiency in the general CSP system and its back up on initial capital invested.

The most important criteria for multiple factor, capacity factor and storage system capacity is maximizing those factors and parameters as much as possible to meet all the other requirements, just as location and configuration of solar field (size, focal length and length, orientation and tilt angle, coating, type and aperture of collectors), reflectivity of the mirrors, diameters of piping system and total DNI.

On the other hand, decisive key operation parameters are the range of operating temperatures (of HTF and of each CSP technology), amount of solar irradiance (solar beam irradiance, incident radiation on reflector surface) and energy conversion efficiencies (solar-to-thermal and mechanical-to-electric, optical and overall efficiency of the CSP plant), where the aim is maximizing these parameters and achieving an improvement of the energetic performance of the CSP plant considering also some limitations on range of temperatures, efficiencies and amount of solar irradiance.

To better match the goals of energy production from CSP and its competitiveness with current electrical markets in USA, MENA countries and Italy, Greece, Spain and Portugal (Southern Europe), as potential regions for CSP investments and installations, it is necessary to have well defined criteria on CSP plants and get a faster return of the initial investment made.

So, many improvements need to be made on these technologies, where is critical to ensure that these improvements can progress quickly from laboratory and projects to pilot plants and commercial applications.

3. Technical description

3.1 Development of a CSP plant model

A proposed model for a CSP (Concentrating Solar Power) plant is developed using the CTR (Central Tower Receiver) technology, as described in the previous section. This CSP plant model, presented in **Figure 3.1**, is developed with MATLAB© software (v. 2010a) and is constituted by three sub-systems: solar thermal energy generation (solar position, heliostats field and tower receiver); heat transfer fluid (HTF) and storage system; and electric generation system.

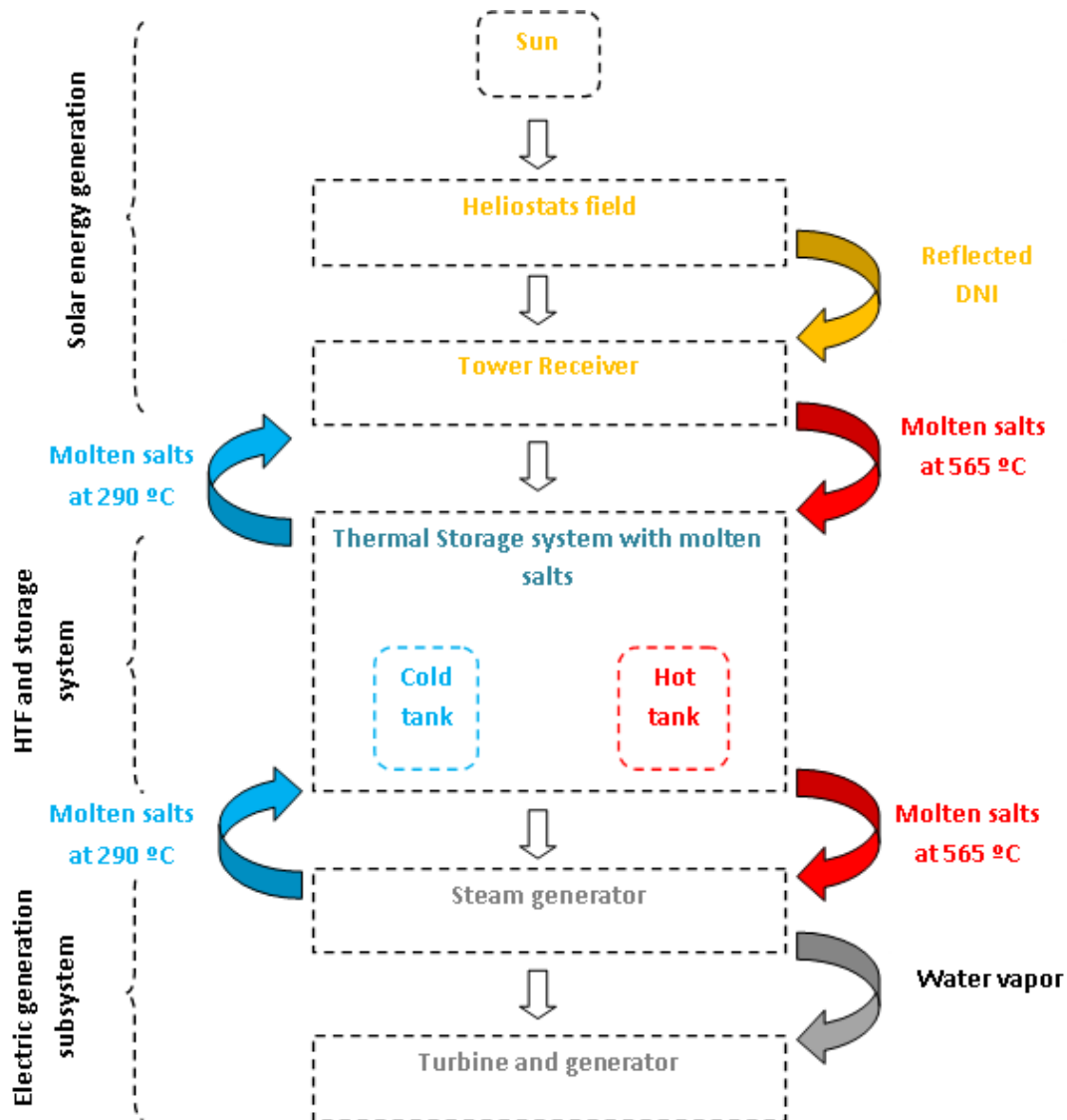


Figure 3.1 CSP plant scheme with the main systems for modeling and simulation with Matlab.

3.1.1 The thermal solar energy generation system

This part of the plant requires modeling the solar radiation over the year of 2012, taking into account the geographic location where the CSP plant will be built, using solar angles and solar radiation equations and defining the solar field parameters, which is going to be a field of heliostats. On section 2.7 the most relevant parameters for a solar field were described, i.e. the optical efficiency, the number of heliostats, the heliostats field layout, the type of receiver, the tilt angle and the type of HTF. The coordinates of the chose location of this plant are $41^{\circ}73'$ N (latitude) and $1^{\circ}83'$ W (longitude), which is a town called Sallent in Catalonia region of Spain. The desired autonomy of this CSP plant is to achieve between one and four hours of electrical power production per day without solar radiation.

3.1.1.1 Solar position

The solar position is very important because the sun is changing every hour during a day and every day during the year, so it's necessary to model the solar coordinate systems (horizontal and equatorial) during the year through solar angles. The horizontal coordinates are the solar altitude angle (α_s) and the azimuth (φ), the latter being consisted by the solar azimuth angle (φ_s) and the surface azimuth angle (φ_{surf}), as shown in **Figure 3.2**. The equatorial coordinates are the declination (δ_s) and the hour angle (h_s).

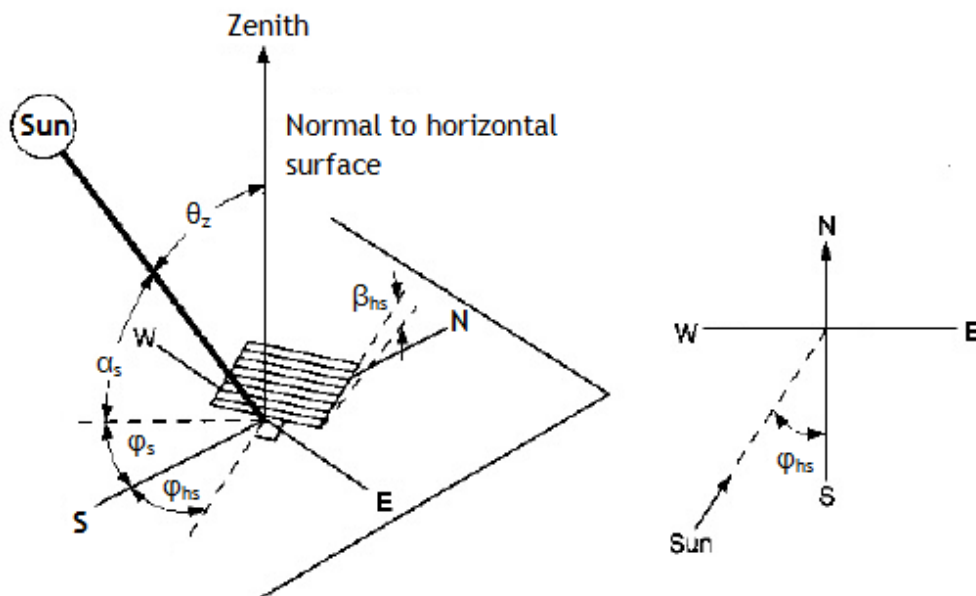


Figure 3.2 Slope, surface azimuth angle, solar azimuth angle and zenith angle for a tilted heliostat surface (left). Plan view showing solar azimuth angle (right). Source: Duffie J.A. and Beckman W.A, 2006.

First of all, one has to calculate the solar declination (δ_s), the solar altitude angle (α_s), the solar hour angle (h_s), the solar azimuth angle (φ_s) and the solar zenith angle (θ_z), which their equations, are presented below.

The solar declination was calculated through the equation (1), proposed by Duffie J.A. and Beckman W.A, 2006, where N is the number of days during the year of 2012 starting from the 1st of January.

$$\delta_s = 23,45 \cdot \sin\left(\frac{360}{365}(284 + N)\right) \quad (1)$$

Plotting the declination is obtained the solar declination angle over the year of 2012, as presented on **Figure 3.3**, which has its maximum value during the summer time and the lowest value on the winter time.

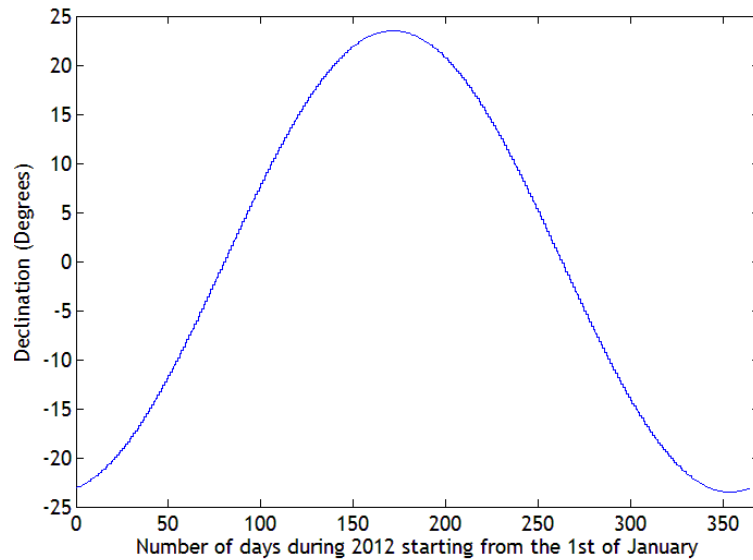


Figure 3.3 Solar declination angle for the year of 2012 and for the latitude and longitude proposed.

The solar hour angle (h_s) is calculated following the same literature (Duffie J.A. and Beckman W.A, 2006) using equation (2), where the solar hour, also known as solar time, is the apparent solar time of the day (starting on 0 till 24):

$$h_s = (\text{Solar hour} - 12) \cdot 15^\circ \quad (2)$$

The solar altitude angle (α_s) is computed with the next equation (3) proposed by the same authors (Duffie J.A. and Beckman W.A, 2006), where all the parameters are calculated and defined previously in this chapter.

$$\alpha_s = \sin^{-1}(\cosh h_s \cdot \cos \delta_s \cdot \cos \phi_{lat} + \sin \delta_s \cdot \sin \phi_{lat}) \quad (3)$$

Figure 3.4 shows the plot of the solar altitude angle over the year of 2012, which is negative during the night periods, 0 at the sunset or at the sunrise and positive during the day (when is 90° means that the sun is at the equinox).

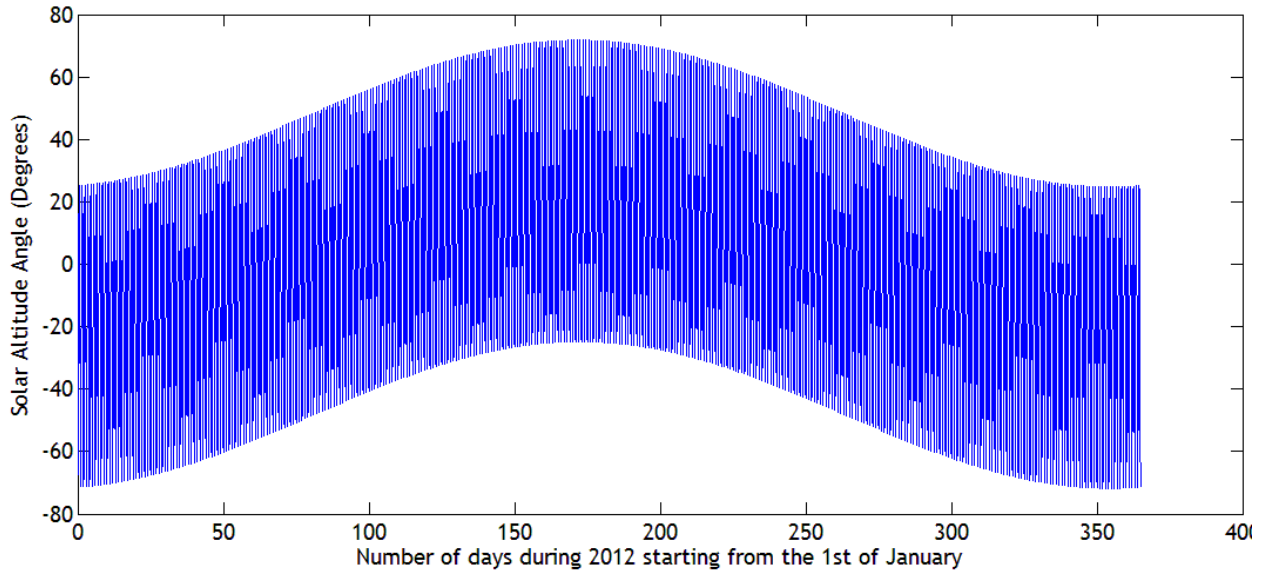


Figure 3.4 Plotting the solar altitude angle over the year 2012.

A more detailed perspective of this angle is presented in Figure 3.5 in order to show its behavior along a day during the highest periods of irradiation.

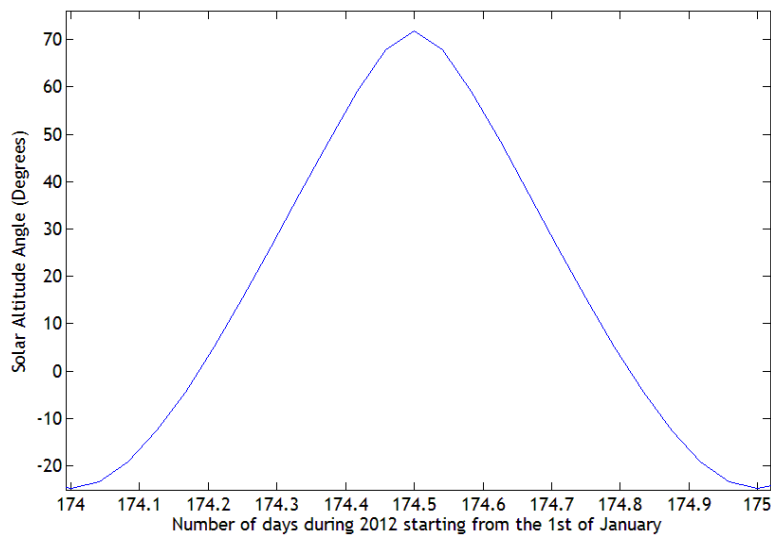


Figure 3.5 Plotting the solar altitude angle over one day of the year 2012 which is the day number 174 (22nd of June)

The solar zenith angle (θ_z) is obtained as a function of α_s (Duffie J.A. and Beckman W.A, 2006), subtracting 90° to this angle as presented in equation (4):

$$\theta_z = 90^\circ - \alpha_s \quad (4)$$

The solar azimuth angle (φ_s) was computed based in a literature work which considers a solar azimuth factor (φ') and the solar hour angle conditions, for getting such angle more accurately (Shen C., et al, 2008), as presented on the following equations (5), (6) and (7):

$$\varphi' = \sin^{-1}\left(\frac{\cos\delta_s \cdot \sin h_s}{\sin\theta_z}\right) \quad (5)$$

The solar hour angle conditions proposed are:

If $\cos h_s \geq \left(\frac{\tan \delta_s}{\tan \phi_{lat}}\right)$, then:

$$\varphi_s = 180^\circ - \varphi' \quad (6)$$

Else: $\cos h_s \leq \left(\frac{\tan \delta_s}{\tan \phi_{lat}}\right)$, then:

$$\varphi_s = 180^\circ + \varphi' \quad (7)$$

The surface azimuth angle (φ_{surf}) was obtained following the methodology proposed in the same work (Shen C., et al, 2008), which is conditioned by the positive or negative difference between the solar azimuth angle and the solar azimuth factor, as shown in equations (8) and (9):

If $\varphi_s - \varphi' > 0$, then:

$$\varphi_{surf} = \varphi' + 90^\circ \quad (8)$$

Else $\varphi_s - \varphi' < 0$, then:

$$\varphi_{surf} = \varphi' - 90^\circ \quad (9)$$

After obtaining the solar coordinates the next step is to calculate the rotation angles of each heliostat, which are consisted by the slope of each heliostat during the total hours of the year (β_{hs}) and the azimuth angle relative to the tower receiver for each heliostat during the year (φ_{hs}).

Those two rotation angles are represented in **Figure 3.6** where the rotation of one heliostat to west or east is defined as φ_{hs} (taking as reference the south direction), and the slope (inclination) from 0° till 90° , is defined as β_{hs} .

