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ABSTRACT

This project introduces the design of a parabolic trough solar thermal power plant with molten salt thermal storage and a nominal power of 50MW in Gibraleón, Huelva. From a first approach to parabolic trough technology, justifying its choice among other existing solar thermal solutions, the different stages of the system will be discussed, highlighting the main improvements that are susceptible of being implemented in the plant and validating the values obtained in the design stage through computer simulation. In addition, a first approach to the environmental assessment of the project, the different maintenance needs of the plant, grid connection procedure and a brief economic analysis will be developed in order to provide a more global view of the discussed topics. Finally, all the different results obtained during the different stages will be used to extract the main conclusions of the project.
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"Gratitude is a quality similar to electricity: it must be produced and discharged and used in order to exist at all"

- William Faulkner-
CHAPTER 1:
INTRODUCTION

1.1. Justification and scope of the project.

The increase in the price of fossil fuels, as well as the need for preserving the environment in all its extension, allows to expect a smooth substitution of traditional power production system by other innovative technologies based on the renewable resources of our planet. Among these technologies, it is possible to find solar thermal power plants, as they play an essential role in the decrease of toxic emissions without compromising the productive capacity of the energy sector. This project, the design of a solar thermal power plant in Gibraleón, will be developed through different process explanations, computer simulation and design schematics in order to ensure that the reader is able to understand the discussed topics.

For each stage of the project, the different alternatives will be discussed, justifying the selected solution as well as the different improvements related to it. At the same time, the different materials of the power plant elements will be discussed, developing a sizing stage through different calculations, a first approach to the maintenance needs of the plant, grid connection procedure, environmental impact assessment and brief economic analysis. Due to the complexity of these plants, which would require a great engineering effort, this project will only introduce a very general approach to its design, discussing all the main topics but dismissing those less relevant systems in order to accomplish with the timing of the project, which is established in 4 months.

1.2. Regulations and legislation.

The parabolic trough solar thermal power plant must meet the standards established by the Spanish Administration and so, regulations and legislation will be studied from national, autonomic and local approach, in order to ensure the accomplishment of all the requirements. Despite being a relatively new technology in the country, several regulations are found, which helps to reaffirm
the Spanish Government as a committed administration when it comes to solar thermal power plants. At the same time, the great amount of plants that have been developed during the last years in Southern Spain (mostly in Andalusia) have been crucial in the development of specific normative, although most of the legislation has been developed taking into account renewable energies as a global concept and not according to specific technologies. After a intensive research process, it can be concluded that solar thermal power plants are basically ruled by the following normative:

- **ROYAL DECREE 1955/2000, December 1st**, which regulates transmission, distribution, commercialization, supply and authorisation procedures for electrical energy systems.
- **ROYAL DECREE 436/2004, March 12th**, which establishes the methodology for actualization and systematization of the juridical and economical regimes for the electrical energy production activity in Special Regime.
- **LAW 9/2006, April 28th**, which evaluates the effects of determined plans and programmes on the environment.
- **AUTONOMIC LAW, 2/2007, March 27th**, renewable energies, efficiency and energy saving enhance in Andalucia.
- **ROYAL DECREE 661/2007, May 25th**, which regulates the electrical energy production activity in Special Regime.
- **LAW 1/2007, July 4th**, that modifies the **LAW 54/1997, November 27th**, of the Electrical Sector in order to adapt it to the regulations established by the **DIRECTIVE 2003/54/CE, June 26th**, common regulations for the inside electricity market.
- **ORDER ITC/1673/2007, June 6th**, which approves the application conditions of power supply to the electrical system for determined producers and consumers who contribute to guarantee the electrical supply security.
- **ROYAL DECREE-LAW 6/2009, April 30th**, which approves determined measures in the energetic sector and social bonus.
- **ORDER ITC/1723/2009, June 26th**, which introduces a revision for the access fees after July 1st 2009, as well as for rates and raws of determined Special Regime systems.
• **ROYAL DECREE 1565/2010, November 19th**, which regulates and modifies determined aspects related to electrical energy production activity in Special Regime.

• **SECRETARY OF STATE OF ENERGY RESOLUTION, November 24th 2010**, which introduces a competitive tendering procedure in order to obtain an additional economic regime to the electrical energy production market for innovative solar thermal electrical energy production projects.

• **ROYAL DECREE 1614/2010, December 7th**, which regulates and modifies determined aspects related to electrical energy production activity in Wind and Solar Thermal technologies.

• **ROYAL DECREE-LAW 14/2010, December 23rd**, which establishes urgent measures in order to correct the electrical sector tariff deficit.

• **ORDER ITC/2914/2011, October 27th**, which modifies the ORDER ITC/1522/2007, May 24th, which establishes the regulation for the guarantee of renewable and high efficiency cogeneration systems electrical energy.

• **ROYAL DECREE 1544/2011, October 31st**, which introduces the access fees to transmission and distribution grids required to electrical energy producers.

• **ORDER IET/3586/2011, December 30th**, which establishes the access fees after January 1st 2012, as well as the rates and raws for Special Regime systems.

• **ROYAL DECREE-LAW 1/2012, January 27th**, which removes the retribution preassignment procedures and economic incentives for new cogeneration, renewable energies and waste electrical energy power plants.

• **ROYAL DECREE 681/2003, Health and security protection for those workers exposed to the intrinsic risks of explosive atmospheres**

• **ROYAL DECREE 400/1996, Elements, devices and protection systems for explosive atmospheres**

Please notice that other regulations such as the ones referred to general job security, fire protection and efficiency requirements, as well as other specific legislation such as the Spanish Low Voltage Electrotechnical Regulation (REBT) for auxiliary services, among many others, are assumed. Finally, despite not being former regulations, it is necessary to introduce other documents of reference that should be taken into account while developing the project:

• **National Energy Commission**¹ (CNE) answer related to regulation aspects of solar thermal electrical production technology, May 13th 2009.

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- National Energy Commission (CNE) resolution of the conflict related to the access of a solar thermal power plant access to transmission grid, January 26th 2011.


- Andalusian Energy Sustainability Plan 2007-2013 (PASENER 2007-2013), edited by the Andalusian autonomic government\(^3\).

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\(^2\) Spanish Diversification and Energy Saving Institute (IDAE), http://www.idae.es

\(^3\) Junta de Andalucía, http://www.juntadeandalucia.es (accessed March 2\(^{nd}\), 2012)
CHAPTER 2: FIRST APPROACH TO SOLAR THERMAL ENERGY


The Sun is a star composed by hydrogen and helium in which, due to the huge temperatures and pressures inside it, a nuclear fusion reaction is developed, providing immense amounts of energy. In order to use this energy, it is necessary to understand the radiation process.

The Earth describes three movements according to the Sun: a translation movement around it and according to an elliptic orbit, a rotation movement over itself and around an imaginary axis that crosses the poles and a nutation movement which is related to the variation of the position of this axis around its average position.

The axis that traverses the poles is slightly inclined according to the normal plane of the ellipse, being responsible for the fact that the solar beams hit the Earth with a different angle along the year. This angle is called declination, and varies from -23,45° to +23,45°. Taking this feature into account, it is possible to highlight four dates:

- **Summer Solstice (22nd June)**: the Earth is at its furthest position from the Sun, and declination achieves its maximum value of +23,45°.
• **Winter Solstice (23\textsuperscript{rd} December):** the Earth is at its closest position from the Sun, and declination achieves its lowest value of \(-23,45^\circ\).

• **Vernal Equinox (21\textsuperscript{st} May):** the Earth is in the middle point of the elliptic orbit, with null declination.

• **Autumnal Equinox (23\textsuperscript{rd} September):** the Earth is in the middle point of the elliptic orbit, with null declination.

![Diagram showing the Earth's position relative to the Sun during different seasons.]

**Figure 1. Variation of the declination angle along the year.**
[Source.- http://www.itacanet.org (accessed March 2\textsuperscript{nd}, 2012)]

Taking into account the information above, it could be concluded that declination is related to the day of the year, being possible to calculate its approximated value for any date according to the *Cooper* expression:

\[
\delta = 23,45 \cdot \sin \left( 360 \cdot \frac{284 + n}{365} \right)
\]  

(1)

Where:

\(\delta\) = declination, in sexagesimal angles.

\(n\) = ordinal number of the year (\(n=1\) for January 1\textsuperscript{st}, and \(n=365\) for the 31\textsuperscript{st} of December). During leap years, February will be rounded to 28 days.

In order to simplify calculations, it is possible to use tables or also a *reference day* which represents the monthly declination according to its average declination value, as it is shown in the following table.

**Table 1. Average declination according to reference day.**

<table>
<thead>
<tr>
<th>Reference Day</th>
<th>Declination [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>17</td>
</tr>
<tr>
<td>February</td>
<td>15</td>
</tr>
<tr>
<td>March</td>
<td>16</td>
</tr>
<tr>
<td>April</td>
<td>15</td>
</tr>
<tr>
<td>May</td>
<td>15</td>
</tr>
<tr>
<td>June</td>
<td>10</td>
</tr>
</tbody>
</table>
2.2. Determination of the position of the Sun.

2.2.1. Time coordinates.
Before explaining the required process in order to determine the position of the Sun, it is necessary to introduce some concepts:

- **Latitude ($\psi$)** is the angle [$^\circ$] between the parallel of the selected location and the terrestrial equator. Positive latitudes will be related to the northern hemisphere and negative latitudes will be related to the southern hemisphere.

- **Longitude ($\lambda$)** is the angle [$^\circ$] determined by an East-West location over the surface of the Earth, taking as reference the Greenwich meridian. Positive longitudes will be related to eastern directions and negative longitudes will be related to western directions.

- **Hour angle ($\omega$)** is the angle [$^\circ$] between the meridian plane through the selected location and the meridian plane through the Sun. The hour angle varies along the day, with positive values during the morning and negative values during the evening. At midday, the hour angle is null, and this situation is called **culmination**.

- **Solar Hour (SH)**. The length of the day varies along the year, as well as the rotation speed of the Earth. As a result, the solar hour will be related to the hour given by a clock that divided the solar day (defined as the time required in order to ensure that the Sun crosses twice the same meridian) in 24 hours and varied these along the year.

- **Civil Hour (CH)** is the hour related to the division of the solar day in 24 hours, but considering a constant rotation speed of the Earth along the year. The civil hour is the hour given by conventional clocks.

- **Advancement ($\epsilon$)** is the amount of advanced hours taking as a reference the CH, established according to energetic policies.

- **Time Equation (TE)** is the difference between the CH and the SH. In order to simplify its calculation, it is possible to use reference tables as well as the following expressions:

\[
D = \frac{360}{364}(n - 81) \tag{2}
\]

\[
TE = 9,87 \cdot \sin(2D) - 7,53 \cdot \cos(D) - 1,5 \cdot \sin(D) \tag{3}
\]

Now that the main parameters are known, it is possible to establish some relations between them. Taking into account that a complete circumference has
360° and a complete day has 24 hours, it is possible to affirm that each hour of the day is related to a 15° angle. Through this value, it is possible to divide the Earth in 24 time zones, each of them with 15° of amplitude and a middle meridian. As a result, the hour angle is given by the following expression:

$$\omega = (12 - SH) \cdot 15$$  \hfill (4)

The SH depends on the exact longitude of the selected location, but the CH is related to the time zone. This fact shows a difference between the reference meridian and the meridian that crosses the selected location. In this longitude difference, \( \lambda_m \) will represent the longitude of the meridian of the chosen time zone and \( \lambda \) will be the longitude of the meridian that crosses the location from which the position of the Sun will be determined. Taking all this into account, the different parameters can be related through the following expression:

$$SH = CH - \varepsilon + \frac{\lambda_m - \lambda}{15} + TE$$  \hfill (5)

2.2.2. Angular coordinates.

There are also other procedures in order to determine the position of the Sun, as this can also be found taking as a reference the tangent plane to the surface of the Earth in the selected location, also known as horizon. As a result, two new parameters are required:

- **Azimuth (\( \alpha \))**: is the angle [°] comprised between the direction of the projection of the Sun over the horizontal plane and the southern direction. Positive azimuth values will be related to western locations, and negative values will be related to eastern locations according to a southern direction reference.

- **Height (\( h \))**: is the angle [°] between the position of the Sun and its projection over the horizontal plane, taking the horizon as a reference. In other words, height is related to the angle with which the observer sees the Sun over the horizon, independently of its orientation, reaching positive values during the morning and negative values during the evening.

For those latitudes of the tropic, it is possible to related the angular coordinates with the time coordinates through the following formulas:

$$\sin(h) = \sin(\psi) \cdot \sin(\varnothing) + \cos(\psi) \cdot \cos(\varnothing) \cdot \cos(\omega)$$  \hfill (6)

$$\sin(\alpha) = \frac{\cos(\varnothing) \cdot \sin(\omega)}{\cos(h)}$$  \hfill (7)

For a given latitude (\( \psi \)) and declination (\( \varnothing \)), related to a specific location and a specific day, it is possible to estimate the sunset hour by only establishing a null height (\( h \)).
2.3. Solar radiation.

The incident solar radiation is a key factor in order to select the location of the solar thermal power plant, as it is the main resource that allows to perform the electrical energy production procedure. As it has been previously mentioned, the Sun provides the Earth with huge amounts of energy. Among this, a 97.8% is comprised between a wavelength value of 0.2 and 3μm, with a 9% of ultraviolet radiation, a 40% of visible light and a 51% of infrared radiation.

When the solar radiation crosses the atmosphere, a very important amount of it is absorbed by the molecules and particles that compose it. Each molecule introduces a specific actuation range, as ozone is responsible for the absorption of ultraviolet radiation and carbon dioxide is responsible for the absorption of infrared radiation, for example. As a result, the amount of radiation that reaches the surface of the Earth depends on its composition and the width of the atmosphere, which varies along the planet, as well as on the angle with which this radiation hits the atmosphere. According to this features, it is possible to introduce the following concepts:

- **Irradiance (I):** it is the radiant energy per time unit that hits a surface, indicated in \( [\text{W/m}^2] \), \( [\text{MJ/m}^2\cdot\text{h}] \) or \( [\text{cal/cm}^2\cdot\text{min}] \).

- **Direct Normal Radiation (DNI):** it is the solar radiation that hits the surface of the Earth without noticing more direction variations that the ones related to atmospheric refraction. The DNI is typically given in \( [\text{kWh/m}^2] \).

- **Diffuse radiation:** it is the portion of solar radiation that comes from the decomposition of the solar beams in the atmosphere, which varies its direction and has a uniform distribution along the celestial hemisphere.

- **Albedo or Reflection Coefficient:** it is the portion of solar radiation that comes from the reflection of both direct normal and diffuse radiation over the surfaces of the environment, with undefined direction.

- **Global Radiation:** it is the sum of the direct normal radiation and the diffuse radiation.

- **Total Radiation:** it is the sum of the direct normal radiation, diffuse radiation and albedo.

Once that the main parameters have been introduced, it is possible to continue with the development of the project.

2.4. Operating principle.

Solar radiation is an energy source with huge possibilities. If it is wisely collected, it is susceptible of being used in a great amount of applications, highlighting electricity production. There are many technologies focused on this solar-to-electricity conversion, although all of them follow the same main scheme, which is shown in the following figure.
As it can be seen, solar radiation is collected by the collector system and focused on the receiver system, which transfers the thermal energy provided by the Sun to a working fluid. This fluid, which reaches high temperatures, is directed to the transport-storage system and later distributed to the power conversion system where the thermal energy provided by the fluid is used to generate electricity through very different procedures. In some solar thermal power plants, a portion of this thermal energy is stored in order to be used during periods of small solar resource, while other plants that introduce a backup fossil-fuel system to solve this issue by providing thermal energy to both the transport-storage system or the power conversion system.

There are lots of typologies and technologies that allow this solar-to-electricity conversion and, as a result, it is essential to introduce the main configurations in order to determine which one, according to economic, environmental and technical criteria, is the best choice for a commercial scale power plant.

2.4.1. Advantages of Solar Thermal Power Plants.

Solar thermal power plants introduce several advantages. Through appropriate systems, they allow to store the thermal energy provided by the Sun in order to produce electricity even during periods without solar light. What is more, the great inertial of the generating system (typically performed by a turbine and an alternator) allows to adequate the output of the plant to the grid requirements, reinforcing its stability against punctual consumption variations.
Solar thermal technology is a clean, safe and renewable energy which, except from those fossil-fuel hybrids, does not require any kind of fossil fuel, reducing this way the energetic dependence of the country and the total amount of toxic emissions to the atmosphere. At the same time, it introduces great opportunities in the generation of jobs and the economic and social development of the nearby regions, which according to the fact that the highest direct normal radiation values are typically found on relatively undeveloped regions is a great point and must be highlighted.
CHAPTER 3: EXISTING TECHNOLOGIES AND JUSTIFICATION FOR THE CHOICE

As it has been explained in the previous chapter, there are several solar thermal power plant configurations, but it is possible to highlight the following collecting technologies:

- Parabolic trough concentrators.
- Solar power tower concentrators.
- Stirling engine dish concentrators.
- Fresnel reflection concentrators.

3.1. Parabolic trough concentrators.

3.1.1. Operating principle.

Parabolic trough solar thermal power plants focus solar radiation onto a linear receiver that is located in the focal line of the parabola and through which a heat transfer fluid (HTF) flows, increasing its temperature.
The heat transfer fluid will be closely related to the operating temperatures of the solar field, varying from simple demineralised water to synthetic oils. In order to maximize the solar radiation collection, the parabolic trough collectors move along the day depending on the position of the Sun, typically around parallel axis located in the focal line of each collector. This is critical, as solar concentrators can only collect direct normal radiation. Parabolic trough technology enjoys a proved commercial success, with initial experiences developed during the 80s, and both the design and the implementation of this kind of technology are notably more advanced than other solar thermal systems.

3.1.2. Power generation using parabolic trough concentrators.

In SEGS (Solar Electricity Generating Systems) power plants, the different parabolic trough collectors are distributed in parallel rows with serial connection. Thanks to the collection of direct normal radiation, this solar assemblies increase the temperature of the HTF, which is directed to a heat exchanger in order to produce the superheated steam that will be used in the steam turbine to produce electricity, generally through a Rankine steam cycle. While the HTF provides its thermal energy, its temperature decreases and, once that all the heat exchange has occurred, this cold heat transfer fluid is sent to the solar field in order to repeat the process.

Typical SEGS power plants do not have any kind of thermal storage and, as a result, their output is limited to those hours with sufficient solar resource. In order to complement the process and to continue with electricity production even during those periods with no solar resource, these plants tend to introduce backup fossil-fuel boilers. However, new solar thermal plants use the exceeding thermal energy of the HTF to heat a molten salt storage system and electricity production is ensured without the need for an auxiliary boiler.

Another common solution is hybridization. Parabolic trough power plants can be hybridized with other conventional power plants, being able to highlight the Integrated Solar Combined Cycle System (ISCCS), which is based on the combination of a parabolic trough solar thermal power plant and a combined gas turbine cycle. This technology uses the solar resource to increase the thermal energy of the exceeding heat from the gas turbine, obtaining higher steam temperatures and, consequently, higher Rankine cycle efficiencies at lower operating cost. This hybridization concept is not restricted to combined gas turbine cycles, as it is possible to implement it with other technologies such as
coal power plants, reducing the total amount of coal required to achieve the nominal output of the plant and increasing the global efficiency of the plant.


Figure 4. shows the main functioning of a parabolic trough SEGS power plant. It is possible, then, to establish a comparative with the general scheme introduced in Figure 2, in order to verify its validity. According to this last one, the incident solar radiation is collected by a collecting system which focuses it on a receiver system trough which a heat transfer fluid flows. In SEGS power plants, the solar field, composed by the different parabolic trough collectors and the different linear receivers, represent this collector-receiver system. The HTF, as it has been said before, will depend on the average operating temperatures and the nominal output of the plant.

In Figure 2, it was possible to notice a divergence in the receiver system that allowed to distinguish two operating modes. In those solar thermal power plants with no thermal storage, the high temperature HTF was directly directed to the power conversion system in order to generate electricity. This power conversion system is composed by the superheater, the steam generator, the preheater, the reheater, the expansion vessel, the deaerator, the low pressure reheater, the condenser and the steam turbine, according to Figure 4. However, in those solar thermal power plants with thermal storage, the high temperature HTF was not directly sent to the power conversion system but to the transport-storage system trough a pumping system.

There are several thermal storage system and a global approach on them will be made in the following chapters of this project, but it is necessary to highlight the two-tank thermal storage system as this is largely the most common technology in commercial solar thermal power plants. In these tanks, the thermal energy is stored in order to be used when the solar resource is not enough to provide
sufficient thermal energy to the power generating system. As it can be seen in Figure 4, this option is also considered, highlighting its optional character by indicating it between parentheses.

Finally, Figure 2. showed the possibility of including an auxiliary backup fossil fuel boiler (this must not be confused with the concept of hybridization) in order to increase the thermal power of the plant. According to this, this auxiliary fossil fuel system allows to provide thermal energy to both the transport-storage system and power conversion system. In the parabolic trough SEGS power plant showed in Figure 4, this backup system is performed by the HTF heater and the boiler, which is optional. It is proved, then, the validity of the general scheme established in Figure 2, as it is possible to indentify the different elements of a real parabolic trough power plant as well as the general systems common to any solar thermal electricity generation process.

3.1.3. Advantages and disadvantages.

Parabolic trough solar thermal technology is completely available today. However, its implementation is limited by a higher electricity cost when compared to other conventional power plants, as well as by a higher initial investment. Despite this fact, the introduction of backup fossil-fuel based systems and the hybridization with other power generating technologies can help to perform a first introduction of this technology in the power market until pure solar electricity generation is economically competitive.

As an advantage, parabolic trough SEGS power plants introduce a relatively low technological risk, which allows to estimate an important decrease in the cost of future plants thanks to the introduction of technological improvements, chain production of the elements and new suppliers that will be responsible for smaller electricity costs. This is critical, as other solar thermal systems are still in a development stage and parabolic trough power plants currently enjoy a small advantage that will be maintained until power tower and Stirling engine dish systems reach a higher commercial experience.

At the same time, several advantages are found in terms of environmental protection. By reducing the total amount of fossil-fuel and, consequently, the toxic emissions to the atmosphere, parabolic trough power plants (and generally, any kind of solar thermal technology) are a great allied in the fight against climate change. Other economic (higher radiation values are typically found on undeveloped regions and these can be reactivated thanks to new jobs and the introduction of new systems) and energetic (reinforcing of the electrical grid against punctual consumption peaks, especially in summer when the increase in consumption is compensated by the higher solar resource availability) advantages can also be found. The introduction of new backup fossil-fuel systems, the possibility of hybridization with other conventional power plants and the innovative two-tank thermal storage systems introduce parabolic trough power plants as real supporting option for the electrical system of the selected location.

Unfortunately, not all are advantages, as this technology is facing different limitations. According to the environmental preservation, the decrease in the consumption of fossil-fuel and the consequent reduction of toxic emissions to the atmosphere is not very noticeable in those hybrid power plants, as well as the fact that the different working fluids can be responsible for great damages to the
environment in case of accidental spillage. At the same time, these plants require huge amounts of land, as well as great amounts of water depending on the selected cooling technology, introducing important environmental impacts in the selected location. A deeper approach on these issues will be made in the following lines.

![Image of a solar thermal power plant in Granada](image)

**Figure 5.** Andasol I parabolic trough power plant in Granada.  

As it has been said, the implementation of the solar field required in order to collect the direct normal radiation in parabolic trough solar thermal power plants requires huge land extensions that cannot be used in other purposes, introducing a direct relation between the solar field area and the nominal output of the plant. However, it is necessary to mention that some studies establish that the land requirement of parabolic trough technology is smaller than other renewable technologies such as wind turbines, biomass or hydraulic. This is very important, as it introduces a critical advantage in a technology where the higher the solar field is, the cheaper is to produce electricity.

Finally, in order to develop the electricity generation activity in parabolic trough SEGS plants a huge amount of water is required, most of it to be consumed in the cooling system (if an evaporative cooling method is chosen, which will be discussed in the next stages of the project) and in the steam generating train. As a result, water resource is critical to ensure the success of a parabolic trough power plant, so it is essential to find an appropriate balance between the solar resource and water resource availability when selecting the location of the plant. When the different processes of the plant are finished, this water will need to be treated before it is returned back to the region in order to ensure that the ecosystem is not damaged.

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3.2. Solar power tower concentrators.

3.2.1. Operating principle.
Solar power tower plants are based on mobile reflectors which focus the direct normal radiation on a heat exchanger located on the top of a tower.

![Diagram of solar power tower technology](image)

**Figure 6.** Power tower solar thermal technology.

3.2.2. Power generation using solar power tower concentrators.
As it happened in the parabolic trough technology, a heat transfer fluid is used to provide thermal energy to the power block. Again, this HTF will depend on the average operating temperatures and the special features of the plant, being possible to find solar power tower plants with molten salt thermal storage as well as hybridized plants with conventional fossil-fuel systems.

![Diagram of solar power tower SEGS plant](image)

**Figure 7.** Solar power tower SEGS plant with two-tank molten salt thermal storage.
Initial power tower systems used the direct normal radiation provided by the Sun to generate directly the steam used in order to produce electricity in the turbine, but this system was not very efficient and was finally substituted by molten salt based heat exchangers\textsuperscript{6}, increasing the global efficiency of the process and allowing two-tank thermal storage systems in order to continue with the electricity production even during periods with insufficient solar resource.

3.2.3. Advantages and disadvantages.

The main problem that solar power tower plants face is the fact that this technology is not modular and introduces as a result bigger land requirements than other solar thermal technologies such as parabolic trough and Stirling engine disc systems. At the same time, as it happened in the parabolic trough power plants, in order to obtain electricity through a Rankine steam turbine cycle it is necessary a relatively important water resource, especially if evaporative wet cooling is chosen for the plant. This water, again, will need to be treated before being reintroduced in the ecosystem.

Solar power tower is, with parabolic trough systems, one of the most developed solar thermal power generating technologies and have proved to be successful in a commercial scale. They are based on higher temperatures than parabolic trough power plants (as these are classified as medium temperature systems and solar power tower are classified as high temperature systems) and they represent a higher environmental impact related to the height of the central tower. Despite this higher development, solar power tower plants are still being overcome by parabolic trough collectors due to their smaller land use and large previous commercial experience, which are related to smaller costs. However, the main efforts are made on introducing this technology in the energetic market trough hybridization with other conventional power plants until the technology is sufficiently mature to be operating by itself.


It has been mentioned above that solar power tower plants introduce higher costs when compared with parabolic trough power plants. This feature is mainly related to the fact that the second ones enjoy a much larger commercial scale experience and power tower systems are still provided by very specific suppliers, typically under command and at a higher price. In addition, it is more difficult to find qualified employees, as parabolic trough power plants have already identified very specific professional profiles of contrasted validity.

The environmental impact related to the central tower is unfortunately not the only disadvantage of these systems. Although a hybridization with conventional power plants, required to introduce this technology in the marked, is responsible for a reduction in fossil-fuel consumption and toxic emissions, this values are still far from the zero emission estimations of a pure solar thermal system. As it happened with parabolic trough thermal storage systems, power tower plants base their thermal storage on molten salt mixtures that may be dangerous in case of accidental spillage.

Due to the higher temperatures of this technology, no HTF is needed in the plant as all the thermal energy transmission is directly performed with molten salt mixtures. It is difficult, however, to establish great differences between solar power tower and parabolic trough power plants according to environmental criteria, as they both introduce very similar advantages and disadvantages. Despite this fact, a curiosity can be easily highlighted. Solar power tower plants need special systems in order to ensure that birds do not cross the reflected solar beam, as if this happens they are immediately inflamed and die. Initial power tower experiences showed alarming bird killing rates, as most of them, unaware of the danger, flew through the reflected solar beam. Actual deterrent systems include acoustical signals and visual barriers, among many others.

Finally, from a technical point of view, some issues need to be solved yet, such as the development of a cheaper azimuth control system (current technology rotates the heliostat around a perpendicular axis to the ground in order to follow the Sun and to focus the solar radiation on the central tower, so each heliostat requires its own rotating drive) or higher efficiency central tower heat exchangers, as well as maintenance issues.

### 3.3. Stirling engine dish concentrators.

#### 3.3.1. Operating principle.

The parabolic disc technology, also known as Stirling engine dish systems, are autonomous units composed by a parabolic disc concentrator and a thermal Stirling engine. The optical assembly focuses the solar radiation on the engine, which through the expansion and contraction of a gas (typically, hydrogen, nitrogen, helium or air) produces work that can be used to generate electricity. In order to ensure the maximum efficiency of the collector, the different Stirling engine dish units introduce double axis rotating systems.

The thermal exchange process between the parabolic collector and the working gas can be given in two different ways: focusing the incident solar radiation on different tubes through which the working gas flows, or directly vaporizing a liquid metal (sodium, mainly) which condenses on the surface of these tubes transferring its thermal energy to them.
The Stirling engine dish technology has proved to provide higher efficiencies than other solar thermal systems such as the parabolic trough and solar power tower technologies, introducing higher concentrating rates that allow to achieve very high temperatures. However, all the experiences developed on this technology have been experimental and very scarce, introducing much higher costs than other currently developed solar thermal systems.

In order to focus the incident solar radiation on the thermal receiver of the engine, it is common to introduce metallised crystal or plastic concentrators, introducing a proportional relation between the solar collecting surface and the size of the Stirling engine. The higher the solar collecting surface is, the more power is available and the higher will be the size of the engine in order to manage it. From an optical point of view, the ideal collecting surface is a revolution parabola, although it is possible to find Stirling engine dish systems based on spherical concentrators that achieve an approximation of this shape which, despite being less efficient, introduce much lower costs.
The optimization of the optical system of the concentrator allows to increase the value of the concentrating ratio, understood as the quotient between the average solar flux collected by the receiver of the Stirling engine and the total amount of direct normal radiation in the selected location, so lots of efforts are focused on solving this issue.

As it has been previously mentioned, the parabolic concentrator is responsible for focusing the incident direct normal radiation on the receiver of the Stirling engine in order to ensure that this is able to carry out the electrical energy generating process. There are two main receiver types: on one hand, in the Direct Illumination Receivers (DIR), the thermal exchange is directly carried out in the working fluid of the engine (typically helium or hydrogen) and, as a result, very high working temperatures are reached. On the other hand, Indirect Illumination Receivers (IIR) are based on a HTF that collects the thermal energy provided by the concentrator and transfers it to the working fluid of the engine. Through IIR, a liquid metal is vaporised and, when it condenses on the hot side of the Stirling engine, it transfers all its thermal energy to it in a more uniform way than through the DIR procedure.

![Diagram of Stirling engine with liquid sodium IIR technology.](image)

**Figure 11. Stirling engine with liquid sodium IIR technology.**


3.3.2. **Power generation using Stirling engine dish concentrators.**

The thermal Stirling engine is responsible for converting the thermal energy provided by the solar collector into electric energy. There are also other dish systems which introduce Rankine steam or Bryton turbine gas cycles in order to carry out this conversion, although the most common system is based on the Stirling thermal engine due to the fact that they introduce higher efficiencies of around 40%\(^7\) with a much simpler infrastructure.

In the Stirling engines, a gas is heated and cooled in a continuous cycle that is responsible for its contraction and expansion in a cylinder. This contraction and expansion movement in the cylinder moves a piston and allows to obtain

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mechanical energy. There are several types of Stirling engine configurations, although it is possible to highlight three main configurations:

![Diagram of Stirling engine configurations]

**Figure 12.** Stirling engine main configurations.


Solar thermal Stirling engine dish systems are typically based on the Beta-Configuration, as it allows to reduce the size of the engine, but it is possible to find other configurations depending on the specific conditions of each project.

3.3.3. Advantages and disadvantages.

Solar Stirling engine dish systems introduce several advantages. It is necessary to highlight the high efficiencies reached during the solar-to-electricity conversion process when compared to other solar thermal systems, their lower environmental impacts (very small toxic emissions and much smaller working fluid), the possibility of operating in an autonomous way by installing microprocessors in each unit or SCADA (Supervisory Control And Data Acquisition) systems in those bigger plants, as well as in a modular way and, as it happened with the solar power tower and parabolic trough technologies, the possibility of hybridization with other conventional fossil-fuel based power plants in order to ensure a first introduction of Stirling engine dish systems in the power market.

However, despite this technology introduces great possibilities for the future, it is currently in a development stage and is not sufficiently mature in order to be implemented in commercial scale power generating plants, introducing much higher costs than other solar thermal systems. It is important to mention, that, despite the fact that Stirling engine dish systems are not sufficiently mature for commercial scale applications, some experiences have already been carried out in small isolated regions, introducing great results in the development of punctual power generating systems for small population nucleus located in inaccessible regions where, due to the specific meteorological, topographic and orographic features, cannot be provided with an electrical supply through other solar thermal technologies (as parabolic trough and solar power tower systems require great amounts of plain land).
3.4. Fresnel reflection concentrators.

3.4.1. Operating principle.

The Fresnel reflection concentrator technology is based on large flat mirror rows that focus the incident solar radiation in a central receiver which is parallel to their rotating axis and located a few meters high. It is quite a similar procedure than the one introduced by the parabolic trough technology, with similar concentrating ratios and operating temperatures but at a lower cost.

![Fresnel reflection concentrator diagram](image)

**Figure 13.** Fresnel reflection concentrator.


3.4.2. Power generation using Fresnel reflection concentrators.

All the experiences with Fresnel reflection concentrators have been limited to very few experimental plants, so the commercial viability of these kinds of systems is still to be proved. During these experimental studies, the selected configuration was the **Compact Linear Fresnel Reflector (CLFR)**, which is based on the conjunction of several linear Fresnel receivers in a compact module. Under this configuration, it is not possible to rotate them, as it could increase mutual shading to unbearable levels. However, this distribution allows the reflected solar radiation to impact on different linear receivers at a time, increasing the available thermal energy for the steam generating process and, consequently, the final output of the plant.

The Fresnel linear receivers are based on the same technology that was introduced for the parabolic trough power systems, being nothing but an absorber tube through which a HTF flows. This transfer fluid will depend on the final output of the plant and the average operating temperatures of the system, varying from simple demineralised water for small applications and molten salt fluids for big plants (this is, in fact, the selected HTF in case that a commercial scale linear Fresnel power plant was developed). The electricity generating procedure is simple: again, the thermal energy collected from the Sun is used to generate steam, which will be directed to a steam turbine in order to produce
mechanic energy. This mechanic energy will finally be used to drive an alternator in order to produce electrical energy.

3.4.3. Advantages and disadvantages.

As it has been previously mentioned, the main advantage of the Fresnel reflection technology is its lower cost when compared to other solar thermal generating systems. The flat mirrors that compose the concentrator are easier to produce than the curved elements required in the parabolic trough or Stirling engine dish technology and, consequently, they do not need to be manufactured by specific suppliers, which is responsible for an important cost reduction in these elements.

At the same time, the distribution of the different Fresnel collectors along the solar field does rarely reach very important heights, reducing the complexity of the standing mechanic structure and the total amount of material required to mount it. This is critical, as by introducing smaller and much simpler supporting structures, the plant is able to continue operation even under wind speeds that would imply the shutdown of other solar thermal technologies.

![Fresnel reflection prototype, Belgium, 2002.](image)

This simpler supporting structure is also responsible for easier maintenance operations and, consequently, maintenance costs. Another saving is given by the fact that CLFR systems do not required high pressure rotating joints because no rotation is produced.

From an environmental point of view, the different environmental impacts associated to Fresnel reflection technology are practically the same to the ones introduced for parabolic trough or power tower plants, with special importance of accidental HTF spillages and water consumption depending on the selected cooling technology. It is also possible to hybridize Fresnel reflection systems with
other conventional fossil-fuel power plants, ensuring a first introduction in the power market (as it has previously been mentioned for other solar thermal technologies) until the technology is sufficiently mature to operate in an autonomous way.

Regarding to the disadvantages of the Fresnel reflection technology, it is necessary to highlight the high land requirements of the CLFR power plants, much higher than other solar thermal systems for the same reference output power. As a result, Fresnel reflection technology introduces several advantages, especially in terms of cost reduction, but unfortunately there is not any commercial experience that ensures the viability of these systems as real power generating options as most of the projects involving this technology are restricted to very small prototypes and plants that are not representative.

3.5. Justification for the choice.

Solar thermal power plants are little by little entering the different power markets as the generating costs of the conventional fossil-fuel power plants are increasing. However, there are still several issues that are slowing down this introduction, being necessary to support these systems through different politic and financial measures in order to consolidate this environmental friendly solution as a real power generating option.

Once that the main solar thermal power technologies have been introduced, it is the time to select the one that, due to its specific features, is the best option for the development of a commercial scale plant. If this exercise had been carried out 10 years ago, this would have been a very easy choice, as parabolic trough power plants have largely been the only viable technology in a commercial scale. However, during the last years, several technological improvements have been performed in other solar thermal systems such as the solar power tower technology, which has been introduced in the power market with a proven reliability and a contrasted success as it is shown in the different solar power tower plants developed in Southern Spain. As a result, it is necessary to perform a comparison between the main advantages and disadvantages provided by each of the solar thermal technologies in order to choose the best option.

![Figure 15. Comparison between the different solar thermal technologies.](source-url)

In order to ensure that Figure 15 is understood, it is necessary to introduce the concepts of solar efficiency, understood as the quotient between the output net power and the incident solar radiation) and capacity factor (CF), understood as the value obtained by dividing the annual solar operating hours between the 8760 hours of a year. These concepts, in addition to other parameters related to land use or concentrating ratio, will provide a global idea of the efficiency of each system that will allow to make a decision.

Regarding to production capacity, parabolic trough, Fresnel reflection and power tower technologies are theoretically able to provide output values from few MW to hundreds of MW. It is understood, then, that in order to maximize the benefits of a solar thermal power plant it is necessary to maximize the annual energy output of the plant, as benefits are produced by selling this energy. Taking this into account, Stirling engine dish systems are likely to be more useful in isolated generating applications developed in inaccessible locations and with a small size, as they are autonomous units with reduced output capacity.

Figure 15 introduces the different concentrating ratio values for each solar thermal technology. It is easy to observe a clear advantage introduced by Stirling engine dish systems, followed by solar power tower, parabolic trough and CLFR technologies. Concentrating ratio could be defined as the quotient between the reflective area of the concentrator and the collector surface of the receiver, which can be simplified to be a measure of the optical quality of the system. As a result, under the same direct normal radiation, those systems with higher concentrating ratios will focus higher amounts of solar radiation, increasing the thermal energy provided to the HTF and resulting in higher outputs.

To this point, it could be concluded that, according to the discussed features, the best option is given by the central power tower technology, as this provides good output values with high concentrating ratios while the other solar thermal technologies provide good output values with a bad concentrating ratios or vice-versa. However, if the comparison is carried on, it can be observed that the peak solar efficiency provided by Stirling engine dish systems is the highest of all the solar thermal technologies, with proven values around 29%. Parabolic trough and power tower plants are in second position, with very similar values of approximately 20%. As it has previously been mentioned, all the Fresnel reflection experiences have been limited to small size applications so it is not possible to provide comparable proven solar peak efficiencies. Despite the fact that Figure 15 introduces the possibility of solar peak efficiencies of around 20%, these are nothing but theoretical estimations and must not be understood as real values.

Solar peak efficiency is important, but it is necessary to have in mind that this is a maximum efficiency value that will not be given under conventional operating conditions. If efficiency is the relation between the output net power and the incident solar radiation, it is much more critical to discuss the different technologies in terms of annual solar efficiency, as this is the average value for each technology during a whole operating year and all the different generation and benefit estimations, among many others, will be developed according to this value. It could seem that annual solar efficiency should be proportional to peak solar efficiency, but the results are surprisingly. If the peak solar efficiency of Stirling engine dish systems was established at around 29%, their proven annual solar efficiency is comprised between 16% and 18%, with 8-10% annual solar
efficiency values for power tower systems, 9-11% in Fresnel reflection systems (theoretical) and 10-15% in parabolic trough solar systems. According to these values, there is a small difference between Stirling engine dish and parabolic trough annual solar efficiencies, while the first ones had previously been established as the best option according to solar peak efficiency, and it is possible to observe that power tower technology introduces relatively small annual solar efficiencies when compared to other solar thermal technologies.

Regarding to the efficiency of the power generating cycle, this is identical for each of the four considered solar thermal technologies, which is not surprising taking into account that the values introduced in Figure 15. are given for a Rankine steam cycle in which only the way that the steam is produced varies, but not the way that this steam is used. This Rankine cycle, however, cannot be applied to the Stirling engine dish technology, as this is based on the expansion and contraction of a gas, as it has been previously mentioned. Please notice that the combined and gas turbine cycle values have not been discussed, as they are not included in the scope of this project. Taking into account all the information above, it is possible to see that solar power tower systems are overcome by parabolic trough power systems, as these second ones introduce the most balanced values in terms of output capacity, concentrating ratio and efficiency. Stirling engine dish and linear Fresnel reflection technologies are established as worse solutions due to their small output capacities and the fact that no commercial scale experiences have been developed yet, so the different values cannot be taken as proven ones.

It is the time to discuss the capacity factor, as this plays an essential role in the final output of the plant. Taking this parameter into account, parabolic trough power plants have demonstrated capacity factors up to 24%, while not contrasted information is provided for the other solar thermal technologies introduced in Figure 15. According to this limitation, this parameter must not be used in order to determine the best option for the solar thermal power plant, as more details would be needed in order to ensure a good choice. According to theoretical estimations, capacity factors between 25% and 70% are expected in parabolic trough, power tower and linear Fresnel power plants in the following years, with values around 25% in Stirling engine dish applications.

Before establishing parabolic trough solar thermal technology as the most advisable option for developing a commercial scale power plant, there is still a last parameter to consider. Regarding to land use, central power tower and Stirling engine dish power plants require higher land areas of around 8-12 m²/MWh-year, followed by parabolic trough power plants with values around 6-8 m²/MWh-year and linear Fresnel power plants, with estimated land use values around 4-6 m²/MWh-year.

In order to select the best option, a comparison system based on a 1 to 4 scale has been developed, where 4 represents the best option and 1 represents the worst option. In case different technologies introduce the same values these will be given the same score, and proven values will be prioritized against theoretical ones. According to all this previously mentioned features, the comparison between the different solar thermal power technologies is developed in the following table:
Table 2. Comparison between the different solar thermal power technologies.
[Source.- Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>Parabolic Trough</th>
<th>Fresnel</th>
<th>Power Tower</th>
<th>Stirling Dish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Concentrating Ratio</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Peak Solar Efficiency</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Annual Solar Efficiency</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Thermal Cycle Efficiency</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Land use</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<tr>
<td>TOTAL</td>
<td>23</td>
<td>18</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

As it can be seen, parabolic trough solar thermal technology is the best option of the different discussed systems. This is such a logical result, especially taking into account that this is largely the concentrating solar technology with higher commercial experience, which results in a proven technical and economic viability of these plants. According to the values obtained, this project will develop the design of a parabolic trough solar thermal power plant with thermal storage, as this is understood to be the best option.

3.6. Cooling technologies

Water is required in several processes through the plant’s operation, as it is essential for steam generation, cooling and cleaning processes, among others. It is essential, then, to provide sufficient water supply to the parabolic trough power plant, and it may be obvious that the existence of a natural source of water is responsible for a huge cost reduction as bringing water from other regions is neither easy, neither cheap.

Regarding to this concern, it is important to define a general estimation of water consumption for the plant, because if the required daily water supply is known it is easier to find a suitable location. Cooling is an essential stage in the Rankine cycle, as it is necessary to condense steam and complete the thermal cycle. According to the United States National Renewable Energy Laboratory (NREL), cooling can be provided through four main ways:

- Once-through water cooling: water is pumped from the source to the heat exchanger and then returned back. It is the simplest cooling system and
its use is restricted to specific applications, usually not very common in solar power plants. Despite the fact that little water is consumed during the cooling process (as practically the totality of the income water is returned back to the source), this cooling method has a big environmental impact caused by a reintroduction of hot water to the original ecosystem and the increase of aquatic life mortality, as living organisms are pulled through the system.

- **Evaporative water cooling:** it is based on the dissipation of waste heat from the power plant by evaporation of water in the cooling tower. This cooling method needs great amounts of water, as a typical parabolic trough power plant requires approximately 2030 litres of water for MWh (800 gallons per MWh)\(^8\). These 2030 litres/MWh are usually distributed in a 90% expense for cooling processes, 8% for steam generation cycle and 2% for concentrator washing\(^9\). Evaporative water system is a simple, economic and high performing cooling method, features that introduce it as the most typical cooling method for solar thermal power plants. The water pumped from the natural source contains suspended minerals and particles that once the water is evaporated, tend to remain in the process and can be responsible for damages in the system. In order to avoid these damages, water is usually treated with chemical substances and periodically drained in a process called blowdown that may introduce a potential environmental hazard. At the same time, chemicals used in water treatment can be evaporated with the water and drifted in the atmosphere and so, appropriate attention must be paid to the evaporating process.

- **Dry cooling:** this cooling method uses air to carry out the heat exchange in the power plant and so, requires very little water. This heat exchange is provided by a temperature difference between the condenser temperature and the ambient temperature. On hot days, the condenser temperature has to increase to ensure cooling and so does the condenser pressure which in turn, reduces the efficiency of the steam turbine. If efficiency (and consequently, the power output of the plant) decreases on hot days, this becomes a critical problem that reduces the potential output of the plant for example, in summer, when the solar availability is the highest and dry technology is more expensive than wet cooling systems too.

- **Hybrid wet/dry cooling:** this cooling method is based on a parallel combination of wet and dry systems. Under conventional operating conditions dry cooling is carried out and, on hot days, a fraction of the steam from the turbine is redirected to a wet cooling system. Through this simple method, the condenser temperature on hot days suffers no variation and the efficiency of the turbine remains the same. Hybrid wet/dry cooling requires less amount of water as the cooling tower for the wet side is smaller, and so it is the air condenser on the dry side. Again, hybrid cooling is more expensive than wet cooling systems, but it is also


cheaper than dry cooling systems. As a result, hybrid cooling becomes a strong option for those locations with hot climate and small water availability, which usually provide the highest direct normal radiation values.

**Table 3. Comparison of existing cooling systems in parabolic trough power plants**

[Source: Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet cooling</td>
<td>Lowest installed cost</td>
<td>High water consumption</td>
</tr>
<tr>
<td></td>
<td>Low parasitic loads</td>
<td>Water treatment and blowdown required</td>
</tr>
<tr>
<td></td>
<td>Highest power cycle efficiency</td>
<td>Cooling tower plume in cold weather</td>
</tr>
<tr>
<td></td>
<td>Best cooling in arid areas</td>
<td></td>
</tr>
<tr>
<td>Dry cooling</td>
<td>No water consumption</td>
<td>More expensive equipment</td>
</tr>
<tr>
<td></td>
<td>No water treatment required</td>
<td>Higher parasitic loads</td>
</tr>
<tr>
<td></td>
<td>No cooling tower or blowdown</td>
<td>Lower efficiency in hot environments</td>
</tr>
<tr>
<td></td>
<td>Lower costs</td>
<td></td>
</tr>
<tr>
<td>Hybrid wet/dry cooling</td>
<td>Reduced water consumption</td>
<td>Highest capital cost</td>
</tr>
<tr>
<td></td>
<td>Lower costs compared to dry cooling</td>
<td>Complicated system</td>
</tr>
<tr>
<td></td>
<td>Good performance in hot environments</td>
<td>Same disadvantages than wet cooling, but in minor degree</td>
</tr>
</tbody>
</table>

Table 3. shows the main advantages and disadvantages of the different cooling methods currently available. Location will have a critical impact in the cooling method of the parabolic trough power plant and so, locations with sufficient water availability will be preferable to those with higher radiation values but poor water resource, as the first ones may result in lower costs. Under these considerations, it must be concluded that dry cooling is not the best option for the parabolic trough power plant, as this technology requires more expensive equipment and underutilizes the available solar source. Dry cooling has its lower operating efficiency in hot summer afternoons11, as the high ambient temperature reduces the cooling effect of the condenser. However, these are indeed the best moment for the plant’s output, as the highest direct normal radiation is achieved. As a result, it can be concluded that despite providing great savings in terms of water resource, reduced maintenance (as water does not require any kind of treatment) and lower infrastructure cost (no cooling

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11 Ibid. [10]
tower neither blowdown pond is required), this advantages do not worth the lower performance in hot environments, the expensive equipment and the high parasitic loads.

Regarding to **Table 3.,** it can be concluded that wet cooling is the best option if there is sufficient water resource in the area, as it is the cheapest option and provides the highest turbine efficiency values (previous water treatment and periodic maintenance must, however, be taken into account). At the same time, the hybrid wet/dry cooling technology introduce the same disadvantages mentioned in wet cooling, but in minor degree as it requires much less water to carry out the heat exchange and this water would require, consequently, less treatment and less maintenance needs. However, hybrid cooling need higher capital cost when compared to wet systems and costs tend to be higher too (these are, however, minor than the costs introduced by dry cooling), so it is a matter of balance in between water availability and cooling cost: if there is sufficient water, wet cooling would be preferable and if water resource is limited, it would be interesting to choose the hybrid wet/dry technology.

**Table 4. Water requirements and approximate penalties of a parabolic trough power plant depending on the chosen cooling method.**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Water type</th>
<th>Litres/MWh</th>
<th>Performance penalty [%]</th>
<th>Cost penalty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporative cooling water</td>
<td>3030 - 3785</td>
<td>1 - 4</td>
<td>8</td>
</tr>
<tr>
<td>Dry cooling</td>
<td>285 - 300</td>
<td>4,5 - 5</td>
<td>2 - 9</td>
</tr>
<tr>
<td>Hybrid cooling</td>
<td>378,5 - 1800</td>
<td>4,5 - 5</td>
<td>2 - 9</td>
</tr>
</tbody>
</table>

The **performance penalty** introduces the annual energy output loss regarding to the most efficient cooling system: evaporative water cooling. Please notice that once-through water cooling is not considered in **Table 4.,** as this cooling technology is not available for parabolic trough power plants. The **cost penalty** shows the added cost to electricity production, and introduces an economic comparison between the available cooling options taking as reference evaporative water cooling electricity cost. Regarding to **Table 4.,** it is easy to observe that evaporative water cooling requires great amounts of water for the plant’s operation (from 3030 to 3785 litres per MWh produced) when compared to other technologies. In second position regarding to water consumption, hybrid cooling needs lots of water too, but its requirements are mucho lower than those introduced by wet evaporative cooling. However, this reduction in water consumption carries a 1% to 4% efficiency reduction in the turbine and up to an 8% of electricity cost increase, so hybrid cooling must be studied deeply before its implantation in order to ensure an optimal balance between water saving and final output. Finally, dry cooling provides the lowest water requirements (from 285 to 300 litres per MWh), far away from evaporative and hybrid technologies.

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12 Ibid. [8]
and so, it is a great option for those locations with water shortage. However, Table 4. shows performance penalties around 5% and cost penalties up to 9% and so, this option may not be the best when regarding hot environments as suitable locations for a parabolic trough power plant.

To sum it up, evaporative water cooling is the best option due to its cost reduction and large commercial experience in parabolic trough power plants and so, the chosen option will be a parabolic trough solar thermal power plant with thermal storage through molten salt tanks and evaporative water cooling.
CHAPTER 4:
PARABOLIC TROUGH
SOLAR THERMAL
POWER PLANT
PROJECT

Now that the basis of solar thermal technology have been introduced, and so has the demonstration of parabolic trough concentrating systems to be the best option among other solar thermal concentrators in electrical power plants, it is the time to focus on the design of a parabolic trough solar thermal power plant with thermal storage in molten salt tanks. The project will be developed in three main sections, according to the general scheme of a solar thermal power plant:

- Solar field
- Thermal storage
- Steam cycle

In order to justify and validate the results obtained during the following stages, it will be necessary to introduce, discuss and select between different options that will give a more tangible view for our parabolic trough power plant, providing not only general conclusions but specific results bounded in defined studying conditions.

In a parabolic trough SEGs power plant, solar radiation provides the thermal energy required to produce the steam used in the turbine. This solar radiation is collected in the solar field, consisting of a combination of numerous parabolic trough concentrator parallel rows. It becomes, then, an essential part of the plant, as the optimisation of sunlight collection is directly related to the amount of thermal energy provided to the heat transfer fluid and so, related to the energy output of the power plant.

Despite the fact that parabolic trough concentrators play an essential role in the collection of solar radiation, their success is extremely related to its combination with the optimal location, appropriate HTF, efficient absorber tubes, distribution of the solar field and many other factors that will be introduced and discussed in subsequent pages. Solar field must be well designed, efficient and has to be maintained in the optimal working conditions, as it is responsible for the thermal supply of the plant and, as a consequence, responsible it success in terms of energy output and economic expenses.

4.1.1. Location.

The very first consideration that must be taken into account when designing a parabolic trough solar thermal power plant is location, as the appropriate selection of it can be responsible both for the success or failure of the project. Solar radiation varies along the surface of the earth and so, we must choose those locations that provide best incident radiation conditions in order to maximize the thermal supply of the plant and the electrical output of it.

However, surface direct radiation is not the only concept that must be taken into consideration when discussing the best location for a solar thermal power plant, as great amounts of solar radiation are useless without sufficient water supply (essential for steam turbine cycle, refrigeration, plant maintenance and other purposes), adequate distribution infrastructure or sufficient electrical demand. This handicap is clearly evidenced when discussing the possibility of taking a desert as a suitable location for a solar thermal power plant, despite the great possibilities that these provide in terms of solar radiation.

It becomes necessary to establish the main features that must be considered when starting up a solar thermal power plant project, which could be summarised in the following:

- **Solar availability**: energy cost is closely related to the amount of available solar radiation. Greater availabilities are responsible for smaller energy cost and so, radiation data must be studied and discussed in order to ensure the optimal decision. Solar thermal concentrating systems depend on the amount of direct radiation for their success, as diffuse radiation is not enough to provide the HTC with sufficient thermal energy. However, it is not easy to find direct radiation data on a specific location, as most of the available information provide global radiation values (understood as the combination of both direct and diffuse radiation). As a result, it is important to ensure great amounts of global radiation in order to provide enough profitable direct radiation to the solar field.
• **Meteorological conditions:** as direct radiation is the main prime matter our solar thermal power plant requires, we must ensure that the flux of solar radiation to the surface is not bothered by meteorological conditions such as cloudiness. High moisturising levels could affect the solar thermal plant's operation, strong winds could introduce unsafe working conditions resulting in temporary shutdown of the plant, heavy rains could be responsible for damage in devices and so, it is essential to study the location of the plant from a meteorological point of view as smaller weather risk can compensate for higher solar radiation values on a specific location.

• **Topography and orography:** a solar thermal parabolic trough power plant requires important amount of land, used primarily to host the parabolic trough concentrator solar field. The higher power output the plant provides, the higher space is needed, being necessary to choose a location with enough land resource. At the same time, the selection of a convenient orography when discussing the possibility to build a solar thermal power plant can reduce meteorological impact, highlighting an important wind impact reduction on the system.

• **Water availability:** water is essential in a solar thermal power plant, as it is necessary for many operations such as steam generation, cleaning and maintenance processes and refrigeration, among others. It is critical to ensure a sufficient water supply in the selected location, as bringing water from distant regions would increase energy cost to an unsustainable level.

• **Accessibility and development:** even though some of the previously mentioned handicaps can be solved with external supply, this is only possible if there is sufficient accessibility to the location. Providing water to an isolated location will be easier (and cheaper) if carried out by road than by helicopter, and so will be eventual parts required if a device is damaged or employee arrival to work. However, this feature becomes vital when referred to proximal electrical infrastructure and demand, as huge electrical outputs worth nothing without the possibility to inject them to a grid or sell the energy to proximal consumers, as energy losses increase with the distance. In order to ensure their success, solar thermal power plants must be settled down in key locations introducing a balance between energy production, energy distribution and energy demand.

• **Rules and regulations:** solar thermal power plants provide clean, renewable energy to the grid. However, the cost of the energy is still higher when compared to conventional power plants based on fossil fuel or hybrid power plants that combine both systems. In order to enhance solar thermal technology, governments play an essential role as they can introduce specific regulations to strengthen their position towards conventional generating systems through fiscal benefits and subsidies. Solar thermal energy is a real option that provides great opportunities for renewable energy and needs to be powered over traditional energy production systems and so, governments should introduce enhancing policies to help to their consolidation in the power market. Locations introducing these powering policies may look more attractive than others where no help is provided.
Location will be discussed under solar thermal pre-existence criteria, where the best location for a solar thermal power plant is determined by the conjunction of previous solar thermal experiences and high radiation values\textsuperscript{13}. It is not easy to determine a specific direct normal radiation range, as recommended values tend to vary depending on the consulted information source.

**Table 5.** Recommended annual direct normal irradiation for solar thermal power plants [kWh/m\(^2\)]
[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Source</th>
<th>Minimum</th>
<th>Optimal</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>South African Department of Energy</td>
<td>1.800</td>
<td>2.600</td>
<td>White paper on renewable energy</td>
</tr>
<tr>
<td>European Commission</td>
<td>1.800</td>
<td>2.500</td>
<td>European research on Concentrated Solar Thermal Technology</td>
</tr>
<tr>
<td>IDAE</td>
<td>1.500</td>
<td>2.000</td>
<td>Manuales de energías renovables 4. Energía Solar Térmica</td>
</tr>
</tbody>
</table>

**Table 6.** Determination of required annual direct normal irradiation [kWh/m\(^2\)]
[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Bank of Washington D.C.</td>
</tr>
<tr>
<td>South African Department of Energy</td>
</tr>
<tr>
<td>European Commission</td>
</tr>
<tr>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IDAE</td>
</tr>
<tr>
<td>TOTAL</td>
</tr>
</tbody>
</table>

\textsuperscript{13} Téllez, F.M. Energetic, Environmental and Technological Investigation Centre (CIEMAT), \url{www.ciemat.es}
Maintaining the solar thermal pre-existence criteria and looking at the values introduced by Table 5. and Table 6., it is possible to conclude that the best location for the parabolic trough power plant is a region with previous solar thermal experiences and Annual Direct Normal Insolation values (ADNI) over 2060 kWh/m²-year:

\[
A.D.N.I = \frac{10300\, \text{kWh} / \text{m}^2}{5} = 2060\, \text{kWh} / \text{m}^2 \cdot \text{year}
\]  

(8)

It is essential then, to find annual direct normal insolation data over the surface of the earth in order to determine feasible locations. In order to contrast data, it will be necessary to calculate the average daily direct normal insolation required for the parabolic trough solar thermal power plant. If a 2060 kWh/m² yearly sum of direct normal insolation is taken as a feasible value (as it has been demonstrated above), average Daily Direct Normal Insolation (DDNI) can easily be found through the following expression:

\[
D.D.N.I = \frac{2060\, \text{kWh} / \text{m}^2}{365 \text{ days}} = 5.64\, \text{kWh} / \text{m}^2 \cdot \text{day}
\]  

(9)

![Map of solar thermal regions](image)

**Figure 16.** Average Daily Direct Normal Insolation [kWh/m²·day].

[Source.- World Resources Institute, http://www.wri.org, (accessed March 26th 2012)]

**Figure 16.** shows the average daily direct normal insolation over the surface of the earth and highlights the most suitable regions for a solar thermal power plant to be built, establishing direct normal insolation values over 5 kWh/m²·day as those necessary for **Concentrating System Technologies**. This strongly reaffirms our D.D.N.I estimated value of 5.64 kWh/m²·day as an optimal direct normal insolation value. As a result, it is possible to differentiate 8 main feasible locations regarding to solar resource:

- **South-western United States**
- **Western Mexico**
- **Greenland**
• **Northern and Southern Africa**
• **Western Madagascar**
• **Southern Spain**
• **South-western and Central Asia**
• **Australia**

The optimal location for the parabolic trough solar thermal power plant was defined as a region with previous solar thermal experiences and Annual Direct Normal Insolation values over 2060 kWh/m²·year (5,64 kWh/m²·day). However, the 8 possible locations discussed above do only satisfy half of that premise, as it is necessary to filter those regions with previous solar thermal projects:

### Table 7. Major operational solar thermal projects today

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>Location</th>
<th>Concentrating technology</th>
<th>First operation year</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEGS I*</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1984</td>
<td>13,8 MW</td>
</tr>
<tr>
<td>SEGS II</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1985</td>
<td>30 MW</td>
</tr>
<tr>
<td>SEGS III</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1985</td>
<td>30 MW</td>
</tr>
<tr>
<td>SEGS IV</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1989</td>
<td>30 MW</td>
</tr>
<tr>
<td>SEGS V</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1989</td>
<td>30 MW</td>
</tr>
<tr>
<td>SEGS VI</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1989</td>
<td>30 MW</td>
</tr>
<tr>
<td>SEGS VII</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1989</td>
<td>30 MW</td>
</tr>
<tr>
<td>SEGS VIII</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1989</td>
<td>80 MW</td>
</tr>
<tr>
<td>SEGS IX</td>
<td>California (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>1989</td>
<td>80 MW</td>
</tr>
<tr>
<td>Saguaro</td>
<td>Arizona (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>2006</td>
<td>1 MW</td>
</tr>
<tr>
<td>Nevada Solar One</td>
<td>Nevada (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>2007</td>
<td>75 MW</td>
</tr>
<tr>
<td>Andasol I*</td>
<td>Granada (Spain)</td>
<td>Parabolic Trough</td>
<td>2008</td>
<td>50 MW</td>
</tr>
<tr>
<td>Andasol II*</td>
<td>Granada (Spain)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>50 MW</td>
</tr>
<tr>
<td>Solnova I</td>
<td>Seville (Spain)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>50 MW</td>
</tr>
<tr>
<td>Solnova III</td>
<td>Seville (Spain)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>50 MW</td>
</tr>
</tbody>
</table>

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Data obtained from the NREL website: http://www.nrel.gov, (accessed March 27th 2012)
<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Technology</th>
<th>Year</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solnova IV</td>
<td>Seville (Spain)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>50 MW</td>
</tr>
<tr>
<td>Alvarado I</td>
<td>Badajoz (Spain)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>50 MW</td>
</tr>
<tr>
<td>Ibersol</td>
<td>Ciudad Real (Spain)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>50 MW</td>
</tr>
<tr>
<td>Holaniku at Keahole Point</td>
<td>Hawaii (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>2009</td>
<td>2 MW</td>
</tr>
<tr>
<td>Archimede *</td>
<td>Sicily (Italy)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>5 MW</td>
</tr>
<tr>
<td>La Florida*</td>
<td>Badajoz (Spain)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>50 MW</td>
</tr>
<tr>
<td>Colorado ISP</td>
<td>Colorado (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>2 MW</td>
</tr>
<tr>
<td>Extresol 1*</td>
<td>Badajoz (Spain)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>50 MW</td>
</tr>
<tr>
<td>Extresol 2*</td>
<td>Badajoz (Spain)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>50 MW</td>
</tr>
<tr>
<td>MNGSEC</td>
<td>Florida (EE.UU.)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>75 MW</td>
</tr>
<tr>
<td>Majadas I</td>
<td>Cáceres (Spain)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>50 MW</td>
</tr>
<tr>
<td>Palma del Río II</td>
<td>Córdoba (Spain)</td>
<td>Parabolic Trough</td>
<td>2010</td>
<td>50 MW</td>
</tr>
<tr>
<td>Andasol III*</td>
<td>Granada (Spain)</td>
<td>Parabolic Trough</td>
<td>2011</td>
<td>50 MW</td>
</tr>
<tr>
<td>La Dehesa*</td>
<td>Badajoz (Spain)</td>
<td>Parabolic Trough</td>
<td>2011</td>
<td>50 MW</td>
</tr>
<tr>
<td>Manchasol I</td>
<td>Ciudad Real (Spain)</td>
<td>Parabolic Trough</td>
<td>2011</td>
<td>50 MW</td>
</tr>
<tr>
<td>ISCC Argelia</td>
<td>Hassi R’Mel (Algeria)</td>
<td>Parabolic Trough</td>
<td>2011</td>
<td>25 MW</td>
</tr>
<tr>
<td>ISCC Morocco</td>
<td>Ain Beni Mathar</td>
<td>Parabolic Trough</td>
<td>2011</td>
<td>470 MW</td>
</tr>
<tr>
<td></td>
<td>(Morocco)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planta Solar 10</td>
<td>Seville (Spain)</td>
<td>Power Tower</td>
<td>2007</td>
<td>11 MW</td>
</tr>
<tr>
<td>Planta Solar 20</td>
<td>Seville (Spain)</td>
<td>Power Tower</td>
<td>2009</td>
<td>20 MW</td>
</tr>
<tr>
<td>Sierra SunTower</td>
<td>California (EE.UU.)</td>
<td>Power Tower</td>
<td>2009</td>
<td>5 MW</td>
</tr>
<tr>
<td>Gemasolar*</td>
<td>Seville (Spain)</td>
<td>Power Tower</td>
<td>2011</td>
<td>20 MW</td>
</tr>
<tr>
<td>Kimberlina STPP</td>
<td>California (EE.UU.)</td>
<td>Linear Fresnel</td>
<td>2008</td>
<td>5 MW</td>
</tr>
<tr>
<td>Puerto Errado 1</td>
<td>Murcia (Spain)</td>
<td>Linear Fresnel</td>
<td>2009</td>
<td>1,4 MW</td>
</tr>
<tr>
<td>Maricopa SP</td>
<td>Arizona (EE.UU.)</td>
<td>Dish Stirling</td>
<td>2010</td>
<td>1,5 MW</td>
</tr>
</tbody>
</table>

* Molten salt thermal storage

Table 7. shows the major operational solar thermal projects around the globe nowadays, and it is easy to observe a clear trend in project location, as the
The majority of them are located in Southern Spain and South Western United States, and only few commercial projects have been yet developed in other regions such as Algeria, Morocco and Italy. **Table 7.** supports the initial solar thermal technology choice too, as there is a great predominance of parabolic trough power plants that can be explained by its larger commercial experience. New projects are to be developed in the next years, as there are numerous solar thermal power plants currently under construction (2 plants located in the United States, 10 in Spain and 1 in Egypt) and many other with a signed agreement (15 in the United States, 3 in Spain and other plants located in Jordan, Saudi Arabia, India, Iran, South Africa), that help to reaffirm the Southern Spain and South Western United States as the most appropriate locations for carrying out a commercial solar thermal project. It is important, however, to mention the fact that most of the solar thermal projects currently operational in the Southern United States were started in the 1980s and that the Spanish first experiences get back to the year 2008. This may introduce a light advantage for the Spanish locations, as there is a more recent experience in the field. Now that Southern Spain and South Western United have been introduced as the best locations for the parabolic trough power plant in terms of solar radiation and previous solar thermal experience, it is the time to discuss which one is the best choice. In order to answer this question, it will be necessary to study both regions in terms of the main features introduced before:

**Figure 17.** Annual concentrating solar power data in the United States [kWh/m²·day]. [Source.- NREL, http://www.nrel.gov (accessed March 28th 2012)]
**Figure 18.** Annual sum of direct normal irradiation in Spain [kWh/m²].

**Figure 17.** and **Figure 18.** show the direct normal irradiation values in the United States and in Spain, respectively. As it is possible to observe, both Southern Spain and South Western United States provide DNI values over 2060 kWh/m²·year (equivalent to 5,64 kWh/m²·day) and so, they can be both considered as feasible locations for the parabolic trough power plant. This just reaffirms the conclusions obtained from **Figure 16.** and **Table 7.**, so it may be necessary to discuss other features in order to find the best choice. However, it is important to highlight the fact that DNI is higher in South Western United States, providing values up to 8 kWh/m²·day in large locations such as California, Arizona, Nevada and New Mexico.

As important as the direct normal irradiation values on the selected location, the total amount of sun hours must be taken into account. It is worthless to have high DNI values if solar collection is constantly interrupted by clouds and so, it is essential to determine the amount of available **sun hours**.
Figure 19. Average annual sunshine in the United States.

Figure 20. Average annual sunshine in Spain (1600 h. – 3000 h., 200 h. scale).
**Figure 19.** and **Figure 20.** introduce average annual sunshine in the United States and Spain, respectively. There is a great difference between both locations, as South Western United States enjoy high average annual sunshine values over 3200 hours (reaching more than 4000 hours of sunshine in small regions of California and New Mexico) that really contrast with average sunshine values of 2600 hours found in Southern Spain (reaching values around 2800 hours in specific locations such as Badajoz, Seville, Almeria and Alicante, and punctual 3000 hour values in the southern part of Tenerife). This fact gives a clear advantage to South Western United States locations, as they provide higher direct normal irradiation values with higher sunshine availability.

Meteorological conditions play an essential role in the plant’s success. As mentioned before, heavy rains and strong snows can damage devices, moisture can be responsible for system malfunctioning and wind can introduce unsafe operating conditions resulting in a temporary shutdown of the plant. It is critical to define and study the main weather conditions in both regions, in order to find the one that introduces lower meteorological risk. The best location will be the region that provides lower wind speed, lower snowfalls and balanced rainfalls (water resource is essential for plant’s operation, and this can only be provided naturally under sufficient rain conditions). Under these considerations:

![Average annual rainfall in the United States](image)

**Figure 21. Average annual rainfall in the United States.**
Figure 22. Average annual snowfall in the United States.

Figure 23. Average annual wind speed in the United States.
Figure 24. United States climate zones.

Figure 25. Average annual rainfall in Spain [0 mm. – 2000 mm., 200 mm. scale].
Figure 26. Average snow days in Spain [0 days – 40 days., 5 day scale].

Figure 27. Average annual wind speed in Spain at 30m high [m/s].
Figures 21-28. introduce the main meteorological features of the United States and Spain, providing rainfall, snowfall, wind resource and climate data. It is now time to discuss which location provides the best weather conditions for carrying out the parabolic trough power plant. Regarding to rainfall, Figure 21. shows the average annual rainfall in the United States, allowing to highlight rain values of 8-16 inches (203,2 – 406,4 mm) among most of the South Western locations, combined with large regions of extremely low rainfall under 8 inches (southern parts of California, Western Arizona, Southern Nevada and punctual regions in Utah). It is possible to conclude that average annual rainfall in South Western United States is poor, which could be responsible for difficulties regarding to water supply if there are not other fluvial resources on the selected area. These mentioned areas do share a poor average annual snowfall too (Figure 22.), which in this case becomes an advantage with average annual snow values under 203,2 mm that ensure safe operating conditions for the parabolic trough power plant.

As mentioned before, wind plays a critical role in the plant’s operation and so, it is very important to select those regions with minor wind presence. Figure 23. introduces South Eastern United States as the best location relating to wind presence, with wind speeds under 6,4 m/s when measuring at 50 meters high, which is considered as non relevant. However, these regions do not provide sufficient DNI values and it has been yet determined that South Western United States provides the best radiation conditions. South Western United States does not follow a homogenous wind distribution, as punctual wind variations are spread all over the region. These values move from unclassified wind class
(speeds under 6.4 m/s), class 3 winds (6.4-7 m/s), class 4 winds (7-7.5 m/s) and very rare class 5 winds (7.5-8 m/s) that in any case introduce potential danger for the parabolic trough power plant.

Table 8. Wind power class\textsuperscript{15} at 50 meters high
[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Wind power class</th>
<th>Speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0 - 5.6</td>
</tr>
<tr>
<td>2</td>
<td>5.6 - 6.4</td>
</tr>
<tr>
<td>3</td>
<td>6.4 - 7.0</td>
</tr>
<tr>
<td>4</td>
<td>7.0 - 7.5</td>
</tr>
<tr>
<td>5</td>
<td>7.5 - 8.0</td>
</tr>
<tr>
<td>6</td>
<td>8.0 - 8.8</td>
</tr>
<tr>
<td>7</td>
<td>8.8 - 11.9</td>
</tr>
</tbody>
</table>

On the other hand, Figure 25. shows the Spanish average annual rainfall distribution, introducing a general trend in Southern regions of around 400 mm of rainfall per year, with increasing values up to 600 mm in Huelva, Northern Seville, Northern Cordoba and Northern Jaén and 1000 mm values located in Northern Granada (in particular, located in the Sub-betic mountainous region) and over the border between Cádiz and Málaga. It must be highlighted the fact that Eastern Andalucía is characterized by a strong mountainous distribution and so, Western regions would provide better land conditions for the plant’s construction. Regarding to snowfall, Figure 26. shows extremely low snow values in Southern regions, with average values around 0 to 1 day of snow per year. Punctual snow concentration may be found in the mountainous systems of Eastern Andalucía, with average values up to 30 days of snow per year in the highest locations, but as it has been mentioned before, it is this mountainous distribution indeed what makes it unadvisable to carry out a parabolic trough power plant (even more when large plane regions are fully available on Western zones).

Wind distribution in Southern Spain (Figure 27.) follows an almost general pattern, with general wind speed values between 4.5 to 5 m/s in most of the locations (except for 5.5 to 6 m/s speed values in Cádiz and Málaga), measured at 30 meters high. It is relevant to say that wind values are smaller than those found in South Western United States locations, but it is also correct to affirm that there is too small difference between them to become a strong advantage.

To sum it up, South Western United States is a clear candidate for the parabolic trough power plant’s location, as it is characterized by poor snowfall, infrequent rains (which could become a potential handicap if there is no access to a

permanent water supply in the selected region) and small wind presence (punctual strong winds must, however, be taken under consideration in the preliminary designing stage), framed in an *Arid to Semiarid* climate zone (Figure 24.) On the other hand, Southern Spanish regions provide small rainfall too, but rain values are slightly higher and this could make a difference regarding to the water issue mentioned above. Snowfall is practically null, apart from the mountainous system located in Eastern Andalucía where considerable values can be found, and wind presence is limited (up to 6 m/s in most windy regions) and appears to follow a constant distribution with no punctual increases. Southern Spain enjoys a rich climate distribution, as Figure 28. shows, introducing a *Mediterranean coast climate* in the most Southern areas, *Mediterranean continental wet climate* in Huelva and Cádiz, *Mediterranean continental warm summer climate* in some regions of Granada, punctual *Mountainous climate* in Cádiz and Western Andalucía and *Mediterranean Arid and Semiarid climate* in the most Eastern regions of Southern Spain such as Murcia and Almeria.

Finally, regarding to 2010 Global Climate Risk Index (*CRI*), which indicates the level of exposure to climate disasters, both South Western United States and South Spanish regions are defined as a *very safe location*. This Index compares the number of events, absolute losses in millions of dollars and number of casualties during the 1990-2008 period and, taking into account the level of development of the country, allows to obtain a value for the existing climate risk. According to Germanwatch, United States is the 34th safest country in the world and Spain is in the 27th position.

**Figure 29. Global Climate Risk Index 2010**

Table 9. collects all the conclusions exposed above:

<table>
<thead>
<tr>
<th></th>
<th>South Western United States</th>
<th>Southern Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>Very poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Snowfall</td>
<td>Very poor</td>
<td>Very poor</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Small (under 7.5 m/s)</td>
<td>Very small (under 6 m/s)</td>
</tr>
<tr>
<td>Type of Climate</td>
<td>Arid to Semiarid</td>
<td>Mediterranean, many types</td>
</tr>
<tr>
<td>CRI Rank</td>
<td>34</td>
<td>27</td>
</tr>
</tbody>
</table>

Once the meteorological conditions have been discussed, it is necessary to study both possible locations from a geographical point of view, comparing them in terms of Topography and Orography. The solar field requires large land availability in order to maximize the plant’s energy output. At the same time, this land must be very plane to avoid shadow interference and achieve the optimal collecting efficiency.

Figure 30. Landform distribution in the United States
Studying Southern Spain and South Western United States from a topographical point of view, it can be concluded that both locations provide optimal conditions for the parabolic trough power plant, as there are enough plane zones to settle down the plant. Regarding to Figure 30., South Western United States provide a huge plateau distribution (flat terrain located in an area of high land) combined with several mountainous regions and punctual plain distribution. On the other hand, Southern Spain’s landform (Figure 31.) is represented by a relative plain distribution in Western regions combined with several mountainous regions on Eastern locations, that may introduce the first ones as the best locations for the plant.

It has been mentioned before the fact that a convenient location may introduce great advantages in terms of wind impact reduction. Despite having been discussed in previous stages (Figure 23. and Figure 27.), it is important to mention that the best location for the parabolic trough power plant would be a plain region surrounded by mountainous landforms (these must however be sufficiently away from the plant in order to avoid shades on the solar field), as wind speed would be importantly reduced and so would the damages caused by it on the plant. Under these acknowledge, South Western Spain may provide better conditions, as regions like Huelva, Seville and Cadiz are located on what is called as Guadalquivir’s Depression, a large plain region at approximately 100 meters over the level of the sea surrounded by the mountains of Sierra Morena and the Peni-betic mountainous region that shelters the Guadalquivir river.
Once that the main cooling technologies have been introduced and evaporative water cooling has been introduced as the best option (due to its cost reduction and large commercial experience in parabolic trough power plants, mainly), it is the time to study the available water in South Western United States and Southern Spain. In order to introduce a global point of view, water availability will be studied among superficial flows (rivers) and water reservoirs, as any of the mentioned sources are likely to provide cooling water to the parabolic trough plant. Subterranean waters are not considered due to the huge increase in costs related to their extraction. Annex I shows the main water resources in Andalucía. As it can be seen, the region is rich in water resources, with several large rivers and many water reservoirs, so it must be concluded that there is enough water resource to stand a parabolic trough power plant in several locations.

On the other hand, regarding to the main lakes, rivers and water resources of California, Nevada, Utah, Colorado, Arizona, New Mexico and Texas, selected as the most suitable South Western United States locations for the parabolic trough power plant, it can be seen that water resource is also plentiful (except for Middle Nevada regions, which are practically deserted) and its primarily provided by rivers. However, these rivers are widely separated and there is no water source in between them, so location must be very near in order to ensure water supply, and it is critical to choose those regions with sufficient stream flow. Again, Southern United States locations are suitable regarding to water resource, being necessary to locate the parabolic trough power plant conveniently due to the large separation between water sources.

Now that the water issue has been discussed, location will be studied from a accessibility and development point of view. A huge power output worth nothing if there is not any electrical infrastructure to distribute it to consumers. At the same time, a bad accessibility increases operating costs. The bigger the distance is, the higher the energy losses are, and more expensive is to bring any kind of resource (employees, new parts), so it is essential that the chosen location provides the best conditions in terms of grid proximity and development (qualified employees required for the plant may be cheaper if they can be hired there than if they have to be brought from further regions, so a nearby university becomes a great point of advantage, for example). Both South Western United States and Southern Spain are developed regions with good road networks and so, location will only be discussed in terms of electrical grid proximity.

Regarding to Annex I, which shows the Andalusian energy system, it is easy to see that there are several high voltage lines that could allow the output power provided by the parabolic trough power plant, so it can be concluded that Andalucía provides great possibilities in terms of electrical distribution, as electricity could be injected and sold easily.
Figure 32. United States transmission grid
[Source: Department of Geography of PennState University, http://www.e-education.psu.edu (accessed April 6th 2012)\textsuperscript{16}]

South Western United States provides good transmission facilities, as high voltage transmission lines are available. However, it must be highlighted that they are relatively isolated transmission lines whereas on Eastern regions of the United States the electrical grid is much denser. This may be related to the fact that South Western regions of the United States are typically arid and semi-arid regions where there is not much demographic concentration, as this tends to be focused on the more favourable conditions provided by Eastern locations. Despite this small grid density, South Western United States still provides enough electrical transmission facilities to carry out a parabolic trough power plant.

Finally, there is only one feature to be taken into account, and is the one related to rules and regulations. Due to solar thermal electricity’s higher energy cost when compared to other conventional fossil power plants, this technology needs fiscal incentives and subsidies to consolidate its position in the power market and, little by little, become the main source of energy of the region. Solar thermal electricity is environmentally friendly, as it is a renewable source of energy, and it provides energy independence from fossil fuels (which in countries such as Spain, with foreign energy dependence around 70\%\textsuperscript{17}, becomes essential). It is nonsense to discuss both Spanish and United States solar thermal regulations, as a deep approach to them would require a huge analysis. However, it can be understood that, due to the previous solar thermal experiences developed in both regions (which have been mentioned before) and


\textsuperscript{17} Spanish Minister of Foreign Issues and Cooperation, http://www.maec.es
taking into account their level of development, both Spain and United States provide a real commitment to solar thermal energy and no fear must be shown in this issue, apart from the economic cuts currently introduced as a result of the actual worldwide financial crisis that may have restricted previously higher fiscal benefits and subsidies to lower values.

**Table 10. Final comparison between South Western United States and Southern Spain as feasible locations for the parabolic trough power plant**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>South Western United States</th>
<th>Southern Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunshine</td>
<td>3200 – 4000 hours of sun/year</td>
<td>2600 – 2800 hours of sun/year</td>
</tr>
<tr>
<td>Solar resource</td>
<td>2200 – 2900 kWh/m²-year</td>
<td>2000 – 2300 kWh/m²-year</td>
</tr>
<tr>
<td>Previous experiences</td>
<td>14 operational parabolic trough power plants</td>
<td>14 operational parabolic trough power plants, recent construction</td>
</tr>
<tr>
<td>Meteorological</td>
<td>Up to 406,4 mm rain/year</td>
<td>Up to 1000 mm rain/year</td>
</tr>
<tr>
<td>conditions</td>
<td>Up to 203, 2 mm snow/year</td>
<td>Average 1 day of snow/year</td>
</tr>
<tr>
<td></td>
<td>Wind speed up to 8 m/s (50m high)</td>
<td>Wind speed up to 6 m/s (30m high)</td>
</tr>
<tr>
<td></td>
<td>Arid to semi-arid climate</td>
<td>Mediterranean continental, arid and semi-arid climate</td>
</tr>
<tr>
<td></td>
<td>34th safest country in Risk Index</td>
<td>27th safest country in Risk Index</td>
</tr>
<tr>
<td>Topography and</td>
<td>Plateaus, plains and mountainous regions</td>
<td>Plains, mountainous regions and Guadalquivir depression</td>
</tr>
<tr>
<td>orography</td>
<td>Isolated available water resource, may condition location</td>
<td>Available water resource</td>
</tr>
<tr>
<td>Water availability</td>
<td>Road network, developed regions but isolated, available high voltage grid but may condition location</td>
<td>Road network, developed regions, available high voltage grid</td>
</tr>
<tr>
<td>Accessibility and</td>
<td>Commitment to solar thermal energy</td>
<td>Commitment to solar thermal energy</td>
</tr>
<tr>
<td>development</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To this point location has been deeply discussed and it is the time to make a decision. Taking into account all the features introduced before, it can be concluded that Southern Spain provides the best conditions for the parabolic trough power plant. There is not a clear advantage from South Western United States locations, as in general trends the features provided are similar and even more favourable in punctual concerns (such as sun shine and solar resource, indeed). However, the main reason for the Southern Spanish choice has been the recent boom in parabolic trough solar thermal power plants that may provide the best conditions in terms of cost reduction (qualified employees availability, numerous solar thermal parts suppliers, recent experience, subsidies, grid connection facilities, regulated selling price, among many others), whereas most
of the American experiences get back to 1980’s. Furthermore, Southern Spain provide better wind conditions and better water resource facilities, as most of the water available in South Western United States is provided by rivers widely separated that may condition the plants location when discussed electrical connection to the grid (isolated water resources may collide with the specific grid distribution, while water resource in Southern Spain is widely spread along the region and may fit better to the transmission grid requirements). Under these considerations, it must be concluded that Southern Spain is the best option for the parabolic trough power plant’s location and so, this will be located in:

Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva)

Latitude: 37,315562   Longitude: -7,036548

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Figure 33. Main features of the chosen parcel

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Figure 34. Cadastral reference of the chosen parcel
**Figure 35.** Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva).

This choice provides the best global conditions for the parabolic trough power plant, highlighting the following advantages:

1. Large land availability, with a total area of 4,570.671 m² (457,0671 ha) according to the Spanish Cadastral Survey. This is widely enough to stand the solar field and provides the possibility to increase its area in the future.

2. The average altitude of Gibraleón is 26m over the level of the sea\(^\text{18}\) and its land distribution is primarily plain, providing great soil conditions for the solar field (which must not exceed slope values of 1% in order to maximize the

\(^{18}\) Gibraleón Town Hall website http://www.gibraleon.com
solar concentration). This confirms the features introduced by Figure 31., that described the Guadalquivir depression and its surroundings as suitable locations for the parabolic through power plant.

3. Good land communications, with direct access through road N-431 and Quinto Centenario Highway (exits number 99 and 94).

4. Great solar resource, as the selected location may provide direct normal radiation values up to 2150 kWh/m²-year with an average annual sunshine of 2600 hours of sun/year, according to Figure 18. and Figure 20. Due to the critical importance of this resource for the plant’s success, deeper study of this issue will be developed in the following stages of the project.

5. Proximity to sufficient water resource, as the parcel is located 7km away from the water supply channel of the industrial zone of Huelva and very near to the water reservoirs of Piedras (28 km), El Sancho (20 km) and Los Machos (14 km), which according to Annex I, provide water for industrial use and could be used in a parabolic trough power plant. Other water features of the different reservoirs are provided in Annex I., as well as the standard application for water supply19.

6. Very favourable climatologic conditions, with average maximum temperatures up to 40°C and minimum temperatures that rarely reach 0°C, small rainfall with very punctual maximum values up to 80 mm in the most rainy months (however, there is apparently a tendency in rainfall decrease during the last years that may introduce even better conditions in terms of rain) and moisture levels that follow the typical distribution of a Mediterranean coast climate, as shown in Figure 28. It can be concluded, then, that these features do confirm the values provided by Figure 25. and Figure 26., that introduced small rainfall, snowfall and wind presence for the chosen region. Deeper approach to Gibraleon’s climate conditions is provided in Annex I.

7. Small wind presence (Annex I.), with average speeds around 2 m/s and very punctual speeds up to 6 m/s, especially during the 2003-2009 period. During the last years, however, there has been a decrease in wind speed and 2011 values and wind speed measures to the present day have not exceeded 4,5 m/s, so this tends to confirm the low wind impact forecasted by Figure 27.

8. Grid connection facilities and possibility to carry out power injection into the electrical system, thanks to the planned installation of a new 220 kV transmission line between Costa de la Luz Substation (Dehesa del Piorno, Lepe township, Huelva) and Onuba Substation (Huelva township), as described in the Spanish Official State Bulletin (BOE n°274, 12th November 2010). Further information is provided in Annex I.