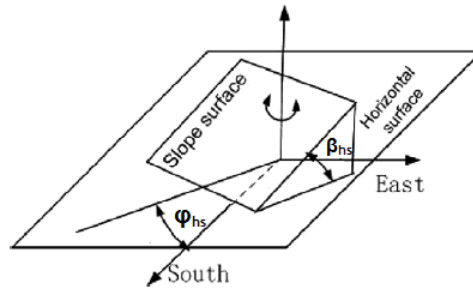


Figure 3.6 Slope of each heliostat during the total hours of the year (β_{hs}) and the azimuth angle relative the tower receiver for each heliostat during the year (φ_{hs}). Source: adapted from (Shen C., et al, 2008)

The heliostat field layout with 624 heliostats was developed following the disposition of the heliostats on PS10 (solar plant 10), taken as an example. Using *Plot Digitizer v.2.5.0* software (Huwaldt J. A., 2010) it is possible to determine the exact coordinates proposed for PS10 heliostat field that gives the exact position of each heliostat on the solar field, as shown in **Figure 3.7**. This way, the distances from each heliostat to the tower base and to the tower receiver are known.

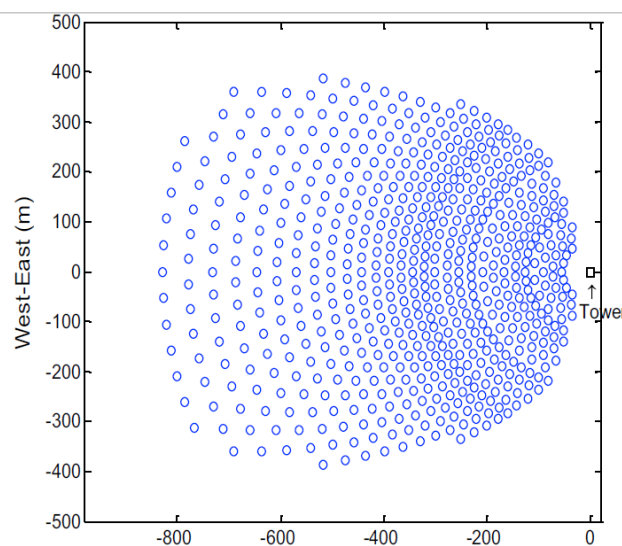


Figure 3.7 Proposed PS10 field layout with the tower receiver on position. Source: (Wei X., et al, 2010)

After getting the coordinates of each heliostat relative to the tower receiver (x_{hs} , y_{hs}) (**Figure 3.8**) and admitting the tower's receiver reference coordinates (x_{tr} , y_{tr}) as zero, it's possible to import this data to the workspace of Matlab and then use it for calculating the heliostat rotation angles.

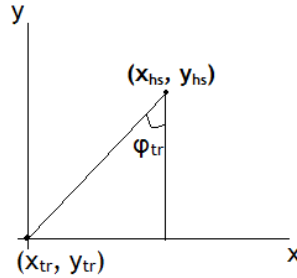


Figure 3.8 Solar azimuth angle of each heliostat (φ_{tr}) relative to the tower receiver (x_{hs} , y_{hs}).

On equation (10) is presented the calculation of the solar azimuth angle of each heliostat relative to the tower receiver and it's the first rotation angle obtained for each heliostat, which is going to be called the solar azimuth angle of each heliostat during a year relative to the tower receiver (φ_{hs}).

$$\varphi_{tr} = \text{atan}\left(\frac{y_{tr} - y_{hs}}{x_{tr} - x_{hs}}\right) \quad (10)$$

On equation (11) is presented the formula for the solar altitude angle of the tower receiver for each heliostat (α_{tr}) and illustrated in **Figure 3.9**, which is defined by the tower height (h_{tr}), the height of each heliostat (h_{hs}) and the distance of each heliostat from the tower base (d_{tb}).

$$\alpha_{tr} = \text{atan}\left(\frac{h_{tr} - h_{hs}}{d_{tb}}\right) \quad (11)$$

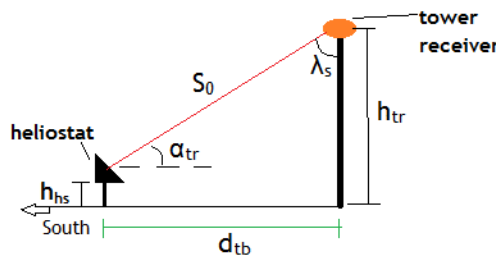


Figure 3.9 Solar altitude angle of the tower receiver relative to each heliostat position on the solar field.

For obtaining the distance of each heliostat from the tower base (d_{tb}), the Pythagorean theorem is implemented. On equation (12), x_{tr} and y_{tr} are the tower position coordinates, and x_{hs} and y_{hs} are the position coordinates for each heliostat on the heliostat field, as shown in the previous **Figure 3.8**.

$$d_{tb} = \sqrt{(x_{hs} - x_{tr})^2 + (y_{hs} - y_{tr})^2} \quad (12)$$

Finally, the determinations of the rotation angles of each heliostat (β_{hs} and φ_{hs}), in order to reflect the incident radiation on them and direct it to the tower receiver, are obtained according to Snell's law (Weisstein E. W., 1996-2007) and shown in equations (13) and (14):

$$\beta_{hs}(\alpha_{tr} + \alpha_s) = \frac{\alpha_{tr} + \alpha_s}{2} \quad (13)$$

$$\varphi_{hs}(\varphi_{tr} + \varphi_s) = \frac{\varphi_{tr} + \varphi_s}{2} \quad (14)$$

The calculation of the previous angles is used for getting the solar incidence angle on each heliostat (θ_s), which depends also on the latitude (ϕ_{lat}), the solar declination (δ_s), the solar hour angle (h_s) and the slope of each heliostat along each hour of the day and each day of the year (β_{hs}), as described in equation (15).

$$\begin{aligned} \theta_s = \cos^{-1} [& (\sin \phi_{lat} \cdot \sin \delta_s \cdot \cos \beta_{hs}) - (\cos \phi_{lat} \cdot \sin \delta_s \cdot \sin \beta_{hs} \cdot \cos \varphi_{surf}) + \\ & (\cos \phi_{lat} \cdot \cos \delta_s \cdot \cos h_s \cdot \cos \beta_{hs}) + \\ & (\sin \phi_{lat} \cdot \cos \delta_s \cdot \cos h_s \cdot \sin \beta_{hs} \cdot \cos \varphi_{surf}) + \\ & (\cos \delta_s \cdot \sin h_s \cdot \sin \beta_{hs} \cdot \sin \varphi_{surf}) \end{aligned} \quad (15)$$

The tower receiver design is very important in order to absorb the maximum reflected radiation from the solar field and for getting the expected thermal energy on the receiver to warm up the molten salts to desired temperatures. Therefore, three angles are important to define and calculate, such as, the receiving angle of the reflected rays on the aperture receiver (θ_{tr}), as presented in **Figure 3.10**, the tilt angle of the aperture plane relative to the

vertical direction (δ_{tr}) and the angle between reflected sun rays and the vertical direction (λ_s), which are going to be considered as constant for all the hours of the year.

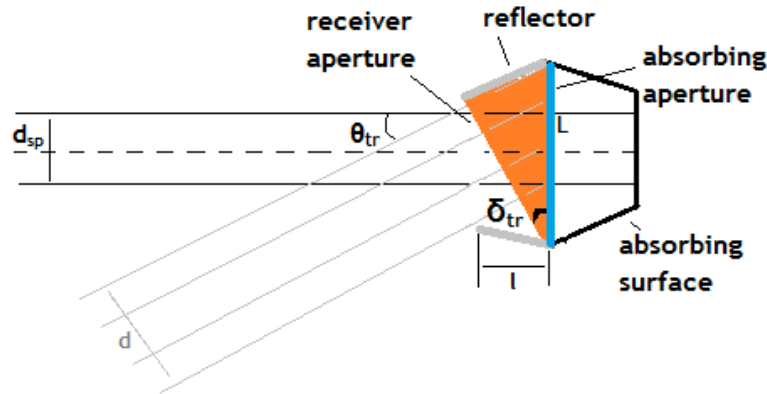


Figure 3.10 Definition of the tower receiver characteristics and θ_{tr} . Source: adapted from (Wei X., et al, 2010)

For the value of δ_{tr} it was considered the same angle as the PS10 tilt angle of 12.5° (Wei X., et al, 2010). The determination of θ_{tr} is described in equation (16) and the determination of λ_s is presented in equation (17):

$$\theta_{tr} = \arcsin \left(\frac{-2 \cdot d_{sp} \cdot l + L \sqrt{4 \cdot l^2 + L^2 - d_{sp}^2}}{4 \cdot l^2 + L^2} \right) = 28.36^\circ \quad (16)$$

$$\lambda_s = 90^\circ - \theta_{tr} = 61.64^\circ \quad (17)$$

After getting all the solar angles needed and defining the solar field layout, it is also important to define the optical efficiency of the solar field, which is obtained by the product of the cosine efficiency, atmospheric attenuation efficiency and reflectivity efficiency. Other parameters such as blocking and shadowing and interception were not considered, due to the lack of information. Thus, on equation (20) is proposed a calculation for the optical efficiency of the heliostats field, where the other parameters, namely $\eta_{\cosine}$ and η_{at} , are presented in equations (18) and (19), respectively:

$$\eta_{\cosine} = \frac{\sqrt{2}}{2} \cdot (\sin \alpha_s \cdot \cos \lambda_s - \cos(\varphi_{surf} - \varphi_s) \cdot \cos \alpha_s \cdot \sin \lambda_s + 1) \quad (18)$$

$$\eta_{at} = 0,99321 - 0,0001176 \cdot S_0 + 1,97 \cdot 10^{-8} \cdot S_0^2 \quad (19)$$

$$\eta_{opt} = \eta_{cosine} \cdot \eta_{at} \cdot \eta_{ref} \quad (20)$$

The η_{ref} efficiency is obtained according to the characteristics of the heliostats mirror reflectivity from PS10, presented in **Table 3.1**, which resumes the pre-defined and calculated parameters of the heliostat field in terms of geographic location of the CSP plant, heliostats and tower receiver parameters.

Table 3.1 Heliostat and tower receiver parameters. Source: adapted from (Noone C. J., Torrilhon M., Mitsos A., 2012)

Location	
Latitude	41°73' N
Longitude	1°86' W
Heliostats	
Number	624
Width	12.84 m
Height	9.45 m
Area	$A_{hs} = 121.34 \text{ m}^2$
Mirror reflectivity efficiency	$\eta_{ref} = 0.88$
Tower Receiver	
Tower height (h_{tr})	110 m
Absorbing aperture height (L)	20 m
Diameter of the reflected spot (d_{sp})	10 m
Reflector length (l)	8 m
Tower receiver efficiency	$\eta_{tr} = 0.90$
Tilt angle of the receiver aperture	$\delta_{tr} = 12.5^\circ$
Receiving angle of the reflected rays on the aperture receiver	$\theta_{tr} = 28.36^\circ$
angle between reflected sun rays and the vertical direction	$\lambda_s = 61.64^\circ$

3.1.1.2 Solar radiation

For modeling the incident radiation on the tower receiver it is mandatory to calculate the extraterrestrial radiation (G_0), the beam irradiance normal to the solar beam (B_{0c}), the solar beam irradiation on an inclined surface (B_{ic}) and to define the linke atmospheric turbidity factor (Tlk), the relative optical air mass (m_{opt}) and the Rayleigh optical thickness at air mass m_{opt} (dr_m). The extraterrestrial radiation normal to the solar beam (G_0) is computed as a function of the solar constant ($G_{sc} = 1670 \text{ W.m}^{-2}$), the number of each day during the entire year of 2012 (N) and the zenith solar angle (θ_z), as defined in equation (21):

$$G_0 = (G_{sc} \cdot (1 + 0,033 \cdot \cos \frac{360N}{365})) \cdot \cos \theta_z \quad (21)$$

After getting this value for every hour of the year, the beam irradiance normal to the solar beam (B_{0c}) is calculated through equation (22) based on a model by the *JCR's Institute of Energy and Transport* (Huld T., Dunlop E.D., 2012), which is dependent also on the parameters Tlk , m_{opt} and dr_m that are going to be calculated through upcoming equations.

$$B_{0c} = G_0 \cdot \exp(-0,8662 \cdot Tlk \cdot m_{opt} \cdot dr_m) \quad (22)$$

For computing the relative optical air mass (m_{opt}), a condition for the solar altitude angle (α_s) is used, as suggested in the literature (Bason F., 2012) and described below on equations (23) and (24):

If $\alpha_s > 30^\circ$:

$$m_{opt} = \frac{1}{\sin \alpha_s} \quad (23)$$

Else $\alpha_s \leq 30^\circ$:

$$m_{opt} = \frac{1,002432 \cdot \sin^2 \alpha_s + 0,148386 \cdot \sin \alpha_s + 0,0096467}{\sin^3 \alpha_s + 0,149864 \cdot \sin^2 \alpha_s + 0,0102963 \cdot \sin \alpha_s + 0,000303978} \quad (24)$$

The Rayleigh optical thickness at air mass m (dr_m) is obtained with two empirical equations suggested by Bason F. (2012), as demonstrated in the following equations (25) and (26).

If $m_{opt} \leq 20$:

$$dr_m = \frac{1}{6,6296 + 1,7513 \cdot m_{opt} - 0,1202 \cdot m_{opt}^2 + 0,0065 \cdot m_{opt}^3 - 0,00013 \cdot m_{opt}^4} \quad (25)$$

Else $m > 20$:

$$dr_m = \frac{1}{10,4 + 0,718 \cdot m_{opt}} \quad (26)$$

After all the previous formulated equations it is essential to define the last parameter for getting B_{0c} , which is the Linke atmospheric turbidity factor (Tlk). This factor is defined in

Table 3.2 and is directly related to the different atmospheric conditions.

Table 3.2 The Linke turbidity factor under typical atmospheric conditions. Source: (Bason F., 2012)

Atmospheric properties	Linke Turbidity Factor
Pure Rayleigh atmosphere	1
Extremely clear, cold air	2
Clear, warm air	3
Moist, warm air	4-6
Polluted atmosphere	8

For this work a Pure Rayleigh atmosphere is considered (Tlk=1), so as to obtain an optimized scenario for perfect atmospheric conditions and clear sky; otherwise the irradiation will be decreased as the atmospheric properties are worst, i.e. as Tlk is getting bigger till a polluted atmosphere, as the city of Ulan Bator in Mongolia that is considered the second most polluted city in the world during 2011 (Time Science - Ecocentric, 2011).

Finally and after calculated the B_{0c} which is depending on G_0 , Tlk, m_{opt} and dr_m , is explained how to get the solar beam irradiation on an inclined surface (B_{ic}) - that is going to be each

heliostat defined as a function of B_{0c} and the sine of the solar incidence angle on each heliostat (θ_s) in every hour of the year 2012, through equation (27).

$$B_{ic} = B_{0c} \cdot \sin \theta_s \quad (27)$$

After obtaining the value of irradiation for all the year and for each heliostat, the solar thermal power received at the tower receiver (Q_{tr}) is calculated as the sum of this irradiation for each heliostat j and for each hour of the year i multiplied by each heliostat area (A_{hs}) and its optical efficiency (η_{opt}), i.e., on each hour it's obtained the total irradiation reflected by the 624 heliostats at the tower receiver, as presented in equation (28):

$$Q_{tr} = \sum_{\substack{i=[1,8760] \\ j=[1,624]}} B_{ic}(i,j) \cdot A_{hs} \cdot \eta_{opt} \quad (28)$$

By creating a plot for Q_{tr} , it is expectable that the maximum power is obtained during the summer time and the lowest during the winter time because it is proportional to the amount of solar beam irradiation on these periods of the year, as shown in **Figure 3.11**.

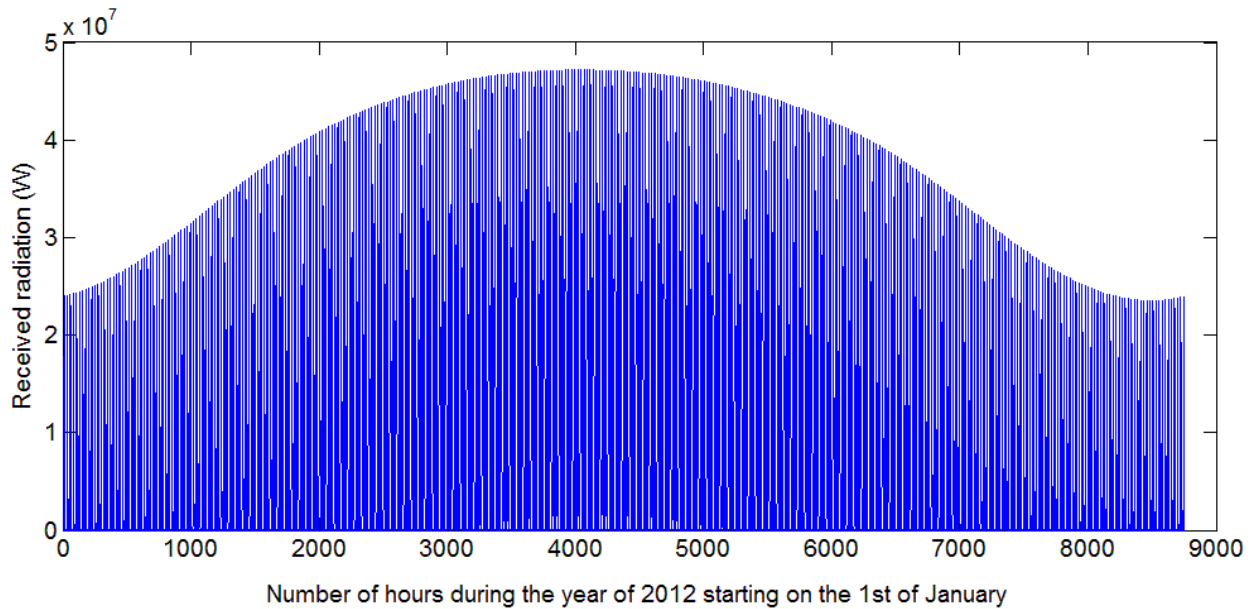


Figure 3.11 Solar thermal power on the tower receiver (Q_{tr}) in each hour of the year 2012.