9. Key location, as there is not currently any parabolic trough power plant Huelva’s surroundings. Annex I. introduces the main solar thermal projects in Southern Spain till the year 2009, and adding the information provided in Table 5. to include new plants appeared until 2012, we can observe the following statement:

Table 11. Andalusian provincial capitals and nearby solar thermal power plants [Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Solar thermal power plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huelva</td>
</tr>
<tr>
<td>No operational plants yet</td>
</tr>
<tr>
<td>Sevilla</td>
</tr>
<tr>
<td>Solnova I, Solnova III, Solnova IV, Planta Solar 10, Planta Solar 20, Gemasolar, Lebria I, new ones in building stage</td>
</tr>
<tr>
<td>Cádiz</td>
</tr>
<tr>
<td>No operational plants yet, new plants in building stage</td>
</tr>
<tr>
<td>Córdoba</td>
</tr>
<tr>
<td>Palma del Río I, Palma del Río II, Solar III, new plants in building stage</td>
</tr>
<tr>
<td>Málaga</td>
</tr>
<tr>
<td>Not considered, small sun radiation (Figure 18.), small sunshine (Figure 20.)</td>
</tr>
</tbody>
</table>
Table 11. introduces Huelva as an unexploited region and so, it provides huge possibilities in terms of benefits as there is not current competence in the region.

10. According to Gibraleon Town hall’s website, the town has got a population of 12,392 inhabitants<sup>20</sup>, mainly based on wholesale and retail sale, vehicle reparation, construction, transport and storage, tourism and financial activities. The new parabolic trough power plant could enhance Gibraleon’s economic status and provide new jobs, becoming a positive impact on the town’s economy and gaining this way people’s consent to develop the project.

Under knowledge of the advantages mentioned above, it is possible to conclude that the best location for the parabolic through power plant is: **Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva).**

The mentioned legislation and regulations introduce the main characterisations for the parabolic trough power plant once that location has been selected. Regarding to the technical features of the plant regulated in those documentation, it is necessary to highlight two main statements, as they will characterise the parabolic trough power plant:

1. According to R.D. 661/2007, the parabolic trough solar thermal power plant is classified as Category b (power plants based on renewable not combustible energies, biomass or other types of bio fuel, as long as its owner does not carry out other production activities in the Ordinary Regime), and inside this category, Group b.1 (power plants based on solar energy), Subgroup b.1.2 (power plants based only in thermal processes to convert solar energy into electrical energy, including fuel hybrid power plants with average annual fuel-based electricity production inferior to 12% of the total amount, when referred to group a) of Article 24.1, or 15% when referred to b) of Article 24.1). The R.D. 661/2007 uses this classification to introduce the retribution regime under which the parabolic trough power plant will be operating and that will be discussed in the following stages of the project.

2. In order to be subjected to the Special Regime, the Law 54/1997, November 27<sup>th</sup>, of the Electrical Sector establishes a power limit of 50MW<sup>21</sup> and so, this will be the power selected for the parabolic trough power plant. This power choice is reaffirmed by the Secretary of State Energy Resolution, November 24<sup>th</sup> 2010, which establishes a minimum value of 45MW and a maximum

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<sup>20</sup> 2010 population values extracted from Gibraleon’s Town hall’s website: http://www.gibraleon.com

<sup>21</sup> The optimal power value may, however, be found between 100MW and 200MW, according to the Renewable Energy 2011-2020 Plan, edited by the Spanish Diversification and Energy Saving Institute (IDAE).
value of 50MW for single major solar thermal power plant projects that can be increased in 30MW through one or more small projects with a maximum power of 15MW per project. This feature would, however, remove the Special Regime characterisation of the plant, which would enjoy an additional economic regime (developed in the mentioned resolution) instead.

An economic approach to the parabolic trough power plant will be developed in next stages of the project, and so, new attention will be paid on the regulations above.


The parabolic trough power plant’s success depends on the availability of sufficient solar radiation on the selected location, as this is the main resource that allows the plant to produce electrical energy. As it has been proved in previous paragraphs, Gibraleón provides great conditions in terms of solar resource, with average annual direct normal irradiation values around 2100 kWh/m²-year (optimal locations should provide direct normal irradiation values over 2060 kWh/m²-year in order to ensure success, according to (8)) and high sunlight values around 2600 hours of sun per year. However, the parabolic trough solar thermal power plant cannot be developed under approximate resource values and so, it is essential to specify and quantify properly the available solar resource in Gibraleón.

Parabolic trough solar collectors focus direct normal irradiation on the absorber tube through which a heat transfer fluid flows, in order to increase the temperature of the mentioned fluid that will be used to generate steam. According to the terms introduced in 2.3 Solar radiation, Direct Normal Irradiation (DNI) can be defined as the fraction of solar radiation that reaches the surface of the Earth without experimenting any variation in direction (except the one introduced by atmospheric refraction). Diffuse Irradiation (DI) is, then, the fraction of solar radiation that comes from de decomposure of solar beams in the atmosphere and is dispersed in many directions, being the Global Irradiation (GI) the sum of both direct normal and diffuse irradiations. Parabolic trough collectors (in fact, any kind of solar concentrator technology) focus the solar beams on a specific direction (the absorber tubes) where the heat exchange is carried out and, because of that, diffuse irradiation values are not relevant, as their trajectory cannot be defined and reflection is consequently carried out in an uncertain and unprofitable direction.

Once that the main features of the solar resource have been introduced, it is the time to determine the amount of real direct normal irradiation available in Gibraleón. In order to obtain the mentioned data, one main source will be consulted:

- Solar Radiation Software\(^2\), developed by the Thermodynamics and Renewable Energy Group of the Industrial Cooperation and Investigation Association of Andalucía (AICIA).

This software is based in the information provided by 94 meteorological stations distributed by the Andalusian Agroclimatic Information Network (RIA) along the

\(^2\) http://www.agenciaandaluzadelaenergia.es
andalusian geography, which provide several solar radiation and meteorological data with high resolution (maximum of 15 minutes between samples). It also processes the information provided by the Engineering School of Seville, the National Institute of Spatial Techniques (INTA) and the Almeria Solar Platform (PSA), allowing to reaffirm AICIA Solar Radiation Software as a reliable source.

It has to be highlighted the fact there is a nearby meteorological station (El Tojalillo-Gibraleón) located very close to the chosen state and so, it can be concluded that the data provided by this source will be enough accurate. The parabolic trough power plant will be located in Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva). Latitude: 37,315562 ; Longitude:-7,036548 , so both Latitude and Longitude values were introduced in the Solar Radiation Software, obtaining:

![Radiación Directa (kWh/m²)](image)

**Figure 37.** Average monthly direct normal irradiation in the selected location.

[Source.- http://www.agenciaandaluzadelaenergia.es (accessed April 17th 2012)]

**Figure 37.** shows the average monthly direct normal irradiation in Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva), in kWh/m² (daily and hourly values are specified in Annex I.) The average annual direct normal irradiation can be easily calculated by summing up the different average monthly values and so:

\[
\text{Annual average } DNI = 2069.01 \text{ kWh} / \text{m}^2 \cdot \text{year}
\]  

(10)

Equation (8) established 2060 kWh/m²-year (5,64 kWh/m²-day) as the required annual direct normal irradiation to ensure the success of the parabolic trough power plant and so, the annual average Direct Normal Irradiation (DNI) obtained in (10) can be considered as a good value. This annual average value is equivalent to:

\[
\text{Daily average } DNI = 5.67 \text{ kWh} / \text{m}^2 \cdot \text{day}
\]  

(11)

Now that the amount of direct normal irradiation has been found, it is necessary to calculate the average number of sun hours available in the selected location.
Figure 38. Sunlight in Andalusia [hours sun/year]

Figure 38. shows the average sunlight in Andalusia from 2006 to 2010. Due to the lack of specific data for the Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón, this will be equated to the average sunlight in Huelva in order to simplify mathematical operations. As the monthly distribution is more relevant for the project’s development (as provides more accurate information that directly dividing the annual average sunlight by 12), 2010 values will be considered for further stages of the project.

Table 12. Available DNI and sunlight in the selected location
[Source.- Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>Direct Normal Irradiation [kWh/m²-month]</th>
<th>Sunglight [Hours of sun/month]</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>85,7</td>
<td>114</td>
</tr>
<tr>
<td>February</td>
<td>124,2</td>
<td>109</td>
</tr>
<tr>
<td>March</td>
<td>157</td>
<td>181</td>
</tr>
<tr>
<td>April</td>
<td>165,4</td>
<td>220</td>
</tr>
<tr>
<td>May</td>
<td>196,3</td>
<td>349</td>
</tr>
<tr>
<td>June</td>
<td>273,2</td>
<td>304</td>
</tr>
<tr>
<td>July</td>
<td>298,3</td>
<td>382</td>
</tr>
<tr>
<td>August</td>
<td>261,9</td>
<td>339</td>
</tr>
<tr>
<td>September</td>
<td>172,6</td>
<td>274</td>
</tr>
<tr>
<td>October</td>
<td>130,9</td>
<td>218</td>
</tr>
<tr>
<td>November</td>
<td>110,4</td>
<td>150</td>
</tr>
<tr>
<td>December</td>
<td>93,2</td>
<td>114</td>
</tr>
</tbody>
</table>
4.1.3. Parabolic trough concentrators

The efficiency of the power plant depends largely on the parabolic trough concentrators, as they are responsible for the collection of the solar resource. The more direct normal irradiation is collected, the more output power the plant is able to provide. However, it is difficult to choose a specific type of parabolic trough solar concentrator, as different technologies and systems have appeared during the last years in the research of lower costs and higher solar collecting values. As a result, it is necessary to carry out a general approach to the existing solar parabolic trough concentrators, in order to find the most appropriate option for the power plant in Gibraleón. Regarding to the concentrator structure, which is responsible for the subjection of the different components of the parabolic trough collector such as mirrors and absorber tubes (that will be studied in further stages of the project), protects the system from wind and allows sun tracking, it is possible to differentiate three main technologies:

- **Torque-box concentrators**, consist on a central strut on which the mirror supporting structures are mounted. Based on the SEGS solar thermal experiences in California, the first torque-box concentrators appeared in 1998 providing great achievements in terms of structure deformation (mainly caused by wind and total weight of the different components) reduction. Torque-box concentrators reduce torsion and bending during operation, introducing an axis of rotation located at the centre of mass of the concentrator which reduces its moment of inertia, providing easier control conditions.

![Torque-box parabolic trough solar concentrator](image)

**Figure 39. Torque-box parabolic trough solar concentrator**


**Figure 39.** highlights the steel squared cross section that supports the parabolic arms that will subject the mirrors. As the torque-box configuration is only composed by for different components, this type of concentrator is cheaper to produce, easier to mount and easier to transport than other parabolic trough concentrators. At the same time, torque-box parabolic trough concentrators introduce several advantages, such as higher structural resistance, less shading, lighter structures, simple manufacturing and maintenance and higher collector length (the larger the collector is, the lower tracking devices and heat transfer fluid pipes the collector needs, reducing losses and consequently, costs), among others.
• **Torque-tube concentrators**, which was the first parabolic trough concentrator configuration used in a commercial power plant (*Luz International*, in California) and, despite having been overcome by the torque-box technology during the last decades, it has recently returned to the parabolic trough systems. Torque-tube concentrators follow the same configuration as their torque-box homonyms, but instead of a square cross structure, mirror supporting arms are mounted on a tube whose diameter depends on the required structural resistance to wind.

![Torque-tube parabolic trough solar concentrator](image)

**Figure 40. Torque-tube parabolic trough solar concentrator**


Torque-tube concentrators are made of steel too, introducing as well several advantages such as light structure weight, low manufacturing, assembling and maintenance costs due to its chain production system and higher resistance to torsion efforts, among others.

• **Space-frame concentrators.** As well as the previously mentioned designs, space-frame concentrators were firstly introduced in the SEGS power plants in California. This type of concentrator introduces a main advantage in terms of structure material, as the structure is performed in aluminium, and provides great manufacturing and corrosion resistance features. According to the *United States National Renewable Energy Laboratory*, space-frame structure is lighter than in the torque-box and torque-tube steel technologies, it does not require field alignment nor welding, and they are easy to assembly.

![Space-frame parabolic trough solar concentrator](image)

**Figure 41. Space-frame parabolic trough solar concentrator**


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23 According to CSP Parabolic trough report: costs and performance, assemble times can be reduced by 50%.
Once that the main existing parabolic trough concentrator configurations have been introduced, it is the time to discuss the best option for the parabolic trough power plant located in Gibraleón. The comparison will be based on Figure 42. And Figure 43.

![Collector Type Installed Capacity](image)

**Figure 42.** Existing parabolic trough solar concentrators depending on their type  

![Collector Type Overview](image)

**Figure 43.** Current state of the different parabolic trough solar concentrator types  

Figure 42. introduces the torque-box structure configuration as the most used during the latest years (350 unities since 2006), followed by the space-frame system (164 unities since 2006, among a total amount of 354 unities) and finally by torque-tube collectors (56 unities since 2006, among a total amount of 220 unities). As a result, torque-tube technology is dismissed, because its small implantation during the last 6 years may become a problem in terms of cost and...
construction time (greater experience in torque-box and space-frame systems may introduce cheaper elements and may reduce construction and maintenance efforts). Among the torque-box configurations, the most relevant experiences have been:

- **ET100 and ET150**: developed by the Eurotrench European Consortium (Abengoa Solar\(^{24}\), CIEMAT\(^{25}\), SOLEL solar systems\(^{26}\), FLAGBEG Solar international\(^{27}\), etc.)

- **SKAL-ET**: used in Andasol 1, 2 and 3 power plants, developed by Flagsol\(^{28}\) and Solar Millennium AG\(^{29}\).

- **Solucar TR**: used in Solnova 1, 2 and 3 power plants, developed by Abengoa Solar.

- **SAMCA Trough**: used in La Florida and La Dehesa power plants, developed by SAMCA Group\(^{30}\).

Regarding to the space-frame technology, there is a specific model that has achieved great success in commercial parabolic trough power plants, receiving both *R&D100 Magazine 2009 Award* and *CSP Commercialized Technology Innovation of the Year 2010 Award* from *CSP Today*:

- **Skytrough**: used in Sunray power plant and developed by Skyfuel\(^{31}\) and Reflectech\(^{32}\), in conjunction with the United States National Renewable Energy Laboratory (NREL).

Each type introduces their own advantages and disadvantages and there is not great difference in between them, as most of the differences answer to commercial criteria or structural variations. However, what it seems proved is the fact that initial eutrotrench collectors (ET100, ET150) have been overcome by newer versions, especially by types such as SKAL-ET or Skytrough which introduce several advantages when compared to the first models. Under these considerations, the chosen option for the parabolic trough solar thermal power plant with molten salt thermal storage in Gibraleón will be: *Parabolic trough space-frame Skytrough concentrator*, manufactured by Skyfuel Ltd. The main features of the Skytrough parabolic trough concentrator are specified in **Annex II. Skytrough** concentrators have been chosen due to their high-performance,

\(^{24}\) [http://www.abengoa.com]

\(^{25}\) Energy, Environment and Technology Investigation Centre (CIEMAT) of the Spanish Economy and Competitiveness Ministry, [http://www.ciemat.es](http://www.ciemat.es)

\(^{26}\) [http://www.solel.com](http://www.solel.com)

\(^{27}\) [http://www.flagbeg.com](http://www.flagbeg.com)

\(^{28}\) [http://www.flagsol-gmbh.com](http://www.flagsol-gmbh.com)

\(^{29}\) [http://www.solarmillenium.com](http://www.solarmillenium.com)

\(^{30}\) [http://www.samca.es](http://www.samca.es)

\(^{31}\) [http://www.skyfuel.es](http://www.skyfuel.es)

\(^{32}\) [http://www.reflectechsolar.com](http://www.reflectechsolar.com)
cost reduction (especially in those features referred to their innovative reflective mirror panels and construction time, discussed in the following chapters) and lower weigh (due to the aluminium space frame) when compared to torque-box steel-based technologies, which in turn will result in smaller solar tracking devices.

Each Skytough module has a length of 14m and width of 6m, allowing to assemble up to 8 modules in a same raw, with a total length of 115m, including pylons, control and drive system and one ball joint at each end. Skytough parabolic trough concentrator has been design to work in conjunction with the SCHOTT PTR80/90 absorber tube, Therminol VP-1 heat transfer fluid, which will be introduced in next stages), and ensures good operating conditions up to a limit of 64 km/h 3 second wind gust (16,7 m/s) or 40 km/h (11,1 m/s) continuous wind speed, and structural resistance up to 135 km/h (37,5 m/s) of 3 second wind gust.

The wind limits introduced above highlight the fact that wind plays an important role in the solar field and so, it is essential to find the better resting positions for the collectors in order to minimize wind impact on them. Through different aerodynamics studies\textsuperscript{33}, where drag, lift, torsion and mean pressure effects on the collector’s structure were studied in function of the rotation angle, and taking into account the fact that external raws are more exposed to wind than other internal ones (as external raws reduce wind impact on the internal ones), some different rotation positions have been determined:

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
Characteristic Effect & “External” collector & “Internal” collector \\
\hline
Safety position & -120 & -120 \\
Nelting position & 0 & 0 \\
Maximum torque effect & -30 & -15 \\
Maximum bending action on the torque tube & +60 & +30 \\
Maximum drag force & +75 & -45 \\
Maximum lift force & +120 & -45 \\
Maximum crush force & +30 & +30 \\
\hline
\end{tabular}
\end{center}

\textbf{Figure 44. Characteristic positions for a parabolic trough solar collector}

[Source.- Salomoni, V.A. et. al. 2010. New trends in designing parabolic trough solar concentrators and heat storage systems in solar power plants, University of Padua. ENEA\textsuperscript{34}]

Even that the best resting position for a parabolic trough collector would be at 180°, this is not possible due to structural pylons and so, -120° becomes the best safety position for the collector. It must be said that the strongest force due to wind on the collectors is the one related to the torque effort, and structural design must keep this fact into consideration.

\textsuperscript{33} Salomoni, V.A. et. al. 2010. Structural design of parabolic trough solar concentrators. University of Padua. ENEA.

\textsuperscript{34} Agency for New Technologies, Energy and Environment of Italy, http://www.enea.it
The manufacturer provides some general performance values too, highlighting a 73% of thermal efficiency\textsuperscript{35} (under direct normal irradiation values of 1000 W/m\textsuperscript{2} and 350\degree C heat transfer fluid temperature), optical efficiencies over 77\% thanks to its innovative reflecting surface (Reflectech), discussed in the following stages of the project, and an average 2ha/MW-e land use (this feature makes it possible to make a first estimation of the area required by the solar field, which for the selected 50 MW-e output power of the plant would be around 100 ha of land).

The fact that Skytrough collector has been developed not only by Skyfuel and Reflectech companies, but with the inestimable help of the NREL, provides great amounts of contrasted performance data, such as the strong weather resistance of the Reflectech film, which has been tested for 20 years in the NREL Ultra Accelerated Weather System. As an important feature, it is possible to observe that the Skytrough collector allows a 4\% land slope along the solar field, which strongly contrasts with the typical 1\% admissible slope for other conventional parabolic trough collectors.

\textbf{Annex II.} introduces some power generation data too such as design point efficiency, capacity factor and typical annual average efficiency values for the Skytrough collector. These values have been provided through its operation in previous plants (Sunray power plant in Dagget, California) and answer to a great amount of specific working conditions. As a result, these values cannot be taken as constant because they will change depending on many parameters, being necessary to calculate them regarding to the specific conditions of this project, which will be carried out in following chapters.

However, it is possible to have a general estimation of the typical steam temperature and pressure for the plant, which are established around 373\degree C and 100 bar\textsuperscript{36}, and an approximate water consumption for the selected wet cooling system of 3220 litres per MW/h-e plus 45-55 l/MWh-e for mirror washing and 150 l/MWh-e for other general processes (blowdown, water treatment, etc.), which result in an estimated 3420 l/MWh-e water consumption (again, these values can only be taken as estimated and will depend on the specific conditions of each project).

Water is, then, a critical resource, as according to the selected evaporative wet cooling method, this requirement will have an important impact on the water level of the different water reservoirs of the region. At the same time, this water will not be evaporated completely, being necessary to develop an accurate water treatment process in order to ensure that the ecosystem to which this water is returned back is not affected in a significant way.

Focusing on the general performance of the Skytrough parabolic trough solar collectors, it is interesting to study the thermal efficiency of the collector depending on the temperature of the heat transfer fluid, as well as to determine the thermal performance curve of the device. These references can easily be found in \textbf{Annex II.}, and are shown in the following figures:

\textsuperscript{35} Ibid. [9]

\textsuperscript{36} Kelly, B. and D. Kearney. 2006. Thermal storage commercial plant design study for a 2-tank indirect molten salt system. NREL.
Figure 45. Skytrough thermal efficiency curve
[Source.-Skyfuel Inc., http://www.skyfuel.com (accessed April 22nd 2012)]

Figure 46. Skytrough thermal performance curve
[Source.-Skyfuel Inc., http://www.skyfuel.com (accessed April 22nd 2012)]

Figure 45. and Figure 46. show the thermal behaviour of the Skytrough collector, obtained through previous experiences developed in California. Although both figures answer to specific operating conditions, independent testing at the NREL have validated the thermal efficiency and thermal performance prediction models developed by Skyfuel, which will be later used to determine Gibraleon’s power plant results. Finally, it must be said that Skytrough collectors enjoy a 5 years Thermal Efficiency Performance Guarantee and a 15 years Specular Reflectance Guarantee.
4.1.4. Mirrors or reflectors

Now that the Skytrench parabolic trough solar concentrator has been chosen, it is the time to discuss the mirrors and reflective surfaces that will be attached to the collector’s structure and will be responsible for solar concentration on the absorber tube. Several technologies have been developed to carry out this process, but glass-based reflectors have been the most common option for many years and have introduced great performance values despite having some specific problems. According to the reflective surfaces used in parabolic trough solar collectors, it is possible to highlight:

- **Glass-based reflectors**: this kind of reflectors is obtained by adding different chemical substances to a glass-based surface. The most typical composition is carried by a first silver impression on the back side of the glass that is later covered by copper and finally painted with an epoxy primer, obtaining a high reflective surface. Among the glass-based reflectors, two systems can be distinguished: thin glass reflectors (under 1.5mm) and thick glass reflectors (over 3mm)\(^{37}\). The main difference between both technologies answers to an economical and time saving approach, as thick glass reflectors can directly be blended in a parabolic shape by hot laminating so they can directly be mounted on the concentrator structure (which is time saving but increases manufacturing costs) and thin glass reflectors are sticked to a metallic parabolic shaped surface thanks to their flexibility (which is cheaper but requires more mounting time).

![Figure 47. Pilikington Optiwhite reflective mirror](Source.-Pilkington Inc., http://www.pilkington.com/solarenergy (accessed April 23\(^{39}\) 2012))

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Thanks to this procedure, glass-based reflectors can easily achieve reflection values around 90-92%\textsuperscript{38}, depending on the manufacturing procedure, chemical composition and supplier, among others. However, glass based reflectors introduce a great handicap related to the fact that glass is fragile (mirror breakage due to wind has been observed near the edges\textsuperscript{39}) and so, periodic maintenance is required in order to maximize solar collection.

- **Metallic-based reflectors**: this configuration is commonly achieved by directly polishing aluminium plates which are later blended into a parabolic shape. It is largely the cheapest option, as manufacturing process is extremely reduced and mounting time is reduced to the minimal, but it is not used in power generation as their reflection values rarely overcome 85%\textsuperscript{40}. This feature, added to the fact that aluminium plates are deeply damaged by weather conditions when operating outside (plates get dirty, rusty and reduce dramatically their optical performance), unable metallic-based reflectors for the parabolic through power plant in Gibraleón, as this technology is designed for other small reduced-cost applications.

- **Plastic-based reflectors**: this technology follows the same idea as the glass-based reflectors, as they usually introduce an aluminium or silver coating over a plastic material. As a result, a reflective plastic surface is obtained, which must be sticked to a parabolic shaped structure before mounting them on the concentrator. Initially, plastic-based reflectors used to introduce more weather dependence, as reflectance (which in the beginning was as good as glass-based reflectors or even better) tended to decrease while operating outside, as suspended particles in the air scratched the reflective surface and dust accumulated in major grade due to electrostatic wind charging of the reflector. However, recent developments in plastic-based reflecting technology have introduced it as a real (and cheaper) alternative to the glass-based reflectors, as it is in this project, indeed.

![Design of a Solar Thermal Power Plant](image)

**Figure 48. ReflecTech PLUS reflective film**

[Source.- ReflecTech Inc., http://www.reflectechsolar.com (accessed April 23\textsuperscript{rd} 2012)]

\textsuperscript{38} According to Pilkington Inc. Optiwhite, Optiwhite S and Microwhite solar reflectors data, http://www.pilkington.com/solarenergy. However, Flagsol devices introduce reflection values up to 94%, according to their own studies, http://www.flagsol-gmbh.com


\textsuperscript{40} Ibid. [37]
Now that the main reflective technologies have been introduced, and taking into account the chosen Skytrough parabolic trough solar collector from Skyfuel Inc., the selected reflective technology for the collector is ReflecTech PLUS mirror film. According to the information introduced above, glass-based have largely been the most used reflecting technologies, as plastic-based reflective surfaces introduced more maintenance costs due to their weather degradation when operating outside. However, ReflecTech PLUS mirror film has been chosen because of its great features (for which it has received multiple awards) and small cost when compared to typical glass-based reflecting surfaces, as will be shown below.

**Table 13.** Estimated reflective technology cost [€\(^{41}\)] per square meter

<table>
<thead>
<tr>
<th>Material</th>
<th>€/m(^{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished aluminium</td>
<td>1,90</td>
</tr>
<tr>
<td>Thin glass reflector</td>
<td>3,03</td>
</tr>
<tr>
<td>Thick glass reflector</td>
<td>1,70</td>
</tr>
<tr>
<td>Reflecting polymer</td>
<td>1,13</td>
</tr>
</tbody>
</table>

ReflecTech PLUS mirror film is composed by a plastic polymer covered in silver. It has been developed by ReflecTech Inc. in conjunction with the NREL, and it is only used in Skytrough parabolic concentrators from Skyfuel Inc. This innovative plastic-based reflecting surface is high reflective, cheaper and lighter than traditional glass-based reflectors and abrasion and weather resistant, features that introduce it as the best option for the parabolic trough power plant in Gibraleón. In order to obtain the parabolic shape, ReflecTech PLUS is sticked to a thin aluminium sheet which is later inserted in the concentrator structure (this process can be carried out on-site, which reduces cost and construction time) and, during its transport to the selected location, it is covered by a peel-off plastic liner that protects the device from any damage.

![Figure 49](http://www.reflectechsolar.com) **Figure 49.** Comparison between ReflecTech PLUS and conventional glass reflectors


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\(^{41}\) Applying a conversion rate of 1 U.S. $ = 0,758€

\(^{42}\) Ibid. [9]
Previous plastic-based reflecting surfaces tended to reduce their reflectivity through air suspended particles scratching and dust accumulation (due to electrostatic charge of the surface caused by wind), but ReflecTech PLUS introduces a transparent coating that prevents the surface from abrasion and keeps the optical features of the device unvaried. This allows the collectors to be periodically brushed even with the typical scrub brushes and chemical substances used in conventional glass-based surfaces. What is more, this transparent coating provides a great moisture resistance, as ReflecTech PLUS can stand 60 days of water immersion (so rain becomes no problem for the collector’s optical performance, as no delamination or loss of adhesion is produced).

Regarding to the main features provided in **Annex II**. it can be concluded that ReflecTech PLUS mirror film, with a 94% of reflectance, is a great option for the parabolic trough power plant in Gibraleón when inserted in the Skytrough collector system. ReflecTech PLUS does not only provide advantages in terms of cost reduction and optical performance, but also in environmental behaviour:

![Embodied Energy of Trough Collectors, Including End-of-Life Impacts (MJ/m² of aperture area)](image)

**Figure 50.** Embodied energy of life cycle comparison: ReflecTech PLUS vs. SKAL-ET  

As it can be seen in **Figure 50.**, ReflecTech PLUS introduces up to a 61% embodied energy reduction when compared with other conventional parabolic trough systems, such as the SKAL-ET Eurotrough collector, used for example in the Andasol power plants in Granada (Spain). If embodied energy is defined as the total amount of energy [MJ/m²] required to manufacture a material from prime material extraction to manufacturing processes, this value can be taken as an approximation to the required energy to produce this material. If we add the end-of-life impacts related to disposal or recycling, it is possible to have an idea of the environmental cost of the material (the more embodied energy the material requires, the less environmental friendly the material is). The fact that ReflecTech PLUS is more environmental friendly than other conventional parabolic trough systems becomes another reason for its choice, as parabolic

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43 Ibid. [32]
through technology is one of the nowadays available renewable energies and so, ecological impact must not be forgotten when designing the parabolic trough power plant in Gibraleón. To sum it up:

![SkyTrough® Specifications](image)

**Figure 51. Recommended (and chosen) reflector for the Skytrough concentrator**


More data, as well as the result of the different abrasion, moisture, delamination and weather resistance tests, can be found in Annex II. This document includes environmental studies and the ReflecTech PLUS user’s guide too, among other interesting information.

4.1.5. **Linear receivers or heat collection elements.**

Solar collection in a parabolic trough solar field is carried out, as has been intensively explained, by the parabolic trough collectors. To this point, the parabolic trough structure and reflective surface have been chosen, but there is another device that must not be forgotten, as it plays an essential role in the plant: the linear receiver. The linear receiver or heat collection element acts as the interface between the collected direct normal radiation and the heat transfer fluid (that will be chose in following stages of the project), allowing the transmission of thermal energy to the system. It becomes an essential device, as its efficiency will directly result in a higher thermal performance and, consequently, higher output power. The more thermal energy the linear receiver is able to collect, the more energy will be provided to the steam cycle and thermal storage system. It is critical, then, to ensure the highest standards of quality, selecting the most appropriate device for each specific project and carrying out periodical supervision of the system in order to maximize benefits.

The linear receiver consists of two concentric tubes: an inner metallic pipe (usually steel) through which the heat transfer fluid flows and which will be responsible for thermal transmission to it, and an external glass tube that will reduce thermal losses due to convection by maintaining the vacuum between both surfaces. As a way of improving thermal efficiency of the system, the metallic pipe is usually covered in a special coating (primarily nickel, although its composition will vary depending on operating temperature, specific working conditions, selected heat transfer fluid or commercial criteria, among many others⁴⁴) in order to reduce thermal losses due to radiation (lower infrared emissivity) and to increase thermal absorbance of the pipe. Heat collection elements are usually shorter than the parabolic trough collector modules and, as a result, each collector raw will require many linear receivers connected in series.

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⁴⁴ A new metal-ceramic material called cermet (cer for ceramic and met for metal) is introducing high efficiencies and may provide great results in a short-time period.
in order to cover the total length of the line (115m for the 8-module Skytrough assembly).

![Diagram of Solar Thermal Power Plant](image)

**Figure 52. Main parts of a solar linear receiver**

[Source.- Zarza, E. Medium temperature solar concentrators (parabolic troughs concentrators). Unit of Solar Concentrating Systems. PSA.]

Both metallic and glass pipes of a linear receiver are mechanically assembled with a **metallic expansion bellow**. Glass and metal expand when their temperature increases. This expansion is, however, different for each material and, as a result, they cannot be assembled with rigid junctures because that would break them. The metallic expansion bellow carries out an intelligent assembly between both materials, allowing them to expand in different ways without compromising the mechanical resistance of the device. This device is not, however, infallible, as it must be protected from the Sun to avoid high temperatures, and must not be exposed to strong mechanical efforts as it is a weak point of the heat transfer fluid system.

Some collectors introduce aluminium structures to reinforce the expansion bellow, as well as to protect these devices from solar radiation. **Figure 52.** shows another two essential devices of the linear receiver. On one hand, *getters* are responsible to maintain the vacuum in the best conditions, catching any gas that may have been generated by high-temperature decomposition of the heat transfer fluid, and on the other hand, a *glass pin* which is designed for purging the thermal circuit, taking away any air bubbles contained in the system.

An anti-reflective treatment can be done to the external glass tube of the receiver in order to maximize solar transmission to the inner metallic pipe, increasing the efficiency of the system, although real experiences have demonstrated that this anti-reflective coating is very expensive and does not introduce very good results, so it is not a very recommended solution for the linear receivers of the parabolic trough power plant.

Now that a first approach to the linear receiver has been carried out, it is the time to choose the best option for the parabolic trough power plant in Gibraleón. Skytrough parabolic trough collector has been designed to work in conjunction with **SCHOTT PTR 80**, as shown in the following figure:
The manufacturer’s recommendations are really taken into account, as it is considered that it provides those features that ensure the best operating conditions. However, when a research for the main features of the recommended device was carried out, a great lack of information of this specific SCHOTT PTR80 linear receiver was noticed and, in order to obtain the information not provided in the net, some e-mails were sent to the manufacturer’s different delegations45 explaining the educational purpose of this project and asking for some information about the SCHOTT PTR80 heat collection element, but no answer was received. There is, however, a previous model, the SCHOTT PTR70 with plenty of information freely available online and with contrasted success in many parabolic trough power plants (Andasol I, Nevada Solar One, etc.). Under this lack of information, the selected linear receiver for the parabolic trough power plant in Gibraleón is the SCHOTT PTR70. Among the reasons that have led to this choice (existence of a nearby Spanish Schott Solar AG Delegation in Aznalcóllar, Seville), there is a clear intention of maintaining the recommended manufacturer for the Skytrough collector (other manufacturers such as UVAC or Siemens provide linear receivers for parabolic trough power plants too, but the SCHOTT PTR70 is more likely to accomplish with the thermal requirements of the solar field, according to Skyfuel) and so, this is the chosen option.

45 Spanish delegation (solar.sales@schottglobal.com), United States Delegation (general@us.schottglobal.com, customer_service@us.schottglobal.com), German Delegation (http://www.schottglobal/de) and French Delegation (http://www.schottglobal/fr)
*SCHOTT PTR70* introduces a new absorbed coating, developed in conjunction with the *United States National Renewable Energy Laboratory*, with great results in terms of thermal stability up to 450°C and reduced heat losses (less than 250W/m² at 400°C, when other receivers introduce values up to 450 W/m²)\(^{46}\). Mechanical stability and vacuum are ensured by a combination of similar materials in terms of thermal expansion coefficients, as well as an improved expansion bellow design which shelters the *getter* (increasing its lifetime up to a 30% when compared with other receivers with absorber tube-positioned *getter*)\(^ {47}\).

![Design of a Solar Thermal Power Plant](image)

**Figure 55.** *SCHOTT PTR70* expansion bellow (blue circle shows getter location).

![Heat Loss Comparison](image)

**Figure 56.** Comparison between *SCHOTT PTR70* and *UVAC 2008* heat losses

In order to confirm what it has been mentioned before, **Figure 56.** plots the amount of heat loss in W/m depending on temperature above ambient. As it can be observed, for the same reference temperature *SCHOTT PTR70* introduces less heat losses, which is an important feature in terms of total efficiency of the plant. The less thermal is lost during solar collection, the more output power the plant will be able to provide, increasing its benefits. Other physical and chemical properties of the *SCHOTT PTR70* are provided in **Annex II.**


\(^{47}\) Ibid. [46]
4.1.6. **Heat transfer fluid system.**

As essential as the linear receiver is for solar collection, the heat transfer fluid plays a critical role in the plant’s performance. This substance keeps the thermal energy obtained from the sun, increasing its temperature. Later, this high temperature fluid will be responsible for both thermal energy transmission to the molten salt thermal storage system and steam generator.

There are different heat transfer fluids depending on the operating temperature of the system. According to the parabolic trough technology selected for Gibraleón’s power plant, which is classified as medium temperature concentrating technology\(^{48}\), temperatures around 400°C will be expected in the solar field heat transfer system and so, some kind of synthetic oil must be chosen for the thermal transmission. Demineralised water and Ethylene-Glycol mixtures are dismissed due to the necessity of high pressures in the system to keep them liquid, as the only way to unable evaporation is to maintain operating pressure over the saturation pressure. The higher the operating temperature is, the higher the saturation pressure is and so, even higher pressures should be kept to avoid evaporation, reaching values up to 100bar\(^{49}\). However, by selecting synthetic oils saturation pressure is dramatically reduced and much lower pressures are required to ensure optimal operation of the plant. The mentioned values will depend on the specific features of the plant and so, it will be necessary to calculate them in order to validate the real operating pressure of the plant.

Synthetic oil is not the only heat transmission fluid available for parabolic trough concentrators, as lately there is a tendency in using a mixture of molten salts\(^{50}\) (sodium and potassium nitrate, at different concentrations) which introduces stability values for operating temperatures up to 600°C. The more temperature the heat transfer fluid, the more thermal energy this is able to provide to the steam generator and to the thermal storage system. At the same time, by using the same molten salt mixture that is present in the thermal storage system, it is possible to reduce the thermal interface (heat exchanger) between the synthetic oil from the solar field and the molten salt mixture from the thermal storage system, increasing the plant’s output and decreasing costs. As a result, both synthetic oil and molten salt mixture are susceptible of becoming the selected heat transfer fluid for the parabolic trough solar thermal power plant in Gibraleón. However, for this specific project, the choice will be conditioned by the selected concentrator, as Skythrought concentrators are designed to work in conjunction with SCHOTT PTR80 linear receivers (as has been previously explained) and recommend a synthetic diphenyl oxide/biphenyl mixture as the heat transfer fluid. In order to ensure the maximum efficiency of the solar field, the selected heat transfer fluid will be the *Therminol VP-1 diphenyl oxide/biphenyl synthetic oil*, manufactured by *Solutia Inc*\(^{51}\). It must be said that

\(^{48}\) Ibid. [9]

\(^{49}\) Ibid. [37]

\(^{50}\) Salomoni, V.A. et. al. 2010. New trends in designing parabolic trough solar concentrators and heat storage systems in solar power plants, University of Padua. ENEA.

\(^{51}\) http://www.therminol.com
this choice answers to a reliance on the manufacturer, who establishes this option as the best one for the Skytrough collector.

**Figure 57. Recommended (and chosen) HTF for Skytrough concentrator**

*Therminol VP-1* is an eutectic mixture of 73.5% diphenyl oxide (DPO) and 26.5 biphenyl. This synthetic oil provides a good *bulk temperature* (defined as the maximum temperature that, according to the manufacturer, oil keeps its properties unvaried), ensuring good stability up to 395°C. *Therminol VP-1* introduces, however, a handicap when solidification temperature is discussed, as this is carried out at 12°C. This feature requires pipe heating during the coldest periods of the year in order to avoid solidification of the heat transfer fluid, which can increase operational costs.

Regarding to the minimum temperatures in Gibraleón during the last 22 years (*Annex I.*), it can be seen that temperatures under 12°C are easily reached during winter, being necessary to consider this fact during the design stage. According to what it has been explained above, pressure must be increased during operation in order to avoid the evaporation of the heat transfer fluid, as the boiling temperature for *Therminol VP1* is established at 257°C when kept at an ambient pressure of 1013mba. Under this acknowledge, the heat transfer system must be pressurized with an inert gas (nitrogen, argon, etc.) during normal operation of the solar field, as temperatures above 257°C are easily reached. It is important not to leave any oxygen in the system, as the mixture of it with the substances in the heat transfer fluid at high pressure can be dangerous.

**Figure 57.** shows that not only *Therminol VP1* can be used as heat transfer fluid, but any other diphenyl oxide/biphenyl synthetic oil is susceptible of being used as heat transfer fluid (in fact, it introduces Dowtherm as an alternative solution). There are effectively other synthetic diphenyl oxide/biphenyl oils with higher *bulk temperatures* and lower *solidification temperatures* (*Syltherm 800*), but they become unsuitable when large projects are carried out, as the great prize difference between them and *Therminol VP1* makes them unworthy. It is largely cheaper to introduce a pipe heating system to avoid solidification during the coldest periods of the year than to choose a different synthetic oil with lower solidification temperature and, at the same time, the increase of economical benefits related to higher *bulk temperatures* (the higher the temperature the heat transfer fluid is capable to stand with stable properties, the higher the thermal energy provided to the steam generator will be, and the higher the

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52 Zarza, E. Medium temperature solar concentrators (parabolic troughs concentrators). Unit of Solar Concentrating Systems. PSA.

53 Ibid. [52]

54 Dow Chemical Company, http://www.dow.com
output of the parabolic trough plant) is smaller to the cost of the oil itself, so Therminol VP1 is truly the best option for the plant.

**Table 14. Economical and thermal comparison between Therminol VP1 and Syltherm 800 diphenyl oxide/biphenyl synthetic oil.**

[Source: Own elaboration⁵⁵]

<table>
<thead>
<tr>
<th></th>
<th>€/kg</th>
<th>Solidification temperature [°C]</th>
<th>Evaporation temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Therminol VP1</td>
<td>2.5</td>
<td>12</td>
<td>400</td>
</tr>
<tr>
<td>Syltherm 800</td>
<td>10</td>
<td>-40</td>
<td>400</td>
</tr>
</tbody>
</table>

Special attention may be paid at heat transfer fluid leaks in critical parts of the system, such as pipes, valves and joints, as inflammable vapors may be leaked to the atmosphere and could punctually be responsible for fire ignition. The manufacturer provides some toxicological data from animal testing, introducing this diphenyl oxide/biphenyl synthetic oil as slightly toxic by punctual ingestion and non-toxic by dermal contact. Other Therminol VP1 physical and chemical properties can be found in Annex II.

In order to distribute the heat transfer fluid along the solar field, the parabolic trough power plant includes a hermetrical heat transfer fluid system, composed by the following devices:

- **Linear receivers or heat collection elements**: responsible for the thermal transmission from solar radiation (collected by the parabolic trough concentrator) to heat transfer fluid, they constitute a hermetrical circuit along the whole solar field through which the heat transfer fluid flows, increasing its temperature. The heat transfer fluid system must be sectorized in order to control the total amount of circulating Therminol VP1 in every moment, allowing some parts of the solar field to be insulated under specific operating conditions to maximize solar collection.

- **Expansion tank**: it is responsible for absorbing the volume variations suffered by the heat transfer fluid (caused by temperature variations along the circuit) and for keeping the system pressurized usually by introducing pressurized nitrogen. Pressure must be kept in every moment over the saturation pressure of the Therminol VP1 for every specific temperature, in order to maintain the heat transfer fluid in a liquid state and avoid its evaporation.

- **Oil tank**: storages the total amount of Therminol VP1 used in the heat transfer fluid system and, as it happened in the expansion tank, this device must be pressurized in order to avoid evaporation of the heat transfer fluid.

- **Auxiliary storage tank**: during plant’s construction and as a result of a preventive maintenance plan, Therminol VP1 diphenyl oxide/biphenyl

⁵⁵ Data obtained from http://www.therminol.com and http://www.dow.com, estimated values obtained from different year’s prize.
synthetic oil may need to be stored separately from the heat transfer fluid. The auxiliary storage tank provides a temporary warehouse for the heat transfer fluid, which is kept over its solidification temperature (electrical resistances introduced in the tank, auxiliary combustible source, etc.) while building operations are still being carried out or just as a backup heat transfer fluid system in case there is a sudden lack of Therminol VP1 in the system (accidental spillage, undetected leakage, etc.).

- **Oil treatment system**: it is responsible for oil treatment, purifying it before introducing the heat transfer fluid back to the circuit. The oil treatment system removes those Therminol VP1 vapors generated by oil degradation (that may appear, for example, by depressurization of punctual sections of the circuit), which are extracted from the heat transfer fluid in conjunction with the exceeding nitrogen introduced in pressurizing procedures.

- **Heat transfer fluid pump**: it is responsible for pumping Therminol VP1 from the expansion tank through the heat transfer fluid system, along the solar field and finally to the steam generator and also to the thermal storage heat exchanger. Depending on the size of the solar field, a higher number of heat transfer fluid pumps will be needed and, under these conditions, the heat transfer fluid circuit must be properly distributed according to the specific features of each pump. As addition points, it is recommended to install some backup pumps in case any of the main ones fails and, due to the variability of solar resource along the year, heat transfer fluid pumps should be able to vary its operating conditions to answer punctual requirements of the system (if any sector of the solar field needs to be insulated for maintenance operations, heat transfer fluid should be able to reduce the pressure of the fluid along the circuit and, once maintenance has been finished, recover initial working conditions). The RPH oil pump, manufactured by KSB A.G., answers to these requirements. More information can be found on Annex II.

- **Pipe heating system**: all of the heat transfer fluid must be kept over Therminol VP1’s solidification temperature (12°C) and so, some kind of pipe heating system must be introduced in the plant. There are several heating technologies currently available, but in order to maintain the ecological approach of the parabolic trough power plant, electric trace heating is introduced as the most recommended option. This heating system is based on an electrical heating element (heating cables, electrical resistances, etc.) which is set in physical contact along the length of a pipe. This electrical heating element transmits its thermal energy to the pipe, raising its temperature and avoiding solidification of the inner fluid, in this case, Therminol VP1. In order to minimize heat losses and retain heat along the pipe, thermal insulation is typically introduced along the circuit.

- **Shut off and non-return valves**: in order to carry out punctual maintenance operations, adapt the solar field to the specific operating conditions and ensure a correct operation of the thermal fluid system.
4.1.7. Solar tracking system.

As it has been explained in initial stages of this project, Sun changes its position during the day, as a result of the different rotation, translation and nutation movements. In order to collect direct normal radiation from the Sun which is later concentrated on the linear receiver, the parabolic trough collector must be appropriately positioned in every moment. As a result, the different collectors of the solar field must introduce a solar tracking system in order to ensure solar incidence over the heat collection element, no matter which the position of the Sun is. These devices must be extremely precise and have to be properly controlled, as a bad configuration of the solar tracking along the day can be responsible for great economical losses.

There are different tracking systems, but it is possible to highlight two of them:

- **Single-axis tracking system**: rotation is produced along a single axis (tracking axis) parallel to the linear receiver. Depending on the selected orientation of the system, it is possible to differentiate two main options: *East-West single-axis solar tracking systems* and *North-South single-axis solar tracking systems*. These orientations are the most typical among parabolic trough solar concentrating technology (although any other may also be feasible), being necessary to discuss each option depending on the specific conditions of every project).

- **Double-axis tracking system**: contrary to single-axis tracking systems, rotation is produced not only along a single axis, but along two of them. While single-axis tracking systems introduce a 180° rotation range, double-axis tracking systems introduce 360° rotation, increasing notably the total amount of direct normal radiation collected by the parabolic trough concentrator.

Single-axis tracking systems are, contrary to what could be expected, the most used solution among parabolic trough power plants. Double-axis tracking systems increase the total amount of collected direct normal radiation and reduce optical losses, as they are capable of following the Sun in a more precise way than single-axis systems, but they are responsible for higher thermal losses and higher operation and maintenance costs (double-axis tracking requires more complex systems than single-axis tracking and, as a result, there are more possibilities of breakage and failure). Single-axis tracking systems are simpler, cheaper and more robust, compensating for lower direct normal radiation collection and so, this will be the selected option.

In order to carry out solar tracking, parabolic trough concentrators must be able to rotate around the tracking axis. This rotation is performed by the drive unit, whose type will depend on the size of the solar field (small collectors may be driven by a combination of an electric motor and a gearbox, but bigger units may require strong hydraulic systems). There is no necessity of installing several drive units along a single raw. Parabolic trough collectors can be connected in series (a 115 meter raw is carried out by a series combination of 8 Skytough collector modules, according to Annex II.) and one single unit can be responsible for the rotation of the whole raw. The type, power and location of the drive unit must be carefully selected in order to optimize solar tracking (rotation must be provided with minimum effort). Tracking system is useless without an appropriate control, as collectors must be kept in the precise position at every
moment. It is essential, then, to determine the exact position of the Sun along the day, which can be calculated through many different ways: on-site measuring devices, specific software, etc. If the position of the Sun is permanently determined, the solar tracking system can be precisely guided in order to maximize the collected direct normal irradiation. At the same time, wind measures must be permanently performed in order to prevent devices from damage. Orientation of the parabolic trough collectors is a very important issue, as it is closely related to their performance. Now that the single-axis tracking system has been chosen as the best option for the parabolic trough power plant in Gibraleón, orientation of the solar field must be deeply discussed in order to find the most suitable position of the collectors.

![Figure 58. Single-axis North-South and East-West solar tracking in a parabolic trough solar collector](image)


Some concepts must be introduced in order to clarify selection criteria:

- **Aperture plane**: defined as the plane formed by the collector aperture length and collector aperture width and related to the rectangular plane that could be noticed by a frontal observer of the concentrator.

- **Incident angle (i)**: it is the angle between the normal to the aperture plane (N) and the direction of the incident solar beams on the collector (S). In order to carry out solar concentration on the linear receiver, the tracking angle (ρ) must be modified to maintain them in the same plane.

![Figure 59. Single-axis solar tracking in a parabolic trough concentrator](image)

Daily variation of the incident angle \((i)\) is higher in East-West single-axis solar tracking, whereas seasonal variation is more noticeable when performing a North-South single-axis solar tracking. Latitudes between 30° and 45° are typically characterised by cold and cloudy winters that contrast with hot and sunny summers. This strong seasonal variation of the solar resource may introduce the North-South single-axis solar tracking as an apparently unadvisable orientation, as this system tends to be more affected by this kind of alteration, and introducing East-West solar tracking as the most recommended option in order to minimize performance penalties. However, through the experience of previous parabolic trough power plants in Spain, it has been demonstrated that despite introducing greater differences between winter and summer collected energy, the total amount of collected energy is higher with a North-South single-axis tracking system\(^{56}\) (although its distribution during the year is more variable). This is, in fact, the most typical orientation of parabolic trough power plants located in Southern Spain (for example, Andasol I-II-III power plants). As a consequence, for the selected location (geographically characterised by Latitude: 37.315562 and Longitude: -7.036548) the chosen option will be a North-South single-axis solar tracking.

As it happened with the heat transfer fluid, the Skytough parabolic trough concentrator is designed to work in conjunction with specific devices and, for this specific issue, North-South single-axis solar tracking will be performed by the OnSun control and drive system, manufactured by Skyfuel.

![OnSun control and drive system](image)

**Figure 60.** Skyfuel’s OnSun control and drive system in a parabolic-trough module  

The OnSun control and drive system consists on the combination of a L30 helical hydraulic rotary actuator from Helac Corporation\(^{57}\) and the Skytrakker electronic control system, manufactured by Skyfuel. This solar tracking systems introduces several advantages, especially in terms of generated torque, reduced parasitic electrical losses (up to a 50% when compared with conventional hydraulic drives, according to OnSun brochure provided in Annex II.), minor operational costs, small mounting time and simple design (smaller number of parts which result in lower possibility of failure). What is more, OnSun drive system does not require any other mechanical structure to stand the loads related to the weight of the


\(^{57}\) http://www.helac.com
parabolic trough concentrators, as these are fully supported by the actuator. Under this powerful advantages, and taking into account the fact that this is the drive system recommended by the Skytrough manufacturer (whose criteria has been taken as a reliable advice during this project), OnSun control and drive system becomes the most adequate solution for the parabolic trough power plant in Gibraleón. The main features of the Skyfuel’s OnSun control and drive system are specified in Annex II.

Due to the power of the hydraulic drive, one single unit is capable of governing a whole parabolic trough collector assembly (consisting on a combination of 8 Skytrough modules with a total length of 115m), reducing dramatically costs. This hydraulic drive is usually located in the central pylon that divides each raw of parabolic trough collector assembly in two.

Figure 61. Location of the solar tracking system along a Skytrough collector raw

[Source.-Own elaboration]

It has been mentioned that this solar tracking drive must be precisely controlled in order to face the Sun in the best conditions. This job is carried out by the Skytrakker electronic control, which is based on a complex solar position algorithm. The Skytrakker system sends real-time information to specific sources, in order to act on the drive system or to monitor the performance of the solar field, and can easily be updated in order to maximize solar collection. These electronics are installed in the same solar field and, despite being a long life device with expected durations around 30 years, this allows to carry out easy and quick on-site maintenance and to change damaged devices with minimal time penalties.

58 Modification of Figure 9. from Silva Pérez, M. 2004. Sistemas termosolares de concentración, University of Seville.

59 Ibid. [31]
The Skytraker control system allows both local and remote control for different applications (maintenance, monitoring, etc.). Remote control can be performed with traditional wired systems (insulated RS-485 wire) or through radio frequency. An additional feature that makes the Skytraker the best option for the parabolic trough power plant in Gibraleón is the fact that it provides a heat transfer fluid temperature monitoring in order to control high temperatures that could be responsible for chemical variations or to prevent freezing of the synthetic oil, which is produced under 12°C. The main specifications of the Skytraker control unit are introduced in Annex II.

4.1.8. Distribution of the solar field.

The solar field of the parabolic trough power plant is composed by different parallel rows which contain a determined number of collector modules connected in series (8 modules for the Skytrough collector assembly). The more collector modules are connected in series, the higher the temperature increase of the heat transfer fluid will be. On the other hand, the number of parallel rows is related to the nominal output power of the plant. The heat transfer fluid’s temperature gradient is usually determined by the manufacturer, as it establishes the total amount of modules that can be assembled in a single raw.
It is easy to notice that larger collector assemblies will result in higher temperature gradients, which in turn will reduce the required number of parallel rows for an equal nominal output power. It is, then, a matter of balance between the length of the different collector assemblies and the number of parallel rows in the solar field, being necessary to determine the best option depending on the specific conditions of each project. In order to carry out this stage, it is necessary to collect all the previous decisions in a table:

**Table 15. Selected devices for the solar field of the parabolic trough power plant in Gibraleón, Spain**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Location</th>
<th>Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available solar resource</td>
<td>2069,01 kWh/m²·year (5,67 kWh/m²·day)</td>
</tr>
<tr>
<td>Sunlight</td>
<td>2754 hours of sun per year</td>
</tr>
<tr>
<td>Concentrator</td>
<td>Skytrough space-frame collector</td>
</tr>
<tr>
<td>Reflector</td>
<td>ReflecTech</td>
</tr>
<tr>
<td>Linear receiver</td>
<td>SCHOTT PTR70</td>
</tr>
<tr>
<td>Heat transfer fluid</td>
<td>Therminol VP1 diphenyl oxide/biphenyl synthetic oil</td>
</tr>
<tr>
<td>HTF Pump</td>
<td>RPH</td>
</tr>
<tr>
<td>Tracking system</td>
<td>North-South single-axis tracking</td>
</tr>
<tr>
<td>Drive unit</td>
<td>OnSun hydraulic drive</td>
</tr>
<tr>
<td>Control unit</td>
<td>Skytrakker</td>
</tr>
</tbody>
</table>

The selected distribution for the solar field follows an H layout. This has been chosen because it is considered a very intelligent distribution, where structurally reinforced collectors can be located in the most external sites of the solar field in order to reduce wind impact in inner zones. External collectors, which act as a wind barrier, require stronger structures than other collectors located in inner parts. At the same time, this external increases thermal efficiency all along the solar field and, specially, in the thermal storage system, as convection losses are strongly reduced. What is more, power block and thermal storage are located in the middle of the solar field not only to reduce thermal losses due to wind action, but to enjoy a privileged location where pipe lengths and operating distances are

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60 Obtained by summing up the different monthly sunlight values provided in Table 12.

61 Ibid. [9]
much smaller than in other solar fields (which in turn results in smaller costs and maintenance efforts).

It is important to respect the North-South single-axis solar tracking distribution and so, precise installation must be performed in building stages. Due to maintenance operations, some space must be left between the different Skytrench rows, in order to allow the collector-cleaning trucks to work under comfortable conditions. However, this distance has to be wisely selected, as it is important to reduce the area of the solar field. The less area the solar field uses, the more area is available for future enlargements of the system. At the same time, shading must be taken into consideration, as very proximal rows can be responsible for shadows over parabolic trough modules and, consequently, responsible for performance reduction. It is, then, a matter of balance between maintenance requirements, shading and land usage.

![Diagram](image)

**Figure 64. Selected distribution for the solar field**


**Figure 64.** shows the selected distribution for the parabolic trough solar field in Gibraleón. Please notice that this is just a general approximation and cannot be considered as the final distribution of the power plant in Gibraleón. The total amount of solar collectors required to provide sufficient thermal energy to the steam turbine must be calculated and so must the total amount of rows along the solar field. In order to determine the total amount of solar collectors in the solar field, manual procedures will be verified trough computer simulation, taking into account the specific features of the selected devices. All this procedures will be developed in the next stages of the project, as it is still too soon to obtain this value.

Returning back to the general operation of an H layout, this configuration provides a symmetrical distribution for the different parabolic trough modules, in order to avoid hot or cold spots along the solar field. If applied to the parabolic trough power plant in Gibraleón, the *Thermol VP1 diphenyl oxide/biphenyl synthetic oil* would flow from the cold header to the different Skytrench modules. During its journey through the 115m collector rows distributed along the solar field, the heat transfer fluid would increase its temperature and would finally
return to the power block (and the thermal storage system, which is not indicated in Figure 64.) through the hot header.

The way the heat transfer fluid flows along a single raw (entering at a small temperature from the cold header and leaving at a higher temperature towards a new raw where the process is repeated) is called a loop. In order to allow this journey of the heat transfer fluid through the different raws that constitute the solar field, every collector module must be connected to the one besides it and so must the different raws. However, this connection must be performed in a way that it allows independent orientation of different raws (depending on the Sun’s position) and here it is where an essential device called ball joint plays an essential role. This is basically a metallic device which is responsible for joining the linear receivers from two consecutive collector modules and for absorbing thermal dilatation of their junctures, without limiting their rotation capacity.

This issue had always been solved by installing flexible hoses between different collector raws and modules, which are just curved metallic pipes that join the linear receivers from adjacent modules in order to constitute the thermal circuit through which the heat transfer fluid will flow. Flexible hoses are typically made of stainless steel and introduce some disadvantages when compared to other technologies, especially in terms of pressure drop (which is increased by friction of the heat transfer fluid through the rough inner surface of the hose) and flexibility (steel hoses must be smoothly bended in order to ensure good operating conditions, and this feature may introduce the necessity of larger pieces of material to perform steep changes).

Ball joints are cheaper, more efficient and reduce pressure drops thanks to their inner graphite juncture (which reduces friction), becoming the most common solution in actual parabolic trough power plants. This device allows to join the different linear receiver of the solar field without increasing material costs due to bending limitations.

Figure 65. Flexible hoses (left) and ball joints (right) in a parabolic trough collector.
[Source.- Zarza, E. Medium temperature solar concentrators (parabolic troughs concentrators). Unit of Solar Concentrating Systems. PSA]
It is important to mention that new solutions are being currently developed in order to solve some issues that have been noticed in ball joints, especially in terms of punctual leakages. A new improvement of the initial flexible hose design has been developed and is currently being tested in Andasol III power plant, obtaining very optimistic results for future parabolic trough power plant applications.

In order to finish with the distribution stage of the plant, it is necessary to introduce a brief approach to the possibility of introducing terraces and water channelling in the solar field. During rainy periods, water can be accumulated in the solar field, being necessary to redirect it outside of it in order to avoid damages in the different collector elements, especially regarding to corrosion. As a way to avoid this accumulation, the land can be distributed in steeped terraces on which individual modules of collectors act as small solar fields. However, this solution requires to divide the solar field in smaller units and the selected H-type layout could not be implemented. This water accumulation problem can easily be solved by introducing water channels along the solar field, with an approximated slope of 1.5%, that will direct rainfall to a common dump or to a water reservoir in order to be filtered and used again. Thanks to this, it is not necessary to divide the solar field into smaller collecting units which will be responsible for more complex systems and higher piping needs. In addition, solar field terraces require land movement operations, increasing the initial investment required by the solar field and resulting in a higher environmental impact. The design stage is carried out in chapter 4.4. Sizing, performance and annual energy production, as previous attention must be paid to the thermal storage system and steam cycle. Only with a global view of the project, performance of the plant will be able to be estimated with enough accuracy and so, design stage must be temporary laid aside in order to define other essential systems of the plant. As a result, the next step is to discuss the possibility of introducing a thermal storage system in order to increase the thermal efficiency and the annual output of the plant, selecting the best option in case that thermal storage is understood as advisable and introducing the main thermal storage systems currently available, as well as the main research and development lines regarding to this kind of systems.

4.2. Thermal storage

Parabolic trough power plants collect direct normal radiation, focusing it over the linear receiver in order to increase the temperature of a flowing heat transfer fluid, which will be lately used to generate the steam required to produce electricity through a Rankine steam turbine. However, this generating process can only be possible while there is enough available direct normal radiation, limiting its efficiency to the available direct normal radiation and sunlight data in the selected location. This becomes an important handicap, as radiation data and the amount of sunny hours are very difficult to estimate with sufficient accuracy and forces to shut down the power plant during periods of low direct normal radiation and at night.

However, this problem can be easily solved by installing a thermal storage system in which thermal energy can be stored until external conditions require its supply to the plant. This allows to increase notably the global performance,
efficiency and output of the plant, reducing start-up time and resulting in a lower energy cost. There are several thermal storage systems nowadays, although only a few of them have proved to be successful in commercial plants. Through the following lines, those feasible thermal storage systems will be introduced, carrying out a comparison between them in order to select the best option for the parabolic trough power plant in Gibraleón and, once that this option has been made, choosing those systems that fit better to the specific conditions of this project.

![Diagram](image)

**Figure 66. Comparison of the load/generation between a power plant with thermal storage and another plant without thermal storage.**


### 4.2.1. Available storage technologies and chosen option

One of the main reasons that introduce parabolic trough power plants as the best option for a commercial-scale power plant is the fact that they can work in conjunction with a thermal storage system which reduces the energy cost. This storage can be developed in different ways, highlighting the following systems:

- **Two-tank indirect storage system**: it has been explained before that the heat transfer fluid (*Thermol VP1 diphenyl oxide/biphenyl synthetic oil* in this project) flows along the different linear receivers of the solar field, increasing its temperature. This hot heat transfer fluid is directed to the power cycle heat exchanger, where it is used to produce the steam required by the Rankine turbine, and finally it is returned back to the solar field in order to repeat the process. A **two-tank indirect storage system** requires another heat exchanger between the heat transfer fluid and the molten salt which is used to retain its thermal energy. It is a simple process indeed: when the steam turbine has reached its nominal power output (50MW for the parabolic trough power plant in Gibraleón), the high temperature heat transfer fluid is redirected to this new heat exchanger, where it is used to heat the cold molten salt storage fluid provided by the **cold tank**. When the molten salt mixture is hot, it is stored in the **hot tank**,
where it remains until there is not enough solar resource. When this happens, the hot molten salt storage fluid is directed from the *hot tank* to the heat exchanger, where it returns back its thermal energy to the heat transfer fluid in order to continue with the steam generation process. After this, the molten salt is stored again in the *cold tank*, ready to repeat this process when the solar resource returns back. This interaction between the synthetic oil heat transfer fluid and the molten salt storage is called *indirect storage*, as both fluids are different.

![Diagram of a parabolic trough power plant with two-tank indirect thermal storage](image)

**Figure 67.** Electrical generation trough in a parabolic trough power plant with two-tank indirect thermal storage


Two-tank indirect storage is currently the most common system in the commercial parabolic trough power plants, although the need for a heat exchanger between the heat transfer fluid and the storage system, as well as the small temperature difference between the hot tank and cold tank molten salt fluid, makes it a very expensive technology.

- **Two-tank direct storage system**: the general idea of this storage system follows the same line as the two-tank indirect storage technology. When the nominal production of the steam turbine is reached, the heat transfer fluid is redirected to the storage system heat exchanger, increasing the temperature of the storage fluid from the *cold tank*, which is later stored in the *hot tank*. When solar resource is not enough to maintain the plant’s production, the hot storage system is redirected to the heat exchanger in order to provide the thermal energy that cannot be collected from the Sun. After this process, the storage fluid is stored again in the *cold tank*. There is, however a main difference: **two-tank direct storage system** introduces no difference between the heat transfer fluid and the storage fluid, which are the same.

Initial experiences at the *SEGS I* power plant allowed this storage system, which was based on the *Caloria mineral oil*. However, the increase of the operating temperatures (needed for higher efficiencies) introduced the necessity of new heat transfer fluids, which was covered by the diphenyl oxide/biphenyl synthetic oils (such as *Terminol VP1*, the chosen option for this project). Nevertheless, this new heat transfer fluids had much higher vapour pressures and, consequently, they could not be stored in the same tanks that were used for the *Caloria*, and the new pressurized
storage tanks required for this new synthetic oils were dramatically expensive and made this system unworthy. Although the two-tank direct storage system was largely abandoned due to its unbearable economic cost, this technology has recently returned back to stage with the new trend in using molten salt for both heat transfer fluid and storage fluid in parabolic trough power plants. By using the same molten salt mixture, there is no need for a heat exchanger between the solar field and the storage system, higher operating temperatures can be reached and no pressurized storage tanks are required, reducing dramatically its cost. This system introduces, however, a great handicap related to the fact that molten salt mixtures have really high freezing temperatures (between 120°C and 220°C, depending on the selected mixture\(^6^2\), becoming a great issue at night when the whole system must be warmed up to avoid damages related to molten salt solidification (remember that the Therminol VP1 heat transfer fluid has a freezing temperature of 12°C, reducing the cost related to auxiliary warming systems). Two-tank direct storage is then a great option due to its great advantages in terms of cost reduction but, unfortunately, it cannot be used in the parabolic trough power plant in Gibraleón due to the use of Therminol VP1 as heat transfer fluid.

- **Single-tank thermocline storage system**: this technology is also based on a direct storage system and, consequently, will not be feasible for the parabolic trough power plant in Gibraleón. Contrary to the two-tank direct storage system, the single-tank thermocline requires (as its own name highlights) a single storage tank where both cold and hot molten salt are kept together. Hot fluid remains on top while cold fluid remains at the bottom. The thermocline is the border between both fluids. This storage system has not been proved to be successful in a commercial scale as only few experimental experiences have been carried out\(^6^3\).

**Figure 68. Thermocline heat storage system**
[Source.- Own elaboration\(^6^4\)]

\(^6^2\) Ibid. [9]


\(^6^4\) From Figure 2. Thermocline test at the Sandia National Laboratories. NREL
**Single-tank thermocline storage** reduces cost due to the fact that it only needs a single tank for its operation (less molten salt will be needed), but in has a main problem related to the fact that it is difficult to maintain the *thermocline* in a middle position and thermal storage capacity is reduced (if a single tank must be shared by both hot and cold storage fluids, there is less space for both of them). Again, it introduces the same problems related to high freezing temperatures of the molten salt mixtures, resulting in the necessity of auxiliary warming systems, but it also is responsible for smaller costs when compared with indirect storage technologies, as no heat exchanger between the solar field and the storage system is required.

- **Solid storage system**: this new storage technology is still far away from being commercially successful, as it is now at a design stage. The main *solid storage systems* that are currently being studied are based in high-temperature concrete, metallic materials (iron and steel, mainly) and ceramic materials (silicium and magnesium bricks). The heat transfer fluid (it does not matter whether synthetic oils or molten salt are used) flows through the solar field in order to increase its temperature. As it happens in other thermal storage systems previously introduced, when the turbine is providing its nominal power, the exceeding heat transfer fluid is redirected to a group of pipes introduced in the middle of solid material blocks, transferring its temperature to the solid media. When thermal energy is required in the steam generator, the heat transfer fluid flows in the opposite direction, absorbing this energy from the hot solid block.

![Figure 69. High-temperature concrete thermal storage](image)

Source: - D. Laing, D. Lehman and C. Bahl. 2008. Concrete storage for solar thermal power plants and industrial process heat. DLR65)

These solid materials are cheaper than the synthetic oil or molten salts used in other storage systems, but on the other hand it is difficult to ensure a good contact between the pipes and the material. At the same time, the pipe’s material must be carefully chosen in order to avoid its
Degradation when introduced in the solid material. There are several organisms working in the development of this new technology, highlighting the German Aerospace Centre (DLR)\(^6\), the Almeria Solar Platform (PSA)\(^7\) and the Spanish Energetical, Environmental and Technological Investigation Centre (CIEMAT)\(^8\).

- **Phase-change materials storage system**: this new storage system is clearly the most undeveloped among storage technologies. In order to transmit the heat transfer fluid’s thermal energy to the storage system, this is driven through different heat exchangers containing different phase-change materials (NaNO\(_3\), NaCl, KNO\(_3\)) with different melting temperatures. Due to the pass of the high temperature heat transfer fluid through the system, these materials experiment a phase change. When the cold heat transfer fluid flows in the inverse direction, these materials recover their initial state by providing its thermal energy back to the fluid, allowing this way to continue with the steam generation even when no solar radiation is available. Contrary to the previously mentioned storage systems (which were classified as *sensible heat storage methods*, where storage is obtained by increasing the temperature of a liquid or solid), *phase-change storage* is a *latent heat storage method*, where storage is carried out through the energy provided by an isothermal phase-change of the storage material.

![Cascade configuration for phase-change storage](image)

**Figure 70. Cascade configuration for phase-change storage.**


As it has been mentioned, no commercial experiences based on this technology have still been carried out, but experimental small-size prototypes have introduced the main handicaps related to this system: the system itself is very complicated and introduces several weak points when compared to other storage methods, there is no knowledge of the average life time of these phase-change materials under the strict conditions that characterise the thermal storage in commercial-scale parabolic trough power plants and, finally, thermal losses are still too high and will proportionally be increased when the higher systems needed in commercial-scale plants are developed.

\(^6\) http://www.dlr.de

\(^7\) http://www.psa.es

\(^8\) http://www.ciemat.es
These features show that this technology is still very young and needs to be improved, but there are great possibilities with the direct-steam generation power plants, due to the cost reduction related to cheaper storage materials and possibility of using these phase-change material to globally preheat, boil and superheat steam without the necessity of a heat transfer fluid. Most of the experiments currently based on this kind of technology are also carried out in the German Aerospace Centre (DLR) and the Spanish Energetical, Environmental and Technological Investigation Centre (CIEMAT).

Now that the main thermal storage technologies have been introduced, it is the time to choose the best option for the parabolic trough power plant in Gibraleón. This time, however, the decision is easily carried out, as both solid thermal storage and phase-change materials thermal storage are still in a developing stage and are not commercially available yet. Furthermore, the Skytrough collectors used in the solar field are designed to work in conjunction with the Therminol VP1 diphenyl oxide/biphenyl synthetic oil as heat transfer fluid, dismissing both two-tank direct storage and single-tank thermocline storage, as a single thermal fluid is used for both heat transfer fluid and heat storage fluid. In conclusion, due to the specific features of the chosen elements of the solar field in Gibraleón’s power plant, the selected thermal storage option is the two-tank indirect thermal storage, with Therminol VP1 as heat transfer fluid and a mixture of molten salts (which will be discussed in the following lines) as heat storage fluid. In addition, this type of thermal storage is largely the most common storage option in commercial parabolic trough power plants (Andasol, Gemasolar, La Dehesa, La Florida, etc.), providing more reliability to the choice.

4.2.2. Determination of molten salts

Molten salts provide great features in terms of chemical stability (small degradation, very low vapour pressures, non explosive, non flammable, etc.), high specific heat and small environmental impact, without resulting in excessive costs. Despite having high solidification temperatures (which makes it essential to introduce auxiliary heating systems in order to avoid this process) and being chemically corrosive to specific types of material (conditioning the pipes and storage tanks required for the storage system and heat exchanging), they are far better the best solution for thermal storage in parabolic trough power plants, due to a very favourable combination of high density, medium specific heat, chemical reactivity, vapour pressure and cost. This condition is clearly shown in Table 7., where molten salt is largely the most common thermal storage in not only parabolic trough power plants currently operative, but also in other solar concentrating power plants: SEGS I, Andasol I, Andasol II, Archimedee, Extresol 1, Extresol 2, La Dehesa, Gemasolar, etc. Due to the specific features introduced by this fluid, and taking into account the fact that this is the most used storing technology in commercial parabolic trough applications, molten salt is largely the best option for the parabolic trough power plant in Gibraleón. It is necessary to discuss, however, the different available mixtures of molten salt, in order to select the best option for the plant according to the specific features of the project.

Molten salt is a term that defines a liquid state of a combination salt. Several types of molten salts are used in a great amount of industrial processes (heat
protection treatments, cleaning procedures, chemical treatment, etc.) but only a few answer to the specific conditions required for carrying out thermal storage in commercial solar thermal power plants. Among these, it is possible to point out the following substances:

- **Solar Salt** (60% NaNO₃, 40% KNO₃)
- **Calcium nitrate mixture** (42Ca(NO₃)₂, 15%NaNO₃, 43%KNO₃)
- **HITEC heat transfer salt** (7%NaNO₃, 40%NaNO₂, 53%KNO₃)

These molten salt mixtures have been highlighted due to the fact that they are currently commercially available and technical and chemical data can easily be found. However, great efforts are being made in order to find new suitable molten salt compositions that improve the features of the actual fluids and reduce the operating costs of the plant (inorganic Na/K/Li/Ca mixtures, ionic liquids such as **imidazolium salts** or new nitrate/nitrile mixtures, among others), and great advances will be achieved in the following years. Thermal storage in parabolic trough power plants requires huge amounts of molten salts of approximately the volume needed to fill completely one of the two storage tanks that constitute the thermal storage system⁶⁹. However, during real operation, a minimum salt level in the tanks is required to avoid crystallization solar salt residues remaining on the tank’s surface. Under this mentioned features, it is critical that, without compromising the thermal properties of the fluid, molten salt is as cheaper as possible. Again, it is all about a cost-feature balance between the thermal properties and the prize of the storage fluid.

**Table 16. Economical comparison between different molten salts**

[Source.- Own elaboration⁷⁰]

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>€/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar salt</td>
<td>Coastal Chemical Co.</td>
</tr>
<tr>
<td>Calcium nitrate mixture</td>
<td>Chilean Nitrate Company (COSACH)</td>
</tr>
<tr>
<td>HITEC heat transfer fluid</td>
<td>Coastal Chemical Co.</td>
</tr>
</tbody>
</table>

**Table 16.** shows an approximate estimation of the different prizes associated to the mentioned molten salt storage fluids. It is curious to see that all of them are cheaper than the **Therminol VP1 diphenyl oxide/biphenyl synthetic oil**, which in **Table 14.** was estimated to cost around 2,5€/kg, but despite this fact it is still important to choose the most economical solution for the parabolic trough power plant in Gibraleón, as cost reduction will result in higher (and quicker) benefits. According to the data provided in it, it is easy to see that **solar salt** is the

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⁷⁰ Data obtained from Engineering evaluation of a molten salt HTF in a parabolic trough solar field, Flagbeg/KJC/Nexant/NREL/Sandia consortium, under a conversion rate of 1$ = 0,754€

⁷¹ There are many manufacturers, but the most relevant ones have been exposed.
cheapest option for thermal storage, with an average cost of 0,37€/kg (which is nearly half the cost introduced by calcium nitrate mixtures and nearly three times cheaper than HITEC heat transfer fluid). This feature is related to the fact that its composition is carried out by relatively common chemical substances (as sodium nitrate and potassium nitrate are used in several industrial applications, such as fertilizer) and the procedure to obtain is not very complex. Calcium nitrate mixtures introduce a higher cost related to the higher amount of substances required to produce it, and so does the HITEC heat transfer fluid. The HITEC molten salt, contrary to the other studied molten salt fluids, was designed not only for thermal storage, but also as a heat transfer fluid. Due to this fact, this fluid must answer several specific conditions for its use along the solar field (smaller viscosity, smaller density, higher thermal performance, etc.) that introduce this additional cost when compared with other pure storage fluids.

To this point, solar salt has been introduced as the most economic choice for the thermal storage system. However, this cost reduction is unfortunately related to worse thermal properties when compared with the other storage fluids currently discussed. A further approach must be carried out in order to understand the main thermal differences between them.

Table 17. Main thermal properties of the different storage fluids
[Source.- Own elaboration72]

<table>
<thead>
<tr>
<th></th>
<th>Liquidus temperature [°C]</th>
<th>Maximum temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar salt</td>
<td>238</td>
<td>600</td>
</tr>
<tr>
<td>Calcium nitrate mixture</td>
<td>133</td>
<td>-</td>
</tr>
<tr>
<td>HITEC heat transfer fluid</td>
<td>141</td>
<td>450-53873</td>
</tr>
</tbody>
</table>

According to the thermal properties provided in Table 17., solar salt has the highest thermal stability, with maximum operating temperatures around 600°C. No data is provided for calcium nitrate mixtures, but the HITEC heat transfer fluid introduces maximum operating temperatures between 450°C and 538°C. Despite introducing smaller maximum temperatures, these are large enough to withstand the typical temperatures reached in the hot tank, around 386°C74. Looking at the solidification temperature, HITEC heat transfer fluid and calcium nitrate mixtures provide much smaller temperatures in comparison to solar salt, where solidification is reached at 238°C. This is clearly a great disadvantage of this fluid, which requires auxiliary heating in order to avoid solidification in the


73 Requires a nitrogen cover gas.

74 Ibid. [69]. Further approach on this issue will be carried out in the following chapter.
storage tank. Despite providing much smaller solidification temperatures, both calcium nitrate mixtures and HITEC heat transfer fluid would require this auxiliary heat too although in a minor degree, as their liquidus temperatures are still high.

It must be observed that a critical feature has been introduced. The HITEC molten salt needs a nitrogen gas cover in order to avoid nitrite from becoming nitrate, corrupting the thermal properties of this fluid. Despite this fact, the HITEC heat transfer provides the best thermal conditions of the three mentioned fluids (at a higher cost, of course). It has been mentioned before that these storage fluids will be stored in tanks and will flow from them to the oil-to-salt heat exchanger through a piping circuit. It is important, then, to ensure that this fluid does not cause corrosion on the system. In order to discuss this feature, it is necessary to choose a specific solar salt manufacturer. According to Table 16., Coastal Chemical Co. is the manufacturer of both HITEC solar salt and HITEC heat transfer fluid. Regarding to the technical properties provided in its website and provided in Annex III., both fluids introduce extremely small corrosion rates (understood as the amount of inches disappeared per month) at the typical operating temperatures of the thermal storage system. Stainless steel provides great features in terms of chemical resistance to both fluids up to 538°C, with maximum values around 0.0156cm/month. Corrosion rates tend to increase when higher temperatures are reached, but as they are not expected to appear in the system under conventional operating conditions, they can be left aside. Both Coastal Chemical’s solar salt and HITEC cause no corrosion on nickel, copper, chromium iron and alloy steels, highlighting small corrosion rates around 0,00015cm/month – 0,00025cm/month for bronze and phosphorized metals which can be neglected as they are not commonly used in the storage system. No data was found for general calcium nitrate mixtures, as their chemical properties depend on the elements introduced in the mixture as well as the concentration of them in it.

Finally, previous experience has played an essential role during the development of this project and so will in this case. Among all the actual operating solar thermal power plants with thermal storage provided in Table 7., Andasol I, Andasol II, Archimede, Extresol 1, Extresol 2, La Dehesa, Gemasolar, absolutely all of them have chosen solar salt (of different manufacturers) as heat storage fluid for two-tank indirect thermal storage. This allows to believe in a reliability of this fluid in order to ensure commercial success of the parabolic trough power plant in Gibraleón.

According to all that has been explained above, the selected thermal storage fluid for the two-tank indirect storage system in the parabolic trough power plant in Gibraleón is the HITEC Solar Salt, manufactured by Coastal Chemical Company75. This choice has been made as a result of the great advantages introduced by this fluid, such as high thermal stability, small corrosion rates, high density, small vapour pressure and, especially, smaller cost. It will be necessary, then, to cope with the handicap of the high solidification temperature by introducing an auxiliary heating system, but the reduced cost of the fluid will definitely compensate for the expense of this. The HITEC heat transfer fluid

75 http://www.coastalchem.com
provides the best thermal properties and introduces a smaller solidification temperature, but due to the fact that it has been designed to work as both heat transfer fluid and heat storage fluid (direct systems), its prize is too high to be used only in the storage system. It has to be mentioned that the chosen solution, the HITEC Solar Salt could also work as a heat transfer fluid for two-tank direct storage plants, but with minor properties.

HITEC Solar Salt is, then, an effective storage fluid in terms of cost and performance, with high heat densities (approximately around 2,7 times greater than conventional liquid metal fluids, according to Coastal Chemical Company and showed in Annex III). Regarding to environmental properties, this fluid is toxic, with an LD₅₀ value of 4g/kg⁷⁶ and must be carefully manipulated. Wasting must be carefully supervised too, as it can be ecologically harmful if it is not disposed properly. A last small consideration should be carried out, and it is the one related to the relative danger introduced by molten salt fluids. Despite being a relatively stable, non-flammable mixture, both sodium and nitrate can be responsible for explosions and fires when being in contact with organic materials at high temperatures. This is, however, a very unlikely situation, but special attention must be paid to the vapours generated by oil’s degradation (Terminol VP1 is synthetic organic oil) and to the leaks along the solar field and storage system, especially in the oil-to-salt heat exchanger. The main features of the HITEC Solar Salt are provided in Annex III. Among them, it is important to highlight its melting point, established at 222°C, and also its maximum temperature of operation, which must not exceed 593°C. As a curiosity, molten salt can be used as fertilizer at the end of its life cycle, which represents a great point in terms of environment protection as no effort must be carried out to achieve its disposal. Deeper approach of this fluid, as well as the specific behaviour in the parabolic trough power plant in Gibraleón, will be developed in further stages of the project.

4.2.3. Storage tanks

Although the heat storage fluid plays an essential role in the final output of the plant, so does the different storage tank that allow this thermal storage. To this point, the chosen option for the parabolic trough power plant in Gibraleón is a two-tank indirect thermal storage with HITEC Solar Salt. It is necessary, then, to define the cold and hot tanks that allow this process, as their design must be accurately carried out in order to minimize losses and maximize benefits.

As it has been mentioned before, direct normal radiation is collected by the Skytrough concentrators and focused by its ReflecTech reflective surface on the SCHOTT PTR70 linear receivers. The different heat collection elements are assembled along each collector assembly, which consists of 8 collector modules joined in series. The different collector rows are also assembled in order to define a thermal circuit along the solar field through which the heat transfer fluid will flow in order to collect thermal energy from the sun. The selected heat transfer fluid for the parabolic trough power plant in Gibraleón is the Terminol VP-1 diphenyl oxide/biphenyl synthetic oil, which enters the circuit at an inlet temperature of 290°C and gets out of it at an outlet temperature of 391°C, according to Annex II.

⁷⁶ Considered as the minimum dose that caused death to the 50% of the studied population.
Under conventional operating conditions, this hot *Therminol VP-1* is directed to a series of heat exchangers in order to generate the steam required to produce electrical energy in the 50MW Rankine steam cycle. However, when the turbine has reached its nominal output, the exceeding thermal energy carried by the heat transfer fluid is redirected to another oil-to-salt heat exchanger where it provides part of this energy to the *HITEC Solar Salt* pumped from the cold tank where it is stored at approximately 293°C\(^77\). Once that this solar salt has been heated in the oil-to-salt heat exchanger, it is stored in the hot tank at an average temperature of 386°C\(^78\). When the direct normal irradiation is not enough to maintain the nominal output of the plant, as well as during time periods with no solar resource, such as during night, the thermal energy is provided by the hot solar salt, which is pumped from the hot tank to the oil-to-salt heat exchanger in order to provide thermal energy to it, and later stored again in the cold tank, ready to repeat the process again. It must be said that the thermal efficiency is smaller during the inverse process (and so is the output of the plant), as the energy provided by the hot solar salt to the heat exchanger will be smaller than the energy provided by the Sun, due to the heat losses occurred through the different heat exchangers and in storage tanks.

Both *hot* and *cold* storage tanks are structurally equal, being the only difference between them the average temperature of the stored molten salt. Due to the low vapour pressure of the *HITEC Solar Salt*, the storage tanks can be similar to conventional oil storage structures. They work at ambient pressure, which allows to build high storage tanks in order to increase the volume of thermal storage fluid and, consequently, the amount of storage-based power output.

The most typical configuration for the cold and hot storage tanks is the cylindrical form, because it introduces easier construction issues and requires minor amount of materials than other geometries, such as the spherical. Despite requiring simpler structures, the cylindrical geometry must be precisely insulated in order to reduce thermal losses due to convection, as it introduces a higher contact surface. Under these considerations and due to the fact that all the two-tank indirect thermal storage power plants introduced in Table 7. are based on cylindrical storage tanks, this will be the chosen option for the parabolic trough power plant in Gibraleón. Let’s introduce the main geometrical properties of a cylindrical storage tank:

![Figure 71. Main geometrical relations in a cylindrical thermal storage tank](source)


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\(^{77}\) Ibid. [69]

\(^{78}\) Ibid. [69]
Cylindrical geometry is simpler, cheaper and requires less structural support. This is critical when it comes to the selection of the optimal insulating materials for the storage tank, as simpler geometries require minor customizing efforts for each specific project.

The amount of heat losses is closely related to the chosen materials of the storage tank and, as a result, these must be precisely chosen and periodically checked in order to maximize the thermal efficiency of the storage system. Thermal storage tanks can be carried out with both concrete, fibre glass and carbon steel, but for big thermal storage systems (as the one carried out in the parabolic trough power plant in Gibraleón) carbon steel structures introduce strong advantages in terms of mechanical strength, cost reduction and construction time, as they can be easily mounted on-site. Due to the size of the thermal storage in the parabolic trough power plant in Gibraleón, fibre glass cannot be considered as it would introduce a great economical expense and require complex mounting. Concrete structures would require great logistic efforts and specific treatment would be needed in order to avoid molten salt penetration in the material, as well as the conventional thermal insulating coating. Under these considerations, carbon steel is the simplest and cheapest option for the parabolic trough power plant in Gibraleón, and so this is the chosen solution.

The carbon steel hot and cold storage tanks introduce self supporting roofs in order to avoid degradation of the molten salt fluid and minimize thermal losses trough the creation of a sealed thermal volume. In order to drag thermal losses to the minimum, each wall and roof must be insulated with mineral wool bats and calcium silicate, as well as any other coating required to avoid corrosion (it must be said that HITEC Solar Salt introduces negligible corrosion rates for carbon steel, according to Annex III., and consequently no anticorrosion coating must be applied). These additional treatments are not, however, the only fact to be taken into consideration when designing the cold and hot storage tank. The carbon steel structures will be subjected to thermal variations of the material, especially in terms of dilatation and contraction which can be responsible for molten salt leakages to the environment. The outside surface of the tank must be conveniently protected against ultraviolet radiation and moisture (for example, with a corrugated aluminium cover), in order to ensure the chemical stability of the heat storage fluid and maximize the lifetime of the storage system. It is important to highlight that, despite this calcium silicate or mineral wool thermal insulation, storage must be carefully planned, ensuring that the stored energy will be used in a relatively small time period. If the hot molten salt is stored during large periods in the hot tank, the small amount of thermal storage fluid remaining in the cold tank will suffer a quicker loss of temperature which in turn could be responsible for a solidification of the fluid despite auxiliary heating systems. It is essential, then, to ensure that the stored energy will be used in a short period of time, in order to avoid these problems.