A more detailed perspective for one period of the day with high irradiation is shown in **Figure 3.12**, to better understand that in the peak hours of the day the energy received on the

tower receiver is at its maximum and out of these periods it's at its minimum, related to the total solar beam irradiation B_{ic} on the solar field.

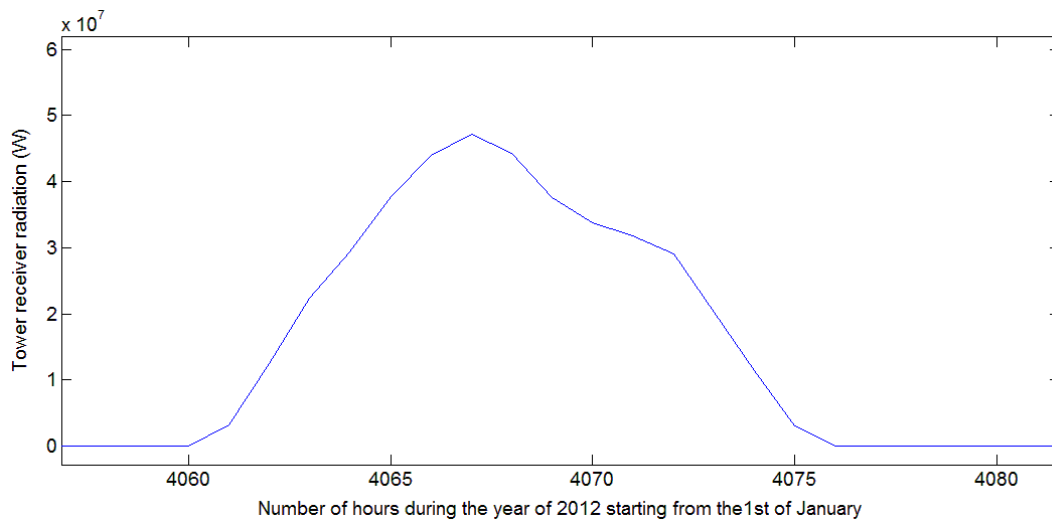


Figure 3.12 Thermal power on the tower receiver along one of the hottest days during the year of 2012 (17th of June).

The highest value of thermal power received on the tower receiver is 47.1 MW_{th} during the month of June (summer) and the lowest value is 23.9 MW_{th} (for the peak hours in the day) during the month of December, as expected.

3.1.2 The storage and electric generation systems

Once computed the amount of energy in the tower receiver during the year of 2012, where the molten salts will warm up from 290 °C to 565 °C (minimum and maximum operation temperatures of the Central Tower Receiver - CTR - plant), it's possible to design the storage system, consisted by a “hot tank” and a “cold tank”, and using dynamic differential equations for the heat transfer between the fluid and each tank, along with energy balances on the cold and the hot tank. The followed criteria to design the storage system are based on the autonomy of the CSP plant, where the goal is to achieve between one and four hours of electrical power production per day without solar radiation. The molten salt is admitted to be a nitrate salt consisted by NaNO₃ and KNO₃ with a specific heat (Cp) equal to 2660.19 J/kg·K at 400 °C as proposed by Sohal, et al (2010). This value will be considered constant during the calculations for different operating temperatures. So, the constant values will be Cp and the mass of molten salts in each tank ($M = V \cdot \rho$) and by assuming that the system doesn't have any losses ($U = 0$; meaning adiabatic operation), the energy balance equation applied to the tower receiver and the turbine cycle is presented by equation (29) (Ingham J., et al., 2000):

$$\frac{dE}{dt} = \dot{m}_i \cdot C_p \cdot T_i - \dot{m}_o \cdot C_p \cdot T_o \quad (29)$$

Where $\dot{m}_i$ is the inlet mass flow rate of molten salt, $\dot{m}_o$ is the outlet mass flow rate of molten salt, C_p is the specific heat, T_i is the inlet temperature of each tank and T_o is the outlet temperature of each tank.

$$M C_p \frac{dT}{dt} = \dot{m} \rho C_p (T_i - T_o) + U A (T_a - T_o) \quad (30)$$

Equation (30) will be used for calculating the temperatures reached during the operation of the CTR plant in the tower receiver and the turbine cycle, where M is the mass of each tank, T_i is the inlet tank temperature, T_o is the outlet tank temperature and T_a is the ambient temperature, U is the global coefficient of heat transfer and A the area of each tank, that are going to be zero because system losses are not considered.

During this model are used many different variables, so **Table 3.3** can be useful along this chapter.

Table 3.3 Resuming table with the most relevant variables.

Variable	Description
$T_{tr,i}$	Inlet temperature at the tower receiver
$T_{tr,o}$	Outlet temperature at the tower receiver
Q_{tr}	Solar power at the tower receiver
$T_{h,i}$	Hot tank inlet temperature
$T_{h,o}$	Hot tank outlet temperature
$T_{turb,i}$	Turbine inlet temperature
$T_{turb,o}$	Turbine outlet temperature
$T_{c,i}$	Cold tank inlet temperature
$T_{c,o}$	Cold tank outlet temperature
M_h	Hot tank total mass of molten salt
M_c	Cold tank total mass of molten salt
P_{dem}	Power demand
$\dot{m}_1$	Mass flow rate between hot tank, turbine and cold tank
$\dot{m}_2$	Mass flow rate between cold tank, tower receiver and hot tank
bypass	Turbine control parameter

For building this model Matlab tool called Simulink is used, being the general view of this model presented in Figure 3.13.

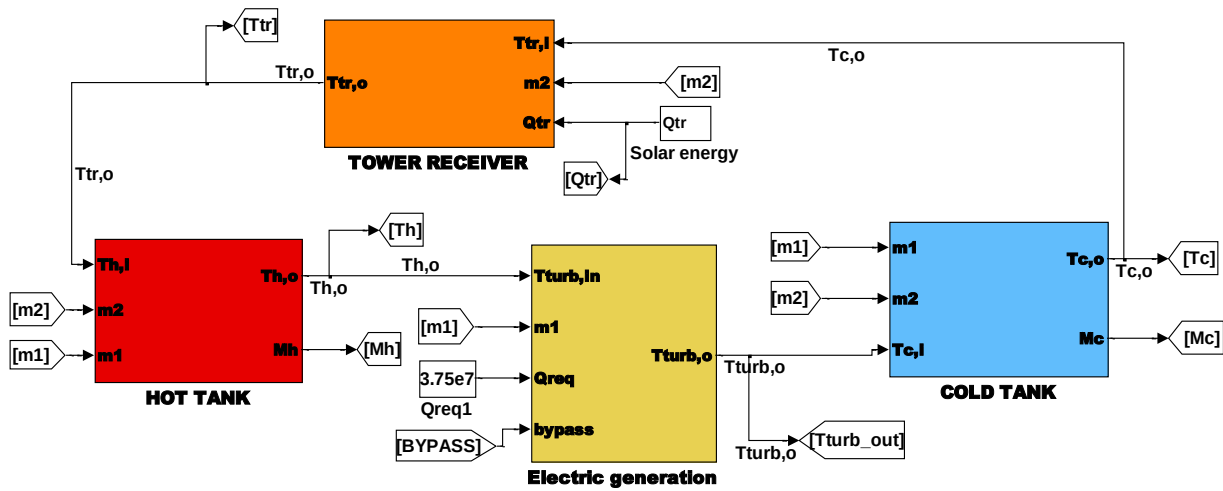


Figure 3.13 Simulink model of the CSP plant with storage system.

Initially two equal mass flows are defined and they are assumed to be constant values, namely $\dot{m}_1$ and $\dot{m}_2$. The mass flow $\dot{m}_1$ is the molten salts flow rate that goes out of the hot tank and passes through the steam generator for providing the steam in order to produce electrical power in the turbine and then continues flowing to the cold tank from the steam generator. The mass flow $\dot{m}_2$ is the molten salts flow rate that goes out of the cold tank into the tower receiver for warming up and then continues towards the hot tank. In order to design the heat transfer fluid mass flow, equation (30) is developed as a function of $\dot{m}$, considering the maximum energy at the tower receiver for obtaining this values, which means that mass is flowing at its maximum flow rate (variable mass flows are not considered on this model), as shown in equation (31):

$$Q_{tr} = \dot{m} C_p \Delta T \leftrightarrow \dot{m} = \frac{Q_{tr}}{C_p \cdot \Delta T} \quad (31)$$

$$\begin{aligned} \dot{m} = \dot{m}_1 = \dot{m}_2 &= \frac{4.7186 \times 10^7 \text{ W}}{2660.19 \text{ J/(kg} \cdot \text{K)} \times (565^\circ\text{C} - 290^\circ\text{C})} = 64.48 \text{ kg/s} \\ &= 232115.75 \text{ kg/h} \end{aligned}$$

The dimensions of the storage tanks determine the autonomy of the CSP plant (to remark the importance of this fact) and the masses that control the cold and the hot tank are defined by

M_c and M_h , respectively. It is admitted that each tank has the same dimensions, with 8 meters of diameter (d) and 4 meters of height (h_{tank}) in a cylindrical shape. Therefore, the volume of each tank is calculated following equation (32):

$$V_{\text{tank}} = \pi \cdot r^2 \cdot h = \pi \cdot \left(\frac{8}{2}\right)^2 \cdot 4 = 201.1 \text{ m}^3 \quad (32)$$

Once the volume of each tank is known, it's possible to get the total mass of molten salt in each tank (M_c and M_h), where the density of molten salts (ρ_{ms}) is extrapolated to 565 °C (for estimating a maximum possible mass in each tank) according to literature values between 20 °C and 400 °C (Sohal M.S., et al, 2010), so the density for 565 °C obtained was 1870 kg/m³. According to the equation (33), the mass of molten salt in each tank is:

$$M_c = M_h = V_{\text{tank}} \cdot \rho_{ms} = 201.1 \text{ m}^3 \times 1870 \text{ kg/m}^3 = 375985.8 \text{ kg} \quad (33)$$

This value is an estimation comparing to the annual electric power demand of Catalonia (7 634 078 Habitants) during 2005 of 5152.8 MW_e (UNESA - Asociación Española de la Industria Eléctrica, 2005). So, this solar plant is designed to supply four towns nearby to the CTR plant location in the Bages County, regarding also the existence of salt mines in this region. The selected towns are Sallent (7061 Habitants), Balsareny (3505 Habitants), Súria (6454 Habitants) and Santpedor (6787 Habitants), according to their updated population (Comarcàlia, 2012), where summing up their estimated power demands, is obtained a total value of power demand in equation (34):

$$\begin{aligned} P_{\text{dem}} &= P_{\text{dem,Sallent}} + P_{\text{dem,Balsareny}} + P_{\text{dem,Súria}} + P_{\text{dem,Santpedor}} \\ &= 4.82 + 2.44 + 4.7 + 5 = 16.96 \text{ MW}_e \end{aligned} \quad (34)$$

The required thermal power in the turbine cycle (Q_{req}) is obtained with equation (35), considering a turbine Rankine power cycle efficiency of 45 % (NJ - CHP, 2012):

$$Q_{\text{req}} = \frac{P_{\text{dem}}}{\eta_{\text{turb}}} = \frac{16.9 \text{ MW}}{0.45} = 37.5 \text{ MW}_{\text{th}} \quad (35)$$

Another control parameter is mandatory to calculate which will be the temperature at which the turbine is turned on or not (T_{stop}) comparing to the minimum temperature of the hot tank. The temperature T_{stop} is calculated following the equation (36), considering an electrical power demand (P_{dem}) of 16.9 MW_e as another design plant criterion, calculated previously in equation (34).

$$T_{stop} = \frac{Q_{req}}{\dot{m}_1 \cdot C_p} + T_{h,ini} = \frac{37.5 MW_{th}}{\frac{232115.75}{3600} kg/s \cdot 2660.16 J/kg \cdot K} + 290^\circ C = 508.6^\circ C \quad (36)$$

After getting those values, which are the initial parameters for the further calculations, it is important to define three states of operation, which are:

- **State 1:** Radiation is available, the hot tank is accumulating mass and the cold tank is flowing mass to the tower receiver and after to the hot tank (consequently, the cold tank is getting empty), so that molten salts are flowing continuously from the cold tank to the hot tank in order to reach maximum temperatures latter;
- **State 2:** Radiation is available, the both tanks are being filled when the mass of molten salt in the cold tank is zero, because the two mass flows of molten salts are continuously flowing in the whole plant, so that the plant is working normally and producing electricity while there is also radiation;
- **State 3:** Radiation is not available and the accumulated mass in hot tank is flowing to the turbine or to the cold tank, depending on the minimum temperatures of the fluid in the hot tank. If the minimum temperature is reached the fluid flows to the turbine, if not flows directly to the cold tank.

The conditions developed for the operation states of the CSP plant for controlling the mass flow in the piping system and the mass in both tanks is defined as shown in **Table 3.4**.

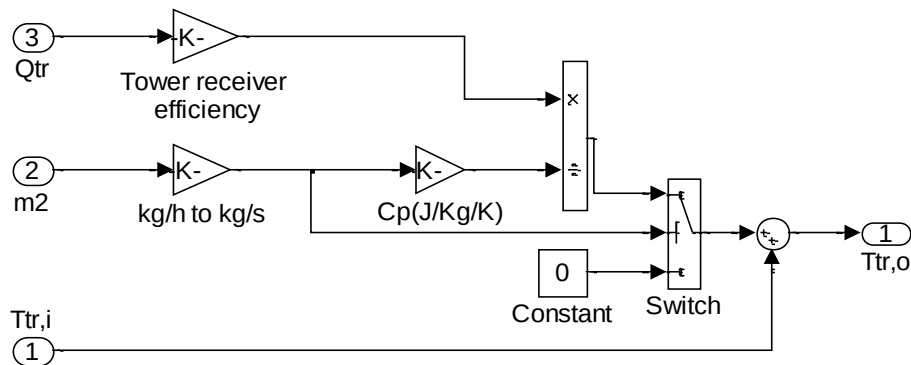
Table 3.4 Control conditions for each operation state of the CSP plant.

Overall plant operation states	Conditions “if”	Mass flows and bypass
State 1	$Q_{tr} > 0$	$\dot{m}_1 = 0$
	$M_c > 0$	$\dot{m}_2 = 232115.75 \text{ kg/h}$
State 2	$Q_{tr} > 0$	$\dot{m}_1 = 232115.75 \text{ kg/h}$
	$M_c = 0$	$\dot{m}_2 = 232115.75 \text{ kg/h}$
State 3	$Q_{tr} = 0$	$\dot{m}_1 = 232115.75 \text{ kg/h}$
	$M_h > 0$	$\dot{m}_2 = 0$
Turbine	State = 2	bypass = 0 (turbine on)
control	$T_h \geq T_{stop}$	

The formula which describes the tower receiver subsystem is an integration of equation (30) as a function of T_o , so it results in equation (37) considering the tower receiver efficiency ($\eta_{tr} = 0.9$, as defined before):

$$T_{tr,o} = \left(\frac{Q_{tr} \cdot \eta_{tr}}{\dot{m}_2 \cdot C_p} \right) + T_{tr,i} \quad (37)$$

In Figure 3.14 is presented the detailed model of the tower receiver subsystem which provides the modeling based in this equation and is working with a block called switch that works as a condition “if” for defining when the mass flow $\dot{m}_2$ is different from zero or is zero, i.e. when this mass flow is zero means that the outlet temperature of the tower receiver ($T_{tr,o}$) is equal to the inlet temperature of the tower receiver ($T_{tr,i}$).


Figure 3.14 Tower receiver subsystem for outlet temperature modeling.

The next step is to model and define the equation of the hot tank subsystem that will describe the outer temperature of the molten salts when they will pass through this tank ($T_h = T_{h,o}$). For this purpose, equation (38) is used for determine the mass balance of this tank as a function of the mass flows, where t is the upper limit saturation (M_h), t_0 is the lower saturation limit (0) and y_0 is the initial condition for this tank which is $\frac{M_h}{2}$, meaning a half filled tank.

$$\frac{dM}{dt} = \dot{m}_2 - \dot{m}_1 \Leftrightarrow M_h(t) = \int_{t_0}^t \dot{m}_2 - \dot{m}_1(t) dt + y_0 \quad (38)$$

Once defined the mass balance, it is necessary to define an energy balance of the tank. Its admitted that $T_{tr,o}$ (outlet temperature of the tower receiver) is going to be the $T_{h,i}$ (the inlet temperature of molten salts in the hot tank) and $T_{h,o}$ will be the new variable to compute as a function of the power received at the tower receiver for each hour of the year (Q_{tr}). Therefore this variable is computed developing the equation (29) as a function of $T_{h,o}$ and considering the mass balance, as follows in equation (39):

$$\begin{aligned} \frac{dE}{dt} &= C_p \cdot T_{h,o} \cdot (\dot{m}_2 - \dot{m}_1) + M \cdot C_p \frac{dT_{h,o}}{dt} = \dot{m}_2 \cdot C_p \cdot T_{h,i} - \dot{m}_1 \cdot C_p \cdot T_{h,o} \Leftrightarrow T_{h,o} \\ &= \frac{\dot{m}_2(T_{h,i} - T_{h,ini})}{M_h(t)} + T_{h,ini} \end{aligned} \quad (39)$$

Equation (39) defines the difference of the inlet and outlet temperatures of the hot tank divided by the molten salt mass in this tank, but it is necessary to define an initial working operation temperature for the hot tank ($T_{h,ini}$) of 290 °C as the minimum operation temperature of the Central Tower Receiver (CTR) plant and taking it as a restriction due the high freezing point of molten salts. After getting the first iteration for the outlet temperature of the hot tank in equation (39), the previous value is used on the new equation (40) and consequently for the next hours along the year, as follows:

$$T_{h,o}^+ = \frac{\dot{m}_2(T_{h,i} - T_{h,o})}{M_h(t)} + T_{h,o} \quad (40)$$

These equations applied to the hot tank modeling are defined with another subsystem in Simulink (Figure 3.15) which represents the math operations for obtaining $T_{h,o}$ and $T_{h,o}^+$. What is made initially is defining a $T_{h,ini}$ when the mass of the tank is zero and then the initial

temperature is considered at the first hour, otherwise is taken the previous value of $T_{h,o}$ and then a next iteration will progress continuously in the next hour.

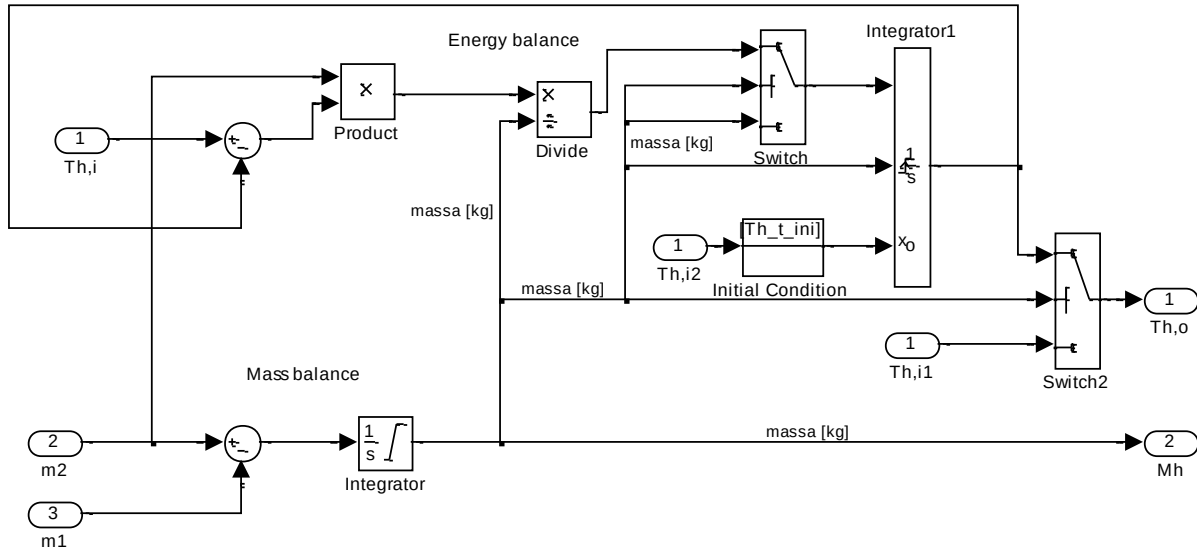


Figure 3.15 Hot tank subsystem designed with Simulink.

After the hot tank modeling is time to define the equations for the electric generation subsystem which includes the turbine outlet temperature ($T_{tur,o}$) and the power generation ($P_{tur,o}$). It is assumed that the outlet temperature of molten salt in the hot tank ($T_{h,o}$) is equal to the inlet temperature of molten salts into the turbine ($T_{tur,i}$) because the vapor cycle, which includes the steam generation, is not included in the scope of this work. The thermal power required (Q_{req}) for the turbine cycle is equal to 37.5 MW_{th} , as demonstrated before and the equation which gives the outlet temperature of the turbine ($T_{tur,o}$) is:

$$T_{tur,o} = T_{tur,i} - \frac{Q_{req}}{\dot{m}_1 \cdot C_p} \quad (41)$$

Equation (41) is presented in Figure 3.16 as another Simulink model in order to define better the conditions involved using *switch* blocks that are restrictions to control $\dot{m}_1$ and bypass conditions. The bypass is made to control the turbine exclusively. If $\dot{m}_1 = 0$ and bypass $\neq 0$, then there's no production of power and if $\dot{m}_1 \neq 0$ and bypass = 0, the turbine is on and there's production of electricity, consequently.

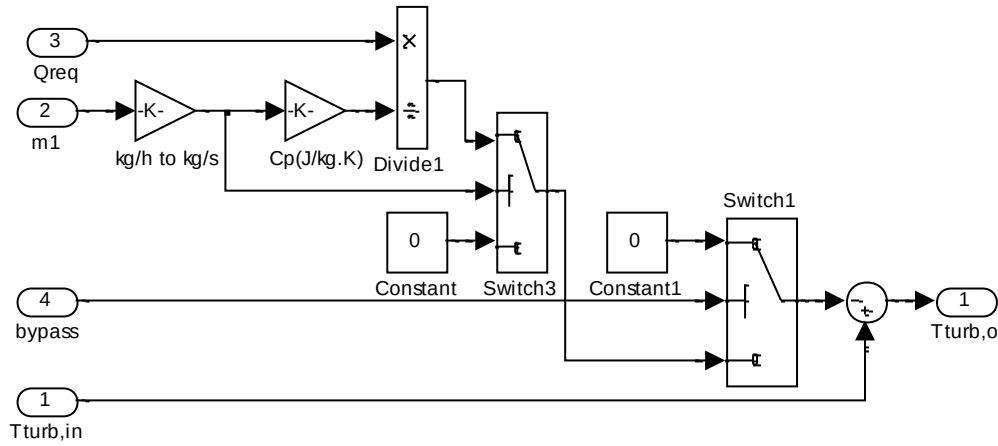


Figure 3.16 Electric generation subsystem designed with Simulink.

Out of this subsystem, another equation was used in order to calculate the power output released by the turbine ($P_{turb,o}$), also known as power demand (P_{dem}), as a function of the solar thermal power required (Q_{req}) calculated before in equation (35), and the turbine Rankine cycle efficiency (η_{turb}) which is 45 % (NJ - CHP, 2012), as defined in equation (42).

$$P_{dem} = P_{turb,o} = Q_{req} \cdot \eta_{turb} \quad (42)$$

The model of this equation is presented below in Figure 3.17 where the conditions for bypass = 0 and $\dot{m}_1 > 0$ are defined on the equation block of Simulink in order to obtain $P_{turb,o}$.

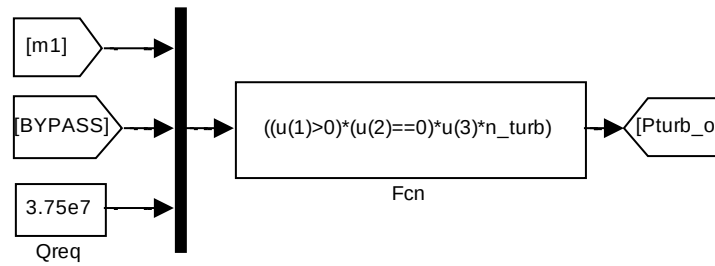


Figure 3.17 Simulink equation model for calculation $P_{turb,o}$ in function of bypass, mass flow and P_{dem} and under control conditions.

Lastly, the other subsystem is the “cold tank” that is very similar to the hot tank equations and Simulink model. The inlet temperature of the cold tank ($T_{c,i}$) will be equal to the outlet temperature of the turbine ($T_{turb,o}$) and so the outlet temperature of the cold tank is calculated developing equation (29 and considering a mass balance, as done for the hot tank and presented in equation (43):

$$T_{c,o} = \frac{\dot{m}_1(T_{c,i} - T_{c,ini})}{M_h(t)} + T_{c,ini} \quad (43)$$

In equation (43) the same conditions as for the hot tank are defined, and the minimum operation temperature of the molten salts inside this tank ($T_{c,ini}$) is the same as for the hot tank (290 °C, considering the high freezing point of molten salts). Once the first iteration of this equation is running on, equation (44) is used for getting a continuous iteration of temperatures in the cold tank using the previous value of $T_{c,o}$ obtained.

$$T_{c,o}^+ = \frac{\dot{m}_1(T_{c,i} - T_{c,o})}{M_c(t)} + T_{c,o} \quad (44)$$

On Figure 3.18 is presented the tank model for this equation that has the same configuration as the hot tank, where the only difference is the mass balance calculation which is calculated by subtracting $\dot{m}_2$ from $\dot{m}_1$, as shown in equation (45):

$$M_c(t) = \int_{t_0}^t \dot{m}_1 - \dot{m}_2(t)dt + y_0 \quad (45)$$

where t is the upper limit saturation (M_c), t_0 is the lower saturation limit (0) and y_0 is the initial condition for this tank, which is $\frac{M_c}{2}$, meaning that at the first hour of simulation both tanks are half filled.

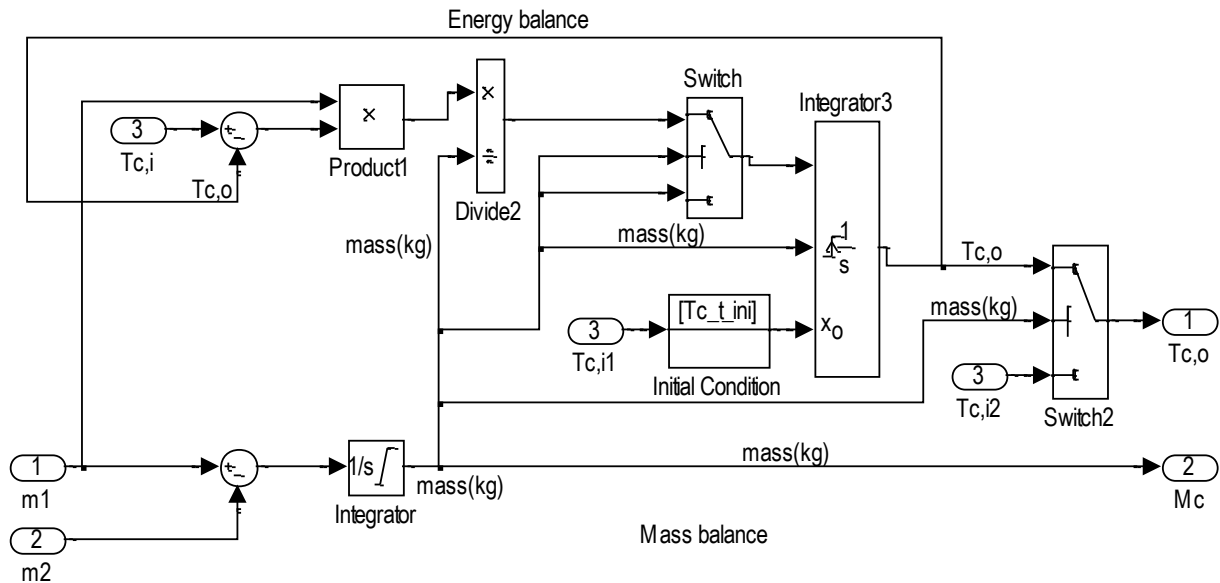


Figure 3.18 Cold tank subsystem designed with Simulink.

3.2 Simulation Results

The simulation parameters are defined with a fixed time step of 0.1 hours (6 minutes) and a simulation time of 8760 hours, which are the total hours of the year 2012, as also considered for the previous calculations. Regarding the three different states of operation, the mass of molten salt in each tank will differ according to the control parameters defined in **Table 3.4**.

Running the simulation for the first day of the year of 2012 it's observed that both tanks are half filled initially, as defined before (initial condition). Then, the cold tank is getting to its maximum mass and the hot tank to its minimum mass during the first six hours of the day, the process proceeding afterwards in a cycle way, as shown in **Figure 3.19**.

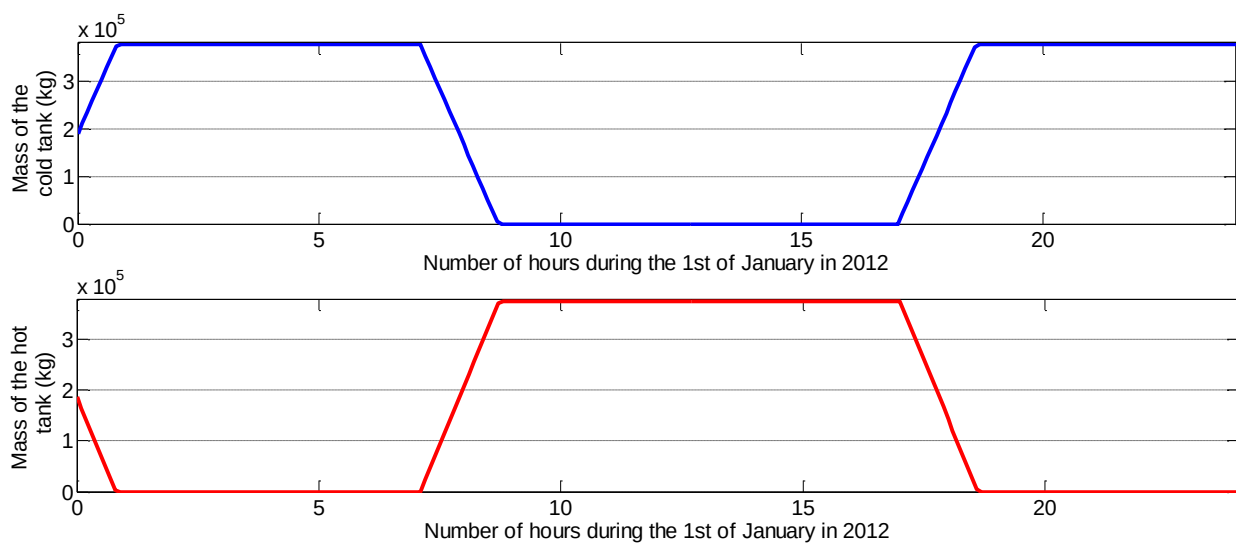


Figure 3.19 Cold and hot tank masses and their variation during the 1st day of January in 2012.

Between 1h00-7h00 and 17h00-24h00 (the hours without radiation) the cold tank is full and the hot tank is empty. On the other hand, in the period 7h00-17h00 (when radiation is available) the cold tank is empty and the hot tank is full, as expected. For the cold and hot tanks, it is observed that they are filled and empty during 7.5 hours of the day, respectively. This simulation was made essentially to show the initial situation in both tanks and the cyclic process, being also observed that the masses of each tank have the same opposite behavior along the year during the different states of operation and in different days of the year as seen in **Figure 3.20**. In this case, the simulation applies for a summer day (27th of June).

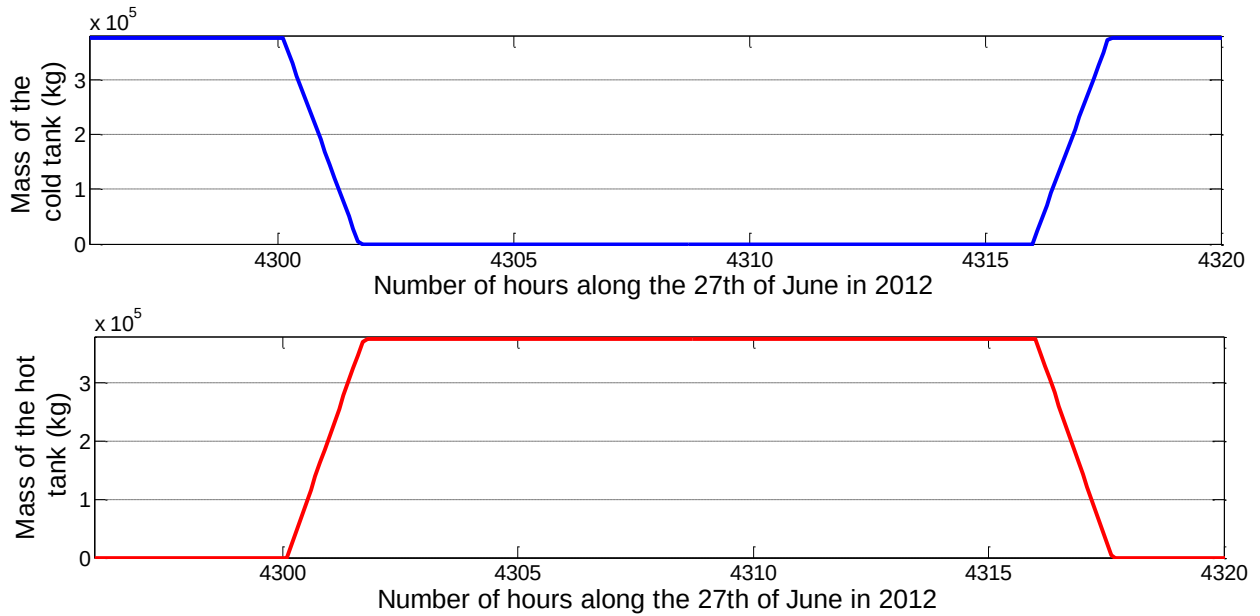


Figure 3.20 Mass simulation of cold tank and hot tank (M_c and M_h) along the 27th of June in 2012.

In the beginning of the day the cold tank is full and the hot tank is empty, according to what occurred during the previous day, so the mass of each tank will have this behavior every day along the year. The day right after will continue following the same pattern, and the mass in each tank which will always be $M_c = 375985.8$ kg/h and $M_h = 0$. Comparing to the winter day (**Figure 3.19**), it can now be seen that both tanks are filled and empty during more hours because there's more solar radiation available; analyzing the **Figure 3.20** above, this fact is confirmed with 14 hours with the hot tank filled and the cold tank empty. This is happening due to the control conditions on each state of operation where both masses are controlled with the mass flow rates $\dot{m}_1$ and $\dot{m}_2$. Such flow rates are determined by the positions of two valves, which are turning on and off depending if the state is 1, 2 or 3. On state 1 $\dot{m}_2$ is “open” and $\dot{m}_1$ is “closed”, on state 2 both mass flows are “open” and along the state 3, $\dot{m}_1$ is “open” and $\dot{m}_2$ is “closed” - cf. **Table 3.4**.