The thickness of the different carbon steel surfaces will depend on the amount of molten salt thermal storage fluid, its density, its pressure and its temperature. It is obvious that a higher amount of solar salt will require thicker walls in order to withstand the mechanical efforts introduced by it. Due to the accumulated pressures of the HITEC Solar Salt, the thickness the wall will vary along the height of the tank, with highest wall thickness at the bottom of the tank and smallest wall thickness at the top. This feature appears not to bother the self
supported roof, which is typically carried out with a 6mm carbon steel sheet\textsuperscript{79}. The thickness of the different carbon steel structures of the storage tanks will be increased by the calcium silicate or mineral wool heat insulating coating. The thicker the coating is, the less thermal losses will be produced. Thermal insulating has a very close relation with the operating temperature of the storage tank and, as a result, thicker insulation will be needed in the hot tank and smaller insulation will be required in the cold tank. The cost of the different carbon steel structures and thermal insulation will be related to the weight and thickness of each system, respectively\textsuperscript{80}. In order to prevent the molten salt from degradation and as a way of maintaining the chemical properties of the heat storage fluid in the best conditions, both cold and hot tanks can be pressurized with nitrogen\textsuperscript{81}, being necessary to carry out a balance connection between both tanks in order to avoid high pressures caused by tank filling.

Both cold and hot tank will sometimes store the total amount of thermal storage fluid and, as a result, their foundations must be precisely calculated and carried out in order to stand the total weigh of a full storage tank.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{molten_salt_storage_tank_concrete_foundation.png}
\caption{Molten salt storage tank concrete foundation. Efforts and limitations. [Source.- Own elaboration\textsuperscript{82}]}\end{figure}

According to \textbf{Figure 72.}, the concrete foundations of each storage tank must not exceed the temperature of 80\textdegree{}C - 90\textdegree{}C in order to preserve their mechanical properties and ensure an optimal support of the tank and the thermal storage solar salt contained in it. It is necessary, then, an appropriate thermal insulation

\textsuperscript{79} Ibid. [36]
\textsuperscript{80} Ibid. [36]
\textsuperscript{81} Thermal energy storage technology, EUROTECNIA, http://www.eurotecnia.it (accessed April 28\textsuperscript{th} 2012).
\textsuperscript{82} Ibid. [81]
between the tank bottom and the concrete structure. This insulation can be carried out with several systems, but the most common one is based on the following elements, from the bottom to the top:

1. **Concrete base**
2. **High temperature concrete thermal foundation**
3. **Foam glass insulation**
4. **Insulation fire bricks**
5. **Steel plate liner**
6. **Perimeter firebrick ring wall**

Once that the concrete foundation has been correctly carried out, the carbon steel thermal storage tank is easily mounted on the perimeter firebrick ring wall. Additionally, carbon steel cooling pipes can be installed between the **concrete base** and the **thermal foundation** in order to carry out a punctual decrease of the foundation’s temperature.

![Figure 73. Typical thermal insulation of the concrete foundation of the storage tank.](image)

[Source.-_Kelly, B. and D. Kearney. 2006. Thermal storage commercial plant design study for a 2-tank indirect molten salt system. NREL.]

The total cost of the foundation and its insulation will depend on the weigh and thickness of the different materials. Finally, it must be said that along the plant’s life, continuous thermal storage system charging and discharging can be responsible for deformation of the tank bottom, increasing the temperature of the concrete foundation, being necessary to take this feature into account at the design stage. A deeper approach on tank’s sizing and thermal storage will be carried out in the following chapters of this project.

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83 Ibid. [36]
4.2.4. Oil-to-salt heat exchanger

When the steam turbine is operating at its nominal power, the hot heat transfer fluid is redirected in order to provide its thermal energy to the heat storage fluid in the molten salt two-tank indirect storage system through an oil-to-salt heat exchanger. It is critical, then, to ensure that the thermal energy transmission between both fluids is carried out with the minimum amount of heat loss. As it has been explained before, when there is not enough solar resource to maintain the plant’s operation, the thermal energy required to continue with the generation process is provided by the storage system. However, the temperature reached by the heat transfer fluid when heated by the hot molten salt will always be smaller than the temperature reached by direct solar concentration on the linear receivers, and so will be the output power provided by the steam turbine\(^{84}\).

This feature is caused by the fact that despite minimizing heat losses in the oil-to-salt heat exchanger, there will always be a small loss of thermal energy at this point. When this thermal energy is supplied by the storage system, the total amount of heat collected by the heat transmission fluid has already passed through two heat exchange processes (oil-to-salt heat exchange during charging and salt-to-oil heat exchange during discharging, both performed in the same heat exchanger) and, as a result, the supplied thermal energy is smaller than direct heat collection in the solar field. This fall in the provided thermal energy caused by heat losses in the heat exchanger is represented by the approach temperature of the heat exchanger, which must not exceed \(100°C^{85}\) of temperature fall in order to ensure a correct operation of the power block. Temperature is not the only feature to consider when designing the heat exchange, as pressure plays an essential role in this process. According to Annex II., the outlet temperature of the Therminol VP-1 heat transfer fluid is 391°C. As no Therminol VP-1 vapour pressure is provided for this specific temperature, it is necessary to interpolate in order to obtain this data. From Annex II.:

**Table 17. Determination of the Therminol VP-1 vapor pressure at 391°C**

[Source.- Own elaboration\(^{86}\)]

<table>
<thead>
<tr>
<th>Vapour pressure [kPa]</th>
<th>Vapour pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>382°C</td>
<td>865</td>
</tr>
<tr>
<td>393°C</td>
<td>1000</td>
</tr>
</tbody>
</table>

\[
\frac{T_{OVER} - T_{UNDER}}{P^{\text{TIMER}}_{OVER} - P^{\text{TIMER}}_{UNDER}} = \frac{T_{OVER} - T}{P^{\text{vapour pressure}}_{OVER} - \text{vapour pressure}(T)}
\]

\(^{84}\) According to [69], a 3% heat loss in the heat exchangers can be responsible for a power penalty of around 1MW.

\(^{85}\) Herrmann, U., B. Kelly and H. Prince. 2004. Two tank molten salt storage for parabolic trough solar power plants.

\(^{86}\) Considering a conversion rate of 1kPa = 0,01bar
\[
\frac{393^\circ C - 382^\circ C}{10 \text{bar} - 8.65 \text{bar}} = \frac{393^\circ C - 391^\circ C}{10 \text{bar} - \text{vapour pressure}(391^\circ C)}
\] (13)

\[
\text{Vapour pressure}(391^\circ C) = 10 \text{bar} - \left[ \frac{393^\circ C - 391^\circ C}{393^\circ C - 382^\circ C} \cdot (10 \text{bar} - 8.65 \text{bar}) \right]
\] (14)

\[
\text{Vapour pressure}(391^\circ C) = 9.7545 \text{bar}
\] (15)

The vapour pressure of the Therminol VP-1 at the outlet temperature of 391\(^\circ\)C is 9.7545\text{bar}. Adding the pressure loss in the heat exchanger and pipes, the pressure at the inlet of the oil-to-salt heat exchanger can be estimated to be 20\text{bar}\(^\text{87}\). On the other hand, it has been mentioned that the pressure of the molten salt in the storage tanks is very small and so, small pressure is required in the heat exchanger in order to circulate the heat storage fluid through it, which can be estimated to be 5\text{bar}\(^\text{88}\). As a result, the heat exchanger must maintain a differential pressure between the Therminol VP-1 and the HITEC Solar Salt of around 15\text{bar} to ensure thermal exchanging. It is also important to ensure that the salt flow rate is higher than the Therminol VP-1 flow rate in order to achieve a correct thermal exchange.

There are several types of heat exchangers. Their configuration, materials and performance will depend on the specific features established by each project. However, under the requirements established above, which introduced the need for maintaining a differential pressure between the heat transfer fluid and the heat storage fluid during heat exchange, the best option is to select a shell and tube heat exchanger, as it provides this possibility at a relatively small prize. The materials must be carefully selected for each stage of the heat exchanger, in order to minimize corrosion and ensure the best operating conditions.

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\(^{87}\) Ibid. [85]

\(^{88}\) Ibid. [85]

\[\text{Figure 74. Main elements of a typical shell and tube heat exchanger.} \]

[Source.-ROTUNDS, http://rotunds.com (accessed May 3\text{rd} 2012)]
The functioning of the shell and tube heat exchanger is simple. During a heat exchange process, a tube side fluid flows through the several parallel pressurized tubes that conform the tube bundle. This tube bundle is located inside a pressurized metallic shell through which another shell side fluid flows. In order to fix the tube bundle and the shell, different support plates called transverse baffles are installed along the device. Through the interaction of both fluids, heat exchange is carried out, allowing to invert the process if the conditions of the system require it. There are lots of different shell and tube types depending on each specific project and so, it is necessary to choose the best device for the solar thermal parabolic trough power plant in Gibraleón.

The interaction of the heat transfer fluid and the heat storage fluid in solar thermal power plants introduce very strict requirements that must be solved in order to ensure the best operating conditions. According to this fact, two main manufacturers have been identified. These two companies have provided heat exchange solutions for practically the totality of the solar thermal projects carried out in Southern Spain:

- **Lointek Ingeniería Técnica y de Montaje**
- **EMbaflle B.V.**, through its close collaboration with Talleres MAC S.A.

**Table 18. Southern Spanish solar thermal power plants with Oil-to-salt heat exchangers provided by Lointek and EMBaffle B.V.-Talleres MAC S.A. consortium.**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Lointek Ingeniería Técnica y de Montaje</th>
<th>EMBaffle B.V. &amp; Talleres MAC S.A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I</td>
<td>La Africana</td>
</tr>
<tr>
<td>Andasol II</td>
<td>La Dehesa</td>
</tr>
<tr>
<td>Extresol I</td>
<td>La Florida</td>
</tr>
<tr>
<td>Extresol II</td>
<td>Termosol I</td>
</tr>
<tr>
<td>Manchasol I</td>
<td>Termosol II</td>
</tr>
<tr>
<td>Manchasol II</td>
<td>Valle I</td>
</tr>
</tbody>
</table>

**Table 18.** proves the large experience of both companies in solar thermal projects carried out in Southern Spain, which help to confirm the reliability of both suppliers in order to select the oil-to-salt heat exchanger for the parabolic trough power plant in Gibraleón. During the research for information about the different devices, it has been noticed that despite EMBaffle B.V. provides great amounts of information about their products, no information can be found at

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89 http://www.lointek.com

90 http://www.embaffle.com

91 http://www.tmac.com

92 From the information provided in the different manufacturer’s website and local newspapers such as La Voz del Ebro (http://www.lavozdelebro.com).
Lointek’s website. In order to find the information required to carry out the comparison between the heat exchangers of both companies, several e-mails were. Contrary to SCHOTT Solar, from whom no answer was received, Lointek’s Commercial Manager, Mr. Víctor Zaldumbide, informed us that due to their privacy policies no information could be provided. As a result, the chosen oil-to-salt heat exchanger for the parabolic trough power plant in Gibraleón is the EMBaffle heat exchanger, manufactured by EMBaffle B.V. and Talleres MAC S.A.

The EMBaffle heat exchanger is a new kind of shell and tube oil-to-salt exchanger, introducing several advantages when compared with other conventional heat exchangers, especially in terms of size reduction, maintenance, construction and installation time, vibration reduction and small cost. This new generation of oil-to-salt heat exchangers require minor volumes of heat transfer fluid and heat storage fluid in order to carry out the thermal exchange, allowing to reduce the number of devices from 6 heat exchangers in conventional parabolic trough thermal storage systems to only 3.


In the EMBaffle heat exchanger, the different transverse baffles are expanded in order to reduce hydraulic resistance, improving the thermal exchange process and introducing a longitudinal flow pattern that reduces vibrations. Thanks to these features, lower pressure drops are achieved with smaller and more economical devices. Another great advantage of the EMBaffle shell and tube heat exchanger is that it requires smaller maintenance:

![Comparison between conventional and EMBaffle oil-to-salt heat exchangers cleaning frequencies](Source:-EMbaffle B.V., http://www.embaffle.com (accessed May 3rd 2012)]
Figure 76. shows the comparison between conventional and EMbaffle heat exchanger cleaning frequencies, according to the results obtained through an experiment carried out in 2004\textsuperscript{93}. As it can be seen, the cleaning frequency of the EMbaffle device is much smaller than the required cleaning frequency of the compared heat exchanger, as for each cleaning process carried out in the EMbaffle shell and tube heat exchanger, almost two cleaning processes are needed in the other. This reduction in maintenance need is responsible for an important cost reduction and, taking into account the rest advantages introduced by the EMbaffle heat exchanger, this is definitely the best option for the parabolic trough power plant in Gibraleón. More information of the EMbaffle shell and tube oil-to-salt heat exchanger is provided in Annex III.

Figure 77. Detail of one of the EMbaffle oil-to-salt heat exchangers installed in La Africana parabolic trough power plant (07/07/10)
[Source.-La Voz del Ebro, http://www.lavozdelebro.com (accessed May 3\textsuperscript{rd} 2012)]

4.2.5. Molten salt pump

In order to carry out the charge/discharge processes in the thermal storage system, the HITEC Solar Salt must flow, from the cold tank to the hot tank or vice-versa, through the EMbaffle oil-to-salt heat exchanger where the thermal energy is caught or provided, respectively. It is essential, then, to install a pumping system in each storage tank which, due to the strict operating conditions established by the heat storage fluid, must be precisely chosen and accurately adjusted. These molten salt pumps must be able to face the high temperatures required in order to maintain the heat transfer fluid in a liquid state (average temperatures of around 293\textdegree C in the cold tank and average temperatures around 386\textdegree C in the hot tank, according to Kopp, J.E. 2009. Two-tank indirect thermal storage designs for solar parabolic trough power plants. University of Nevada, Las Vegas. Furthermore, the specific physical and chemical properties of the HITEC Solar Salt introduce several requirements for these devices, especially in terms of corrosion (materials must be wisely chosen) and density of the heat storage fluid, which can be responsible for important pressure drops and pumping losses if the molten salt pump is not appropriately selected.

\textsuperscript{93} More information is provided at EMbaffle B.V. website [90]
It is also important to install additional auxiliary pumps to support the main pumping system in case of failure or malfunctioning of some of these devices.

Figure 78. Standard GVSO molten salt pump without auxiliary heating system

The conventional design of these high temperature molten salt pumps is based on a vertical long-shafted pump. Each pump is installed vertically in the storage tank, with its motor located over the tank’s structure and its shaft introduced in the molten salt heat storage fluid. The shaft is typically very long and must be adapted to the specific measures of the storage tank in order to ensure that the heat transfer fluid is pumped from the bottom of the tank. In order to avoid solidification of the heat storage fluid, special versions with auxiliary heating systems are also commercially available.

A good molten salt pump must be robust and simple, allowing to substitute damaged parts on-site without dismantling the whole device. Due to the criticity of the molten salt pump (as a failure in it completely disables the thermal storage system of the plant), continuous monitoring of rotation speed, vibrations, temperature and oil composition must be performed, as well as a periodical check of the different sleeves, bearings and screws of the pump. This kind of devices usually introduce their own cooling system, but the specific conditions of each project may introduce the need for an extra cooling method in order to ensure that critical temperatures are not reached in the pump. Typical failures are related to molten salt leakages (the molten salt solidifies and damages the pump), bad lubrication (especially during the first pumping of each storage cycle, due to the fact that until the molten salt flows along the whole shaft some parts of it are operating with no lubrication) and incorrect choice of the device, introducing experience as a great advantage while designing the molten salt pumping system in the thermal storage cycle. At the same time, the selection of the appropriate molten salt pump must be carried out taking into account the main features of the different valves, pumps, pipes and other elements of the solar thermal power plant, in order to ensure the maximum efficiency.

The very first consideration when choosing a molten salt pump for the thermal storage in the parabolic trough power plant in Gibraleón is the operating temperature of this device. Depending on the operating temperatures (293°C for the cold tank and 386°C for the hot tank), different materials must be considered. According to Barth, D. L. 2011. High temperature molten salt pumps, from FRIATEC-Rheinhutte Pumps & Valves LLC, the most common for the mentioned temperature values are Stainless steel 316, 321 and 347SS, Haynes 242 and 717 Inconel, but any other suitable alloy is susceptible of being used if the specific conditions of the project require it.
Figure 79. *Mounting detail of the molten salt pump in the storage tank structure*  

Taking into account the specific operating conditions at which these molten salt pumps will be operating, it is possible to differentiate three main pump designs:

- Vertical cantilever pumps
- Vertical pumps
- Vertical submerged bearing pumps

This is a general classification that differentiates the different bearing combinations, mounting systems, maintenance needs and other features of this special molten salt pumps, but in any case must be taken as a rigid establishment due to the fact that molten salt pumps must be customized to the special requirements of each project and it is very common that these customized designs introduce features from various types. In addition, the different manufacturers follow special nomenclatures and introduce their own classification, being necessary to discuss the feasibility of the molten pump according to the specific features of each model. Contrary to what happened in the oil-to-salt heat exchanger market, several manufacturers provide suitable molten salt pumps for solar thermal power applications, although it must be said that, again, two o three of them have provided this devices to practically most of the currently operating solar thermal power plants. This helps to reaffirm the

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importance of experience\textsuperscript{95} in this field, as new power plants tend to choose the molten pump designs according to the previous experiences in nearby locations. Under these considerations, five main molten salt pump manufacturers have been identified:

- **Flowserve Corporation\textsuperscript{96}**
- **FRIATEC-Rheinhutte Pumps & Valves LLC\textsuperscript{97}**
- **Ruhrpumpen GmbH\textsuperscript{98}**
- **Sulzer Pumps Ltd\textsuperscript{99}**
- **Ensival-Moret\textsuperscript{100}, in collaboration with A.R. Wilfrey and Sons\textsuperscript{101}**

<table>
<thead>
<tr>
<th>Table 19. Comparison between the main manufacturers.</th>
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<tbody>
<tr>
<td>Molten salt pump model and reference projects.</td>
</tr>
<tr>
<td>[Source.- Own elaboration\textsuperscript{102}]</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Molten salt pump</th>
<th>Reference projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowserve Corporation</td>
<td>VTP</td>
<td>Gemasolar</td>
</tr>
<tr>
<td>FRIATEC-Rheinhutte Pumps &amp; Valves LLC</td>
<td>GVS0</td>
<td>Andasol III</td>
</tr>
<tr>
<td>Ruhrpumpen GmbH</td>
<td>VLT API-610</td>
<td>-</td>
</tr>
<tr>
<td>Sulzer Pumps Ltd.</td>
<td>SJT (VCN)</td>
<td>-</td>
</tr>
</tbody>
</table>

According to Table 19, it is clear that *Ensival-Moret/A.R. Wilfrey and Sons* provides the best option in terms of experience, as this company has provide practically the totality of the molten salt pumps for two-tank thermal storage applications. Due to the fact that experience has been considered as a critical issue in the selection of the molten salt pump, the *Ensival-Moret/A.R. Wilfrey and Sons*

\textsuperscript{95} Ibid. [94], "The experience of the pump manufacturer in handling molten salt applications is key to applying the proper design and proven technology to the system."

\textsuperscript{96} http://www.flowserve.com

\textsuperscript{97} http://www.friatec.com

\textsuperscript{98} http://www.ruhrpumpen.com

\textsuperscript{99} http://www.sulzerpumps.com

\textsuperscript{100} http://www.ensival-moret.com

\textsuperscript{101} http://www.wilfrey.com

\textsuperscript{102} From the information provided in the different manufacturer’s website. The reference projects take into account molten salt pumps for thermal storage installations in pure solar thermal power plants.
Sons VE-Y molten salt pump is clearly the most reliable choice for the parabolic trough power plant in Gibraleón. The VE-Y is based on the VE vertical pump with submerged casing for clear liquids or liquids with solid content, manufactured by the same company. The VE-Y, however, introduces special properties (in terms of material choice, mechanic resistance, etc.) in order to ensure the best operating conditions in molten salt thermal storage systems, including the possibility of choosing an auxiliary steam heating system in order to avoid solidification of the molten salt (VE-YR).

Figure 80. Ensival-Moret/A.R. Wilfley and Sons VE-Y molten salt pump


The VE-Y molten salt pump is capable of supplying flows up to 3900 m\(^3\)/h, pumping heights up to 250 m and pressures up to 25bar. The VE-Y model allows operating temperatures up to 593°C (due to a coincidence, this is also the maximum temperature of operation of the HITEC Solar Salt) and it is available in large lengths up to 20m. During the oil-to-salt heat exchanger chapter, it was mentioned that the expected pressure of the molten salt in order to ensure a good thermal exchanges was around 20bar\textsuperscript{103}. The maximum operating temperature when supplying molten salt from the hot tank is expected to be around 386°C, with a reduced temperature of 293°C when pumped from the cold tank (according to previous stages of this project). As a result, the temperature and pressure features provided by the VE-Y are largely enough to withstand the expected operating conditions in the parabolic trough molten salt thermal storage. Even that tank height and flows have not been determined yet, through the different values obtained from currently operative parabolic trough power plants with similar conditions, it can be easily concluded that these requirements will be largely covered with this model. More information about the Ensival-Moret/A.R. Wilfley and Sons VE-Y molten salt pump is provided in Annex III.

\textsuperscript{103} Ibid. [85]
4.3. Steam cycle.

To this point, both solar field and thermal storage systems have been introduced, comparing the different available options and selecting those that provide the best conditions in order to ensure the success of the parabolic trough power plant in Gibraleón. It has been explained how thermal energy is collected from the solar resource, as well as the best way to store it until it is required in the system. It is the time now to discuss not how thermal energy is obtained, but what can be done once that this is available.

As it own name introduces, the parabolic trough power plant in Gibraleón is designed to generate electrical energy, power, as this is the resource that will provide economical benefits through its injection in the grid. In order to generate electricity from thermal energy (both collected and stored), the parabolic trough power plant will use a Rankine steam turbine cycle, whose main parameters are explained in the following lines. Again, a comparison effort will be carried out, highlighting the main elements that conform the power block of the plant and comparing the available devices in order to select those which are critical to this issue.

![Diagram of steam cycle](image)

**Figure 81.** Rankine steam turbine cycle for parabolic trough power plant

[Source.-Own elaboration\textsuperscript{104}]

**Figure 81.** introduces the steam cycle in a parabolic trough power plant with two-tank indirect thermal storage. The steam generator or evaporator is responsible for the generation of the steam that will be used in the steam turbine to produce electrical energy. The thermal energy provided by the heat transfer fluid increases the temperature of the water until a phase change is produced. Once that this steam is obtained, it is directed to the solar superheater, where a second heat exchange process is performed in order to increase the temperature

\textsuperscript{104} From original figure in [5]
of the steam to a sufficient range for the Rankine power cycle of approximately 373°C and 100bar\(^{105}\). This process is carried out in order to improve the thermal efficiency of the cycle, as higher steam temperature and higher steam pressure will result in higher output power in the turbine and minor loss impact along the steam journey. Once that the steam is superheated, it is directed to the steam turbine, which is composed by a high pressure turbine cycle and a low pressure turbine cycle. At each stage of the turbine, steam is expanded in order to provide mechanic energy to the alternator and, consequently, producing electrical energy.

The steam at 373°C and 100bar reaches the high pressure turbine, where it is expanded. Once that this process has been carried out, steam is redirected to two different directions. On one hand, most of the steam is taken to the solar reheater, where a third heat exchange with the heat transfer fluid is produced, increasing again the temperature of the fluid (and consequently, its energy) in order to be redirected to the low pressure turbine, where it arrives at 373°C and 17bar, approximately.\(^{106}\) On the other hand, the rest of the steam is taken to the deaerator in order to remove the oxygen carried in the water from the condenser, through a process that will be later explained. In the low pressure turbine, a part of the high temperature steam is redirected from the middle stage to the low pressure reheater, and the other part is expanded in order to produce mechanic energy. This new expansion process reduces the pressure of the steam to values which are proximal to the condensation pressure. In order to ensure the total condensation of the fluid, the steam is directed to the condenser. In this element, the water from the wet cooling tower reduces the temperature of the steam which, added to a new expansion process which reduces the pressure of the fluid, ensures the total condensation of the steam into water. The smaller the pressure or temperature is, the higher is the efficiency of the condenser cycle.

During this process, small amounts of oxygen could remain dissolved in water, resulting in a lower thermal efficiency and cavitation issues. In order to avoid this problem, the water from the condenser is directed first to the low pressure preheater (where the hot steam from the middle stage of the low pressure cycle increases its temperature) and then to the deaerator. In this element, the hot steam from the high pressure cycle removes the oxygen particles dissolved in the water, concentrating them through convection in the upper parts of the device where they are removed through a difference of pressure. This deoxygenized water is directed to the solar preheater. In this device, the hot heat transfer fluid increases the temperature of the water to values proximal to its evaporating temperature. As it happened with the solar superheater and solar reheater, this device helps to increase the thermal efficiency of the process, reducing the amount of energy required to cause the phase-change in the steam generator, where the whole process is repeated again. It can be concluded, then, that the main elements that conform the steam cycle are the following:

- Solar preheater
- Steam generator or evaporator
- Solar superheater
- Steam turbine

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\(^{105}\) Ibid. [36]

- Solar reheater
- Condenser
- Low pressure preheater
- Deareator

In order to clarify how the steam is used to produce electrical energy, it is important to carry out a general approach to the Rankine steam cycle. As this explanation does not intend to perform a deep study of this thermal cycle, only the Ideal Rankine Cycle will be discussed, introducing the main advantages of superheating and reheating processes when applied to this steam cycle. As a result, this is only an ideal approach and must not be taken as the real behaviour of the parabolic trough power block, where losses and irreversibilities cannot be avoided.

![Figure 82](image_url)  
**Figure 82.** Temperature-entropy diagram of an ideal Rankine cycle.  

Figure 82. shows the temperature-entropy diagram of an ideal Rankine cycle. In this case, no pressure drops are produced in the boiler (which is represented by the steam generator or evaporator in the parabolic trough power plant) or in the condenser, considering a constant pressure along these devices. At the same time, no heat losses are considered and turbine and pump processes are considered as isentropic. Under these considerations, four main processes can be observed:

- **Process 1-2:** isentropic expansion of the working fluid through the turbine, from the saturated steam in 1 to the condenser pressure.
- **Process 2-3:** heat exchange from the working fluid at constant pressure through the condenser, being saturated liquid in 3.
- **Process 3-4:** isentropic compression in the pump to 4, located in the liquid zone.
- **Process 4-1:** heat exchange towards the working fluid at constant pressure through the steam generator.

These 4 processes define the ideal Rankine cycle through which electrical energy is generated in the parabolic trough power plant. However, it has been mentioned before that the thermal efficiency of the cycle could be improved by introducing steam preheating, superheating and reheating. In a conventional Rankine cycle, pressure plays an essential role in the efficiency of the steam turbine. In order to ensure the maximum performance of this device, it is critical to ensure that the steam used in the turbine has the highest **title (x).** This
property indicates the amount of vapour in % contained in a sample of working fluid, and can be obtained through the following expression\textsuperscript{107}:

\[ x = \frac{m_{vapour}}{m_{liquid} + m_{vapours}} \] (16)

As a result, a title of \( x=1 \) is related to saturated vapour and \( x=0 \) is related to saturated liquid. It the title of the steam that arrives to the turbine is too small, the liquid drops contained in hit the turbine blades, causing an erosion which can be responsible of a decrease in the performance of the turbine and an increase in maintenance needs. In order to ensure that steam title is always kept over 90\%, (which according to Moran, M.J and H. N. Shapiro. 2008. Fundamentals of Engineering Thermodynamics. Fourth Edition. Ed. Reverté, is the lowest value that ensures good operating conditions in the turbine), superheating and reheating processes can be introduced in order to maintain adequate pressures in the steam generator and condenser, which in turn will result in higher steam titles in the turbine.

\textbf{Figure 83. Temperature-entropy diagram of an ideal Rankine cycle with superheated steam}


\textbf{Figure 83.} shows the effect of a superheating process in the temperature-entropy diagram of an ideal Rankine cycle. The Rankine cycle with superheated steam introduces higher temperatures and higher vapour titles in the process (stage 2'), increasing the thermal efficiency of the block. As good as superheating is for the turbine’s efficiency, greater performances can be obtained by introducing a reheating process in the cycle, which helps to increase the operating temperatures and steam titles of the system too. Through reheating, the expansion of the steam is not produced in a single stage, as the turbine process is divided in a high pressure cycle and a low pressure cycle. When the steam reaches the high pressure cycle, a first expansion is produced (process 1-2), but then the steam is redirected to a reheating system (the solar reheater, as it has been mentioned before) where its temperature is increased again. After this steam has been reheated, it is directed to the low pressure cycle of the turbine, where a second expansion is produced in order to provide mechanic

energy to the alternator and, after this process, is taken to the condenser. Please notice that no pressure drop is considered in the reheating system, as this is an ideal cycle. **Figure 84.** shows the main processes of a reheated ideal Rankine cycle.

![Temperature-entropy diagram of an ideal Rankine cycle with reheated steam](image)

**Figure 84.** Temperature-entropy diagram of an ideal Rankine cycle with reheated steam  

It is easy to observe the higher steam titles obtained through the reheating process, as stage 4 (which represents reheated cycle) is located more to the right than stage 4′ (no reheated Rankine cycle) in the liquid bell. Now that the main features of the steam cycle, as well as the basis of the Rankine steam cycle, have been introduced, it is the time to discuss the different elements included in the power block in order to select those that introduce the best conditions for the parabolic trough power plant in Gibraleón.

### 4.3.1. Steam generating island.

As it has been explained before, in the parabolic trough power plant located in Gibraleón, the Skytrough collectors focus direct normal irradiation on the SCHOTT PTR70 linear receiver, in order to increase the temperature of the Therminol VP-1 diphenyl oxide/biphenyl synthetic oil to 391°C, approximately. This hot heat transfer fluid is directed to the preheater, where the process water is heated until its temperature is proximal to the evaporation temperature. This hot water is taken to the steam generator or evaporator, where a phase-change is produced and water becomes steam. The superheater increases the temperature and pressure of the steam in order to increase the thermal efficiency of the cycle up to 373°C and 100bar, approximately. This high-pressure superheated steam is taken to the high pressure cycle of the steam turbine, where it is expanded and later redirected to the reheater, where its temperature and pressure is raised again before being taken to the low pressure cycle of the turbine, where a second expansion process is performed in order to generate electrical energy. When this process has finished, the steam is directed to the condenser, where through a heat exchange with the cooling water from the wet cooling tower it is driven back to a liquid state. The combination of a fraction of the steam from the high pressure cycle and the steam from the middle stage of the low pressure of the turbine helps to increase the temperature of the condensed water in order to remove the dissolved oxygen, and the cycle is repeated again.
Through this small summary of the *Rankine* steam cycle of the parabolic trough power plant in Gibraleón, it is possible to observe an extremely close relationship between the different elements that compose the steam cycle, as their interaction must be strongly enhanced in order to ensure the maximum thermal efficiency of the system. Despite being able to be discussed and studied separately, some of these devices are supplied by manufacturers in what is called a *steam generating island*, which is composed by:

- *Preheater*
- *Superheater*
- *Steam generator or evaporator*
- *Reheater*

The main reason for this assembly is the fact that it provides a higher thermal efficiency, through the integration of the different elements in a compact and optimized block. The advantages of this system are very numerous, being able to highlight the fact that the maximum performance is ensured by using elements from the same manufacturer, which in turn results in minor maintenance needs related to small incompatibilities of devices from different providers. The mounting distribution answers to a great amount of tests carried out by the manufacturer, which ensure the best operating conditions and minor losses. This *steam generating island* could, however, be carried out by a combination of individual elements from different suppliers, but it would be necessary to ensure a compatibility of the different systems, materials, life estimation and connecting pipes between them, as well as to design a clever distribution of the system which will surely be less optimal than the one recommended by the manufacturer. At the same time, during the research of information it has been noticed that the main manufacturers of steam generating systems for solar thermal power plants (introduced in the following lines of this project) do not provide separated elements, which helps to reaffirm the great advantages introduced by *steam generating islands*.

![Figure 85. Steam generating island, including preheater, superheater, coil-type steam generator and reheater.](http://www.aalborgcsp.com)  

Despite the compact distribution of the *steam generating island*, it is important to carry out a general approach to the different elements combined in it in order to clarify how does this system work. Firstly, the *preheater* (also called
economizer) is nothing but a conventional oil-to-water heat exchanger between the Therminol VP-1 heat transfer fluid and the process water of the steam cycle. Regarding to the preheater, this device is a header type heat exchangers based on a conventional u-type heat exchanger, which is nothing but a typical shell and tube heat exchanger (explained in previous chapters) whose tube bundle is shaped in a U-shape. However, header type heat exchangers introduce two thick-walled pipes (called inlet header and outlet header) instead of the conventional tube bundle between the oil and water sides, which are introduced in a snake shape instead of the typical U-shape. These features allow header type heat exchangers to introduce minor maintenance needs, longer service life and higher flexibility, as well as mounting facilities due to the fact that they can be mounted both vertically and horizontally. In addition, its coil design provides the least costs and highest reliabilities, due to their simple functioning based on a coil-shaped pipe through which the hot heat transfer fluid flows, introduced in a sealed storage tank containing water. The most common configuration for the solar preheater is the one that introduces the header-type heat exchanging with the heat transfer fluid on the shell side and water on the thick tube side.

![Figure 86. Header-type solar preheater](Image)


The second element, and probably the most important one in the steam generating island, is the steam generator or evaporator, as it is responsible for the evaporation of the process water. There are two main types: kettle-type evaporators and coil-type evaporators\(^{108}\). Coil-type steam generator units are built up from three heat exchangers, also known as drums, mounted in a triangular shape with two drums at the bottom and one drum at the top. The bottom drums, which are two header-type heat exchangers, are responsible for the evaporation of the preheated water through the interaction of the hot heat transfer fluid and the process water. The generated steam is kept in the top drum, flowing through a great amount of pipes from the bottom drums, where it remains until it is needed in the turbine cycle.

Kettle-type evaporators are largely the most common type of steam generators, and they are basically an unclosed shell and tube heat exchanger which is introduced in a metallic enclosure where process water is contained. The Kettle-

type design answers to the requirements of the Tubular Exchanger Manufacturers Association (TEMA)\textsuperscript{109}. When the hot heat transfer fluid flows along the tube bundle, it transfers its thermal energy to the preheated water, starting evaporation. As water is being evaporated, the steam is pumped from the upper side of the evaporator to the superheater, and the saturated water is kept by the walls of the metallic enclosure. When comparing both options, it can be concluded that the Aalborg CSP coil-type evaporator provides better operating conditions, as it has been specially designed for solar thermal applications. The coil-type evaporators produce more steam and require smaller pipe thickness in order to stand the 100bar that are usually needed in the turbine. At the same time, the upper drum collects naturally the steam by a difference of pressure while the saturated water remains in the bottom drums, ensuring this way that steam title is maximized, and so is the efficiency of the turbine.

![Kettle-type evaporator](image1)

![Aalborg CSP coil-type evaporator](image2)

**Figure 87.** Kettle-type and coil-type steam generator units  
[Source.- Aalborg CSP A/S, http://www.aalborgcsp.com (accessed May 7\textsuperscript{th} 2012)]

The third element of the steam generating island is the superheater, which is responsible for the increasing of the temperature and pressure of the steam before this reaches the steam turbine. Again, the superheater is just another header-type heat exchanger, but contrary to the preheater, it is steam what it is

\textsuperscript{109} [http://www.tema.org]
contained on the thick tube side. The hot heat transfer fluid flows through the shell side of the superheater, increasing the temperature of the steam before being pumped to the high pressure cycle of the steam turbine.

![Image of a superheater](image1.png)

**Figure 88.** Header-type solar superheater  

Finally, the last element of the steam generating island is the reheater, which is responsible for increasing the temperature of the steam from the first expansion in the high temperature cycle of the steam turbine. Contrary to the preheater and the superheater, the reheater is a shell and tube heat exchanger, just like the Embaffle, but with in an oil-to-steam cycle instead of the oil-to-salt cycle previously discussed.

![Image of a reheater](image2.png)

**Figure 89.** Shell and tube solar reheater  

It must be mentioned that this is the conventional characterisation of the different elements of the steam generating island, but minor variations may be introduced depending on the specific conditions of each project. These systems are always customized and their components, materials and sizes must be precisely selected in order to maximize the performance of the plant.

Now that the main elements of the steam generating island have been introduced, it is the time to discuss which is the best option for the parabolic trough power plant in Gibraleón. Again, the main manufacturers have been identified and, after comparing the different features and reference projects, four main suppliers are highlighted:
• Aalborg CSP A/G\textsuperscript{110} 
• Foster Wheeler A.G.\textsuperscript{111} 
• Thermax Ltd.\textsuperscript{112} 
• Siemens A.G.\textsuperscript{113}

Experience is a great advantage when selecting the most appropriate steam generating island for the parabolic trough power plant in Gibraleón. As it was done for the molten salt pump manufacturer’s comparison, it is necessary to highlight the main reference projects of the considered manufacturers, in order to determine which of them enjoys a larger experience in this kind of systems. At the same time, it is essential to ensure that the selected option provides the best operating conditions at the minimal cost, considering as a great advantage the fact that it requires the minimum maintenance. This comparison is carried in the following table:

**Table 20. Comparison between the main manufacturers.**
*Steam generating island model and reference projects.*

[Source: Own elaboration\textsuperscript{114}]

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aalborg CSP A/G</td>
<td>Aalborg CSP Steam generator line</td>
</tr>
<tr>
<td>Foster Wheeler A.G.</td>
<td>FW Steam generating train</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermax Ltd.</td>
<td>VLT API-610</td>
</tr>
<tr>
<td>Siemens A.G.</td>
<td>Benson boiler</td>
</tr>
</tbody>
</table>

According to Table 20., Foster Wheeler A.G. is the company with the largest experience in the field of steam generating islands for solar thermal power plants, highlighting the fact that it has provided steam solutions to nine of the biggest solar thermal power plants in Southern Spain. Foster Wheeler A.G. is followed by Aalborg CSP A/G, which has supplied steam generating units to the Solnova parabolic trough power plants located in Seville, as well as to the Godawari parabolic trough power plant in Godawari, India. Thermax Ltd. does not provide any information about their main solar thermal projects, and Siemens A.G. Benson boiler has not been implemented in a solar thermal power

\textsuperscript{110} [http://www.aalborgcsp.com](http://www.aalborgcsp.com)

\textsuperscript{111} [http://www.fwc.com](http://www.fwc.com)

\textsuperscript{112} [http://www.thermaxindia.com](http://www.thermaxindia.com)

\textsuperscript{113} [http://www.energy.siemens.com](http://www.energy.siemens.com)

\textsuperscript{114} From the information provided in the different manufacturer’s website. The reference projects take into account steam generating island installations in pure solar thermal power plants.
plant. According to these features, the choice will be restricted to Aalborg CSP A/G and Foster Wheeler A.G. Regarding to the technical features provided by both steam generator lines, it is difficult to differentiate which of them introduces the best conditions, as both systems have been specially designed for solar thermal applications and introduce the optimized coil-type evaporator. It is not possible to carry out an economical comparison between both elements as there is no data available for the reference projects, and neither of them have a factory in Spanish territory (despite having affiliate companies in the country), so proximity is neither a comparative distinction.

Again, due to the lack of information and, taking into account that the features of the steam generating island are closely related to the specific conditions of its project, the selection will be carried out under an experience criteria, where the FW Steam generating train, manufactured by Foster Wheeler A.G., is the selected option due to its large commercial experience in the solar thermal Spanish market. The FW Steam generating train includes the preheater, superheater and reheater required to carry out the Rankine steam cycle, as well as the steam generator or evaporator. For trains under 30MW, Kettle-type evaporator is the recommended option, being the Coil-type evaporator the best option for those steam trains over 30MW. Taking into account the fact that the nominal output power of the steam turbine in the parabolic trough power plant in Gibraleón is 50MW, the steam generating island could be performed with two 25MW kettle-type steam trains or with a 50MW coil-type train. Unfortunately, there is not any information available about the economical difference between both solutions, although the 50MW coil-type train is considered to be cheaper than a double 25MW kettle-type. At the same type, a single device will reduce the possibility of failure in any part of the steam generating island, as well as minor costs related to fewer connecting pipes. Double train, double possibility of failure and higher losses in the connecting points. More information of the FW Steam generating island is provided in Annex IV.

4.3.2. Condenser.

The condenser of the parabolic trough power plant plays an essential role in the steam cycle, as it is responsible for the conversion of the steam from the low pressure cycle of the Rankine turbine into liquid water. This device is nothing but a steam-to-water heat exchanger, where the steam provides its thermal energy to the cooling water in order to be evaporated in the cooling tower. Through this evaporation (characteristic of the chosen evaporating water cooling system), cooling water reduces its temperature in order to repeat the condensation cycle. The lower the temperature of the cooling water is, the higher the heat exchanging will be, and the highest thermal efficiency will be reached. This is, however, a cooling method that implies a huge amount of water use, as the water from the cooling circuit needs to be periodically replaced due to its evaporation in the cooling tower. This feature was discussed in the initial stages of this project, as Table 4, introduced an average water usage of 3030 – 3785 litres of water per MWh, which is closely related to the amount of steam provided by the turbine, as well as to the title of the steam received. In order to ensure the total condensation of the steam, cooling water must flow in an appropriate rate and speed through the condenser. As a result, the typical configuration of these devices is based on a shell and tube heat exchanger, with cooling water flowing through the tube bundle and steam flowing in the shell side. As well as it
happened with the **E**Mbaffle oil-to-salt heat exchanger, the condenser must be adapted to the different working fluids. Due to the origin of the cooling water in the parabolic trough power plant in Gibraleón, which is brought from the different nearby industrial water reservoirs, it is important to select the different materials carefully\(^\text{115}\), in order to stand corrosion, attached solid particles and biological species that may appear in the cooling system. At the same time, the high vibrations produced by the steam from the turbine, makes it essential to ensure good mechanical resistance of the different elements of the condenser.

![Shell and tube axial steam condenser](image)

**Figure 90.** Shell and tube axial steam condenser

[Source.- Foster Wheeler A.G., http://www.fwc.com (accessed May 14\textsuperscript{th} 2012)]

Condensers can be **axial** or **radial**. While axial condensers introduce higher efficiencies, this configuration is responsible for higher construction requirements and, consequently, higher cost. It is, then, a balance between thermal efficiency (where highest values are provided by **axial** devices), complexity and economical cost (where **radial** condensers are the simplest and cheapest option).

In order to carry out the selection of the condenser for the parabolic trough power plant in Gibraleón, it must be said that this device is identical to the different condensers used in conventional power plants based on a Rankine steam power cycle. Under this consideration, lots of manufacturers can be identified: **Ambassador Heat Transfer Co.\(^\text{116}\), SPX Heat Transfer Inc.\(^\text{117}\), Siemens A.G.\(^\text{118}\), Foster Wheeler A.G.\(^\text{119}\), General Electric Co.\(^\text{120}\), etc. However, due to its

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\(^\text{115}\) According to Energiza.org. Especial Centrales Termosolares October 2011, http://www.energiza.org accessed May 14\textsuperscript{th} 2012), BWG18 is widely used for sweet water applications, whereas Copper-Nickel 90 to 10, BWG20 and Titanium are the most common materials in salty water systems.