After analyzing the mass on the storage system, one should look for the temperatures of the cold and hot tanks, shown in **Figure 3.21**.

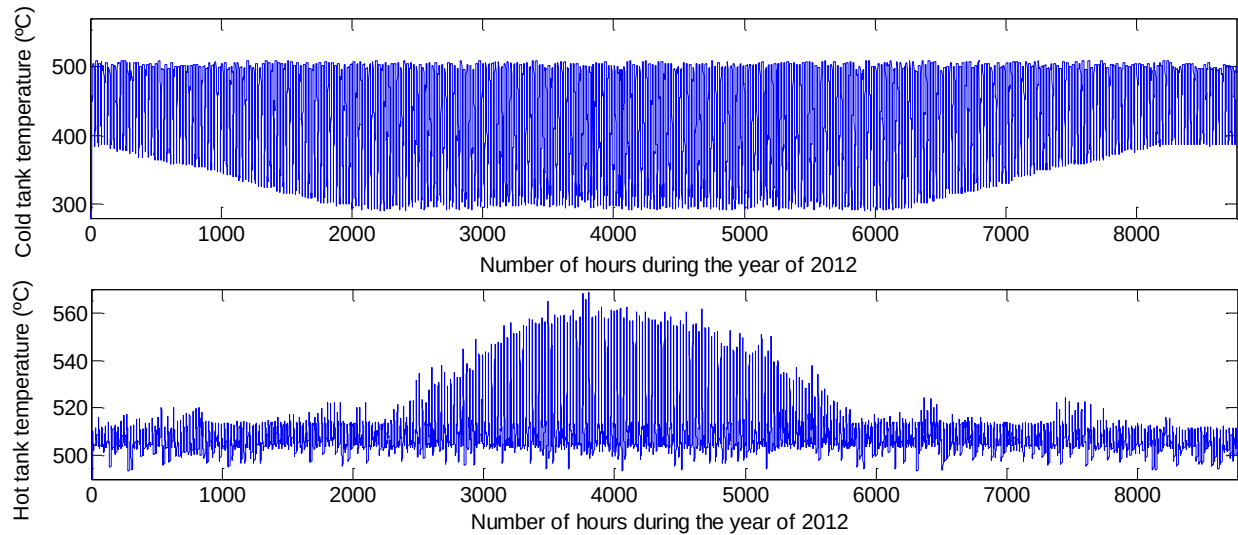


Figure 3.21 Temperatures of cold and hot tank along each hour the year of 2012

This simulation was made for the total hours of the year, and in **Figure 3.21** it can be seen that the limit operation temperatures of the CTR plant referred before (between 290 °C and 565 °C because of the molten salts freezing point and materials resistance) are being accomplished. It is observed that the temperature of the cold tank never goes under 290 °C, as planned, and the maximum temperature reached by this tank is around 510 °C (because it is receiving the hotter molten salts that were heated up on the tower receiver and then released to the hot tank and steam generator where finally were sent back again to the cold tank). On the other hand, the hot tank has its minimum average temperature around 500 °C and the maximum at 565 °C, as required. The temperatures profile in the tanks agrees with the radiation available during the winter period and the summer period, as shown in previous **Figure 3.11** and also repeated on the next image below. The hot tank reached higher temperatures during the summer time according also the highest levels of irradiation, so the highest energy at the tower receiver and more capacity to heating the molten salts. The next plot was made for comparing the electrical power output provided by this plant regarding the amount of solar thermal power received, as presented in **Figure 3.22**.

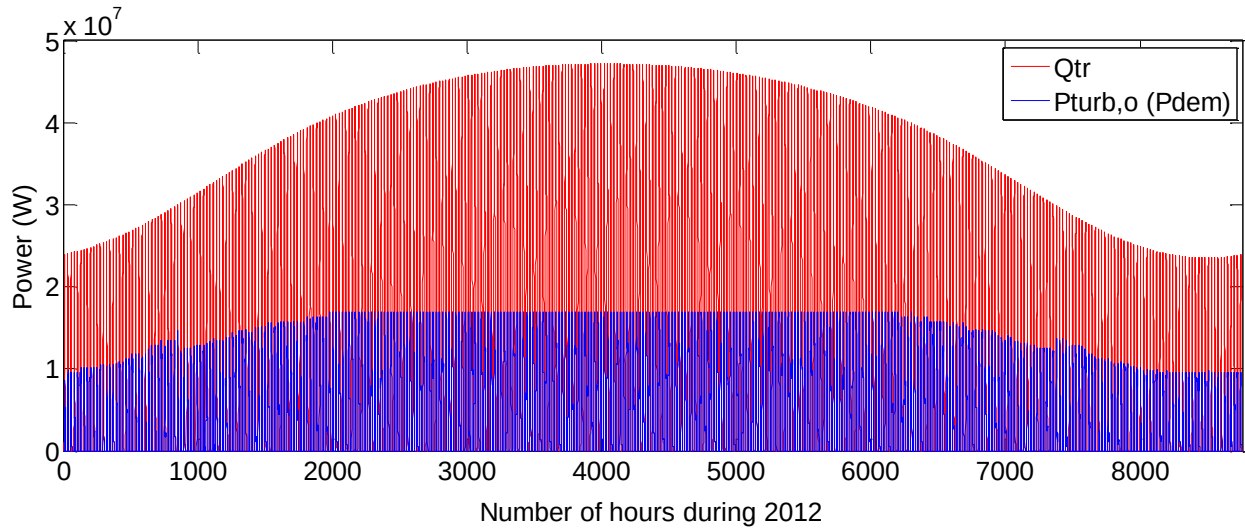


Figure 3.22 Turbine power output ($P_{turb,o}$) and tower receiver solar thermal power (Q_{tr}) along the year of 2012.

The results observed during this simulation shown a clear correlation between the solar thermal power available at the tower receiver and the turbine power output. The turbine is providing a maximum electrical power output of 16.9 MW_e during the peak hours of irradiation in the summer and 10 MW_e during the lowest values of irradiation in the winter.

A more detailed analysis is made in **Figure 3.23** during four specific days in the end of the month of June for having a better perspective of the simulation results over some days during the summer.

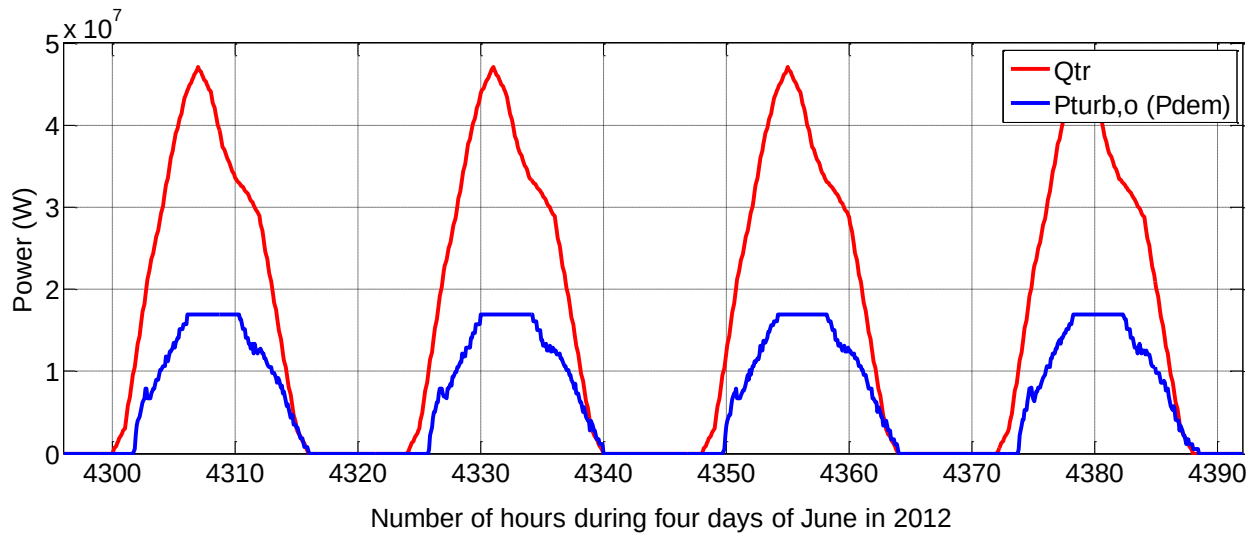


Figure 3.23 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during four days in the summer (27th, 28th, 29th, 30th of June)

It is observed that the plant has a short autonomy during the hours without radiation, and its production of electrical power is only happening when solar thermal power is available. Another conclusion that can be drawn is that the turbine is still producing the nominal output (16.9 MW_e) although the solar thermal power (Q_{tr}) is already decreasing, so the plant is having some moments of “autonomy” featured by the storage system with molten salts; even so this period is not long. **Figure 3.24** shows a more detained perspective of Q_{tr} and $P_{turb,o}$ over one day of simulation in the summer.

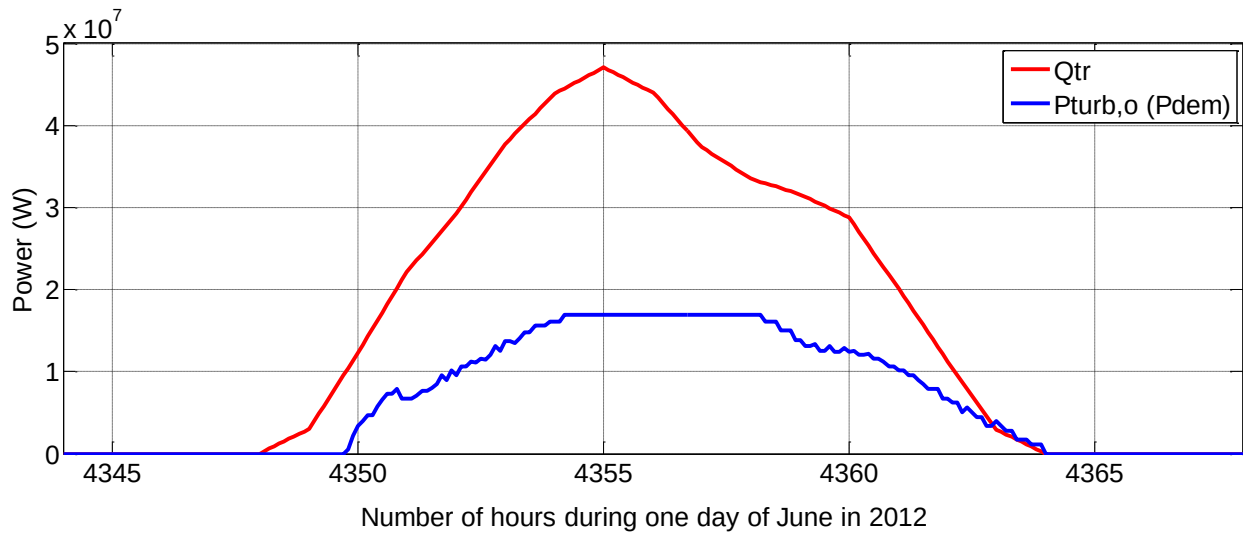


Figure 3.24 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the summer (29th of June)

Upon this simulation it can notably be seen a decouple between the electrical power produced and the solar thermal power, which means that when the solar radiation has variations, the electrical power output is not depending strongly on those variations, which is caused by the inertia of the storage system. Besides when the thermal power is starting to decrease, the nominal power is maintained and the storage system is providing a more stable electrical production.

Another analysis was made for the winter time also along four days in the month of December, as shown in **Figure 3.25** in order to compare with the summer results. The most significant differences are the lower solar thermal powers due to the lower solar radiation. Meanwhile, it is still observed a decouple and an inertia of the system, but not during longer periods as the summer.

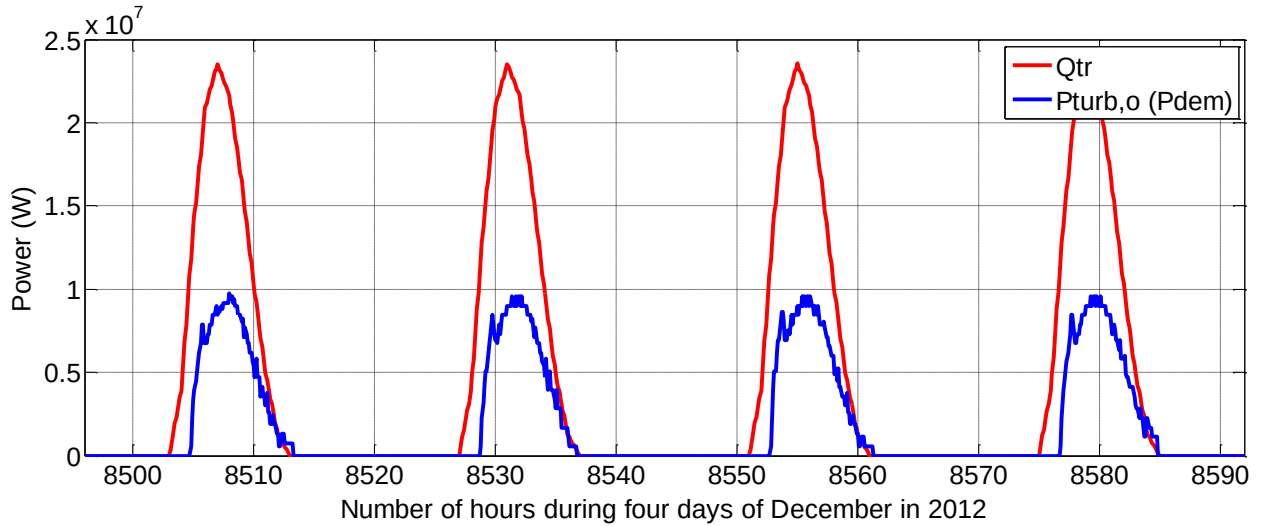


Figure 3.25 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during four days in the winter (19th, 20th, 21th, 22th)

During some days in the winter, the power output provided by the turbine is still not showing almost any autonomy of power production when the solar radiation is not available, as can be better seen over one day of simulation during the 22th of December in **Figure 3.26**.

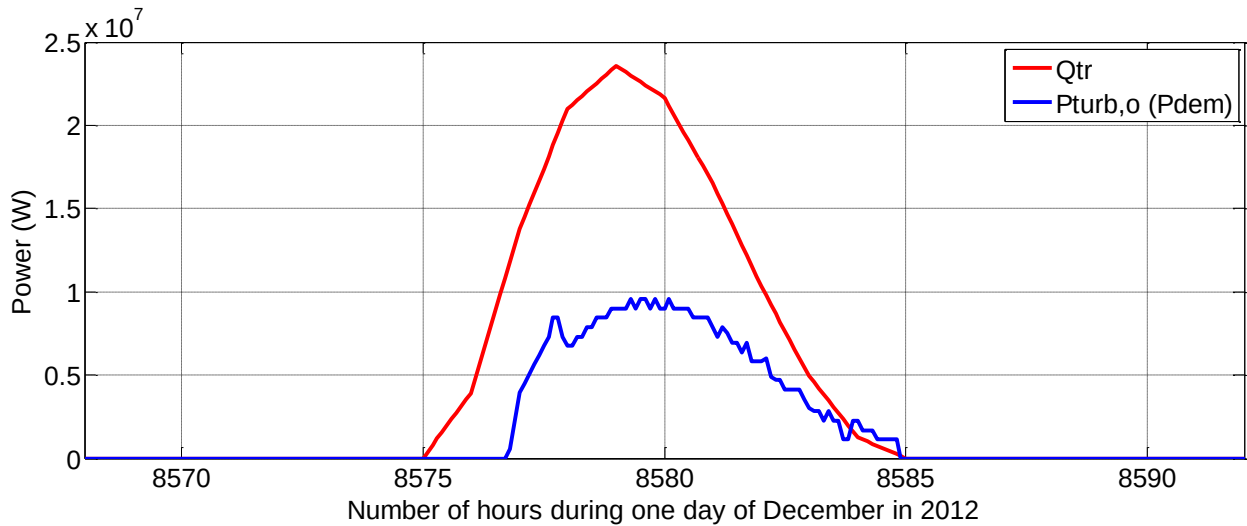


Figure 3.26 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the winter (22th of December)

An obvious explanation for the short autonomy is the fact that the mass of molten salt in each tank is insufficient. When the solar thermal power is starting to increase the system doesn't produce electricity simultaneously because of the storage system which has some inertia and

decoupling the electrical production to the solar thermal power and consequently to the solar radiation.

3.2.1 Effect of mass of molten salt

An additional analysis to evaluate the influence of molten salts mass in the autonomy and decoupling observed was then proposed, the mass of each tank being raised by about five times. Each tank will have now 15 meters of diameter and 6 meters of height so that the following values are obtained through equations (46) and (47):

$$V_h = V_c = \pi \cdot r^2 \cdot h = \pi \cdot \left(\frac{15}{2}\right)^2 \cdot 6 = 1060.3 \text{ m}^3 \quad (46)$$

$$M_c = M_h = V_{\text{tank}} \cdot \rho_{ms} = 1060.3 \text{ m}^3 \times 1870 \text{ kg/m}^3 = 1982737.7 \text{ kg} \quad (47)$$

This new mass is now five times bigger than the previous mass, so a bigger autonomy is expected during the summer and winter times.

A first simulation was run over the total hours of the year in order to verify if the turbine electrical power output ($P_{\text{turb,o}}$) has still the same maximum output value of 16.9 MW_e, which is now constant along the all year, as presented in **Figure 3.27**.