\(^\text{116}\) http://www.ambassadorco.com

\(^\text{117}\) http://spxheattransfer.com

\(^\text{118}\) Ibid. [114]

\(^\text{119}\) Ibid. [111]

\(^\text{120}\) http://www.ge-energy.com
specific solar power design and, taking into account the experience of the company in solar thermal applications, the chosen condenser for the parabolic trough power plant in Gibraleón is the FW Condenser, from Foster Wheeler A.G. This selection is closely related to the fact that the selected steam generating island is also from the same manufacturer as, during the selection of the steam generating island, the combination of elements from a single supplier were considered the best option in order to avoid incompatibilities and to ensure the maximum performance of the system.

The FW condenser is available for any type of steam turbine, so the selection of this device will not be restricted. It introduces a thermal expansion compensation system, reducing damages related to the different temperature changes, as well as a rigid plate mounting in order to reduce the impact of the strong vibrations related to the steam. It is a simple device, allowing to carry out maintenance operations on-site which will result in lower performance penalties. In addition, the FW condenser ensures the maximum efficiency of the system through low pressure drops, minimal leakages and maximum exchanging surface at the minimum size. More information of the FW condenser is provided in Annex IV.

![Figure 91. Main elements of the FW Condenser](Source.- Foster Wheeler A.G., http://www.fwc.com (accessed May 14th 2012))

As it can be seen, the condenser unit is composed by a great amount of tubes trough which the hot steam flow, getting into contact with the cold cooling water from the inlet water box which will result in the condensation of this steam. In order to support the structure, several plates, stiffeners and supporting elements are included, as well as other relevant elements in order to maximize the condensing process.
4.3.3. Low pressure reheater.

During the condensation of the steam, some suspended gases such as O₂ may appear in the water\textsuperscript{121}. In order to avoid problems related to this suspended gases, such as damages in the system, reduction of the condenser efficiency and troubles in water treatment, it is important to remove them. In the low pressure reheater, the hot steam from the middle stage of the low pressure cycle increases the temperature of the water from the condenser. This heated water is directed to the deaerator in order to remove the suspended gases from it through a convection process forced by the hot steam from the high pressure cycle of the turbine. Under these considerations, and taking into account the selected elements of the steam cycle, the chosen device is the FW LP Feed Water Heater, from Foster Wheeler A.G. This element is nothing but a u-type heat exchanger where the hot steam from the middle stage of the low pressure cycle flows through the tube bundle, transferring its thermal energy to the condensed water in the shell. Again, the fact that both the steam generating island and condenser were provided by Foster Wheeler A.G., as well as the great experience of this company in solar thermal power plants, have been critical to its selection.

Table 21. Foster Wheeler’s low pressure reheater reference projects.

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Reference projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foster Wheeler A.G.</td>
</tr>
<tr>
<td>Gemasolar, Samcasol I&amp;II, Valle I&amp;II</td>
</tr>
</tbody>
</table>

The FW LP Feed Water Heater is available in Vertical Design and Horizontal Design, depending on the specific conditions of each project. Vertical designs reduce the amount of space required to install these devices and, as a result, it is recommended for those plants where small space is available, but at a higher price than horizontal designs.

![Diagram of FW LP Feed Water Heater]

Figure 92. FW LP Feed Water Heater vertical (left) and horizontal (right) designs

[Source.- Foster Wheeler A.G., http://www.fwc.com (accessed May 14\textsuperscript{th} 2012)]

\textsuperscript{121} NO₂ and CO₂ can be punctually found, although this is not very common.
Taking into account the specific conditions of the parabolic trough power plant located in Gibraleón, the chosen design is the horizontal one, as cost reduction is considered to be more favourable than the advantages related to the space saving. More information of the FW LP Feed Water Heater can be found in Annex IV.

4.3.4. Deaerator

As it has been mentioned before, the deaerator is responsible for removing the O₂ and any other gases that may be present in the water from the condenser in order to avoid corrosion and other related problems. It is necessary, however, to make a deeper approach to this element in order to select the best option for the parabolic trough power plant in Gibraleón.

Deaeration can be carried out both mechanically and chemically. In chemical deaeration, oxygen scavengers (typically sodium sulphite Na₂SO₃, due to its small cost and high efficiency) are introduced in the storage tank of the deaerator. This process is used when only very small amounts of suspended oxygen are allowed, as chemical deaeration can decrease oxygen presence under 7ppb\(^1\). The different scavengers will depend on each specific project, as high pressures and high temperatures may cause a decomposition of the substance, mixing with the steam and causing problems in the system. Chemical deaeration is, however, commonly used as a complement to other mechanical deaeration systems. Mechanical deaeration carries out a first removal of the dissolved gases, decreasing their presence in order to carry out a second chemical deaeration process that reduces the dissolved gases to the minimal expression.

The higher the temperature of a solution is, the lower the solubility of a gas in this solution is. At the same time, the lower the partial pressure above the solution is, the lower the solubility of a gas in this solution is\(^2\). Through the combination of these two principles, it is possible to remove dissolved oxygen and gases from a substance by spraying water and making it get in contact with a hot steam atmosphere. Thanks to this process, water drops quickly reach their saturation temperature, reducing the solubility of the dissolved gases which are vented outside the deaerator. Among these initial mechanical deaeration systems, it is possible to differentiate:

- **Tray-type deaerators**: vertical domed deaeration element in which the water from the condenser is introduced through a combination of perforated trays. The hot steam from the high pressure cycle of the steam turbine is introduced in the inverse direction through the mentioned perforated trays, increasing the temperature of the water to values proximal to its saturation temperature. By this process, dissolved gases are removed from the water and taken outside by the steam through an upper exit valve, while the deaerated water flows down to the storage vessel ready to be provided to the preheater. It is recommended to carry out a thermal insulation of the deaerator in order to reduce thermal losses.

\(^1\)http://www.cleanboiler.org

\(^2\)According to Henry’s Law.
• **Spray-type deaerators**: horizontal cylindrical storage vessel divided in a *preheating section* and a *deaeration section* by a baffle. In the preheating section, the water from the condenser is sprayed by an upper nozzle and gets into contact with the hot steam from the middle stage of the low pressure cycle of the turbine, which increases its temperature to values proximal to the saturation temperature. Through this process, which is also carried out in tray-type deaerators, the maximum contact surface is ensured and, consequently, the quicker the temperature increase will be. After this process, the heated water flows to the deaeration section, where a bottom steam sparger introduces hot steam from the high pressure cycle in order to remove the oxygen and other dissolved gases that may be present in the water, through a process that has been previously explained. The different dissolved gases are taken outside the deaerator through an upper exit valve located in the deaeration section, while the deaerated water is stored in the bottom of the storage vessel until it is pumped to the preheater.

![Figure 93. Main elements of a Tray-type deaerator](http://www.cleanboiler.org) [Source.- Deaerator, http://www.cleanboiler.org (accessed May 14th 2012)]

![Figure 94. Main elements of a Spray-type deaerator](http://www.stork-thermeq.nl) [Source.- Stork Thermeq, http://www.stork-thermeq.nl (accessed May 14th 2012)]
- **Spray and Tray-type deaerators**: obtained by a combination of a Tray-type and a Spray-type deaerator, it is largely the most common system in solar thermal power plants and other conventional power plants.

![Diagram of a Spray and Tray-type deaerator](image)

**Figure 95. Main elements of a Spray and Tray-type deaerator**


Thanks to this combination, really small rates of dissolved gasses can be reached, as the first tray-based stage reduces the content of dissolved gases to values between 20ppb and 50ppb\(^ {124}\) and the second spray-based stage reach concentrations below 7ppb\(^ {125}\).

Spray-type deaerators require high water temperatures and must not operate under 25%\(^ {126}\) of their design water flow in order to ensure the best operating conditions. These limitations are not found in tray-type deaerators, where the combination of perforated trays ensures good operation regardless from water temperature and water flow, which in combination with its large life (around 40 years) introduces tray-type deaerators as the best option for power plants, despite its higher cost. However, in order to ensure the maximum removal of the dissolved gasses from the process water, the best option is provided by the combination of both designs. As a result, the selected deaerator type for the parabolic trough power plant in Gibraleón is a **Spray and Tray-type deaerator**.

Regarding to the operating conditions of this device, it is very important to ensure that there are not any suspended solid in the water from the condenser, as they can be responsible for obstructions in the perforated trays, water nozzles and other parts of the deaerator. As a result, a proper water treatment must be

\(^{124}\) Ibid. [122]

\(^{125}\) Ibid. [122]

carried out, especially in terms of suspended calcium due to its negative effect on the different elements of the deaeration system (dissolved calcium is accumulated little by little in very critical elements of the deaerator, being responsible for damages in the equipment). It is essential, then, to maintain a periodical maintenance plant in order to check that everything is fine in the deaerator, avoiding this way failures related to suspended solids. In those solar thermal power plants with economizers (also known as preheaters), as in the parabolic trough power plant located in Gibraleón, it is essential to ensure the lowest dissolved oxygen in the process water, as this is the most typical cause of failure in this kind of equipment.\footnote{Ibid. [122]}

In order to ensure the best operating conditions of the preheater, it is recommended to introduce chemical scavengers in the water to reduce oxygen presence to the minimal expression. The selected chemical scavenger for the parabolic trough power plant is the sodium sulphite, due to its high efficiency and low cost. It is important to ensure that only the necessary amount of sodium sulphite is introduced in the system, as exceeding concentrations could be responsible for sodium sulphite presence in the steam provided to the turbine. The specific amount of scavenger, as well as the periodicity of its introduction in the system must be specified in the maintenance plan of the plant.

<table>
<thead>
<tr>
<th>Deaerator malfunction</th>
<th>Possible cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>High level of oxygen</td>
<td>Leakage of air into the deaerator.</td>
</tr>
<tr>
<td>in feedwater</td>
<td>Insufficient residence time.</td>
</tr>
<tr>
<td></td>
<td>Water/steam mixing equipment not designed / installed / operating correctly.</td>
</tr>
<tr>
<td></td>
<td>Flowrate outside design specification.</td>
</tr>
<tr>
<td>Pressure fluctuations</td>
<td>Control valves incorrectly sized.</td>
</tr>
<tr>
<td></td>
<td>Wide temperature variation in the incoming water supply.</td>
</tr>
<tr>
<td>Low outlet temperature</td>
<td>Insufficient steam.</td>
</tr>
<tr>
<td></td>
<td>Water/steam mixing equipment not designed / installed / operating correctly.</td>
</tr>
<tr>
<td>High level of carbon</td>
<td>Feedwater pH is too high.</td>
</tr>
<tr>
<td>dioxide in feedwater</td>
<td></td>
</tr>
</tbody>
</table>

\textbf{Figure 96. Common malfunctions in deaerators}  
[Source.- Spirax-Sarco Ltd., http://www.spiraxsarco.com (accessed May 14th 2012)]

To this point, the most typical deaerator designs have been introduced, establishing the spray and tray-type deaerator as the best option for the parabolic trough power plant in Gibraleón. It is the time, then, to identify the main manufacturers of this kind of equipment in order to carry out a comparison between them. Please notice that this is a very common element in any kind of Rankine-based power cycle and several manufacturers can be found. During the research of information, however, it has been really difficult to find spray and tray-type deaerators with sufficient size for their use in the steam cycle of the parabolic trough power plant, as most of the suppliers provide small to medium units that are not suitable for the specific conditions of this project. In addition, most of the consulted companies supplied spray-type and tray-type deaerators separately, and only few of them had the combined type available. According to the mentioned limitations, some of the main manufacturers are introduced in the following table:
Table 22. Some spray and tray-type deaerator manufacturers.
[Source.- Own elaboration128]

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAP Co.129</td>
<td>FAP Spray-Tray Deaerator</td>
</tr>
<tr>
<td>Ravi industries130</td>
<td>Spray cum Tray type design</td>
</tr>
<tr>
<td>ECODYNE Ltd.131</td>
<td>ECODYNE Spray-Tray Deaerator</td>
</tr>
<tr>
<td>ALSTOM132</td>
<td>ALSTOM Spray-Tray Nuclear Series</td>
</tr>
<tr>
<td>Frost Engineering Service Co.133</td>
<td>Cochrane H-H deaerator</td>
</tr>
<tr>
<td>Karrasch &amp; Eckert GmbH134</td>
<td>DS Spray-Tray deaerator</td>
</tr>
</tbody>
</table>

Now that some of the main utility-size Spray-Tray manufacturers have been indentified, it is the time to choose the best option for the parabolic trough power plant in Gibraleón, as it has been done in previous stages of the project. This time, however, it is not an easy choice, as due to the fact that deaerators are usually customized for each specific project there is small information about their technical features as they need to be agreed with the manufacturer. This is clearly a limitation, as among the six mentioned suppliers, only three of them (FAP Co., Ravi Industries and Frost Engineering Service Co.) provide some kind of information to reinforce the choice. In order to obtain more features, e-mails have been sent to some of the manufacturers and no answer was received. As a result, the choice will be made according to the available information.

The selected deaerator for the parabolic trough power plant in Gibraleón is the Cochrane H-H Spray and Tray-type deaerator, manufactured by Frost Engineering Service Co. This choice answers to a series of advantages when compared to the other considered options:

- **Location**: as Frost Engineering Service Co. is located in Cincinnati (United States of America), whereas Ravi Industries is located in India and FAP Co. is located in Iran. It has been considered that Frost Engineering Service Co. provides better conditions for shipping, as well as a more strict legislation through several quality standards that must be followed (this standards may not be equally strict in India or Iran, probably).

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128 From the information provided in the different manufacturer’s website.

129 http://www.fapdec.org

130 http://www.raviindustry.com

131 http://www.ecodynedeaerators.com

132 http://www.alstom.com

133 http://frostnw.com

134 http://www.karrasch-eckert.de
• **Experience:** while Ravi Industries was founded in 1996 and FAP Co. started its operation in 2002, Frost Engineering Service Co. has more than 58 years of experience in the field of deaerators. As a result, this option may be considered as the most reliable one (experience, as it was in previous stages, is still considered a critical advantage).

• **Available information,** despite the fact that most of it is limited to product brochures and small information is provided. Under this consideration, Frost Engineering Co. provides more information than other considered companies, as Ravi Industries provides a two-page brochure and FAP Co. limits its collaboration to a small table in their website. This information is available in **Annex IV.**

It is important to mention again that this choice has been made according to the available information. If a further approach was made on this kind of devices, establishing contact with the selected manufacturers and specifying the operating conditions of the project, selection could then be made according to other technical features as well as economical criteria.

### 4.3.5. Steam turbine.

It is the time now to introduce the main element of the steam cycle: the **steam turbine.** To this point, all the efforts have been focused on steam production and treatment, but no explanation of how this steam is used to produce electrical energy has been made. It is essential, then, to discuss and select the best steam turbine for the parabolic trough power plant, as this is responsible for generating mechanical energy from hot pressurized steam. By connecting this steam turbine to an electrical alternator, this mechanical energy can be transformed into electrical energy.

Due to the specific operating conditions of solar thermal power plants, it is important to ensure that the selected turbine provides the best features in order to maximize efficiency. Among these specific conditions, it is important to highlight the following requirements:

- The turbine must allow steam extractions from the high pressure cycle and low pressure cycle, in order to complete the steam cycle previously mentioned.

- The turbine must allow quick stops and start ups, as well as a great dynamic flexibility due to the variability of the solar resource. This feature is especially critical in those plants without thermal storage, as they require to be shut down during night periods and to be started up each morning. The quicker the steam turbine is able to reach nominal operating conditions, the greater the final output will be. In the parabolic trough power plant located in Gibraleón, the two-tank indirect thermal storage reduces this problem, as no shut down must be carried out during night. Thanks to the thermal storage system, the turbine can be operated without interruption and power production can be maximized.

- The turbine must be properly insulated in order to minimize thermal losses, especially during cold periods of time.
• Each element of the turbine must be wisely chosen, as the different materials must stand high corrosion and moisture rates under conventional operating conditions. A bad material choice can be responsible for premature failure of the turbine, being necessary to ensure the maximum operating life of the plant by selecting specific materials for the different parts of the turbine.

The conventional steam turbine configuration for solar thermal power plants is based on a two-stage system, with a high pressure cycle and a low pressure cycle. Thanks to this feature, the steam title is maximum and thermal efficiency reaches very high values. At the same time, the most common disposition of the steam turbine is axial, where the steam flows in the same direction as the turbine shaft. This kind of steam turbine are usually characterised by high efficiencies and long operating life, with a high reliability provided through years of experience in power generation. The main elements of the steam turbine are:

• **Stator:** fixed part of the turbine in which the rotor is installed. The stator protects the rotor from external conditions and helps to reduce thermal losses thanks to its thermal insulation.

• **Rotor:** this is the mobile part of the turbine, which spins when crossed by the hot pressurized steam through its different blades. The rotor is, then, the element that transforms the hot steam’s thermal energy and pressure into mechanical rotating energy.

• **Blades:** their special aerodynamic shape allows to transform the steam speed and depressurization into mechanical rotating energy. Typically, fixed blades are installed in the stator in order to direct steam in the correct direction, while mobile blades are installed on the rotor allowing to perform a real-time adaptation to the specific operating conditions of each moment.

• **Bearings:** they are responsible for supporting the turbine’s shaft and allowing its rotation. They must be conveniently lubricated in order to minimize friction and prevent the shaft from a premature failure, and periodical maintenance and supervision must be carried out as they are a very sensitive element of the turbine.

![Image](image_url)

**Figure 97.** Maintenance operations in a CSP steam turbine

Figure 97. shows maintenance operations in a CSP axial steam turbine, allowing to identify the different bearings, shaft, rotor and blades in an opened turbine stator. These are only the main elements of the turbine, but it must be said that they are worthless without other auxiliary systems (lubrication, cooling, shaft positioning systems, monitoring systems, speed regulation, etc) that ensure the correct operation of the device. Now that the main features of the steam turbine have been introduced, it is the time to carry out a comparison between the main manufacturers, selecting the turbine that provides the best conditions for the parabolic trough power plant in Gibraleón. After a deep research among the different steam turbine manufacturers, several companies have been identified as most of the currently operational power plants are based on a Rankine steam cycle. However, due to the specific conditions of solar thermal power plants, only those which provide specific solar power designs have been considered, highlighting the following suppliers:

Table 23. Some CSP steam turbine manufacturers and main reference projects.
[Source.- Own elaboration\textsuperscript{135}]

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Reference projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALSTOM\textsuperscript{136}</td>
<td>Tonopah Power Plant</td>
</tr>
<tr>
<td>MAN Diesel &amp; Turbo.\textsuperscript{137}</td>
<td>Andasol III, Ibersol</td>
</tr>
<tr>
<td>Mitsubishi Heavy Industries Ltd.\textsuperscript{139}</td>
<td>-</td>
</tr>
<tr>
<td>General Electric Company \textsuperscript{140}</td>
<td>PS10, PS20, Palma del Río I&amp;II, Majadas I</td>
</tr>
</tbody>
</table>

According to Table 23., Siemens A.G. is clearly the market leader for CSP steam turbine applications, as most of the solar thermal power plants currently operational are based on their equipment. This feature allows to establish Siemens A.G. as the most recommended option for the parabolic trough power

\textsuperscript{135} From the information provided in the different manufacturer’s website. Only those manufacturers providing specific steam turbines for solar thermal power plants have been considerate.

\textsuperscript{136} Ibid. [152]

\textsuperscript{137} http://www.mandieselturbo.com

\textsuperscript{138} Ibid. [113]

\textsuperscript{139} http://www.mhi.co.jp

\textsuperscript{140} Ibid. [120]
plant in Gibraleón, as most of their reference projects are based on parabolic trough technology. In addition, most of them are located in Southern Spain, which helps to increase the reliability of this choice due to the similarities with this project. Mitsubishi Heavy Industries Ltd. has a great experience in the field of steam turbines for power plants, but all of this is restricted to conventional fossil fuel-based plants and, as a result, this option is dismissed. This criteria must be also applied to ALSTOM as, despite the fact that they have provided a steam turbine for Tonopah solar thermal power plant in Nevada, this feature appears irrelevant when compared to other companies with much more experience in the field. It all comes to a selection between General Electric Company, Siemens A.G. and MAN Diesel & Turbo. All of them provide suitable steam turbine solutions for parabolic trough power plants, with proven success in different solar thermal experiences in Southern Spain. Experience has been a critical advantage in previous stages of this project, and so will be now. The selected steam turbine manufacturer for the parabolic trough power plant located in Gibraleón is Siemens A.G., as it is clearly the most experienced company. This higher experience may introduce maintenance advantages, cost reduction and lower mounting and shipping periods, which will result in a better performance of the plant. Now that the manufacturer has been chosen, it is necessary to determine which model of steam turbine introduces the best conditions for the parabolic trough power plant in Gibraleón:

![Diagram](image)

**Figure 98.** Different Siemens steam turbine models according to power output in MW and steam parameters.


**Figure 98.** introduces the different steam turbine models provided by Siemens A.G. Each of them answer to specific operating conditions, especially in terms of pressure and temperature of the steam that reaches the turbine. The best option will be the one that is able to provide the nominal design output power (50MW) and stand the estimated steam parameters for the parabolic trough power plant in Gibraleón. It is necessary, then, to consider these parameters, which have been previously determined, in order to ensure the best choice.
According to what has been explained in previous chapters of this project, the superheated steam reaches the turbine at 373\degree C and 100bar. The steam cycle introduces preheating, superheating and reheating stages, so steam extractions must be allowed in order to supply these systems. In addition, the most common configuration for the steam turbine is a combination of a high pressure cycle and a low pressure cycle. The superheated steam reaches the high pressure cycle and carries out a first expansion. Once that the steam has been expanded, it is reheated in order to be introduced in the low pressure cycle, increasing the thermal efficiency of the turbine. The nominal output power of the parabolic trough power plant in Gibraleón is 50MW, as this is the maximum admissible output power in order to be subjected to the Spanish Special Regime. However, the plant must generate extra power in order to supply the electrical energy required by the plant (auxiliary services, monitoring, illumination, etc), so the steam turbine must take into account this fact. Due to the variability of the solar resource along the year, the plant will not always provide 50MW of power, so minor output powers (including self-consumption electrical energy) must be accepted. To sum it up, the parabolic trough power plant in Gibraleón requires a double HP-LP\textsuperscript{141} cycle turbine with intermediate steam reheating. The maximum steam temperature will be 373\degree C at a maximum pressure of 100bar. The steam turbine must be able to provide output values over 50MW in order to cope with self-consumption of the plant, as well as lower values in order to adapt to the variability of the solar resource. Under these considerations, the selected steam turbine for the parabolic trough power plant in Gibraleón is the \textit{SST-700 steam turbine}, manufactured by Siemens A.G.

The SST-700 steam turbine answers to the special requirements of this project, allowing output powers up to 175MW, with maximum steam parameters established at 585\degree C and 165bar. It can be observed that, according to output power, maximum steam temperature and maximum steam pressure, different steam turbines are possible, and SST-700 may seem a bit oversized. The SST-700 steam turbine is a dual-casing reheat turbine, with a geared high pressure module and a direct-drive low pressure module. To this point, the main features of the conventional SST-700 steam turbine have been introduced. However, the main reason for choosing this element is the fact that Siemens A.G. provides a special CSP version of the SST-700 steam turbine which has been especially designed for parabolic trough power plants. This special design introduces an innovative HP/IP\textsuperscript{142} module instead of the conventional SST-700 HP module, which is connected to the direct-drive LP module, allowing steam temperatures up to 400\degree C at 100bar of pressure.

It is easy to notice the special adaptation of the turbine to the specific operating conditions of medium temperature parabolic trough technology, where lower temperatures can be reached. This is the main reason for the decrease of the maximum steam temperature from 585\degree C in the conventional SST-700 steam turbine to the 400\degree C in the special CSP parabolic trough design. Despite this temperature reduction, the new HP/IP module helps to increase substantially the thermal efficiency of the turbine, which in turn allows to maintain output power

\textsuperscript{141} High pressure (HP) and Low Pressure (LP)

\textsuperscript{142} High pressure/Intermediate Pressure (HP/IP)
values up to 175MW. It is then, an optimal solution which has been especially design for this kind of technology, increasing thermal efficiency and reducing start-up times. What is more, the large experience of Siemens A.G. in solar thermal power plants introduces a great reliability for the steam turbine, as it has been successfully proved in commercial applications\textsuperscript{143}. More information of the Siemens SST-700 steam turbine is provided in Annex IV.

![Siemens SST-700 steam turbine for CSP applications](image)

**Figure 99.** Siemens SST-700 steam turbine for CSP applications  
[Source.- Siemens A.G., http://www.energy.siemens.com (accessed May 15\textsuperscript{th} 2012)]

4.3.6. **Generator.**

It has been said that the SST-700 steam turbine is responsible for transforming the hot pressurized steam into mechanical energy. However, it is necessary another device, the generator, in order to convert this mechanical energy into electrical energy. Regarding to Figure 99., the generator is mounted between the high pressure and low pressure modules of the steam turbine and, as a result, it is essential that this device is perfectly compatible with the steam turbine system in order to ensure the maximum output power of the plant. Under this requirement, it has been considered that the best option in order to ensure the maximum compatibility of the generator with the SST-700 steam turbine is to select one of the different Siemens A.G. generator models. By choosing the same manufacturer, compatibility is ensured and mounting time is reduced (as they can be mounted together before shipping the whole power unit to Gibraleón), among many other benefits. Taking this into account, the selected generator for the parabolic trough power plant in Gibraleón is the SGen-100A-4P, manufactured by Siemens A.G.

The SGen-100A-4P is a four-pole three-phase synchronous high-voltage generator cooled by air. This element introduces high efficiencies, lower noises and costs and long service life, and can be customized for the specific operating conditions of the parabolic trough power plant in Gibraleón (especially in terms of integration with the steam turbine unit). The SGen-100A-4P generator is based on a solid salient-pole rotor, with brushless excitation supplied by a stationary-

\textsuperscript{143} According to Siemens A.G. (http://www.enargy.siemens.com), the SST-700 steam turbine is used in more than 40 CSP projects worldwide.
field machine with its rotor mounted on the generator’s shaft and end-shield bearings. The whole system is enclosed in a welded casing in order to protect the generator from the difficult operating conditions introduced by the steam turbine (moisture, high temperatures, corrosion, vibrations, etc.).

Figure 100. Siemens SGen-100A-4P synchronous generator

Figure 100. shows the main elements of the selected generator, allowing to highlight the welded case (1), the stator winding and epoxy insulation (2), salient-pole rotor (3), stator core (4), air coolers (5) and brushless exciter system (6). It has been said that the SGen-100A-4P generator is cooled by air, but two different configurations are available: closed air-to-air cooling (CACA) and direct air cooling (DAC), depending on the specific conditions of each project. For the parabolic trough power plant in Gibraleón, the synchronous generator will be operating at high output values and so, direct air cooling is the best option, as filtered air from the outside is directed through the generator increasing cooling rates.

Figure 101. Siemens SGen-100A-4P technical data

Due to the features of the Spanish Electrical Grid, which is operated at 50Hz, this is the selected option. Figure 101. shows the main features of the selected generator. According to the nominal power of the plant, which is established at 50MW (plus additional self-consumption power), the SGen-100A-4P is capable of supplying the mentioned output at an output voltage between 6.3kV and 15kV. The selected configuration is an output voltage of 11kV, which must be increased with power transformers to the nominal voltage of the grid, which for the new
transmission line between *Costa de la Luz Substation* and *Onuba Substation* is 220kV. At the same time, it will be necessary to install other transformers in order to reduce the voltage to the required value for the auxiliary services (400V, 230V, etc.). Other current transformers for protection and monitoring may be necessary too. More information of the SGen-100A-4P is provided in **Annex IV**.

### 4.3.7. Steam cycle pumps.

The main elements that constitute the steam cycle have now been introduced and chosen, explaining how is the steam created and used in order to produce electrical energy. The steam cycle is a closed circuit and so, it is necessary to introduce different pumps along the system in order to supply the different elements with steam or water, depending on the stage in which the pump is considered. According to **Figure 81**. three main pumping systems are required in order to complete the steam cycle:

- **Feed water pump**: this is probably the most critical pump of the steam circuit, as it is responsible for pumping water from the deaerator to the solar preheater in order to begin the steam cycle. This pump must provide high pumping pressures in order to ensure that the superheated steam reaches the turbine at 100bar, due to the different pressure drops along the steam generating island. In order to find the best option for the parabolic trough power plant in Gibraleón, four main manufacturers have been considered:

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowserve Corporation¹⁴⁵</td>
<td>WXH, DMX</td>
</tr>
<tr>
<td>Ruhrpumpen Group¹⁴⁶</td>
<td>HSM</td>
</tr>
<tr>
<td>Sulzer Corporation¹⁴⁷</td>
<td>MBN, MSD, MC/MD, GSG</td>
</tr>
<tr>
<td>KSB A.G.¹⁴⁸</td>
<td>HGC, HGM</td>
</tr>
</tbody>
</table>

Table 24. Some feed water pump manufacturers.  
[Source.– Own elaboration¹⁴⁴]

It is very difficult to select the best option, as all of them introduce specific designs for solar thermal applications, enjoy a large experience in the field and have representation in Spain. However, according to a technical point of view, Ruhrpumpen Group’s HSM feed water pump is quickly dismissed, as it is only capable of providing pumping pressures up to 51 bar when pressures over 100 bar are needed.

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¹⁴⁴ From the information provided in the different manufacturer’s website.

¹⁴⁵ Ibid. [96]

¹⁴⁶ Ibid. [98]

¹⁴⁷ Ibid. [99]

¹⁴⁸ [http://www.ksb.com](http://www.ksb.com)
The final choice for the parabolic trough power plant in Gibraleón is the *HGC horizontal multi-stage high-pressure ring-section feed water pump*, manufactured by *KSB A.G.*, as it answers to the specific requirements of this project. It must be said that, due to the lack of price information, it is not possible to determine whether other feed water pumps from Flowserve Corporation or Sulzer Corporation may introduce a better performance/cost balance. More information about the HGC feed water pump is provided in **Annex IV**.

![KSB A.G. HGC horizontal multi-stage high-pressure ring-section feed water pump](image)

**Figure 102. KSB A.G. HGC horizontal multi-stage high-pressure ring-section feed water pump**


It is important to remember that the whole pumping system in the parabolic trough power plant in Gibraleón must include backup pumping systems, in order to cover punctual failures in the main lines. This idea can be extrapolated to the whole plant, as when designing solar thermal applications redundancy is essential.

- **Condensate pump**: it is responsible for pumping the condensed water from the condenser to the low pressure reheater and deaerator. In order to select the best option for the parabolic trough power plant in Gibraleón, the different feed water pump manufacturers are considered again, regarding this time to their condensate pump designs:

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowserve Corporation</td>
<td>APKD, VPC</td>
</tr>
<tr>
<td>Ruhrpumpen Group</td>
<td>VLT</td>
</tr>
<tr>
<td>Sulzer Corporation</td>
<td>SJD (CEP)</td>
</tr>
<tr>
<td>KSB A.G.</td>
<td>WKT, WKTA, WKTB</td>
</tr>
</tbody>
</table>

**Table 25. Some condensate pump manufacturers.**

[Source.- Own elaboration\(^{149}\)]

\(^{149}\) From the information provided in the different manufacturer’s website.
As it happened during the feed water pump selection process, it is not easy to determine the best condensate pump for the parabolic trough power plant in Gibraleón, as many of the different models listed in Table 25. are suitable for this application and no price information is provided. Please notice that, despite the fact that the selected manufacturer for the feed water pump was KSB A.G., this manufacturer provides condensate pumps up to 40 bar and this pressure may not be enough under punctual operating conditions. As a result, the selected model for the parabolic plant in Gibraleón is the VLT condensate extraction pump, manufactured by Ruhrpumpen Group. More information about this element is provided in Annex IV.

![Image](Image)

**Figure 103.** Ruhrpumpen Group VLT condensate extraction pump

- **Cooling water pump:** it is responsible for pumping the cooling water through the condenser until it is evaporated in the cooling tower. As it had been previously done with both feed water and condensate pumps, the four mentioned manufacturers are compared again in order to select the best system for the parabolic trough power plant in Gibraleón:

<table>
<thead>
<tr>
<th>Manufacturers</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flowserve Corporation</td>
<td>LNN, VCT, VTP</td>
</tr>
<tr>
<td>Ruhrpumpen Group</td>
<td>VCT</td>
</tr>
<tr>
<td>Sulzer Corporation</td>
<td>SMN/SMD, SJM/SJT, ZPP</td>
</tr>
<tr>
<td>KSB A.G.</td>
<td>RLDO, Omega, SEZ, SNW, PHZ</td>
</tr>
</tbody>
</table>

**Table 26.** Some cooling water pump manufacturers.
[Source.- Own elaboration\(^{150}\)]

\(^{150}\) From the information provided in the different manufacturer’s website.
Finally, it is the time to determine which of the models provided in Table 26. is the best option for the parabolic trough power plant in Gibraleón. Again, the main issue is the lack of price information, as most of the listed cooling water pumps provide good operating conditions for this project and it is difficult to determine which one introduces the best performance/cost balance. In addition, each of the mentioned manufacturers has large experience in solar thermal power plant applications and shipping is not a problem due to the fact that all of them have representation in Spain, as it has been previously mentioned. However, this time, the selection of the cooling water pump answers to the fact that KSB A.G. model covers the requirements established by the operating conditions of the parabolic trough power plant in Gibraleón and has previously been chosen for the feed water pumping device. As a result, it has been considered that, as far as it is possible, it would be better to use pumping systems from the same manufacturer, as this will result in lower maintenance problems, lower shipping and mounting time and lower costs. Taking all these considerations into account, the selected cooling water pump for the parabolic trough power plant in Gibraleón is the Omega single-stage axially split volute casing pump, manufactured by KSB A.G. More information about this pump is provided in Annex IV.

![Image](image.png)

**Figure 104.** KSB A.G. Omega single-stage axially split volute casing pump


These elements are a critical part of the steam cycle and, as a result, they must be properly maintained and monitored in order to minimize failure and increase their service life. Each pump system must be redundant, including an auxiliary pump in order to continue with the process in case of failure of any of the main pumping systems. At the same time, due to the great amount of auxiliary services required to optimize the plant’s performance, extra pumping systems may be required.

Now that the last element of the steam cycle has been introduced and chosen, it can be concluded that a first theoretical approach has been made on every part of the parabolic trough power plant, and it is the time now to begin a new designing stage where specific calculations will be carried out in order to determine the sizing, performance and annual energy production of the plant.
4.4. Sizing, performance and annual energy production of the plant.

Along this design stage of the project, the main parameters of the parabolic trough power plant in Gibraleón will be calculated, in order to reinforce the decisions previously made during the general approach and to validate the viability of the power plant. Due to the specific features of this project, which has a clear educational purpose and does not pretend to be a real commercial document, this sizing stage will not include all the different calculations that could be found in real projects as many essential information cannot be provided by manufacturers. However, despite this limitation, this project intends to characterize the most important design stages of a real parabolic trough power plant, ensuring the validity of the results obtained. In order to achieve this objective, the main efforts are focused on determining the final performance and annual energy production of the plant, as these are the main features that will result in the success of the plant. Nevertheless, other essential issues such as collector distribution, determination of thermal losses and sizing of the different elements of the plant must not be forgotten, as they are also critical in the parabolic trough power plant. Under these considerations, it is recommended to summarize the main features of the project, which are provided in the following table:

**Table 27. Main features of the parabolic trough power plant in Gibraleón.**
[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>SOLAR FIELD</th>
<th>Parabolic trough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chosen technology</td>
<td>Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva)</td>
</tr>
<tr>
<td>Location</td>
<td></td>
</tr>
<tr>
<td>Available solar radiation</td>
<td>2069,01 kWh/m²-year (5,67 kWh/m²-day)</td>
</tr>
<tr>
<td>Sunlight</td>
<td>2754 hours of sun/year</td>
</tr>
<tr>
<td>Concentrator</td>
<td>Skyfuel’s Skytrough space-frame collector</td>
</tr>
<tr>
<td>Reflector</td>
<td>ReflecTech’s ReflecTech PLUS mirror film</td>
</tr>
<tr>
<td>Linear receiver</td>
<td>Schott Solar’s SCHOTT PTR70</td>
</tr>
<tr>
<td>Heat transfer fluid</td>
<td>Solutia Therminol VP-1</td>
</tr>
<tr>
<td>HTF pump</td>
<td>KSB A.G.’s RPH</td>
</tr>
<tr>
<td>Solar tracking system</td>
<td>North-South single-axis</td>
</tr>
<tr>
<td>Drive unit</td>
<td>Skyfuel’s OnSun hydraulic drive</td>
</tr>
<tr>
<td>Control unit</td>
<td>Skyfuel’s Skytrakker</td>
</tr>
<tr>
<td>Layout</td>
<td>H type distribution</td>
</tr>
</tbody>
</table>
### THERMAL STORAGE

<table>
<thead>
<tr>
<th>Chosen technology</th>
<th>Two-tank indirect thermal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat storage fluid</td>
<td>Solar salt (60% NaNO₃, 40% KNO₃)</td>
</tr>
<tr>
<td>Oil-to-salt heat exchanger</td>
<td>EMBaffle shell and tube heat exchanger</td>
</tr>
<tr>
<td>Molten salt pumps</td>
<td>Ensival-More/A.R. Wilfley &amp; Sons’ VE-Y</td>
</tr>
</tbody>
</table>

### STEAM CYCLE

<table>
<thead>
<tr>
<th>Steam generating island</th>
<th>Foster Wheeler A.G.’s FW steam generating island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling system</td>
<td>Evaporative water cooling</td>
</tr>
<tr>
<td>Condenser</td>
<td>Foster Wheeler A.G.’s FW condenser</td>
</tr>
<tr>
<td>Low pressure re heater</td>
<td>Foster Wheeler A.G.’s FW LP re heater</td>
</tr>
<tr>
<td>Deaerator</td>
<td>Frost E.S.’s Cochrane H-H Spray and Tray</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>Siemens’ SST-700</td>
</tr>
<tr>
<td>Generator</td>
<td>Siemens’s SGen-100A-4P</td>
</tr>
<tr>
<td>Feed water pump</td>
<td>KSB A.G.’s HGC</td>
</tr>
<tr>
<td>Condensate pump</td>
<td>Ruhrpumpen Group’s VLT</td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>KSB A.G.’s Omega</td>
</tr>
</tbody>
</table>

#### 4.4.1. Introduction to the System Advisor Model and initial start.

Most of the different calculations will be based on the National Renewable Energy Laboratory design software, the System Advisor Model (SAM)\(^{151}\). This is a performance and economic model that allows to perform an estimation of the main parameters of different renewable power plants connected to the Grid, including parabolic trough solar thermal power plants, by introducing the main physical configuration features of a specific project. SAM allows to obtain a system’s energy output, as well as the different annual cash flows for a defined period of time and its main performance parameters.

The Solar Advisor Model is based on the TRYNSYS Simulation Software\(^{152}\) developed by the University of Wisconsin\(^{153}\), which has been dismissed for this project due to its huge complexity. As a result, SAM is a relatively easier simulation software with lots of possibilities in the design of solar thermal and other renewable power plants, although some limitations are found in the fact that this software was especially designed for applications located in the United States.

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\(^{151}\) [http://sam.nrel.gov](http://sam.nrel.gov)

\(^{152}\) [http://www.trynsys.com](http://www.trynsys.com)

\(^{153}\) [http://www.wisc.edu](http://www.wisc.edu)
States and it is sometimes necessary to adapt the different values (solar radiation libraries, manufacturers, system elements, etc.) before carrying out simulation. SAM is, then, a very useful tool in order to acquire a general estimation of the different parameters of a project, but it in any case must be considered as a definitive simulation software. Taking this fact into account, the different results obtained by SAM will be enriched by manual calculations obtained from different sources, in order to give a more realistic approach to the project.

**Figure 105. Initial screen of the System Advisor Model**

When applied to a parabolic trough power plant project, SAM is divided in 13 different modules, where the main features of the plant are introduced:

- System summary
- Climate
- Financing
- Tax Credit Incentives
- Payment Incentives
- Annual performance
- Trough system costs
- Solar field
- SCA/HCE
- Power block
- Thermal storage
- Parasitics
- User variables
During the calculating stages of this project, different modules will be introduced and properly explained, in order to clarify what is being done and why is that being done. It must be said that, despite being a simpler software when compared to TRYSYS, some parameters may be left unvaried with their initial defect value as they are related to a deeper approach that the one that is being made in this project. What is more, SAM includes its own data library, and some of the selected devices for the parabolic trough power plant in Gibraleón may not be available. If this occurs, defect values may be necessary to carry out a simulation of the plant, and that is why the different results obtained with SAM must only be considered as general estimations.

Now that some of the main features of the System Advisor Model have been introduced, it is the time to get started. First of all, when the project is launched, it is necessary to select the desired technology from the different options provided, as it is shown in the following figure:

![Technology selection in System Advisor Model](image)

**Figure 106. Technology selection in System Advisor Model**


The chosen technology is *Concentrating Solar Power*, as this project is based on the design of a 50MW parabolic trough power plant with two-tank indirect thermal storage in Gibraleón, Huelva. **Figure 106.** shows the great amount of simulation options provided by SAM, as it includes several renewable power generating technologies such as photovoltaic systems, wind systems, geothermal applications and biomass power plants, as well as solar water heating systems for domestic applications and buildings and conventional fossil fuel-based power.
plants. When CSP technology is chosen, different concentrating solar systems appear on the screen:

![Available CSP systems in System Advisor Model](image)

**Figure 107. Available CSP systems in System Advisor Model**


It can be observed that SAM covers practically the totality of the currently available concentrating solar power technologies, including dish Stirling applications and direct steam power tower plants. According to the special features of this project, the selected option must be the parabolic trough technology, which is available in two options: *physical model* (based on real parabolic trough power plant experiences developed in the United States) and *empirical mode* (which is based on a general simulation model for parabolic trough applications). As the operating conditions in the United States may be very different to the ones provided by the selected location (Gibraleón, Huelva), it has been considered that the best option in order to simulate the parabolic trough power plant in Gibraleón is the *parabolic trough empirical model*, as it will provide a more objective approach to the project and will not be subjected to specific features that could be very different to the ones that characterize this project.

To this point, the main technical features of the plant have been selected. By introducing the different specific parameters obtained during the theoretical approach, it will be possible to carry out a simulation of the final performance of the plant, as well as other technical parameters that may be considered as important for this project. However, as it has been mentioned, SAM allows to
carry out an economical simulation of the plant too, but it is necessary to determine a specific financing option. This is probably the most unreliable simulation of the project, as it is based on specific United States economical data that may be surely very distinct from the Spanish economical regime. Despite this limitation, it is necessary to select a financing option in order to start simulation, and four financing modes are provided:

![Diagram showing available financing options](image)

**Figure 108. Available financing options in System Advisor Model**


The chosen financing option for the parabolic trough power plant in Gibraleón is the *commercial mode*. It may seem that the description of this financing mode does not represent this project, but it has been chosen as it provides the simplest simulation mode for the project and, as a result, lower information is necessary to ensure a good estimation of the real performance of the plant. This feature becomes a great advantage, as the other financing modes introduce much more complex systems that require a great amount of different economical data, with very specific economical terms related to the United States Economical Regime (*IPP, PPA, IRR, NPV*, etc.). The parabolic trough power plant is located in Southern Spain and, as a result, is nonsense to discuss the economical performance of the plant basing on a different economical regime characterisation. The best option is, then, the commercial mode, as it is the simplest mode and will ensure better results. Once this mode has been chosen, SAM’s main screen launches and the 13 different modules appear. As a result, this initial start has concluded, and it is the time to begin with the different sizing, performance and annual energy output calculations.
4.4.2. **Sizing and performance of the solar field.**

The main features and elements of the solar field have been introduced and discussed in previous stages of the project. The selected collector is the Skytrough parabolic trough space-frame collector, with ReflecTech reflective surface (Table 27.). According to Annex II., each collector assembly includes 8 Skytough modules, with a total length of 115m. The nominal output power of the plant is 50MW, in order to be subjected to the Spanish Special Regime, and it includes a two-tank indirect thermal storage system as has been previously explained.

There is a very close relation between the size of the solar field and the number of hours which can be provided by the thermal storage system. The higher the number of hours the steam turbine is capable of functioning without solar resource, the higher the solar field must be, and more collector modules will be needed. A very small thermal storage system will result in lower collector modules, but the final output of the plant may decrease and the economical balance of the plant may be insufficient. At the same time, a huge thermal storage system will result in more collector modules. This increase in the number of collector modules and thermal storage system will be responsible for an increase in the energy cost, which will make the project non-viable. It is, then, a matter of balance between the size of the solar field and the size of the thermal storage system. In order to find the best option for the parabolic trough power plant in Gibraleón, this balance will be studied with SAM.

The very first thing that must be done is to introduce the specific features of the parabolic trough power plant in Gibraleón in the program. The first design module is the one related to Climate. SAM is developed by the NREL and it is based on solar thermal experiences carried out in different locations of the United States of America. As a result, it is not possible to use none of the supplied climate libraries provided by the program, being necessary to introduce the specific data of the Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huella). Three different TMY2, TMY3 and EPW (accepted weather file formats by SAM) web sources are supplied, but due to the fact that the selected parcel is not located in any of the United States territories, the chosen website is:

- **pps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm**

By selecting Europe among the different available options (which is characterised as WMO Region 6), and specifying Spain in the library directory, the closest weather file is the one related to Huelva. The chosen location for the parabolic trough power plant is 15,6km away from Huelva154 and, although minor direct normal variations may be found between both locations, this is the chosen library for SAM’s climate module. This is a clear limitation of the program, as those applications located out of the United States may not be represented by the different international weather files and this may result in unreliable results. Despite the small distance between Gibraleón and Huelva, many differences are noticed when the downloaded weather file is opened with SAM.

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154 According to Google Maps, http://maps.google.es
Table 28. Comparison between Huelva and selected location’s weather data. [Source: - Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>Huelva</th>
<th>Selected location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>37,26</td>
<td>37,315562</td>
</tr>
<tr>
<td>Longitude</td>
<td>-6,95</td>
<td>-7,036548</td>
</tr>
<tr>
<td>DNI [kWh/m²·year]</td>
<td>1965,6</td>
<td>2069,01</td>
</tr>
<tr>
<td>Wind speed [m/s]</td>
<td>6,7</td>
<td>3</td>
</tr>
<tr>
<td>Average temperature [°C]</td>
<td>18,3</td>
<td>19</td>
</tr>
<tr>
<td>Elevation [m]</td>
<td>35</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 28. shows the main differences between both locations. According to these features, the most critical value is the one related to the direct normal irradiation, which has a value of 1965 kWh/m²·year in Huelva whereas in the Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón this value reaches 2069,01 kWh/m²·year. Please notice that, as it was calculated in previous stages of the project, the minimum annual direct normal irradiation that ensures the success of a solar thermal power plant was 2060 kWh/m²·year. This big difference is explained by the fact that the selected weather file is based on NASA 1991-2005 satellite measurements, while the information provided by the Andalusian Solar Radiation Software is based on a large measuring experience (1990-2012) with on-site meteorological stations from the RIA and as a result, it is considered to be a more reliable source. As SAM is only used to carry out an estimation of the performance of the plant and no real data is expected to be obtained through this program, this solar resource variation is taken into account and simulating process is carried on. The final display of SAM’s climate module is provided in Annex V.

After this first customizing effort, it is the time to introduce the concept of solar multiple. When designing a parabolic trough power plant with SAM, it is necessary to establish some reference conditions (also known as design point) on which the solar multiple will depend. These reference conditions include temperature [°C], direct normal radiation [W/m²] and wind velocity [m/s] data, and can be specified in the solar field module of the program. The solar field area required to provide enough energy to the power block at the design turbine gross output level (total amount of power generated by the turbine, without considering parasitic losses) under reference conditions is called the exact area [m²], and it is related to a solar multiple of 1. Although it has been said that the solar multiple depends on the reference conditions, it must be said that both temperature and wind velocity are not very critical for the sizing of the solar field, as they are mainly used to determine solar field pipe heat losses and linear receiver losses, respectively. On the other hand, direct solar radiation does have a critical impact on the solar multiple and, consequently, on the size of the solar field. It is important to mention that these reference conditions do only have impact on design losses and sizing of the solar field, whereas the weather data selected above will be used to determine the solar resource along the year.
The procedure in order to determine the sizing of the solar field is simple, as SAM allows to carry out a preliminary design procedure by introducing a few key data in the program. First of all, it is necessary to introduce the design turbine gross output and the related estimated gross to net conversion factor, which is related to the impact of parasitic losses on the system. The estimated gross to net conversion factor recommended by the program is 90% \(^{155}\), which means that the amount of parasitic losses plus the power related to self consumption is 10% of the design turbine gross output. As a result, the design turbine gross output is 55MW, and the estimated gross to net conversion factor is 0,9, which are both introduced in the power block module of SAM resulting in an estimated net output at design of 50MW (which is the chosen nominal output for the parabolic trough power plant in Gibraleón). Later, it is necessary to introduce the reference conditions for the project in the solar field module of the program. The temperature and wind velocity values will be selected from the annual average weather data provided in Annex I., which were previously provided in Table 28. The selected direct normal radiation data will be 800W/m\(^2\), as this is the recommended value for those parabolic trough systems located in Southern Spain\(^{156}\). It is important to choose carefully the design point DNI. If this reference is too small, the real collected solar radiation will be greater and this fact will result in dumped energy. At the same time, if the reference DNI value is too high, the solar field will be undersized, resulting in insufficient thermal energy and insufficient output power of the plant. For the wind speed and temperature reference values, the annual average data for Gibraleón will be chosen, which is related to an average wind speed of 3m/s and an average temperature of 19°C.

### Table 29. Preliminary sizing stage key data.

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th></th>
<th>Selected location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design turbine gross output [MW]</td>
<td>55</td>
</tr>
<tr>
<td>Estimated gross to net conversion factor</td>
<td>0,9</td>
</tr>
<tr>
<td>Estimated net output at design [MW]</td>
<td>50</td>
</tr>
<tr>
<td>Wind velocity [m/s]</td>
<td>3</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>19</td>
</tr>
<tr>
<td>DNI [W/m(^2)]</td>
<td>800</td>
</tr>
</tbody>
</table>

By introducing this first values, SAM allows to discuss the cost of generated energy depending on different values of the solar multiple and thermal storage

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\(^{156}\) Ibid. [155]
capacity, in order to select the best option for the parabolic trough power plant in Gibraleón. Once that the optimal solar multiple and thermal storage capacity have been chosen, it is possible to obtain the size of the solar field. Two new concepts have been introduced in the previous lines, and it is necessary to explain them due to their criticality. On one hand, the cost of generated energy is represented by the Levelized Cost of Energy (LCOE), which is given in c€/kWh (c$/kWh in SAM). This is a very important concept, as it allows to compare different options and it is a clear indicator of the commercial success of the plant. On the other hand, another important concept is the number of hours that the thermal storage is able to supply to the steam turbine cycle in order to continue with power generation at the nominal design output power of the turbine. This value is represented by the Equivalent Full Load Hours of TES.

![Figure 109. Preliminary LCOE (nom-w/o incentives) vs. Solar Multiple](image)

**Figure 109.** shows the preliminary comparison between the LCOE (nom-w/o incentives) and the selected Solar Multiple, depending on different values of Equivalent Full Load Hours of TES. According to the plotted values, the best option for the parabolic trough power plant is a Solar Multiple of 1,5 and 2 Equivalent Full Load Hours of TES, as it introduces the lowest LCOE (nom-w/o incentive) value at around 17,05 c€/kWh. It is important to understand why the nominal without incentive LCOE output has been chosen instead of other LCOE (real), LCOE (nom) or LCOE (real-w/o incentives). According to System Advisor Model User Guide - Version 2011.5.23, the real LCOE is a constant dollar inflation-adjusted value that is typically used by the U.S. Department of Energy in parabolic trough project estimations, whereas the nominal LCOE is based in a current dollar value and is the most common option when analyzing parabolic trough power plant applications. Real LCOE is usually lower than nominal LCOE, as far as inflation rate is positive; if inflation rate was zero, both real and nominal LCOE values would be the same.

The most typical LCOE value when analyzing parabolic trough power plant projects is the nominal one and, as a result, this will be the chosen option. In order to ensure the maximum accuracy no incentives will be considered for this preliminary study based on key data.
Now that the preliminary design stage has been carried out, it is the time to choose the best combination of Solar Multiple and Equivalent Full Load Hours of TES for the parabolic trough power plant in Gibraleón. According to Figure 109, a Solar Multiple of 1,5 with 2 hours of Equivalent Full Load Hours of TES is the best option, due to its least LCOE(nom-w/o incentives) value. However, this storage capacity seems very small and, in order to ensure the best conditions, different Equivalent Full Load Hours of TES for some of the operational parabolic trough power plants in Southern Spain are discussed.

Table 30. Conventional Equivalent Full Load Hours of TES in some Southern Spanish operational parabolic trough power plants
[Source.- Own elaboration\textsuperscript{157}]

<table>
<thead>
<tr>
<th></th>
<th>Equivalent Full Load Hours of TES [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I</td>
<td>7,5</td>
</tr>
<tr>
<td>Andasol II</td>
<td>7,5</td>
</tr>
<tr>
<td>Andasol III</td>
<td>7,5</td>
</tr>
<tr>
<td>Extresol I</td>
<td>7,5</td>
</tr>
<tr>
<td>Extresol II</td>
<td>7,5</td>
</tr>
<tr>
<td>La Dehesa</td>
<td>7,5</td>
</tr>
<tr>
<td>Manchasol I</td>
<td>7,5</td>
</tr>
<tr>
<td>Manchasol II</td>
<td>7,5</td>
</tr>
</tbody>
</table>

It has been very difficult to find different LCOE data for the different parabolic trough power plants discussed in Table 30., due to the fact that it is a very representative data and it is usually kept under secret. However, it can be concluded that taking into account the current development of the parabolic trough technology in pure solar thermal power plants, an approximate range of 0,15-0,20 c€/kWh\textsuperscript{158} is considered to provide reasonable rates of success. According to the data introduced above, the selected option for the parabolic trough power plant in Gibraleón is an Equivalent Full Load Hours of TES of 7,5 hours, which in order to ensure the minimum LCOE (nom-w/o incentives) requires a Solar Multiple of 2. Under these conditions, and taking into account that these results are provided by a preliminary analysis based on a few key data and must not be considered as definitive data, the expected LCOE (nom-w/o incentives) will be around 17,2 c€/kWh (0,135 c€/kWh\textsuperscript{159}). This value is even smaller to the recommended range for this kind of solar technology, but it can be expected that it will definitely rise as more specific technical features of the

\textsuperscript{157} Some data has been provided in the different plant promoter’s websites, and others have been calculated manually from the data provided in http://www.nrel.gov. (accessed May 8\textsuperscript{th} 2012)

\textsuperscript{158} Romero Álvarez, M. 2008. Energía Solar Termoeléctrica.

\textsuperscript{159} At a conversion rate of 1$=0,7851€
power plant in Gibraleón are introduced in the program. Now that the optimal Solar Multiple for an Equivalent Full Load Hours of TES value of 7,5 hours has been chosen, it is possible to determine the size of the solar field.

Before beginning with sizing calculations, one extra feature must be considered, and it is the one related to the Rankine cycle conversion Efficiency. As no data is provided in the Siemens SST-700 steam turbine brochure provided in Annex IV., different sources have been consulted in order to define a good performance value for solar thermal power plants based on parabolic trough collectors. During this research, the most reliable values will be the ones related to those similar applications located in Southern Spanish regions, in order to increase the accuracy of the choice, and it has been possible to notice that most of current parabolic trough power plants located in Southern Spain introduce steam turbine efficiencies between 38% and 41%, approximately (38,13% in Andasol I and II, 40,2% in Andasol III, 38,1% in Extresol I, etc.). As a result, the chosen turbine efficiency for the parabolic trough power plant in Gibraleón is 40%, which is an optimistic value that answers to actual steam turbine designs with higher efficiencies. Under these considerations, the sizing of the solar field, based on the different formulas provided by the System Advisor Model User Guide - Version 2011.5.23, begins.

Dividing the gross turbine design energy \( E_{\text{DESIGN GROSS OUTPUT}} \), which is the total amount of energy provided by the turbine including the extra power necessary for self consumption and without considering thermal losses, by the efficiency of the turbine \( \eta_{\text{DESIGN TURBINE GROSS OUTPUT}} \), which has been previously established in 40%, it is possible to obtain the thermal energy required to generate the gross turbine design energy under reference conditions \( Q_{\text{DESIGN TURBINE THERMAL INPUT}} \):

\[
Q_{\text{DESIGN TURBINE THERMAL INPUT}} = \frac{E_{\text{DESIGN GROSS OUTPUT}}}{\eta_{\text{DESIGN TURBINE GROSS OUTPUT}}} = \frac{55 \text{ MW} \cdot \text{h}}{0.4} = 137.5 \text{ MW} \cdot \text{h} \quad (17)
\]

This thermal energy required to generate the gross turbine design energy \( Q_{\text{DESIGN TURBINE THERMAL INPUT}} \) under reference conditions is related to a specific solar field area, which is known as exact area \( A_{\text{EXACT}} \). This exact area is related to a Solar Multiple of 1 and, and can be obtained through the following expression:

\[
A_{\text{EXACT}} = Q_{\text{DESIGN TURBINE THERMAL INPUT}} \left( \frac{DNI_{\text{REFERENCE}} \cdot \eta_{\text{OPTICAL}}}{\eta_{\text{PEAK LOSS}} - Q_{\text{HE LOSS}} - Q_{\text{PIPE LOSS}}} \right) \quad (18)
\]

\[160\] Some of the different variables have been changed into a more clarifying name in order to ensure that the procedure is understood.

\[161\] 19°C of annual average temperature, 3 m/s of annual average wind speed and 800 W/m² as reference DNI.
There are some of these variables that need to be clarified in order to understand the procedure. On one hand, the total amount of heat losses occurred in the different heat collecting elements of the solar field \( Q_{\text{HCE LOSS}} \) takes into account the chosen reference conditions: reference direct normal irradiation \( (\text{DNI}_{\text{REFERENCE}}) \), reference wind speed \( (\text{WS}_{\text{REFERENCE}}) \) and reference temperature \( (T_{\text{REFERENCE}}) \), as well as other specific parameters of the plant: the inlet temperature of the heat transfer fluid \( (T_{\text{INLET}}) \) and the outlet temperature of the heat transfer fluid \( (T_{\text{OUTLET}}) \). According to the selected heat transfer fluid, which was the diphenyl oxide/biphenyl Therminol VP-1 synthetic oil, the inlet temperature of the fluid is 290°C and the outlet temperature 391°C (Annex II.). At the same time, it is necessary to define the main properties of the selected parabolic trough collector (Skytrough), reflector surface (ReflecTech) and solar tracking system (On Sun), provided in Annex II. too, as they are closely related to this kind of thermal losses. In order to do so, it is necessary to define a new user library in the program, introducing the main parameters of the different elements.

**Figure 110.** SAM/CSP trough SCAs library, including Skytrough by manual edition
[Source.- Own elaboration]

**Figure 110.** shows the layout of the SAM/CSP trough SCAs library, allowing to compare some of the Skytrough edited parameters with the features of the defect collector designs. Apart from the specific technical features of the collector, some abstract values such as cleanliness, dust and availability must be introduced. For the Skytrough collector, a reflectance of 0,94 has been chosen. A cleanliness factor of 0,97 has been introduced, regarding to the special features of the ReflecTech reflecting surface that reduce the amount of dust addition and, consequently, introduces lower maintenance needs. All these parameters are chosen according to the ReflecTech brochure, provided in Annex II. The rest of parameters are left with their defect value. Once this has been done, by selecting the defined library in the SCA/HCE module of SAM, the specific features of the Skytrough collector appear immediately in the screen. In order to obtain the total amount of heat losses occurred in the different heat collecting elements of the solar field, it is also necessary to select a heat collection element design. The chosen element for the parabolic trough power plant in Gibraleón is the SCHOTT PTR70. This linear receiver is the one introduced by defect in the SCA/HCE module of SAM, and so, the values will not be modified as no relevant differences between those and the ones from technical data provided in the SCHOTT PTR70 brochure in Annex II. have been noticed. Under these considerations, the total amount of heat losses occurred in the different heat collecting elements of the solar field are:

\[
Q_{\text{HCE LOSS}} = 29,0979W / m^2
\]  

(19)

Please notice that the \( Q_{\text{HCE LOSS}} \) provided by SAM is based on different formulas which are detailed in the System Advisor Model User Guide - Version 2011.5.23.
Design of a Solar Thermal Power Plant

Due to the great calculation effort required to solve them manually, and due to the fact that SAM bases its results on these expressions, the value provided by the program is considered to be correct. The final layout of the SCA/HCE module of SAM is provided in Annex V.

It must not be forgotten that the final intention is to determine the Exact Area related to a Solar Multiple of 1, and as a result, two parameters of (18) still have to be introduced and determined. It is the time now to discuss the total amount of heat loss due to piping in the solar field (Q_{PIPING LOSS}) under reference conditions. This value takes into account different parameters of the plant: the inlet temperature (T_{INLET}) and outlet temperature (T_{OUTLET}) of the heat transfer fluid in the solar field, the reference temperature (T_{REFERENCE}), piping heat loss temperature coefficients 1 to 3 (F_{PHL 1}, F_{PHL 2}, F_{PHL 3}) and heat losses when there is a temperature difference of 316.5°C between the average temperature of the solar field and the ambient temperature (Q_{PIPING LOSS \Delta T=316^\circ C}). As it can be seen, most of these parameters answer to very specific features of the program and cannot be easily obtained from the technical data provided in Annex II. As a result, the inlet temperature will be established at 290°C, the outlet temperature at 393°C and the reference temperature will be 19°C, as has been previously discussed. For the different temperature coefficients and Q_{PIPING LOSS \Delta T=316^\circ C}, defect values will be maintained.

There are, however, other parameters that must be chosen in the Solar Field module of SAM. These parameters are the initial temperature of the solar field (T_{INITIAL}), which has been established at 100°C according to the defect values, as well as the minimum heat transfer fluid temperature (T_{MIN HTF}). As it has been explained before, the diphenyl oxide/biphenyl Therminol VP-1 synthetic oil heat transfer fluid freezes at 12°C and must be permanently kept over this temperature in order to avoid damages in the plant. Despite the fact that the defect value is established at 50°C, it has been considered that it is better to ensure a higher minimum heat transfer fluid temperature of 60°C. This 10°C increase does not affect the heat losses in the piping system of the solar field (it can be seen that the value provided by SAM remains unvaried no matter which value is established) and will only be related to a small increase in electrical heat tracing cost. Under the mentioned conditions, the value provided by the program is:

\[
Q_{PIPING LOSS} = 10,5777 W / m^2
\]  \hspace{1cm} (20)

There is only one unknown parameter remaining, and it is the one related to the average optical efficiency of the solar field (\(\eta_{PEAK OPTICAL}\)). This value is the average of the different optical efficiencies related to the different heat collection elements (SCHOTT PTR70, in this project) and can be found in the SCA/HCE module layout provided in Annex V. This value, obtained from the different SCHOTT PTR70 linear receiver defect parameters (which, as has been previously mentioned, were very similar to the features introduced in the element brochure from Annex II, and defect values were maintained) can be assumed as correct, and so:

\[
\eta_{PEAK OPTICAL} = 0,779195
\]  \hspace{1cm} (21)
Introducing (19), (20) and (21) in the original expression of (18), it is possible to obtain the Exact Area related to the reference conditions (Solar Multiple of 1):

\[
A_{\text{EXACT}} = \frac{137.5 \times 10^6 \text{Wt}}{(800 \text{W} / \text{m}^2 \cdot 0.779195) - 29.4123 \text{W} / \text{m}^2 - 10.5777 \text{W} / \text{m}^2}
\]

(22)

And solving the expression above:

\[
A_{\text{EXACT}} = 235.574,1258 \text{ m}^2
\]

(23)

The value obtained is practically the same that the one provided by SAM (235.574 m²) and so, it can be concluded that it is correct. Now that the Exact Area is known, the next step in the sizing of the solar field is to adapt this area to the chosen Solar Multiple of the parabolic trough power plant in Gibraleón. In previous lines of this stage it had been concluded that the best configuration for this project was the one carried out with an Equivalent Full Load Hours of TES of 7.5 hours, which was related to a Solar Multiple of 2 under minimum LCOE (nom-w/o incentives) conditions. The Exact Area is related to the surface required under reference conditions to provide the gross turbine output power (which was established in 55MW), which in turn means a Solar Multiple of 1. As a result, we can obtain the real area required under a Solar Multiple value of 2 (\(A_{\text{SOLAR FIELD}}\)) as it is shown in the following expression:

\[
A_{\text{SOLAR FIELD}} = A_{\text{EXACT}} \cdot SM
\]

(24)

\[
A_{\text{SOLAR FIELD}} = 235.574,1258 \text{ m}^2 \cdot 2 = 471.148,2516 \text{m}^2
\]

(25)

The real area required by the solar field under a Solar Multiple value of 2 and 7.5 hours of Equivalent Full Load Hours of TES is 471.148,2516 m². This surface does not include the distance between the different Skytrough modules in a collector assembly or the distance between the different collector rows, which will be later discussed. Once that \(A_{\text{SOLAR FIELD}}\) is known, it is possible to obtain easily the total number of Skytrough collectors needed to perform this surface (\(N_{\text{SCA}}\)), by dividing the first value between the aperture area of the Skytrough collector assembly (which according to Annex II. is 656 m²/collector assembly):

\[
N_{\text{SCA}} = \frac{471.148,2516 \text{m}^2}{656 \text{m}^2} = 718.21 \text{ collector assemblies}
\]

(26)

It is obvious that it is impossible to have a real value for the number of collectors, as an entire number is necessary. However, it is important to select the final value carefully. On one hand, the value obtained in (26) cannot be rounded to 718 because a lower number of collectors would not provide sufficient thermal energy to the whole system (no matter how small this difference was, the maximum performance must always be intended), so it is easy to observe that it must be rounded to an upper number. However, 719 is neither a valuable value, as the symmetry of the solar field must be ensured. This time, no huge rounding must be carried out, as the first upper value that answers to this symmetry requirement is 720.
\[ N_{SCA} = 720 \text{ collector assemblies} \quad (27) \]

To sum it up, the parabolic trough power plant located in Gibraleón requires 471.148,2516 m² of collector surface in order to satisfy the nominal output power of the plant and the 7,5 hours Equivalent Full Load Hours of TES, which is carried out with a total amount of 720 Skytrough collector assemblies. Please notice that the value provided by SAM is slightly different (472.320 m²), but the manual value is chosen as it is the most restrictive option. The total amount of solar collector assemblies found manually is just the same value as the obtained with SAM, where the total number of collector assemblies for the exact area is 360 (359,1, which with an upper rounding tends to 360) and if this number is multiplied by the Solar Multiple of 2, the obtained number is also 720. According to the chosen solar field configuration (H-type layout), the different solar collectors are distributed in solar loops as shown in Figure 64. For the Skytrough assembly, each collector loop is divided in a cold side through which the heat transfer fluid enters at a low temperature and a hot collector side through which the heated transfer fluid flows to the power block. Each of the loop side is performed with three Skytrough assemblies, resulting in a total amount of six Skytrough assemblies in each loop.

Some parameters of the solar field, however, have not been determined yet. These parameters are the ones related to the distances between the different elements of the solar field. As a result, it is possible to distinguish between the effective solar field area, which is the one related to the collecting surface of the solar field \( A_{SOLAR\ \text{FIELD}} \), and the total area required to build the solar field \( A_{TOTAL\ \text{SF}} \), including distances between assemblies and rows. While the first one, under a Solar Multiple value of 2 and 7,5 hours of Equivalent Full Load Hours of TES is 471.148,2516 m², the total area must be necessarily bigger, as it takes into account the required distances in order to allow maintenance operations (reflective surface water cleaning with trucks) and to avoid shade impact between collector rows. It is necessary, then, to calculate these distances in order to ensure that no energy loss is caused by mutual shade between consecutive assemblies and to ensure that maintenance operations can be properly performed too.

According to the distance between solar collector assemblies in a row \( d_{SCA-ROW} \), there is no especial criteria as this only has an impact on piping length (and, consequently, piping cost) and total area of the solar field. As a result, it is important to select a distance that, without introducing huge land requirements for the solar field, is wide enough to allow punctual maintenance operations between assemblies, such as the ones related to ball joint substitution or heat transfer fluid leakage control. The selected value is the one provided by defect in SAM for the specific solar field conditions previously introduced, which is established in 1 m. However, greater issue is found when determining the distance between rows along the solar field \( d_{ROW-ROW} \), measured from centre to centre of two consecutive solar collector rows. In order to obtain this value, the reference condition will be the one related to the lowest Sun position of the day, as if mutual shading is avoided for this moment so will be for the rest of the day. As a result, it is possible to elaborate a simplified geometrical approach of two consecutive rows in order to determine the minimum distance that must kept between this elements.
Figure 111. Simplified geometrical approach to two consecutive collector rows
[Source.-Own elaboration]

The determination of the distance between rows in the solar field is nothing but a conventional geometrical problem, where some variables must be fixed. According to the Skytrough technical data provided in Annex II, the module aperture width of the element is 6 m, so $d_{\text{ROW-ROW}}$ can be found by fixing the $h_{\text{ROW-ROW}}$ or $\varphi$. According to Andasol I&II values (which have been largely used in this project as reference due to the great amount of free available information about them), which where $\varphi_{\text{ANDASOL I}} = 18,33^\circ$ and $\varphi_{\text{ANDASOL II}} = 18,04^\circ$, the selected option for the parabolic trough power plant in Gibraleón is $\varphi = 19^\circ$. Please notice that this slightly bigger value results in a smaller total solar field area without compromising the distance between rows. Now that two reference values are known, it is possible to determine the minimum $d_{\text{ROW-ROW}}$ distance for the parabolic trough power plant in Gibraleón through the following expression:

$$d_{\text{ROW-ROW}} = \frac{\text{Module aperture width}}{\text{tg}(\varphi)} \quad (28)$$

$$d_{\text{ROW-ROW}} = \frac{6\text{ m}}{\text{tg}(19^\circ)} = 17,4\text{ m} \quad (29)$$

As a result, the minimum row-to-row distance in the solar field of the parabolic trough power plant in Gibraleón is 17,4 m. Although a higher $\varphi$ has been chosen, due to the higher Skytrough module aperture width (as the ET-150 collector used in Andasol I&II had a 5,7m module aperture width) the obtained distance is very similar to the reference projects, as 17,2m and 17,5m where the chosen distances for Andasol I and Andasol II power plants, respectively. The final distribution of the solar field is shown in Plan n° 3- Floor view of the Plant. Please notice that a distance of 6 meters has been left between solar collector loops ($d_{\text{LOOP-LOOP}}$) in order to ensure sufficient space for the required piping connections.

By introducing these values in the Solar Field module of SAM, the total land area required for the solar field ($A_{\text{TOTAL SF}}$) is 338 acres, or what it is the same, 1.367.843 m². This value can also be expressed in hectares, resulting in a total area of 131,78ha. This is not the only area value that SAM is able to provide, as this total solar field area can be multiplied by a non-solar field area

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162 At a conversion rate of 1 acre = 4.046,872m²
163 At a conversion rate of 1 acre = 0,404685642ha
multiplier in order to obtain the total land area required for the parabolic trough power plant in Gibraleón. The defect value for this multiplier is 1.4. Although it is known that SAM bases this values in real parabolic trough experiences and it is considered to be reliable, the selected multiplier for this project will be 1.5, as it is considered that the total surface required for the power block and thermal storage system of the plant will require at least half of the area used in the solar field in order to take into account future decisions such as introducing a water storage system for maintenance and other kind of facilities that may be required. Under this non-solar field area multiplier, the total land area of the parabolic trough power plant in Gibraleón is 2.047.717,23 m² or 204,77 ha (506 acres).

In order to verify these values, the total area can also be found manually from the distribution provided in Plan no 3- Floor view of the plant. Each Skytrowh solar collector assembly has a length of \(d_{SCA}=115\text{m}\), \(d_{SCA-ROW}\) is 1m, \(d_{ROW-ROW}\) is 17.4m and \(d_{LOOP-LOOP}\) is 6 m. The solar field is divided in two blocks with 60 rows and 6 solar collector assemblies per row. As a result, the total solar field area in the parabolic trough power plant in Gibraleón is:

\[
d_{HORIZONTAL} = 6 \cdot SCAs \cdot (d_{SCA}) + 4 \cdot (d_{SCA-ROW}) + 1 \cdot (d_{LOOP-LOOP}) = 700m
\]

\[
d_{HORIZONTAL} = 6 \cdot SCAs \cdot (115m) + 4 \cdot (1m) + 1 \cdot (6m) = 700m = 1.026,6m
\]

\[
d_{VERTICAL} = N_{ROW-TO-ROW} \cdot (d_{ROW-ROW}) = 1.026,6m
\]

\[
60 \text{ rows} = 59 \text{ row-to-row spaces}
\]

\[
d_{VERTICAL} = 59 \cdot (17.4m) = 1.026,6m
\]

\[
A_{solar \_field \_MANUAL} = 2 \text{ solar field blocks} \cdot 1026,6m \cdot 700m = 1.437.240m²
\]

Please notice that the value obtained manually is bigger than the value provided by SAM. There is a variation of 69.397m², which according to the following expression, results in an error of 5.07%:

\[
\varepsilon = \frac{69.397m²}{1.367.843m²} \times 100 = 5.07\%
\]

The variation between the value provided by SAM and the value calculated manually is 5.07% and so, it is considered to be within the tolerable limits of deviation. As a result, the final solar field area for the parabolic trough power plant in Gibraleón is 1.367.843 m² (131,78ha), and applying the chosen non-solar field area multiplier of 1.5, the total area of the parabolic trough power plant in Gibraleón can be estimated to be 2.047.717,23 m² (204,77 ha). In order to verify the validity of the chosen value, a comparison between different solar field areas in similar parabolic trough power plants in proximal locations is performed:
**Table 31.** Approximated total land area [ha] of some similar Southern Spanish two-tank indirect molten salt heat storage parabolic trough power plants

[Source.- Own elaboration\textsuperscript{164}]

<table>
<thead>
<tr>
<th></th>
<th>Total land area [ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I</td>
<td>195</td>
</tr>
<tr>
<td>Andasol II</td>
<td>195</td>
</tr>
<tr>
<td>Andasol III</td>
<td>200</td>
</tr>
<tr>
<td>Extresol I</td>
<td>225</td>
</tr>
<tr>
<td>Extresol II</td>
<td>200</td>
</tr>
<tr>
<td>La Dehesa</td>
<td>220</td>
</tr>
<tr>
<td>Manchasol I</td>
<td>195</td>
</tr>
<tr>
<td>Manchasol II</td>
<td>195</td>
</tr>
</tbody>
</table>

As it can be seen in **Table 31.**, the total land area obtained with SAM is very similar to conventional land requirements in similar Southern Spanish power plants and so, it can be considered as correct. To this point, practically the totality of SAM’s Solar Field module has been determined, and only a few parameters remain undiscussed, and are the ones related to the orientation of the different solar collectors. It has been previously established that the best option for the parabolic trough power plant in Gibraleón is a North-South single-axis solar tracking system, as this orientation provides higher outputs. According to this fact, and taking into account the values related to each orientation introduced in the *System Advisor Model User Guide* - Version 2011.5.23, the selected **collector tilt** is 0° (as collectors are installed horizontally) and the chosen **collector azimuth**, related to a North-South single-axis solar tracking, is also 0°. At the same time, the **deployment angle** is the angle of the solar collector assembly during the **hour of deployment**, which is the hour before the first morning operation. The selected value for the deployment angle is 0, which is related to a vertical position of the collector assembly facing north. On the other hand, the stow position was introduced as the resting position of the collector (**Figure 43.**), proving that the best stow position is 180°, although structural pylons limited this value to 120°. As SAM does only take this value in order to calculate Sun position along the day, this physical limitation can be dismissed, introducing a **stow angle** of 180°, which is related to a vertical South-facing position. By introducing these values, the final layout of the Solar Field module of SAM is completed, and can be seen in **Annex V.**

Now that the main parameters of the solar field have been found, the next step is to find the required mass flow of heat transfer fluid \(m_{\text{HTF}}\) along the solar field in order to satisfy the conditions previously established. This mass flow can be found through the following expression:

\[ \text{(equation)} \]

\textsuperscript{164} Some data has been provided in the different plant promoter’s websites, as well as from the data provided in [http://www.nrel.gov](http://www.nrel.gov) (accessed May 10\textsuperscript{th} 2012)
Design of a Solar Thermal Power Plant

\[ m_{HTF} = \frac{Q_{SOLAR\ FIELD}}{H_{HTF\ OUTLET} - H_{HTF\ INLET}} \]  \hspace{1cm} (37)

As it can be seen in (37), the mass flow of heat transfer fluid along the solar field depends on the thermal energy required to ensure the gross turbine output under a Solar Multiple of 2 and 7.5 hours of Equivalent Full Load Hours of TES \( (Q_{SOLAR\ FIELD}) \), the enthalpy of the heat transfer fluid at its inlet temperature \( (H_{HTF\ INLET}) \), which is 290°C, and the enthalpy of the heat transfer fluid at its outlet temperature \( (H_{HTF\ OUTLET}) \), which is 391°C. First of all:

\[ Q_{SOLAR\ FIELD} = Q_{DESIGN\ TURBINE} \cdot SM \]  \hspace{1cm} (38)

\[ Q_{SOLAR\ FIELD} = 137.5\ MWt \cdot 2 = 275\ MWt \]  \hspace{1cm} (39)

It is the time now to find the different inlet and outlet heat transfer fluid enthalpies according to the following table:

![Figure 112. Different HTF enthalpies [J/kg] depending on temperature [°C]

According to Figure 112., the inlet enthalpy for the diphenyl oxide/biphenyl Therminol VP-1 synthetic oil can easily be found by applying the following formulas:

\[ H_{HTF\ INLET} = 1.377(T_{INLET})^2 + 1.498 \times 10^3(T_{INLET}) - 1.834 \times 10^4 \]  \hspace{1cm} (40)

\[ H_{HTF\ INLET} = 1.377(290)^2 + 1.498 \times 10^3(290) - 1.834 \times 10^4 \]  \hspace{1cm} (41)

\[ H_{HTF\ INLET} = 529,2757\ kJ / kg \]  \hspace{1cm} (42)

And the same procedure can be followed to determine the outlet enthalpy of the Therminol VP-1 heat transfer fluid:

\[ H_{HTF\ OUTLET} = 1.377(T_{OUTLET})^2 + 1.498 \times 10^3(T_{OUTLET}) - 1.834 \times 10^4 \]  \hspace{1cm} (43)
\[ H_{HTF\ OUTLET} = 1,377 \times (391)^2 + 1,498 \times 10^3 \times (391) - 1,834 \times 10^4 \] (44)

\[ H_{HTF\ OUTLET} = 774,3761 \text{kJ/kg} \] (45)

The required mass flow of heat transfer fluid \((m_{HTC})\), then, can be found by introducing (42) and (45) in the original expression (37):

\[ m_{HTF} = \frac{275 \times 10^6 \text{Wt}}{774,3761 \times 10^3 \text{J/kg} - 529,2757 \times 10^3 \text{J/kg}} = 1122 \text{ kg/s} \] (46)

According to the selected H-type layout of the solar field, it is interesting to find the mass flow of heat transfer fluid in a single collector loop \((m_{HTC\ LOOP})\).

![Diagram](image)

**Figure 113.** Collector loop from the parabolic trough power plant in Gibraleón
[Source.-Own elaboration\(^{165}\)]

**Figure 113.** shows the distribution and main measures of a collector loop in the parabolic trough power plant of Gibraleón. As it can be seen, each collector loop is composed by six Skytrough assemblies with 8 modules or collectors per assembly. The distance between the different assemblies is 1m and the centre-to-centre distance between the two rows of each collector loop is 15m, according to the values previously established. As a result, the mass flow of heat transfer fluid in a single collector loop is given by the following expression:

\[ m_{HTF\ LOOP} = \frac{m_{HTC}}{N_{LOOP}} \] (47)

In order to solve (47), it is necessary to calculate the total number of collector loops along the solar field \((N_{LOOP})\), which is easily found:

\[ N_{LOOP} = \frac{N_{SCA}}{N_{SCA_{LOOP}}} = \frac{720 \text{ collector assemblies}}{6 \text{ collector assemblies/loop}} = 120 \text{ loops} \] (48)

By introducing (48) in the original expression of (47), the mass flow of heat transfer fluid in a single collector loop is:

\[ 165 \text{ Vasquez, R. 2011. Symplified methodology for designing Parabolic Trough Solar Power Plants. College of Engineering of the University of South Florida.} \]
\[ m_{HTF \ LOOP} = \frac{1122 \ \text{kg/s}}{120 \ \text{loops}} = 9.35 \ \text{kg/s} \] (49)

In order to ensure a good thermal exchange, it is necessary to determine whether the heat transfer fluid flows in a turbulent regime, and this can easily be known by calculating the **Reynolds Number (Re)** under the mentioned conditions, which is given by the following expression:

\[ \text{Re} = \frac{v_{HTF} \cdot D_{TUBE} \cdot \rho_{HTF}}{\mu_{HTF}} \] (50)

There are, then, many parameters that need to be determined before obtaining the Reynolds Number. The diameter of the tube is known, as according to the technical data of the SCHOTT PTR70 linear receiver provided in **Annex II.**, this device has a diameter of 70mm. However, it is still necessary to determine the speed of the Therminol VP-1 \( (v_{HTF}) \), its density \( (\rho_{HTF}) \) and its dynamic viscosity \( (\mu_{HTF}) \). Both density and viscosity of the heat transfer fluid will depend on the temperature, and specific mathematical expressions relating them to temperature can be found in **Annex II.**. However, this annex does include tabulated values for some different values, which makes it easier to determine the density and dynamic viscosity of the fluid. The point is to select which temperature is the one to be considered. According to the fact that \( T_{INLET} \) and \( T_{OUTLET} \) have been previously established in 290°C and 391°C, the Number of Reynolds will be discussed for the most favorable situation (290°C), the most unfavorable situation (391°C) and the intermediate situation, which is given by the average temperature between both values (340,5°C). In order to do so, it is necessary to know the different speeds of these fluids for the discussed temperatures, which are given by:

\[ v_{HTF} = \frac{m_{HTF \ LOOP}}{\rho_{HTF} \cdot \pi \cdot (R_{TUBE})^2} \] (51)

The different expressions have been applied for the three reference temperatures, obtaining the following results. Please notice that it has been necessary to interpolate some density and dynamic viscosity from the tables provided in **Annex II.**, as no data is provided for the specific temperatures of 290°C and 340,5°C (although it is for 391°C).

**Table 32. Comparison of HTF different physical properties** [Source.- Own elaboration]

<table>
<thead>
<tr>
<th>( \rho_{HTF} ) [kg/m³]</th>
<th>( \mu_{HTF} ) [Pa·s]</th>
<th>( v_{HTF} ) [m/s]</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>290°C</td>
<td>7,56</td>
<td>0,01142x10⁻³</td>
<td>11,25</td>
</tr>
<tr>
<td>340,5°C</td>
<td>17,28</td>
<td>0,01242x10⁻³</td>
<td>4,92</td>
</tr>
<tr>
<td>391°C</td>
<td>35,00</td>
<td>0,01340x10⁻³</td>
<td>2,43</td>
</tr>
</tbody>
</table>
According to a collector loop mass flow rate of 9,35 kg/s and a linear receiver diameter of 70mm, the values obtained and provided in Table 32. show that high Reynolds Numbers are obtained no matter which the temperature is, moving between a range of 5,21x10⁵ at the inlet temperature of 291°C to a value of 4,44x10⁵ at the outlet temperature of 390°C. It can be concluded that, due to the high Reynolds Numbers obtained, a turbulent regime is always kept by the heat transfer fluid trough the solar field, ensuring this way a good thermal exchange.

To this point, the main elements of the solar field have been determined, as well as the parameters related to them under conventional operating conditions for the selected location. As a result, it is the time to study the performance of the solar field of the parabolic trough power plant in Gibraleón, determining the main efficiencies and parameters that characterise this plant in order to verify the technical feasibility of the plant. At the same time, this manual calculating stage will help to validate some of the results obtained with SAM in previous stages of this project. First of all, it is necessary to introduce the concept of acceptance angle (θ_{ACC}), also known as incidence angle, which is the maximum angle between two direct normal irradiation beams over the surface of the collector in order to ensure that, when they are reflected, they will hit the linear receiver.

![Diagram of a parabolic trough solar collector](image)

**Figure 114. Optical parameters in a parabolic trough solar collector**

[Source.- Silva Pérez, M. 2004. Sistemas termosolares de concentración, University of Seville]

**Figure 114.** shows the optical relation between the acceptance angle (θ_{ACC}) and the specific features of the parabolic trough collector system, such as the diameter of the absorber tube (D) or the aperture angle of the collector (Ω), which are defined by the manufacturer. According to this feature, the concentrating ratio (C) of a parabolic trough collector, which is the relation between the area of the collector (A_C) and the absorbing area of the receiver tube (A_TUBE), is given by the following expression:

\[
C = \frac{A_C}{A_{TUBE}} = \frac{2 \cdot A_{APERTURE}}{L_{TUBE} \cdot \pi \cdot D_{TUBE}} \tag{52}
\]
According to the specific features of the Skytough collector and the SCHOTT PTR70 linear receiver provided in Annex II, the concentrating ratio of the selected collector for the parabolic trough power plant in Gibraleón is:

\[ C = \frac{2 \cdot 656 m^2}{115 m \cdot \pi \cdot 0,07 m} = 51,88 \]  

(53)

As it can be seen, the concentrating ratio for a Skytough assembly is 51,88. Please notice that the length of the absorber tube \( L_{\text{TUBE}} \) is the same as the length of the collector assembly, and not the length of an individual SCHOTT PTR70 element. It is easy to observe that, the bigger the diameter of the absorber tube is, the smaller the concentrating radio will be. It is, then, a matter of balance between concentrating ratio (which can be estimated as the level of concentration of solar radiation onto the absorber tube) and the diameter of the linear receiver, as bigger diameters will stand bigger heat transfer fluid flows and, consequently, bigger outputs will be reached. Once that the concentrating ratio is known, the acceptance angle can easily be determined trough the following expression:

\[ \theta_{\text{ACC}} = \arcsen \left( \frac{1}{C} \right) \]  

(54)

And so:

\[ \theta_{\text{ACC}} = \arcsen \left( \frac{1}{51,88} \right) = 1,1045^\circ \]  

(55)

The maximum acceptance angle \( \theta_{\text{ACC}} \) for the different Skytough assemblies in the parabolic trough power plant of Gibraleón is 1,1045\(^\circ\) and must not be exceeded at any case in order to ensure that the maximum direct normal radiation is collected and optical losses are minimal. The mathematical expression of the solar field global efficiency in a parabolic trough solar field is:

\[ \eta_{\text{SOLAR FIELD}} = K(\theta_{\text{ACC}}) \cdot \eta_{\text{PEAK OPTICAL}} \cdot \eta_{\text{THERMAL}} \]  

(56)

It is necessary to introduce the main parameters of the equation in order to clarify the procedure. The optical efficiency of the solar field will depend on three variables: the optical peak efficiency \( \eta_{\text{PEAK OPTICAL}} \), the thermal efficiency \( \eta_{\text{THERMAL}} \), and, as it has been previously mentioned, the different acceptance angles obtained along the year, which are considered with the modifier per acceptance angle \( K(\theta_{\text{ACC}}) \), also known as insolation clearness index.