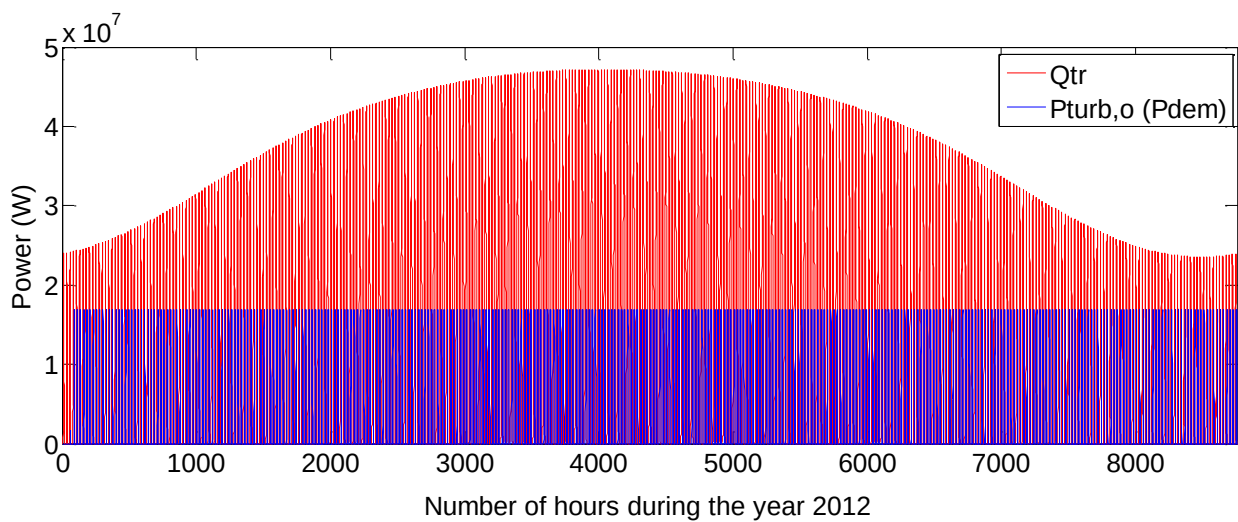


Figure 3.27 Turbine power output ($P_{\text{turb,o}}$) and tower receiver solar thermal power (Q_{tr}) along the year of 2012.

Comparing this new simulation results to the initial graph obtained with a lower mass in **Figure 3.22**, it is observed that the electrical power output isn't smaller during the winter period and isn't bigger during the summer period, although is notably seen during the first days of the plant operation that the power output is zero. In order to demonstrate this situation, **Figure 3.28** shows the behavior of the plant during the first six days of the year, in January; it's verified that the plant doesn't start the production of electrical power on the first days because there is a big inertia. On the third day it is seen a small $P_{turb,o}$ peak and then the production is starting to become more stable.

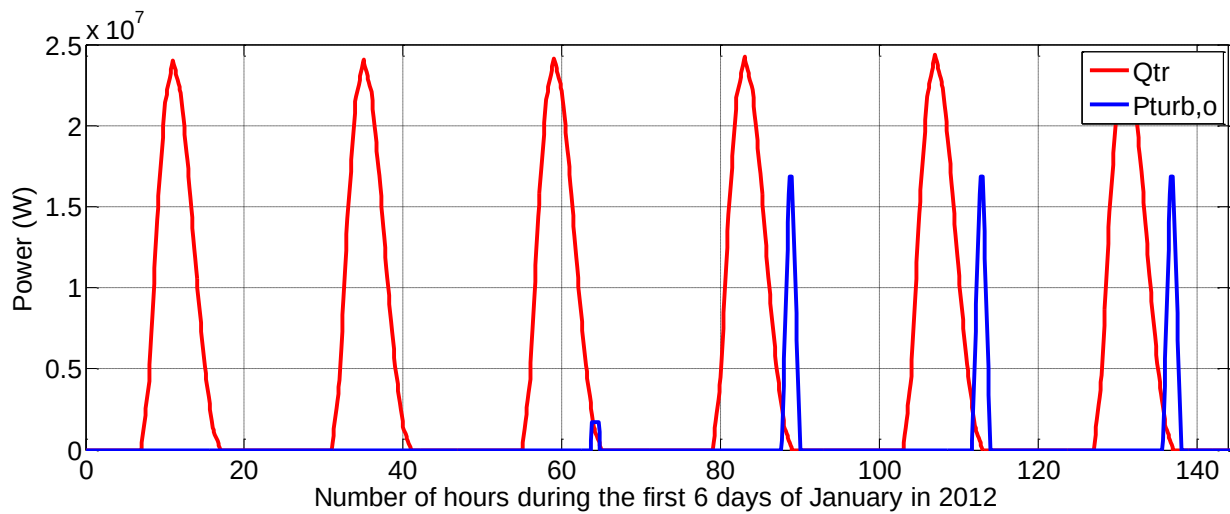


Figure 3.28 Turbine power output ($P_{turb,o}$) and solar thermal power (Q_{tr}) along the first six days of January in 2012.

This is happening because the molten salts take some days to reach the desired minimum operation temperatures for generating vapor and then to produce electrical power. Initially the temperatures at both tanks are defined for 290 °C and they need time to reach the desired 565 °C. So, considering that the plant starts its operation during the first day of the year and that the radiation is lower is normal that this process takes some time especially when the mass to warm up is five times bigger than before, creating a bigger decouple and inertia of the system. Another perspective is shown in **Figure 3.29** along four days during the month of June (27th, 28th, 29th, and 30th) for demonstrating the behavior of the plant during a summer period.

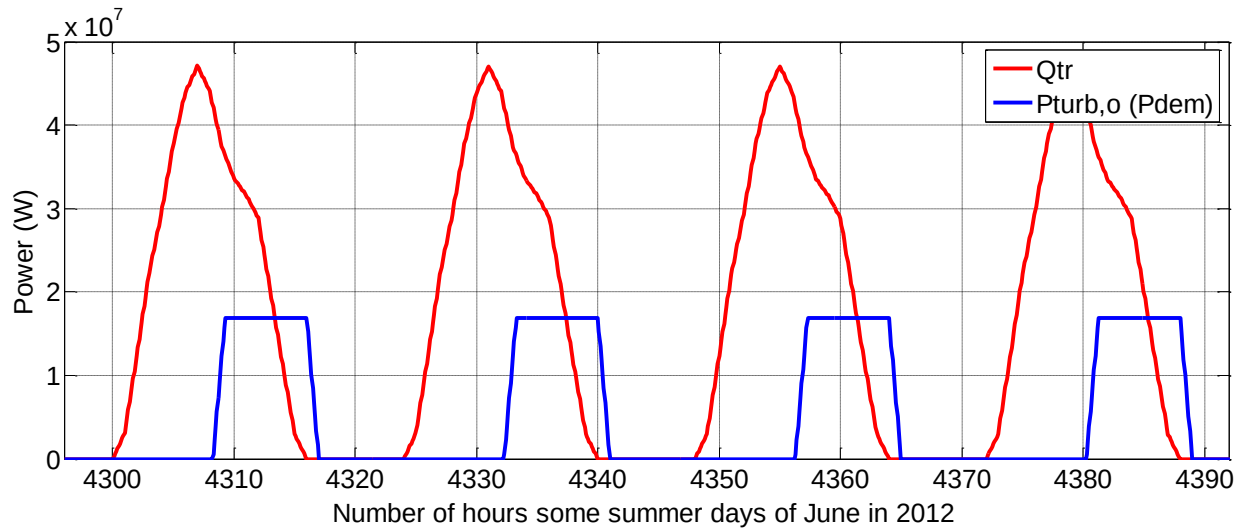


Figure 3.29 Turbine power output ($P_{turb,o}$) and solar thermal power (Q_{tr}) along four days of June in 2012.

At this moment it is observed a better autonomy for the solar plant, during the summer period, the electrical production starts when the solar thermal power reaches its maximum and starts decreasing, provided by the accumulated mass in the storage system. The energy production then occurs for a long time, even when there is no power provided by the solar tower. **Figure 3.30** represents the simulation over one of the four previous defined days during the summer.

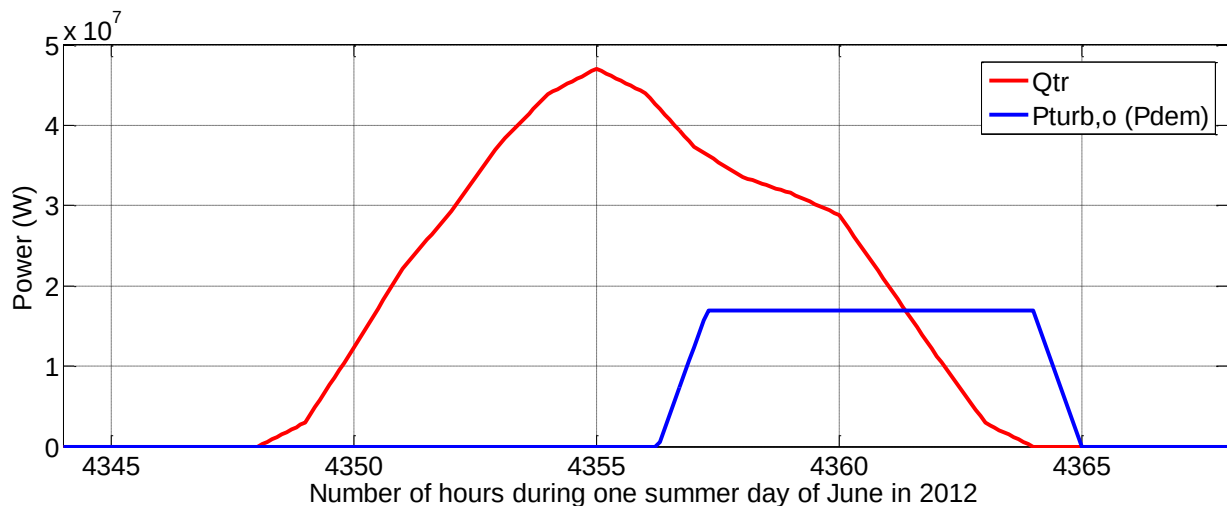


Figure 3.30 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the Summer (29th of June)

Analyzing **Figure 3.30**, it is observed that when the solar thermal power is raising and reaches a peak value at the middle of the day, the electrical production starts latter and when the solar power starts decreasing continuously along the rest of the day, the electrical production starts; a nominal electrical power output is observed that is constant during some hours. This behavior is provided by the inertia of the storage system and by the higher decouple between the thermal power and the electrical power, so that they have a more independent behavior. It is noticed that the steam turbine takes much more time now to start the electrical production comparing to the initial situation (smaller mass of molten salts), in the same day of the summer. This happens because there is a minimum time required to reach the desired temperatures of the hot tank, yielding a higher independence of the electrical system compared to thermal generation system. Meanwhile when there's no more solar radiation and consequently, no more solar thermal power, the CTR plant is still producing electrical power during some time and having its desired autonomy.

In order to make a more specific analysis over the autonomy, **Figure 3.31** illustrates the simulation for the hours when this situation takes place. Therefore, at 17h30 (at 4361.5 hours) in the 29th of June, the CTR plant starts to have an autonomy which is when $P_{turb,o} > Q_{tr}$, and lasts till 21h00 (at 4365 hours) of the same day. This means that the CTR plant has autonomy for 3.6 hours during this summer day in 2012.

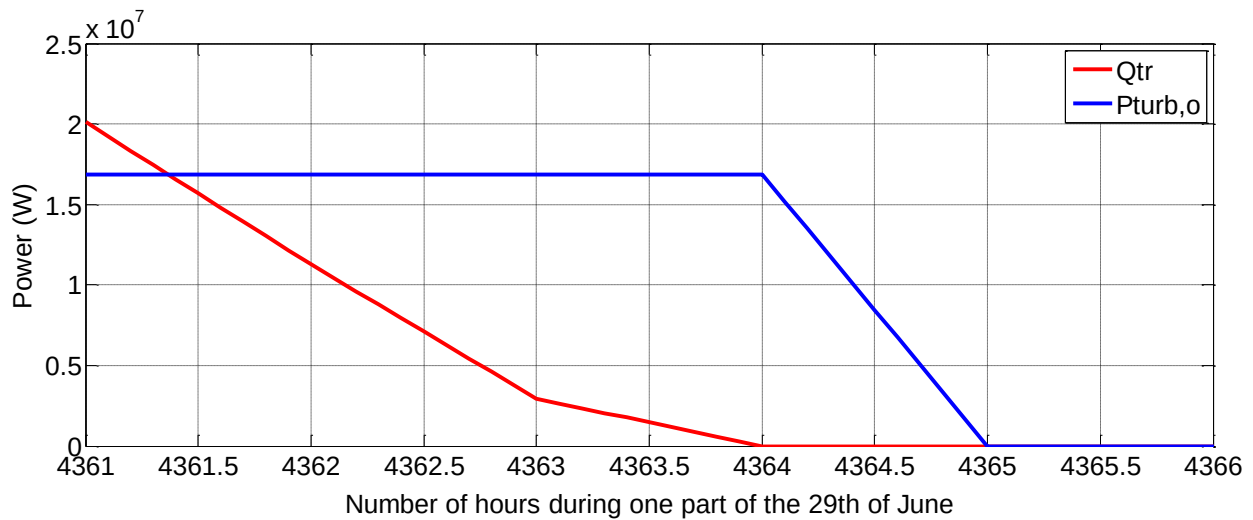


Figure 3.31 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one part of the 29th of June

The same examination is done in the next three figures, but for a winter period. As a result, **Figure 3.32** is showing four days in December (19th, 20th, 21st and 22nd) and the performance of the electrical power production and solar thermal power available for those days.

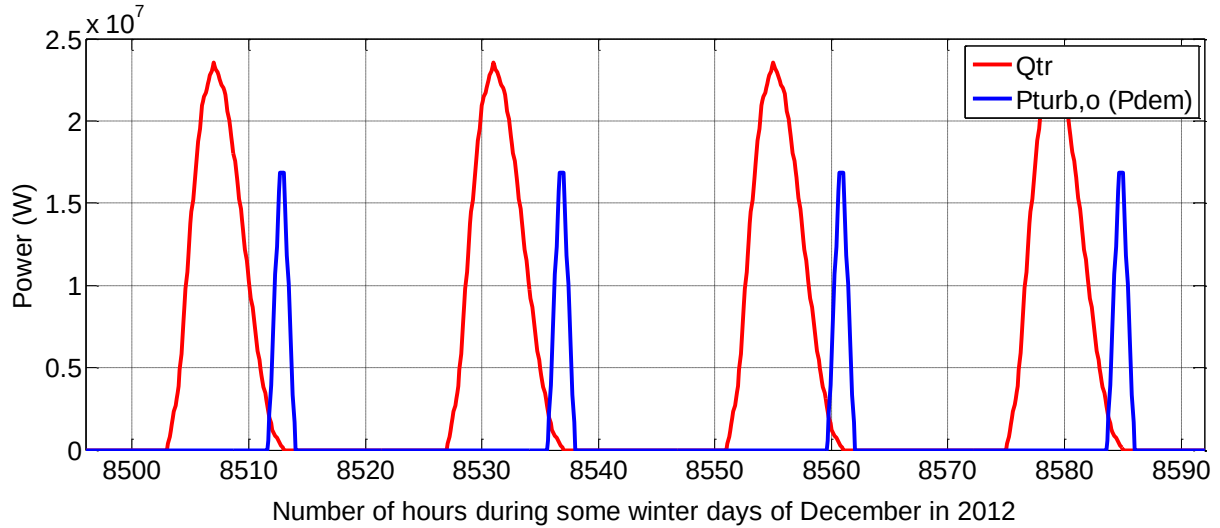


Figure 3.32 Turbine power output ($P_{turb,o}$) and solar thermal power (Q_{tr}) along four days of December in 2012.

It is noticed now a bigger difference between the summer and the winter period. In fact, the electrical power production starts later in each day (and the solar thermal power is restricted to less hours of the day). For having a better analysis, a simulation for the 22nd of December is presented in **Figure 3.33** below:

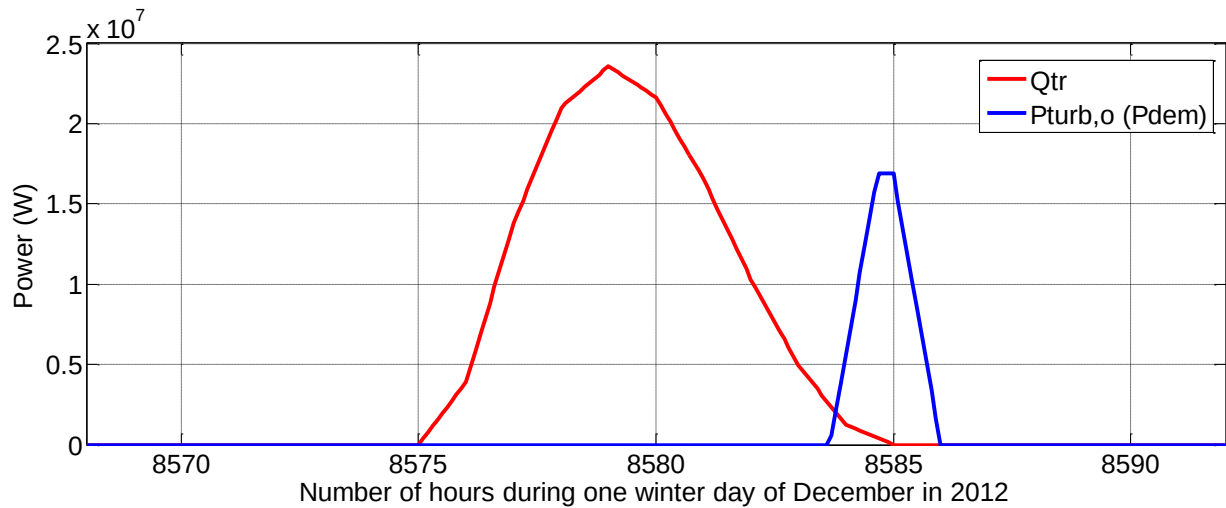


Figure 3.33 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one day in the winter (22nd of December)

In **Figure 3.33** is observed that the solar thermal power from the tower receiver is only available from 7h00 till 17h00, which gives a total of ten hours with solar power at the tower receiver during the 22nd of December. Comparing this value to the 29th of June it is observed six hours less of solar power from the tower receiver, during the 22nd of December. In

addition, during a winter day it is found that the storage system makes the electrical production totally independent of the solar radiation, and because the mass is bigger, the production starts much later than in the summer, provoking a delay effect.

Hence, an analysis during December on the same day (22nd) is made for the amount of hours where the CTR plant has autonomy, as done previously for the selected summer day, shown in **Figure 3.34**.

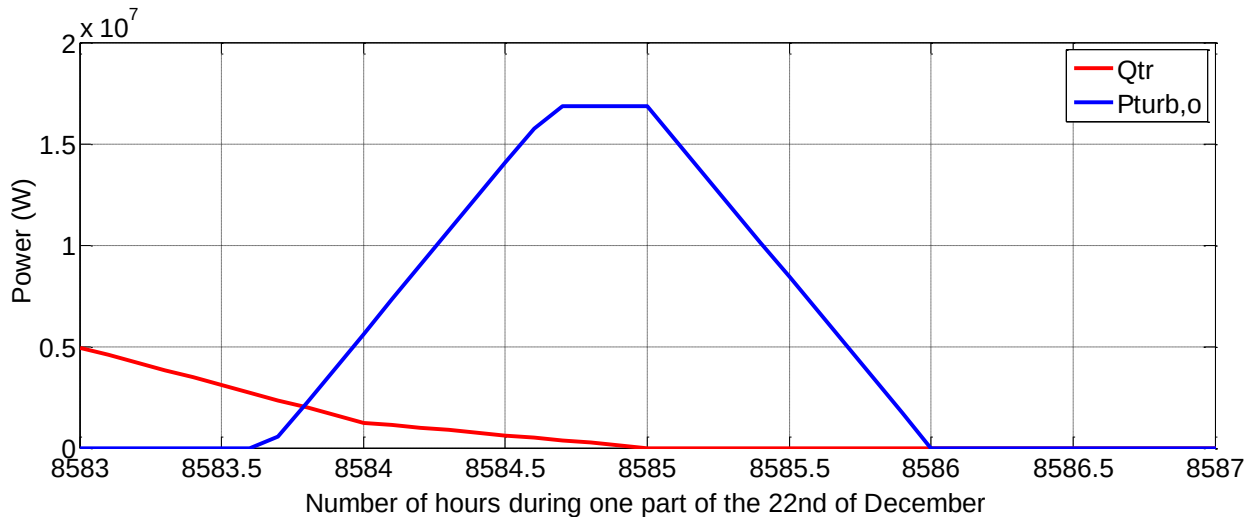


Figure 3.34 Solar thermal power (Q_{tr}) and turbine power output ($P_{turb,o}$) during one part of the 22nd of December

In this figure, the CTR plant autonomy is demonstrated. Around 15h30 (at 8583.6 hours) the electrical power production is beginning and at 18h00 (at 8586 hours) is finishing, so the autonomy of the plant during this winter day is 2.6 hours, which is lower when comparing to the 22nd of June during the summer. The electrical production is starting much later than it started with the initial mass (1/5 of that used herein) creating a delay effect provided by the inertia of the system.

Analyzing all of those simulations it is observed that the plant operation has different performances when the mass of molten salt is 375.9 ton and when the mass is 1982.7 ton. Meanwhile, different performances are observed when the plant is operating during the summer and during the winter period.

One of the most important analyses is the autonomy of the CSP plant because when the mass of molten salt is 375.9 Ton, the plant almost doesn't have autonomy and when the mass is 1982.7 ton the plant has autonomy between 2.6 and 3.6 hours.

The number of operation hours of the plant is determined based on the thermal power generation system and the electrical power production system, so it is depending on the available solar radiation of each day.

Once defined this design and key operation requirements, the molten salts mass should be adapted to different requirements of the plant, to the required electrical power output and solar field area.

4. Conclusions

An approaching for a possible connection of concentrating solar power (CSP) plants to salt mining activities due to the existence of these mines in Catalonia was made, analyzing the use of molten salts as a heat transfer fluid (HTF) and storage media.

A state of the art was done about the salt mining sector worldwide and specifically also in this region of Spain, Catalonia. An analysis of residual salts coming from a mining company in Catalonia was made and some possible residual salt compositions were identified. There are many advantages coming from the use of residual salts and transforming them into molten salts, but the most important are reusing a resource which is in excess or residual from salt mining processes, in addition to the low costs of this residual salt, when compared to other industrial and commercial salts available on the markets. So, the next step for developing this idea should be creating cooperation activities between mining companies, CSP plants investors and R&D technological and research centers for studying further this possibility, which doesn't exist nowadays.

The state of the art analysis about CSP technology tells that the best of those technology is the possibility to accumulate heat for the electrical production, allowing its use even when the sun is not shining, during cloudy periods or night times when it has a storage system. The four existing CSP technologies more studied and developed are: parabolic trough collectors (PTC), central tower receivers (CTR), parabolic dish collectors (PDC) and linear Fresnel reflectors (LFR), with different operations methods, design requirements, HTF's and storage systems. The more developed, constructed and commercial scale production CSP technologies are PTC and CTR, where PTC is the most experienced and mature in commercial production with more electricity produced than any other CSP technology as a thermo electric plant. However, PTC is still very expensive and requires high initial investments for construction and maintenance costs.

The current status of installed capacity and projects developed to produce electricity from thermal energy solar plants (CSP plants) in commercial scale is attracting potential investors and companies, due to successful demonstrations around the world. However, many improvements have to be done for reaching higher efficiencies and for becoming the leading renewable energy technology using sunlight as renewable source.

After the state of the art analysis, the design of a CSP plant was done and model developed which was implemented in Matlab®, followed by the analysis of the simulation results obtained and the control of the CSP plant operation. It was found that, when the solar radiation is higher, the thermal solar power at the tower receiver is proportionally higher and

according to different seasons of the year; so, this thermal power is lower during the winter and higher along the summer.

Analysis over the simulation results shows different performances of the CTR plant when the mass of molten salt is 375.9 ton or 1982.7 ton, and the main differences are the number of operation hours of the CSP plant, which are higher when the mass of molten salt is also higher. The autonomy of the plant, which is determined when the available solar thermal power is lower than the electrical production, is raising when the mass of molten salt is about five times bigger, providing also a higher decouple between those two variables, $P_{\text{turb,o}}$ and Q_{tr} . Apart of the mass variation, the plant has a higher autonomy during a summer period than in a winter period.

This model can be improved and adapted to different conditions required, such as, the weather conditions in a different location, different HTF, bigger or smaller solar field, tower receiver parameters and control conditions. So the developed model can be considered as a starting but important point, to be further adapted to any kind of requirements for developing a CSP plant based in Central Tower Receiver (CTR) technology.

4.1 Objectives accomplished

The main phases designed for this work were successfully reached, namely:

- State of the art of the mining sector;
- State of the art of the CSP technologies, heat transfer fluids and storage system;
- Design of a CSP plant based on Central tower receiver (CTR) technology;
- Development of the model and its implementation on Matlab®;
- Simulation, analysis and control of the CSP plant operation.

4.2 Limitations and future work

Once analyzed the work done, improvements can be made in order to readjust this model into different parameters/conditions, such as:

- Considering a variable mass flow and modeling the steam generator;
- Improvements in the specific heat of molten salts (C_p) can also be made, because instead of considering a constant specific heat it can be variable with the temperature;
- A new analysis focused on analyzing the influence of variable mass flows depending on available solar radiation can be done in a further work;

- Another analysis can be made in the influence of a different linke turbidity factor (Tlk) and the solar radiation;
- Studying how different salt compositions affects the operation of a CSP plant can be also an interesting future work line;
- In this model, the solar field was considered to be in a plane land field, without slopes, so a solar field with different slopes could be considered, as well;
- Another interesting future work would be developing the same model but using a different CSP technology such as, parabolic through collectors (PTC), parabolic dishes collectors (PDC) or linear Fresnel reflectors (LFR).

4.3 Final presentation

The developed work has a connection between mining salt activities in Catalonia and CSP plants and it is stated that there's any connection between those two sectors. On the other hand, this work can open the door for increasing this cooperation and to help CTM on its further projects between mining companies and CSP plants.

The idea of using molten salts as heat transfer fluid and storage media is very interesting and the developed Matlab model of a Central Tower Receiver is the prove that, molten salts can work between different operation temperatures while all the other common heat transfer fluids used, as oils, have restricted operation temperatures.

5. Bibliography

Avellaner J., et al, 1985. *Plataforma Solar de Almería, Proyecto CESA-1: Informe de la primera fase de operación y ensayos.*, s.l.: Ministerio de Industria y Energía.

Barlev D. et al, 2011. Innovation in concentrated solar power. *Solar Energy Materials & Solar Cells*, 95(10), pp. 2703-2725.

Bason F., 2012. *SolData Instruments*. [Online]
Available at: <http://www.soldata.dk/PDF/Bason%20-%20Diffuse%20irradiance%20and%20visibility.PDF>
[Accessed 22 May 2012].

Brosseau D., et al., 2004. Testing of thermocline filler materials and molten-salt heat transfer fluids for thermal energy storage systems in parabolic trough power plants. *Solar Energy Asme*, 127(July), pp. 587-595.

Cohen G.E., et al, 1998. *Performance History & Future Costs of Parabolic Trough Solar Electric System*. Odeillo: 9th International Symposium on Solar Thermal Concentrating Technologies.

Cohen G.E., 1994. *Achievements in Solar Parabolic Trough Technology*. Moscow: 7th International Symposium on Solar Thermal Concentrating Technologies.

Comarcàlia, 2012. *El Bages*. [Online]
Available at: <http://www.comarcalia.com/comarques/bages.asp?xxi=2>
[Accessed 18 May 2012].

Consejo Superior de Colegios de Ingenieros de Minas de España, 1996. La Minería en España. In: *Situación actual y posibilidades de desarrollo, Vol II.*. Madrid: s.n., pp. 215-274.

DeLaquil P., et al, 1991. Solar One Conversion Project. *Solar Energy Materials*, 24(1-4), pp. 151-161.

Duffie J.A. and Beckman W.A, 2006. Solar Engineering of Thermal Processes. In: I. John Wiley & Sons, ed. Third Edition ed. Hoboken, New Jersey: Wiley, pp. 3-41.

EASAC, 2011. *European Academies Science Advisory Council*. [Online]
Available at: http://www.easac.eu/fileadmin/Reports/Easac_CSP_Web-Final.pdf
[Accessed 16 March 2012].

Erhan S. Z., et al, 2005. Chemically functionalized vegetable oils. In: R. L.R., ed. *Synthetics, mineral oils, and bio-based lubricants chemistry and technology*. Boca Raton, FL: CRC Press.

Federación Minerometalúrgica de Comisiones Obreras , 2005. *La Minería en España (I)*.
[Online]

Available at:
<http://www.minerometal.ccoo.es/%5Cficpdf%5C90LamineriaenEspana%C3%B1al.pdf>
[Accessed 15 March 2012].

García C.X., 2001. *La energía solar térmica de alta temperatura como alternativa a las centrales térmicas convencionales y nucleares*. s.l.:s.n.

GeoModel Solar s. r. o., 2010. *SolarGIS - Online data and tools for solar energy projects*.
[Online]

Available at: <http://solargis.info>
[Accessed 14 March 2012].

Gharbi N. et al., 2011. A comparative study between parabolic trough collector and linear Fresnel reflector technologies. *Energy Procedia*, Volume 6, pp. 565-572.

Gil A., Medrano M., et al, 2010. State of the art on high temperature for power generation: Part 1-Concepts, materials and modeling. *Renewable and Sustainable Energy Reviews*, Volume 14, pp. 31-55.

Häberle A., et al, 2002. *The Solarmundo line focusing Fresnel collector. Optical and thermal performance and cost calculations*. [Online]
Available at:
http://www.solarpaces.org/CSP_Technology/docs/solarpaces_fresnel_9_2002.pdf
[Accessed 15 March 2012].

Herrmann U., et al, 2002. *Overview on thermal storage systems. Workshop on Thermal Storage for Trough Power Plants*. [Online]
Available at: http://www.nrel.gov/csp/troughnet/pdfs/uh_storage_overview_ws030320.pdf
[Accessed 20 March 2012].

Herrmann U., et al, 2004. Two-tank molten salt storage for parabolic trough solar power plants. *Energy*, 29(5-6), pp. 883-893.

Huld T., Dunlop E.D., 2012. *JCR's Institute for Energy and Transport - PVGIS - European Commission*. [Online]
Available at: <http://re.jrc.ec.europa.eu/pvgis/solres/solmod3.htm>
[Accessed 21 May 2012].

Huwaldt J. A., 2010. *Plot Digitizer*. [Online]
Available at: <http://plotdigitizer.sourceforge.net>
[Accessed 22 May 2012].

IEA, 2010. *International Energy Agency*. [Online]
Available at: http://www.iea.org/papers/2010/csp_roadmap.pdf
[Accessed 16 March 2012].

Ingham J., et al., 2000. Chemical Engineering Dynamics. In: 2. edition, ed. *Modelling with PC Simulation*. s.l.:Wiley-VHC , pp. 33-35.

Jantzen E., 1996. The Origins of Synthetic Lubricants: The Work of Hermann Zorn in Germany, Part 1: 'Basic Studies of Lubricants and the Polymerization of Olefins'. *Synthetic Lubrication*, 12(4), pp. 283-301.

Kearney D.W., Cohen G.E., 1996. *Current Experiences with the SEGS Parabolic Trough Plants*. Cologne, 8th International Symposium on Solar Thermal Concentrating Technologies.

Kenisarin M. M., 2010. High-temperature phase change materials for thermal energy storage. *Renewable and Sustainable Energy Reviews* , Volume 14, pp. 955-970.

Laurence D.C., 2006. *Why do mines close*. Perth, First International Seminar on Mine Closure, pp. 83-94.

Leibfried U., Ortjohann J., 1995. Convective heat loss from upward and downward-facing cavity solar receivers: measurements and calculations. *Solar Energy Engineering*, 177(2), pp. 75-84.

Miyahara H., et al, 2006. *Breakdown Characteristics of Combined Insulation in Silicone Oil for Electric Power Apparatus*. Bali, 8th International Conference on Properties and Applications of Dielectric Materials, pp. 661-664.

NextEra Energy, Inc., 2012. *NextEra Energy Resources*. [Online]
Available at: <http://www.nexteraenergyresources.com/home/index.shtml>
[Accessed 16 February 2012].

NJ - CHP, 2012. *NJ Combined Heat and Power*. [Online]
Available at: http://njchp.rutgers.edu/files/Steam_Turbines.pdf
[Accessed 17 May 2012].

Noone C. J., Torrilhon M., Mitsos A., 2012. Heliostat field optimization: A new computationally efficient model and biomimetic layout. *Solar Energy*, Issue 86, pp. 792-803.

Paitoonsurikarn S., Lovegrove K., 2006. *A new correlation for predicting the free convection loss from solar dish concentrating receivers*, Canberra: 44th Conference of the Australia and New Zealand Solar Energy Society (ANZSES).

Palacio J.S., 2010. *Aprovechamiento de las aguas de mina en la Cuenca Central Asturiana como recurso energético*, Oviedo: Oviedo University.

Plataforma Solar de Almería, 2008-2009. *Informe Bianual*, Almeria: Ministerio de Ciencia y Innovación; Ciemat.

Prakash M., et al, 2009. Investigations on heat losses from a solar cavity receiver. *Solar Energy*, February, 83(2), pp. 157-170.

Protermosolar, 2011. *Asociación Española de la Industria Solar Termoeléctrica*. [Online] Available at: <http://www.protermosolar.com/mapa.html> [Accessed 16 March 2012].

PSA, 2012. *Plataforma Solar de Almería*. [Online] Available at: <http://www.psa.es/webesp/> [Accessed 20 February 2012].

Radosevich L.G., 1988. *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant*, Livermore, CA: Sandia National Labs.

Shen C., et al, 2008. Modelling and simulation of solar radiation data processing with Simulink. *Simulation Modelling Practice and Theory*, Issue 16, pp. 721-735.

Silva A., 2010. *Estimativa de Produção em Centrais Solares de Concentração*, Oporto: FEUP.

Sohal M.S., et al, 2010. *Engineering Database of Liquid Salt Thermophysical and Thermochemical Properties*, Idaho Falls, Idaho: Idaho National Laboratory.

Tamme R., et al, 2002. *Innovative thermal energy storage technology for parabolic trough concentration solar power plants*. Bologna, Proceedings EuroSun at the 4th ISES Solar Congress.

Taumoefolau T., Lovegrove K., 2002. *An experimental study of natural convection heat loss from a solar concentrator cavity receiver at varying orientation*. Newcastle, Proceedings of 40th Conference of the Australia and New Zealand Solar Energy Society (ANZSES).

Time Science - Ecocentric, 2011. *The 10 most air-polluted cities in the world*. [Online] Available at: <http://ecocentric.blogs.time.com/2011/09/27/the-10-most-air-polluted-cities-in-the-world/> [Accessed 13 June 2012].

Torresol Energy Investments, S.A., 2011. *Connected to the sun - Gemasolar Brochure*. [Online] Available at: http://www.torresolenergy.com/EPORTAL_DOCS/GENERAL/SENERV2/DOC-cw4e88b3bb57c8f/folleto-gemasolar.pdf [Accessed 16 March 2012].

U.S. Department of Energy, 2007. *Mining Industry Bandwidth Study*. [Online]
Available at:
http://www1.eere.energy.gov/manufacturing/industries_technologies/mining.html
[Accessed 19 March 2012].

U.S. Department of the Interior, 1997. *Mineral Industry Survey, Potash*. [Online]
Available at: <http://minerals.er.usgs.gov/minerals/pubs/commodity/potash/560397.pdf>
[Accessed 15 March 2012].

U.S. Department of the Interior, 2011. *Geological Survey: Mineral commodity summaries*. [Online]
Available at: <http://minerals.usgs.gov/minerals/pubs/mcs/2011/mcs2011.pdf>
[Accessed 19 March 2011].

U.S. Department of the Interior, 2012. *Geological Survey: mineral commodity summaries*. [Online]
Available at: <http://minerals.usgs.gov/minerals/pubs/mcs/2012/mcs2012.pdf>
[Accessed 16 March 2012].

UNESA - Asociación Española de la Industria Eléctrica, 2005. *Consumo de electricidad por comunidades*. [Online]
Available at: http://www.unesa.net/unesa/unesa/electricidad/ficha2_7.html
[Accessed 18 May 2012].

Wei X., et al, 2010. A new method for the design of the heliostat field layout for solar tower power plant. *Renewable energy*, Issue 35, pp. 1970-1975.

Weisstein E. W., 1996-2007. *Wolfram Research*. [Online]
Available at: <http://scienceworld.wolfram.com/physics/SnellsLaw.html>
[Accessed 21 May 2012].

Zalba B., et al., 2003. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Energy*, Volume 23, pp. 251-283.

6. Annex I: Energy efficiency solutions

Energy efficiency in mining is more focused on how resources are managed and extracted, being the optimized models for resource extraction developed by mining engineers, geologists and metallurgists. It was reported that mining industry in the USA has the potential to reduce energy consumption by 61 %, employing the best practical minimum energy consumption. This percentage was obtained by implementing best practices (reducing 21 %) and developments that improve energy efficiency of mining and mineral processing technologies. Meanwhile, the literature about energy efficiency and sustainable mines is not many, but approaches like an analysis study of Kennecott Utah copper's operations was done. This study concluded that is better to produce for as long as possible from existing mines, than exploiting new mines without future perspectives, if the existing mines are sustainable.

Until today, connections between mining sector, compressed air energy storage and geothermal energy have been implemented as storage and energy recovery systems.

Compressed air energy storage is usually used in places with large voids, such as salt mines and limestone cavers. It works using off-peak electricity from renewable energy sources (wind or excess output from the mineral resource) to compress air that will be stored under pressure underground and released through a gas turbine, generating electricity during periods of peak demand.

Another implemented option was the use of geothermal energy recovery, where ground source heat pumps are often used that extract energy from shallow groundwater or soil. The heat to be stored can be from combined heat and power generation, waste heat from power stations and incineration plants, or heat produced from a renewable source, like on this case. Classifications of mechanical compression heat pumps are described elsewhere (Palacio J.S., 2010), and geothermal water heat pumps and their diverse dispositions applied to mine water exploitation operating in an open circuit system (open-loop) and non-reversible dispositions.

The heat is flowing naturally from high to low temperatures (2nd thermodynamic law). However, it's technically possible to force heat flowing on reverse direction using relatively low work quantities. For making this happen, heat pumps are used, which transfer heat (pumping) from natural sources at low temperatures (cold source), such as air, water or own field, towards the interior dependencies that are supposed to be warmer (hot source). The utilization of intermediate thermal storage is the correct solution, providing higher energetic efficiencies of heat pumps.

Two intermediate storage models are presented (**Figure 6.1** and **Figure 6.2**) where domestic hot water has to be high enough for justifying an exclusive use of a heat pump for this purpose.

For higher consumers, like an hospital institution, it is proposed that hot water thermal storage on heating system is considered as an intermediate hot source for a third heat pump that supplies hot water at 60 °C to also a third thermal storage, for its further use on the domestic hot water (DHW) network. As observed in **Figure 6.1**, mine water is at 20 °C and the water that returns from heating circuit at 30 °C, controllably binds, through a three-way valve, with water that is flowing out of evaporator from a third pump at 15 °C to supply the water that enters in evaporator at 20 °C. In the condenser, water flows out at 60 °C and returns at 55 °C.

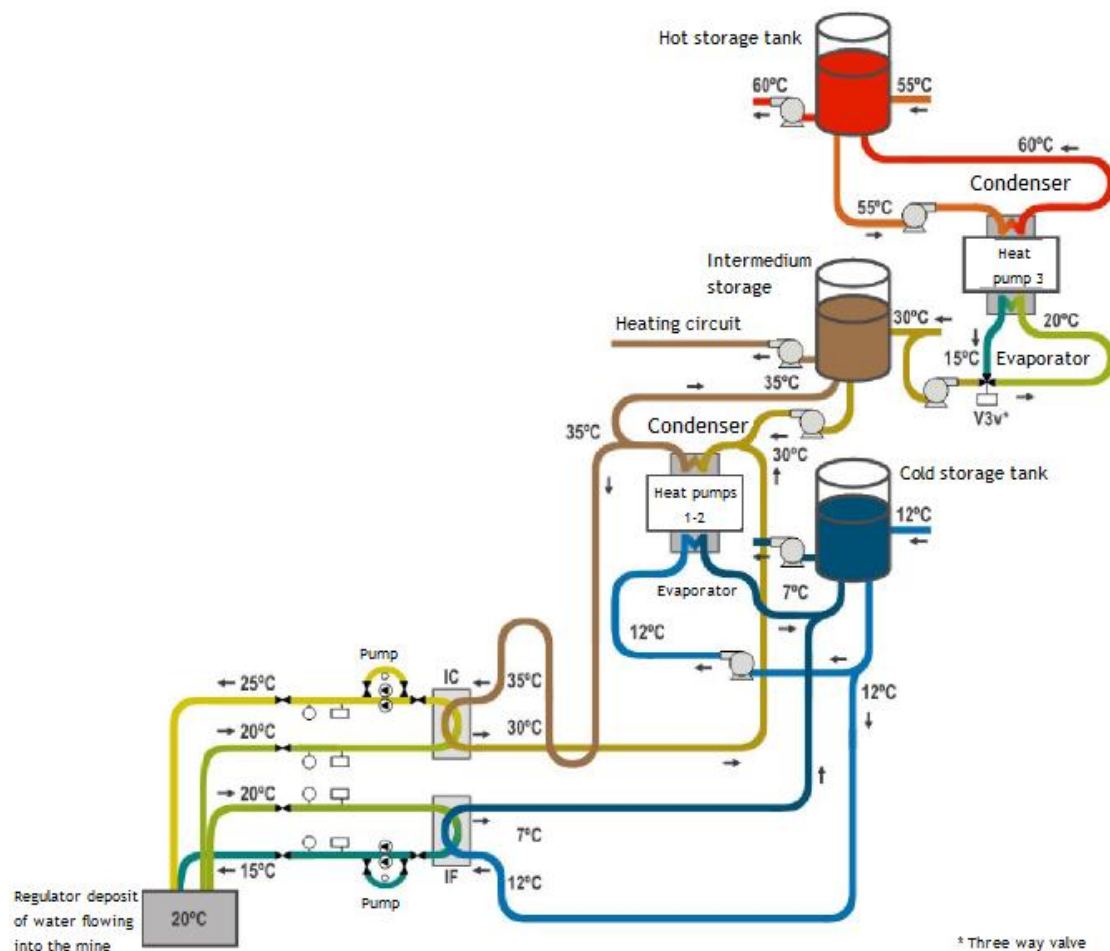


Figure 6.1. Basic scheme of three heat pumps with intermediate heating storage and DHW storage.

Source: (Palacio J.S., 2010)

For medium consumers a scheme is proposed composed by a feeding group of one or two heat pumps from the water mine tank regulator (**Figure 6.2**) which supplies cold water for cooling at 7 °C and hot water for heating at 45 °C.

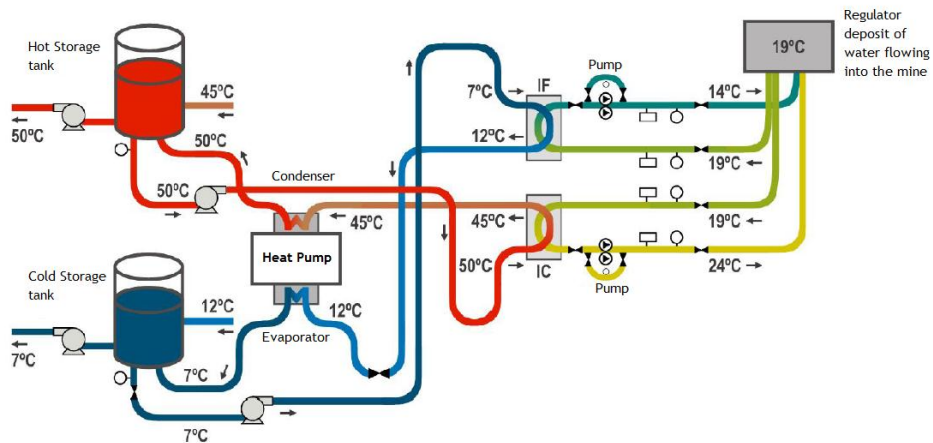


Figure 6.2 Basic scheme of heat pump with water from the mine and storage system (cold and hot).

Source: (Palacio J.S., 2010)

The direct exploitation of hot water used for heating from a thermal plant placed nearby the curb of any mining reservoir wells is cheaper than heating systems based on gas boilers.

7. Annex II: Matlab code (script) for solar position angles and solar radiation

```
% Definition of variables and constants for solar position, solar radiation
```

```
% and optical efficiency of each heliostat during a year
```

```
clear all;
```

```
close all;
```

```
clc;
```

```
% Loading (x,y) heliostats positions from the working folder
```

```
load('xy_coord');
```

```
% Loading variable number of heliostats in column vector
```

```
load('n_colun');
```

```
% Loading variable number of heliostats in row vector
```

```
load('n_row');
```

```
% Loading theta variable
```

```
load('theta');
```

7.1 Variables days and hours of a year

```
N=8760;
```

```
timestep = 1;
```

```
long_year=8760;
```

```
hour_year = zeros(size(N));
```

```
for i=1:N
    hour_year(i)=i;
end

hour_day = zeros(size(N));
a=1;
for i=1:N
    hour_day(i)=a;
    a=a+1;
    if a==25
        a=1;
    end
end

days = zeros(size(N));
for i=1:N
    days(i)=ceil(i/24);
end
```

7.2 Geographic location

```
%Local latitude
lat = zeros(size(N));
for i=1:N
    lat(i)=41.73;
end

% Local longitude
long = zeros(size(N));
for i=1:N
    long(i)=1.51;
end
```

7.3 Declination of north pole (degrees)

```
delta = 23.5*sind((360/365)*(284+(days)));
```

7.4 Equation of time

```
B = ((360/364)*((days)-81)); % Factor B
```

```
ET = ((9.87.*sind(2*B))-(7.35.*cosd(B))-(1.5.*sind(B)))./60; % Equation of time (hours per day)
```

7.5 Solar hour angle

```
h_angle = ((hour_day)-12).*15;
```

7.6 Solar elevation angle

```
alpha = asind((cosd(h_angle).*cosd(delta).*cosd(lat))+(sind(delta).*sind(lat)));
```

7.7 Solar zenith angle

```
omega = 90 - alpha;
```

7.8 Solar azimuth factor

```
phi_std = asind((cosd(delta).*sind(h_angle))./(sind(omega)));
```

7.9 Solar azimuth angle

```
phi_solar = zeros(size(N));
```

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

```
    if cosd(h_angle(i))>=(tand(delta(i))/tand(lat(i)))
```

```
        phi_solar(i) = 180 - phi_std(i);
```

```
    elseif cosd(h_angle(i))<=(tand(delta(i))/tand(lat(i)))
```

```
        phi_solar(i) = 180 + phi_std(i);
```

```
    end
```

```
end
```

7.10 Surface azimuth angle

```
phi_surf = zeros(size(N));
```

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

```
if (phi_solar(i) - phi_std(i)) > 0
    phi_surf(i) = phi_std(i)+90;
elseif (phi_solar(i) - phi_std(i)) < 0
    phi_surf(i) = phi_std(i)-90;
end
end
```

7.11 Tower receiver parameters (constants)

```
d=10; % diameter of reflected spot of heliostat field (m)
l = 8; % lenght of reflector surface (m)
L=20; % diameter of absorbing aperture (m)
h_tower=110; % altitude from tower base till the receiver aperture (m)
```

7.12 Receiving angle of reflected rays on tower receiver (degrees)

```
theta_R = zeros(size(N));
for i=1:N;
    theta_R(i)=(asind((( -2*d*l)+(L*(sqrt((4*l^2)+(L^2)-(d^2)))))/((4*l^2)+(L^2))));
end
```

7.13 Angle between reflected ray and vertical direction (degrees)

```
lambda = zeros(size(N));
for i=1:N;
    lambda(i) = (90-theta_R(i));
end
```

7.14 Tilt angle of the aperture plane to the vertical direction (degrees)

```
delta_R = zeros(size(N));
for i=1:N;
    delta_R(i) = 12.5;
```

end

7.15 Azimuth angle of each heliostat during a year

yt = 0; % y axis tower position

xt = 0; % x axis tower position

phi_t = atand((yt-y)./((xt-x))); % Tower azimuth

phi_h = zeros(624,8760); % azimuth angle of each heliostat during a year

for i=1:624

 for j=1:8760

 phi_h(i,j)=(phi_t(i)+phi_solar(j))./2;

 end

end

7.16 Inclination angle of each heliostat during a year

dT = sqrt((x-xt).*(x-xt)+(y-yt).*(y-yt)); % Distance of each heliostat to tower base (m)

alpha_t = atand((h_tower-0)./dT); % Tower altitude angle (degrees)

beta_h = zeros(624,8760); % inclination angle of each heliostat during a year (degrees)

for i=1:624

 for j=1:8760

 beta_h(i,j)=(alpha_t(i)+alpha(j))./2;

 end

end

7.17 Solar incidence angle

theta = zeros(624,8760);

for i=1:624

 for j=1:8760

 theta(i,j) = acosd((sind(lat(j))*sind(delta(j))*cosd(beta_h(i,j)))-

```
(cosd(lat(j))*sind(delta(j))*sind(beta_h(i,j))*cosd(phi_surf(j)))+(cosd(lat(j))*cosd(delta(j))*cosd(h_angle(j))*cosd(beta_h(i,j)))+(sind(lat(j))*cosd(delta(j))*cosd(h_angle(j))*sind(beta_h(i,j))*cosd(phi_surf(j)))+(cosd(delta(j))*sind(h_angle(j))*sind(beta_h(i,j))*sind(phi_surf(j))));
```

```
end
end
```

7.18 Cosine efficiency

```
cos_ef=(sqrt(2)./2).*(((sind(alpha).*cosd(lambda))-(cosd(phi_surf-phi_solar).*cosd(alpha).*sind(lambda))+1).^0.5);
```

7.19 Atmospheric attenuation Efficiency

```
S0 = sqrt(dT.^2+h_tower^2);
att_ef = 0.99321 - (0.0001176.*S0) + (1.97e-8*S0.^2);
```

7.20 Heliostat reflectivity efficiency

```
ref_ef = zeros(size(624));
for i=1:624
    ref_ef(i)=0.88;
end
```

7.21 Optical efficiency

```
opt_ef = zeros(624,8760);
for i=1:624
    for j=1:8760
        opt_ef(i,j) = cos_ef(j)*att_ef(i)*ref_ef(i);
    end
end
```

7.22 Extraterrestrial irradiance

```
Gsc = 1367; % solar constant (W/m2)
G0 = Gsc*(1+(0.033*cosd((360.*days)/365))).*cosd(omega); %Extraterrestrial irradiation (w/m2)
```

7.23 Beam irradiation

```

m = zeros(size(N)); % relative optical air mass coefficient (dimensionless)

for i=1:N

    if alpha(i)>30

        m(i) = 1./sind(alpha(i));

    elseif alpha(i)<=30

        m(i)=((1.002432.*((1-
cosd(2.*alpha(i)))./2)+(0.148386.*sind(alpha(i)))+0.0096467)./(((3.*sind(alpha(i))-
sind(3.*alpha(i)))./4)+(0.149864.*((1-
cosd(2.*alpha(i)))./2)+(0.0102963.*sind(alpha(i)))+0.000303978)));

    end

end

dr_m = zeros(size(N)); % Rayleigh optical thickness at optical air mass(m)

for i=1:N

    if m(i)<=20;

        dr_m(i)=1./(6.6296+(1.7513.*m(i))-(0.1202.*m(i).^2)+(0.0065.*m(i).^3)-
(0.00013.*m(i).^4));

    elseif m(i)>20;

        dr_m(i) = 1./(10.4+(0.718.*m(i)));

    end

end

Tlk = zeros(size(N));

for i=1:N

    Tlk(i) = 1; % atmospheric turbidity factor (pure rayleigh atmosphere)

end

B0c = zeros(size(8760));

Bhc_s = zeros(size(8760));

Bic = zeros(624,8760);

for i=1:624

```

```
for j=1:8760
    B0c = G0*exp((-0.8662*TIk(j))*m(j)*dr_m(j)); % Beam irradiation normal to the solar
beam
    Bhc_s = B0c(j)*sind(alpha(j)); % beam irradiation on horizontal surface
    Bic(i,j) = B0c(j)*sind(theta(i,j)); % beam irradiation on inclined surface
end
end
```

7.24 Total incident beam irradiation on tower receiver for a year

```
nt_ef = zeros(size(8760)); % tower receiver efficiency
for j=1:8760
    for i=1:624
        n_sum = 0;
        n_sum = n_sum + Bic(i,j);
    end
    Qin(j)=max(0,n_sum); % total incident irradiation
    nt_ef(j)=0.90;
end
```

Published with MATLAB® 7.10

8. Annex III: Plot Digitizer v. 2.5.0

Plot Digitizer is a Java program used to digitize scanned plots of functional data (Huwaldt J. A., 2010). Often, data is found in reports and references as functional X-Y type scatter or line plots. In order to use this data, it must somehow be digitized. This program will allow once to take a scanned image of a plot (in GIF, JPEG, or PNG format) and quickly digitize values off the plot just by clicking the mouse on each data point. The numbers can then be saved to a text file and used where ever needed. Plot Digitizer works with both linear and logarithmic axis scales.