To this point it is necessary to remember how simulation was performed in SAM, in order to ensure that the decisions taken in the program are also applied to this calculation. The peak optical efficiency of the solar field was based on two main parameters, the total amount of heat losses occurred in the different heat collecting elements \( Q_{\text{HEAT LOSS}} \) and and heat losses when there is a temperature difference of 316,5\(^\circ\)C between the average temperature of the solar field and the ambient temperature \( Q_{\text{RISING LOSS}} \). For the first value, the SCHOTT PTR70 was
selected in the SCA/HCE module (it was the defect linear receiver, in fact) and through different internal calculations based on self developed formulas specified in the System Advisor Model User Guide - Version 2011.5.23., a value of $Q_{HCE \, LOSS}$ of 29,0979W/m² was obtained. The procedure for the piping losses was a bit more complex, as several parameters were taken into account: the inlet temperature ($T_{INLET}$) and outlet temperature ($T_{OUTLET}$) of the heat transfer fluid in the solar field, the reference temperature ($T_{REFERENCE}$), piping heat loss temperature coefficients 1 to 3 ($F_{PHL, 1}$, $F_{PHL, 2}$, $F_{PHL, 3}$) and heat losses when there is a temperature difference of 316,5°C between the average temperature of the solar field and the ambient temperature ($Q_{PIPING \, LOSS \, AT=316°C}$). Although the inlet, outlet and reference temperatures were introduced from the values provided in Annex II., the different coefficients and other specific values were taken for the defect ones for the SCHOTT PTR70, as they had been obtained from real experiences in parabolic trough power plants of the United States and were considered as reliable. With all this features into account, the total amount of piping losses $Q_{PIPING \, LOSS}$ were estimated to be 10,5777W/m². Through the combination of both heat collecting elements and piping losses, the peak optical efficiency of the solar field was estimated to be 77,9195%.

It is necessary, however, to validate this result before determining the global efficiency of the solar field, as it plays an essential role in its final value. As a result, as it is required to apply the following expression:

$$\eta_{OPTICAL}^{\text{PEAK}} = Rf \cdot F_{CLEANING} \cdot \gamma \cdot \tau \cdot \sigma$$  \hspace{1cm} (57)

Five new parameters have been introduced. First of all, reflectivity of the reflecting surface ($Rf$) and the cleanliness of the collector ($F_{CLEANING}$) must be considered, as their values are critical. If the reflecting surface does not work properly or it is dirty, this will surely result in a minor solar peak efficiency in the solar field, and so, it is very important to select the best reflector (which has been already done due to the fantastic features of the chosen ReflecTech reflecting surface) and to carry out a deep maintenance effort in order to ensure that the optical characteristics of the different elements of the solar field are kept within acceptable levels. The reflectivity of the ReflecTech reflecting surface can easily be obtained from the specific features provided in Annex II., and it is established in a 94%. At the same time, in order to ensure that the same reference conditions that were used in SAM are considered, the chosen cleanliness factor is the same that was introduced in the SCA/HCE module of SAM (Annex V.), which is 97% (mirror cleanliness factor). The interception factor ($\gamma$) accounts for the total amount of energy that, once that the solar beam has been reflected, hits the absorber tube. This value is not available in SAM, although due to the similarity to the bellow shadowing input, as it also accounts for a reduction in the amount of profitable reflected radiation, the same 96,3% value has been chosen. The next parameter is related to the glass solar transmittance ($\tau$) of the absorber tube (not all the solar radiation that is reflected on the absorber tube is able to hit the absorber surface of the receiver), which according to the technical features of the SCHOTT PTR70 linear receiver provided in Annex II. is 96,5% and, according to SAM, is 96,3%. As both values are very similar and the reference values are the ones introduced in SAM, the selected transmittance value for the parabolic trough power plant in Gibraleón is 96,3%. Finally, the tube absorbance ($\sigma$) is related to the amount of solar radiation that
the absorber surface of the linear receiver is able to get. According to Annex II., this value is 96%, approximately, which is just the same as the value provided by SAM and so, this will be the selected option.

![Figure 115. Related optical parameters in a parabolic trough solar collector](image)

[Source.- Silva Pérez, M. 2004. Sistemas termosolares de concentración, University of Seville]

Once that the main parameters are known, the peak optical efficiency is:

\[
\eta_{\text{peak, optical}} = 0.94 \cdot 0.97 \cdot 0.963 \cdot 0.963 \cdot 0.96 = 0.81175
\] (58)

According to (58), the peak optical efficiency of the solar field is 81.175%. Please notice that this value is higher than the peak optical efficiency provided by SAM, which, as it has been said, was estimated in 77.9195%. It can easily be observed that both values are reasonably similar, as the difference between them is of approximately 4% and can be considered within acceptable variation limits. In order to ensure that the global efficiency of the solar field, which depends on the peak optical efficiency, is as real as possible, the chosen peak optical efficiency value for the parabolic trough is 77.9195%, as it is the most restrictive one. On the other hand, the thermal efficiency of the linear receiver can be directly taken from the data provided in Annex II., which is established in 96%.

![Figure 116. Thermal exchanges in a parabolic trough linear receiver](image)

[Source.- Silva Pérez, M. 2004. Sistemas termosolares de concentración, University of Seville]
This thermal efficiency is usually provided by the linear receiver manufacturer, and takes into account the different thermal exchanges carried out during conventional operating conditions in the heat collecting element. **Figure 116.** Shows some of these thermal exchanges, being possible to observe the thermal energy provided by the incident solar radiation ($Q_{e-abs}$), the thermal exchange to the heat transfer fluid ($Q_{e-t,conv}$) as well as the different thermal losses occurred in the device due to convection ($Q_{e-sa,conv}$) or radiation processes ($Q_{e-s,rad}$). The only parameter that remains unknown is the modifier per acceptance angle (or insolation clearness index) of the Skytrough collector. In order to determine them, location’s latitude and longitude have been introduced in the NASA Solar Survey\textsuperscript{166}, obtaining the following results:

**Table 33.** Average, maximum and minimum insolation clearness index (1983-2005) for the selected location of Gibraleón.

<table>
<thead>
<tr>
<th>K($\theta_{ACC}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
</tbody>
</table>

More information about the NASA insolation clearness index is provided in Annex VI. By introducing the values provided in Table 33, in the original expression (56), it is possible to obtain not only the average modifier per acceptance angle value, but also two upper and lower solar field efficiency limits:

\[
\eta_{SOLAR FIELD(MIN)} = 0.47 \cdot 0.779195 \cdot 0.96 = 0.3516
\]  
(59)

\[
\eta_{SOLAR FIELD(MAX)} = 0.67 \cdot 0.779195 \cdot 0.96 = 0.5012
\]  
(60)

\[
\eta_{SOLAR FIELD(AVERAGE)} = 0.58 \cdot 0.779195 \cdot 0.96 = 0.4429
\]  
(61)

The average solar field efficiency for the parabolic trough power plant in Gibraleón is, then, 44.29%, which depending on the acceptance angle along the year can reach efficiencies of approximately 50.12% or decrease to values around 35.16%. In order to verify these values, it has been considered interesting to compare different solar field efficiencies in similar parabolic trough power plants in Southern Spain:

\textsuperscript{166} http:// eosweb.larc.nasa.gov

\textsuperscript{167} Ibid. [166]
Table 34. Comparison of the different $\eta_{\text{SOLAR FIELD}}$ values for similar Southern Spanish parabolic trough power plants

<table>
<thead>
<tr>
<th>Solar Plant</th>
<th>$\eta_{\text{SOLAR FIELD}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I</td>
<td>43%</td>
</tr>
<tr>
<td>Andasol II</td>
<td>43%</td>
</tr>
<tr>
<td>Extresol I</td>
<td>43%</td>
</tr>
</tbody>
</table>

As it can be seen in Table 34., the average 44.29% value obtained before is very similar to usual solar field efficiencies in similar size power plants located in Southern Spain, and so, it can be concluded that it is a good value. In fact, it is slightly higher than other solar efficiencies in Andasol I, Andasol I and Extresol I plants, which is remarkable. However, what does this solar field efficiency refer to?

Figure 117. Solar field losses in a parabolic trough power plant
[Source.- Silva Pérez, M. 2004. Sistemas termosolares de concentración, University of Seville]

As a result, solar field efficiency accounts for the efficiency of the process shown in Figure 117., related to the conversion of the solar resource (Available Direct Normal Irradiation) into profitable thermal energy (Thermal Energy Provided by the Solar Field). As it can be seen, during this conversion process, different shading, optical, thermal and transmission losses occur, and solar field efficiency is related to the amount of energy that remains after these losses. Please notice that transmission losses have not been considered in this project, as due to the fact that if good maintenance operation is performed, these can be neglected.

4.4.3. Sizing of the thermal storage system.

Now that the main features of the solar field have been calculated and justified, it is the time to define the different parameters of the thermal storage system. In order to do this, the same procedure will be carried out, combining SAM results with manual solving of the different expressions. It is recommended to remember the selected option for the parabolic trough power plant in Gibraleón,
which is based on a cylindrical two-tank molten-salt indirect thermal storage with 7,5 hours of Equivalent Full Load Hours of TES. The expression that relates the different parameters of the thermal storage system is well known:

\[ Q_{SALT} = m_{SALT} \cdot Cp_{SALT} \cdot dT \]  

(62)

Where \( Q_{SALT} \) represents the total amount of thermal energy stored in the tanks, \( m_{SALT} \) is the total mass of molten salt, \( Cp_{SALT} \) is the calorific capacity of the selected molten salt mixture and \( dT \) is the temperature differential. It is important to know the total mass of molten salts required to perform the thermal storage system, as it is a critical element with a considerable cost. At the same time, it is essential to ensure that the amount of molten salt is able to store and provide enough thermal energy, in order to maximize the output of the plant. It is possible to obtain the total mass of molten salt through the following procedure:

\[ Q_{SALT} = m_{SALT} \cdot \int_{T_{COLD}}^{T_{HOT}} Cp_{SALT} \cdot dT \]  

(63)

The calorific capacity of the molten salt mixture depends on the operating temperature, but the total mass does not and can be considered as a constant. Finally, isolating \( m_{SALT} \) from (42), the final expression for the molten salt mass is found:

\[ m_{SALT} = \frac{Q_{SALT}}{\int_{T_{COLD}}^{T_{HOT}} Cp_{SALT} \cdot dT} \]  

(64)

There are several parameters that must be determined before introducing them in the formula above. First of all, the total amount of thermal energy stored in the tanks \( Q_{SALT} \) is obtained by multiplying the thermal energy required to generate the gross turbine design energy under reference conditions \( Q_{DESIGN TURBINE THERMAL INPUT} \) and the chosen Equivalent Full Load Hours of TES value for the plant:

\[ Q_{SALT} = Q_{DESIGN TURBINE THERMAL INPUT} \cdot \text{Equivalent Full Load Hours of TES} \]  

(65)

\[ Q_{SALT} = 137,5 \text{MWt} \cdot 7,5 \text{ hours} = 1.031,25 \text{MWh} \]  

(66)

Please notice that the value obtained is equal to the value provided by SAM (Annex V.) and so, it can be concluded that it is correct. On the other hand, it is necessary to solve a defined integral. In order to do so, it is necessary to remember the different storage tank temperatures, which were established at 293°C for the cold tank \( T_{COLD TANK} \) and 386°C for the hot tank \( T_{HOT TANK} \), approximately. This is a simple equation indeed, but it is necessary to find the
expression that relates the calorific capacity of the molten salt mixture with the operating temperature on the storage system\(^{168}\):

\[
C_p_{SALT} = 1.443 + 0.172T
\]  

(67)

Please notice that (67) is a general Cp expression for any 60%NaNO\(_3\) + 40%KNO\(_3\) molten salt mixture and minor variations may appear when using the selected HITEC solar salt mixture, although they have been considered as non relevant. It is important to ensure that temperatures are introduced in [K], becoming 566K for the cold tank temperature and 659K for the hot tank temperature. Introducing (67) in the integral expression allows it to be solved:

\[
\int_{T_{COLD}}^{T_{HOT}} C_p_{SALT} \cdot dT = \int_{T_{COLD}}^{T_{HOT}} (1.443 + 0.172T) \cdot dT
\]  

(68)

\[
\begin{align*}
\int_{T_{COLD}}^{T_{HOT}} (1.443 + 0.172T) \cdot dT &= \left[1.443T + \frac{0.172T^2}{2}\right]_{T_{COLD}}^{T_{HOT}} \\
&= \left[1443 \cdot (659K) + \frac{0.172 \cdot (659K)^2}{2}\right] - \left[1443 \cdot (566K) + \frac{0.172 \cdot (566K)^2}{2}\right]
\end{align*}
\]  

(69)

As a result, the expression obtained id (69) is evaluated for both hot tank and cold tank temperatures in [K], as it is shown in (70).

\[
\left[1443 \cdot (659K) + \frac{0.172 \cdot (659K)^2}{2}\right] - \left[1443 \cdot (566K) + \frac{0.172 \cdot (566K)^2}{2}\right]
\]  

(70)

It is possible now to know the value of the integral, which is:

\[
\int_{T_{COLD}}^{T_{HOT}} C_p_{SALT} \cdot dT = 143.996,55 \quad \frac{J}{kg}
\]  

(71)

Once that all the parameters required to obtain the total mass of molten salt storage fluid in the thermal storage system of the parabolic trough power plant in Gibraleón, it is only a matter of introducing both values in the original expression. However, as the molten salt mass must be given in [kg], the total amount of thermal energy stored \((Q_{SALT})\) cannot be introduced in [MWht]. A previous conversion step must be carried out, in order to convert these [MWht] into the [J/s] required to obtain the molten salt mass in [kg] (or multiples):

\[
Q_{SALT} = 1.031,25 \text{MWht} \cdot \frac{3600 \text{MJ}}{1\text{MWht}} = 3.712,500 \text{MJ}
\]  

(72)

\(^{168}\) Ferri, R., A. Cammi and D. Mazzei, 2008. Molten Salt Mixture properties in RELAP5 code for thermodynamic solar power applications. Specific Cp expression for 60%NaNO\(_3\) + 40%KNO\(_3\) solar salt, in [J/kg·K]
Finally:

\[ m_{SALT} = \frac{3.712.500 \times 10^6 J}{143996,55 \frac{J}{kg}} = 25.787,24 t \]  

(73)

In order to ensure a good performance of the plant with a cylindrical two-tank indirect molten salt storage system with 7,5 hours of Equivalent Full Load Hours of TES, 25.787,24 tons of HITEC solar salt are needed. This huge amount of solar salt is related to the large Equivalent Full Load Hours of TES value selected for the parabolic trough power plant in Gibraleón. Experimentally, other thermal storage capacities (the ones considered in the solar field sizing stage) have been studied in order to observe how big the variation is in the required amount of molten salt mass:

**Table 35. Comparison of the different \( m_{SALT} \) values and cost depending on Equivalent Full Load Hours of TES.**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Equivalent Full Load Hours of TES [h]</th>
<th>( m_{SALT} ) [t]</th>
<th>Molten salt cost [€](^{169})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,5</td>
<td>8.593,96</td>
<td>3.179.543,2</td>
</tr>
<tr>
<td>5</td>
<td>17.187,91</td>
<td>6.359.526,7</td>
</tr>
<tr>
<td>7,5</td>
<td>25.787,24</td>
<td>9.539.290,1</td>
</tr>
<tr>
<td>10</td>
<td>34.375,82</td>
<td>12.719.053,4</td>
</tr>
</tbody>
</table>

As it can be seen, the higher the Equivalent Full Load Hours of TES value is, the higher the mass of molten salt mixture is required to ensure the nominal output of the turbine under reference conditions. This is a quite logical value and could have been expected without need of calculating it, but it has been considered as interesting in order to take into account the huge economical variation related to an increase of only 2,5 hours of thermal storage capacity. This fact reinforces the establishment introduced in previous stages, where thermal storage capacity was recommended to be wisely discussed due to the great impact that this has on the total cost of the plant.

To this point, the total mass of molten salt is known, but not a word has said spoken in relation to the storage tanks. In previous stages of the project, both hot and cold storage tanks were discussed, explaining their main features and selecting the best materials and shape for the parabolic trough power plant in Gibraleón. It is the time now to carry out the sizing of these structures, as the final performance and economical cost of the heat storage system will be closely related to this fact. First of all, it is necessary to calculate the volume related to the total amount of molten salt mass. In order to find this value, it is necessary to find some expression that relates some of the already known parameters with

\(^{169}\) Considering the estimated price of 0,37€/kg introduced in **Table 16**.
the volume. It is known that volume is related to density through the following expression:

\[ V_{SALT} = \frac{m_{SALT}}{\rho_{SALT}} \]  

(74)

As \( m_{SALT} \) is known, it is only necessary to determine the density of the molten salt mixture in order to find the related volume. The density of the solar salt depends on the operating temperature of the fluid and, as a result, different densities (and consequently, volumes) will be found for cold and hot tanks. However, before this distinction is done, it is necessary to find some expression that relates the temperature of the molten salt mixture with its density. Regarding to the same source\(^{170}\) consulted for (67), one suitable expression is found:

\[ V_{S_{SALT}} = \frac{1}{2090 - 0,636T} \]  

(75)

As it can be seen, (76) establishes a relation between the specific volume \( V_{S_{SALT}} \) and the temperature of the molten salt fluid. Due to the fact that specific volume is related to density \( \rho_{SALT} \) through the following formula:

\[ V_{S_{SALT}} = \frac{1}{\rho_{SALT}} \]  

(77)

It is possible to obtain the final expression required to related molten salt density and temperature:

\[ \rho_{SALT} = 2090 - 0,636T \]  

(78)

Beginning with the sizing of the hot tank, it is important to remember that its temperature must be introduced in [K] in order to obtain a density value in [kg/m\(^3\)]. As this temperature has been previously calculated (659K or what it is the same, 386 ° C), it is possible to obtain the density of the hot molten salt mixture:

\[ \rho_{HOT_{SALT}} = 2090 - 0,636 \cdot (659K) = 1670,88 \frac{kg}{m^3} \]  

(79)

Consequently, the volume of hot molten salt is:

\[ V_{HOT_{SALT}} = \frac{25,787,24 \times 10^3}{1670,88 \text{kg} / \text{m}^3} = 15,433,33 \text{m}^3 \]  

(80)

The same procedure can be applied to the density and volume of the cold molten salt, which is stored at a temperature of 293°C (566K):

\(^{170}\) Ibid. [168]
\[
\rho_{\text{Cold Salt}} = 2090 - 0.636 \cdot (566 \, K) = 1730.02 \, \frac{\text{kg}}{\text{m}^3}
\]  
\[
V_{\text{Cold Salt}} = \frac{25.787.24 \times 10^3}{1730.02 \, \text{kg/m}^3} = 14.905.75 \, \text{m}^3
\]

As it can be seen, the density of the molten salt mixture tends to increase as the temperature of the fluid decreases, which in turn results smaller molten salt volumes. Now that these two critical parameters have been obtained, it is possible to determine the size of the different molten salt storage tanks, as this procedure is nothing but a conventional optimization problem, largely used along the career. The selected shape for the hot and cold molten salt storage tanks was cylindrical, as this is the most common configuration due to its smaller cost and minor construction requirements. Regarding to Figure 71., the volume of a cylindrical molten salt storage tank is related to its radius \((R_{\text{TANK}})\) and height \((h_{\text{TANK}})\) through the following expression:

\[
V_{\text{TANK}} = \pi \cdot R_{\text{TANK}}^2 \cdot h_{\text{TANK}}
\]  

Beginning with the hot tank, the volume of the storage structure \((V_{\text{TANK}})\) must be a little bit higher than the volume of the hot molten salt mixture \((V_{\text{HOT SALT}})\) in order to ensure that all the amount of molten salt can be stored no matter which the operating temperature or the size of the molten pump are. When temperature varies, as well as when some devices of the thermal storage system are introduced in the storage fluid, the total volume of molten salt can increase. The selected value for the parabolic trough power plant in Gibraleón is an extra 10\%\textsuperscript{171} of the volume at 659K (386°C) of the HITEC solar salt:

\[
V_{\text{HOT TANK}} = V_{\text{HOT SALT}} + 0.1 \cdot V_{\text{HOT SALT}} = 15.433,33 \, \text{m}^3 + 0.1 \cdot 15.433,33 \, \text{m}^3
\]  

\[
V_{\text{HOT TANK}} = 16.976,66 \, \text{m}^3
\]

By introducing (85) in the original expression of (83):

\[
16.976,66 \, \text{m}^3 = \pi \cdot \left( R_{\text{HOT TANK}} \right)^2 \cdot h_{\text{HOT TANK}}
\]  

In order to solve an optimization problem, it is necessary to define a function \(f(x)\). These function must be derived \(f'(x)\), and by equaling the derived function to zero \(f'(x)=0\), maximum and minimum values can be obtained. In this case, as there are two unknown variables in the expression (86), it is necessary to find another alternative formula that relates both of them. Solving:

\textsuperscript{171} Ibíd. [168]
\[ h_{\text{HOT TANK}} = \frac{16.976,66}{\pi \cdot \left( R_{\text{HOT TANK}} \right)^2} \]  

(87)

According to Figure 71, again, the selected function is the one related to the surface area of a cylindrical storage tank, as the smaller the surface area is, the smaller the heat losses will be:

\[ A_{\text{HOT TANK}} = 2\pi \cdot R_{\text{HOT TANK}} \cdot \left( R_{\text{HOT TANK}} + h_{\text{HOT TANK}} \right) = 2\pi \cdot \left( R_{\text{HOT TANK}} \right)^2 + 2\pi \cdot R_{\text{HOT TANK}} \cdot h_{\text{HOT TANK}} \]  

(88)

Introducing (87) in the optimizing function:

\[ f\left( R_{\text{HOT TANK}} \right) = 2\pi \cdot \left( R_{\text{HOT TANK}} \right)^2 + 2\pi \cdot R_{\text{HOT TANK}} \cdot \left( \frac{16.976,66}{\pi \cdot \left( R_{\text{HOT TANK}} \right)^2} \right) \]  

(89)

Simplifying the expression above:

\[ f\left( R_{\text{HOT TANK}} \right) = 2\pi \cdot \left( R_{\text{HOT TANK}} \right)^2 + \frac{33.953,33}{R_{\text{HOT TANK}}} \]  

(90)

Now it is possible to derivate the optimizing function (o), obtaining:

\[ f'\left( R_{\text{HOT TANK}} \right) = 2 \cdot \left( 2\pi \cdot \left( R_{\text{HOT TANK}} \right)^2 \right)^{-1} + \frac{(33.953,33) \cdot R_{\text{HOT TANK}}}{R_{\text{HOT TANK}}} - 33.953,33 \cdot \left( R_{\text{HOT TANK}} \right)' \]  

(91)

\[ f'\left( R_{\text{HOT TANK}} \right) = 4\pi \cdot R_{\text{HOT TANK}} \]  

(92)

The next step in order to minimize the surface area of the storage tank is to equal the derived function (92) to zero:

\[ f''\left( R_{\text{HOT TANK}} \right) = 4\pi \cdot R_{\text{HOT TANK}} - \frac{33.953,33}{\left( R_{\text{HOT TANK}} \right)^2} = 0 \]  

(93)
Solving the expression above:

\[ 4\pi \cdot R_{\text{HOT TANK}} = \frac{33.953,33}{\left( R_{\text{HOT TANK}} \right)^2} \]  \hspace{1cm} (94)

\[ \left( R_{\text{HOT TANK}} \right)^3 = \frac{33.953,33}{4\pi} = 2.701,92 \]  \hspace{1cm} (95)

\[ R_{\text{HOT TANK}} = \sqrt[3]{2.701,92} = 13.93m \]  \hspace{1cm} (96)

In order to verify that this value is effectively a minimum, it is necessary to derivate again expression (92):

\[ f''(R_{\text{HOT TANK}}) = 4\pi \cdot \left( \frac{33.953,33}{R_{\text{HOT TANK}}^2} - \frac{33.953,33}{R_{\text{HOT TANK}}^2} \right) - \frac{67.906,66}{R_{\text{HOT TANK}}^3} \]  \hspace{1cm} (97)

\[ f''(R_{\text{HOT TANK}}) = 4\pi + \frac{67.906,66}{13.93^3} = 37.69 \]  \hspace{1cm} (98)

Now, the tank radius value (R_{\text{TANK}}) is introduced in \( f''(R_{\text{TANK}}) \), obtaining:

\[ f''(R_{\text{HOT TANK}}) = 4\pi + \frac{67.906,66}{13.93^3} = 37.69 \]  \hspace{1cm} (99)

\[ f''(R_{\text{HOT TANK}}) > 0 \]  \hspace{1cm} (100)

It can be observed that, when the R_{\text{TANK}} that it has been previously found is introduced in the second derivative of the optimizing function, the value obtained is positive and, as a result, it can be concluded that the radius of the hot storage tank has been minimized. The height of the storage tank can be found by substituting (96) in the original expression of (87):

\[ h_{\text{HOT TANK}} = \frac{16.976,66}{\pi \cdot 13.93^2} = 27.85m \]  \hspace{1cm} (101)

As a result, the hot tank storage tank size that minimizes the surface area and, consequently, the total amount of thermal losses, is the one related to a radius of 13.93m and a height of 27.85m. In order to obtain integer values of both parameters (which in turn will result in smaller construction issues), both values will be rounded to the upper integer, resulting in a final radius of 14m (28 meters of diameter) and a height of 28m for the hot tank structure. Please notice
that despite natural rounding in this case tends to upper values, smaller values
to the ones obtained in the expressions above must not be taken, as they would
not answer to the specific volume requirements of the hot molten salt module.

In order to verify these values, it has been considered interesting to compare
some of the Southern Spanish currently operative parabolic trough power plant
heat storage tank sizes in order to see if they are similar to the ones obtained for
the parabolic trough power plant in Gibraleón:

Table 36. Comparison of hot tank thermal storage system sizing in some
Southern Spanish operational parabolic trough power plants

| Source: Own elaboration\textsuperscript{172} |

<table>
<thead>
<tr>
<th>TES [h]</th>
<th>m\textsubscript{SALT} [t]</th>
<th>Q\textsubscript{SALT} [MWht]</th>
<th>Hot tank height [m]</th>
<th>Hot tank diameter [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I&amp;II</td>
<td>7,5</td>
<td>28.500</td>
<td>1010</td>
<td>14</td>
</tr>
<tr>
<td>Project</td>
<td>7,5</td>
<td>25.787,24</td>
<td>1031,25</td>
<td>28</td>
</tr>
</tbody>
</table>

It can be observed that, under very similar thermal storage conditions, the hot
storage tank of the parabolic trough power plant in Gibraleón introduces some
differences when compared to the hot storage tanks used in Andasol I and
Andasol II power plants, especially in terms of height. This difference may be
related to the fact that smaller tank heights require smaller construction efforts
and building cost is reduced. However, this saving is performed by increasing the
surface area of the storage tank, which not only is related to bigger thermal
losses in the tank, but to the fact that more tank surface area results in bigger
insulating requirements as these structures must be conveniently covered with
different insulating materials, as it has been previously mentioned. It is then, a
balance between construction issues and insulating issues. While Andasol designs
introduced smaller but wider heat storage tanks, the selected option for the
parabolic trough power plant in Gibraleón is this new design, which sacrifices a
cost and mounting time reduction in construction stages of the thermal storage
system in order to achieve higher thermal efficiencies at a lower insulating cost,
which in turn will result in higher power output. The same procedure must be
carried out in order to determine the sizing of the cold storage tank of the
parabolic trough power plant in Gibraleón. Again, an extra 10% of volume will be
needed in the cold storage tank in order to absorb the different volume
variations of the fluid that may occur during normal operating conditions. The
temperature of the cold tank is 566K (293°C) and, as a result:

\[
V_{\text{COLD TANK}}^{\text{COLD SALT}} = V_{\text{COLD SALT}}^{\text{COLD SALT}} + 0,1 \cdot V_{\text{COLD SALT}}^{\text{COLD SALT}} = 14.905,75 m^3 + 0,1 \cdot 14.905,75 m^3 \quad (102)
\]

\[
V_{\text{COLD TANK}}^{\text{COLD SALT}} = 16.396,33 m^3 \quad (103)
\]

\textsuperscript{172} Some data has been provided in the different plant promoter’s websites, as well as from the
data provided in http://www.nrel.gov. (accessed May 18\textsuperscript{th} 2012)
This cold tank volume is introduced in the general volume expression for cylindrical storage tanks (83) provided in Figure 71.,

\[
16.396,33 m^3 = \pi \cdot \left( R_{COLD\ \text{TANK}} \right)^2 \cdot h_{COLD\ \text{TANK}}
\]  

As it happened in the sizing stage of the hot storage tank, it is a matter of optimization and so, it is necessary to relate the two unknown parameters in a single equation. This requirement can be fulfilled by isolating the height of the cold tank from the expression above:

\[
h_{COLD\ \text{TANK}} = \frac{16.396,33}{\pi \cdot \left( R_{COLD\ \text{TANK}} \right)^2}
\]  

Again, the objective is to minimize the surface area of the cylindrical storage tank in order to reduce thermal losses and insulating costs. Regarding to Figure 71., and as it has been done in the hot tank sizing stage, the optimizing function for the cold storage tank of the parabolic trough power plant in Gibraleón is:

\[
A_{COLD\ \text{TANK}} = 2\pi \cdot R_{COLD\ \text{TANK}} \cdot \left( R_{COLD\ \text{TANK}} + h_{COLD\ \text{TANK}} \right) = 2\pi \cdot \left( R_{COLD\ \text{TANK}} \right)^2 + 2\pi \cdot R_{COLD\ \text{TANK}} \cdot h_{COLD\ \text{TANK}}
\]  

Introducing (105) in the optimizing function:

\[
f\left( R_{COLD\ \text{TANK}} \right) = 2\pi \cdot \left( R_{COLD\ \text{TANK}} \right)^2 + 2\pi \cdot \frac{16.396,33}{\pi \cdot \left( R_{COLD\ \text{TANK}} \right)^2}
\]

Simplifying the expression above:

\[
f\left( R_{COLD\ \text{TANK}} \right) = 2\pi \cdot \left( R_{COLD\ \text{TANK}} \right)^2 + \frac{32.792,65}{R_{COLD\ \text{TANK}}}
\]

Now it is possible to derivate the optimizing function (108), obtaining:

\[
f'\left( R_{COLD\ \text{TANK}} \right) = 2 \cdot \left( 2\pi \cdot \left( R_{COLD\ \text{TANK}} \right)^{2-1} \right) + \left( 32.792,65 \cdot R_{COLD\ \text{TANK}} - 32.792,65 \cdot \left( R_{COLD\ \text{TANK}} \right)^2 \right) \cdot \frac{1}{R_{COLD\ \text{TANK}}} \cdot \left( R_{COLD\ \text{TANK}} \right)^2
\]  

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Design of a Solar Thermal Power Plant

\[ f'(R_{\text{COLD TANK}}) = 4\pi \cdot R_{\text{COLD TANK}} - \frac{32.792.65}{\left(\frac{R_{\text{COLD TANK}}}{2}\right)^2} \] (110)

By equaling the derived function to zero, the radius of the cold storage tank can be minimized:

\[ f'(R_{\text{COLD TANK}}) = 4\pi \cdot R_{\text{COLD TANK}} - \frac{32.792.65}{\left(\frac{R_{\text{COLD TANK}}}{2}\right)^2} = 0 \] (111)

Solving the expression above:

\[ 4\pi \cdot R_{\text{COLD TANK}} = \frac{32.792.65}{\left(\frac{R_{\text{COLD TANK}}}{2}\right)^2} \] (112)

\[ \left(\frac{R_{\text{COLD TANK}}}{2}\right)^3 = \frac{32.792.65}{4\pi} = 2.609.56 \] (113)

\[ R_{\text{COLD TANK}} = \sqrt[3]{2.609.56} = 13.77 \text{m} \] (114)

As it was done before, in order to verify that this value is effectively a minimum, it is necessary to derivate again the first derivative function (110):

\[ f''(R_{\text{COLD TANK}}) = 1 \cdot (4\pi \cdot R_{\text{COLD TANK}}^{1-1}) - \left(\frac{32.792.65}{\left(\frac{R_{\text{COLD TANK}}}{2}\right)^2}\right) - \frac{32.792.65}{\left(\frac{R_{\text{COLD TANK}}}{2}\right)^2} \] (115)

\[ f''(R_{\text{COLD TANK}}) = 4\pi + \frac{65.585.30}{R_{\text{COLD TANK}}^3} \] (116)

If the tank radius value (R_{\text{TANK}}) is introduced in f''(R_{\text{TANK}}), obtaining a positive value, it can be concluded that the cold storage tank radius obtained in (114) is a minimum, indeed:

\[ f''(R_{\text{COLD TANK}}) = 4\pi + \frac{65.585.30}{13.77^3} = 37.69 \] (117)

\[ f''(R_{\text{COLD TANK}}) > 0 \] (118)
The value of the second derivative of the optimizing function for the determined cold storage tank radius is positive (and surprisingly the same value obtained in the hot storage tank sizing stage) and, as a result, it can be concluded that this value is, effectively, a minimum. Finally, the height of the storage tank can be found by substituting \( u \) in the original expression of \( r \):

\[
h_{\text{COLD TANK}} = \frac{16.396.33}{\pi \cdot 13.77^2} = 27.53m
\]  

(119)

Although the values obtained for the cold storage tank are smaller to the ones calculated for the hot storage module, there is only a small difference between them. In fact, when the upper rounding is applied, the final radius of the cold storage tank is 14m with a height of 28m, just the same as the hot storage sizing values. This is in fact a verification of the correction of the values obtained, as both hot and cold storage tanks in parabolic trough power plants are typically the same size (differences may be noticed when comparing vessel width, materials and insulating requirements). If the same comparison is performed for this system:

**Table 37. Comparison of cold tank thermal storage system sizing in some Southern Spanish operational parabolic trough power plants [Source.- Own elaboration\(^{173} \)**

<table>
<thead>
<tr>
<th>TES [h]</th>
<th>( m_{\text{SALT}} ) [t]</th>
<th>( Q_{\text{SALT}} ) [MWht]</th>
<th>Cold tank height [m]</th>
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<td>1031,25</td>
<td>28</td>
</tr>
</tbody>
</table>

It is easy to notice that both **Table 36.** and **Table 37.** are identical, as both hot tank and cold tank have the same sizes. Please notice that, again, the selected option for the parabolic trough power plant in Gibraleón introduces height values that are notably bigger to the ones used in Andasol power plants (which has been chosen as a reference, but does not mean to be the correct option). This choice answers to an intention of decreasing thermal losses and thermal insulating costs by reducing the surface area of the storage tank to the minimum, despite introducing higher construction time and cost at initial stages of the project. Due to the technology currently available (there are enough molten salt pump lengths, materials and solutions in order to cover these heights) and taking into account that these sizes have largely been used in other application such as petrol storage and chemical industries, among many others, this option is considered to be surely available. Now that the main parameters of the heat storage system have been discussed, determined and validated, it is the time to introduce the different values in SAM’s Thermal Storage module in order to allow the simulation of the performance of the plant. The Equivalent Full Load Hours of TES has been established in 7,5 hours in the two-tank indirect molten

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\(^{173}\) Some data has been provided in the different plant promoter's websites, as well as from the data provided in http://www.nrel.gov. (accessed May 24\(^{th}\) 2012)
salt thermal storage system of the parabolic trough power plant in Gibraleón. These parameters can easily be introduced as the answer to what has been previously determined. However, there are new input variables that must be characterised before simulation is carried out.

First of all, the turbine efficiency TES adjusting factor (TES\textsubscript{ADJ,EFFICIENCY}) is related to imperfections in heat exchange processes in the thermal storage system. The defect value is 98.5% and, as this value is considered to be reliable due to the fact that SAM is based on real experiences, this is also the chosen factor for the parabolic trough power plant in Gibraleón. The turbine TES gross output factor (TES\textsubscript{ADJ,GROSS}) is related to the maximum TES discharge rate of the power plant. The selected value is 99.8%, as the discharge rate of the storage system will be typically operating at a 100% and only very punctual problems may reduce its efficiency. Simulation will be performed taking into account that there is no thermal energy stored in the system at the start and so, initial thermal storage is zero. It is the time not to select a value for the tank heat losses of the system. In order to do so, the System Advisor Model User Guide - Version 2011.5.23 provides the following table:

<table>
<thead>
<tr>
<th>System Description</th>
<th>Hours of Thermal Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>100 MW Two Tank Indirect VP-1/Nitrate Salt</td>
<td>0</td>
</tr>
<tr>
<td>200 MW Two Tank Indirect VP-1/Nitrate Salt</td>
<td>0</td>
</tr>
<tr>
<td>200 MW Two Tank Direct Hitec Salt</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 118.** Suggested tank heat losses [MW] values for different thermal storage capacities [h]


As the selected configuration for the parabolic trough power plant in Gibraleón is not available, the chosen value will be obtained by interpolating the different values for 100MW and dividing them by 2:

\[
\frac{9h - 6h}{1,23MW - 0,96 MW} = \frac{9h - 7,5h}{1,23MW - x}
\]

(120)

\[
x = 1,23 - \left( \frac{9h - 7,5h}{9h - 6h} \right) \cdot (1,23MW - 0,96 MW) = 1,095MW
\]

(121)

\[
\text{Thermal Losses}_{50,MW} = \frac{1,095MW}{2} = 0,5475 MW
\]

(122)

As a result, the thermal loss value for the parabolic trough power plant in Gibraleón is 0,5475MW and so it is introduced in SAM. According to the introduced inputs, SAM provides some results: the \textit{maximum energy storage} is 1031,25 MWht, which is just the same value that was previously obtained by
manual solving, and the heat exchanger duty which is established in 1 and it is given by the following expression:

\[
\text{Heat Exchanger Duty} = SM - 1 = 2 - 1 = 1 
\]  

(123)

Once that the heat exchanger duty has been determined, it is possible to obtain the maximum power to storage, which is given by:

\[
E_{\text{MAX TO STORAGE}} = \frac{Q_{\text{DESIGN TURBINE}}}{\text{THERMAL INPUT}} \cdot \text{Heat Exchanger Duty} 
\]  

(124)

\[
E_{\text{MAX TO STORAGE}} = 137.5 \text{MWt} \cdot 1 = 137.5 \text{MWt} 
\]  

(125)

Finally, the maximum power from storage is:

\[
E_{\text{MAX FROM STORAGE}} = E_{\text{MAX TO STORAGE}} \cdot TES_{\text{ADJ.GROSS}} \cdot TES_{\text{ADJ.EFFICIENCY}} 
\]  

(126)

\[
E_{\text{MAX FROM STORAGE}} = 137.5 \text{MWt} \cdot 0.985 \cdot 0.998 = 134.08 \text{MWt} 
\]  

(127)

Please notice that this value is lower than the value provided by SAM, which is 139,315MWt. The chosen value is 134,08MWt, as it is not possible that the thermal system provides more than the energy it receives from the solar field, due to heat losses in the heat exchangers and tanks. Now that the main parameters of the thermal storage system have been determined, it is the time to carry out a general approach to the thermal storage dispatch control, in order to explain the main parameters this simulates.

The thermal storage dispatch control is used to decide whether to operate the power block or not depending on the amount of stored energy in the storage system and the thermal energy provided by the solar field. The selected schedule for the parabolic trough power plant in Gibraleón is the Generic Summer Peak dispatch schedule, which is divided in 6 periods of time along the year. It is possible, however, to specify different dispatch schedules according to the specific features of each project, but for this project the Summer Peak distribution is considered a good option. The dispatch schedule of SAM is based on different parameters:

- **Storage dispatch with sun**: during periods of sunshine, the thermal storage system will provide energy to the power block only when there is insufficient solar resource to operate the turbine at its nominal operating conditions and the stored energy is equal or greater to the product of the storage dispatch factor with sun and the maximum energy in storage.

- **Storage dispatch without sun**: when there is no solar resource, the power block will only be driven by the thermal storage system when the stored
energy is equal or greater to the product of the storage dispatch factor without sun and the maximum energy in storage.

- **Turbine output fraction:** the turbine output fraction, design turbine thermal input and the cycle part load thermal to electrical factors are related through the following expression:

\[
Q_{toPB_{Min}} = Q_{PB_{Design}} \cdot (F_{ET_4} \cdot F_{PB_{Min}}^4 + F_{ET_3} \cdot F_{PB_{Min}}^3 + \\
F_{ET_2} \cdot F_{PB_{Min}}^2 + F_{ET_1} \cdot F_{PB_{Min}} + F_{ET_0})
\]

\[
Q_{toPB_{Max}} = Q_{PB_{Design}} \cdot (F_{ET_4} \cdot F_{PB_{Max}}^4 + F_{ET_3} \cdot F_{PB_{Max}}^3 + \\
F_{ET_2} \cdot F_{PB_{Max}}^2 + F_{ET_1} \cdot F_{PB_{Max}} + F_{ET_0})
\]

**Figure 119.** Relation between the turbine output fraction, design turbine thermal input and cycle part load thermal to electrical factors


Through this combination, it is possible to specify maximum and minimum load level limits at which the thermal storage system provides thermal energy to the power block.

- **Fossil fill fraction:** it is related to fossil-fuel backup systems in the storage system, and as the parabolic trough power plant in Gibraleón is a pure solar thermal plant, all the input parameters are zero.

- **Payment allocation factor:** it is used to adjust the price of the electricity depending on the hour of operation. As SAM is only used in order to perform a technical simulation, it is not relevant for the simulation and defect values are left in the system.

Now that the main parameters of the thermal storage system have been introduced, discussed and verified, the final layout of SAM’s Thermal Storage module is provided in **Annex V**.

**4.4.4. Sizing and performance of the steam cycle.**

The steam cycle of the parabolic trough power plant in Gibraleón is largely the most conventional system of the thermal solar technology, as despite minor variations these kinds of systems are practically the same as the conventional steam cycles typically used in conventional fossil fuel-based power plants. As a result, a general approach will be carried out in order to give a general perspective of the power block, but all the efforts will be focused on determining the efficiency of the steam cycle. Taking this feature into account, and due to the complexity of all the different steam cycle parameters that need to be determined in order to ensure a good characterization of the power block which would in fact constitute a single project themselves, some reference values have been taken from Kelly, B. and D. Kearney. 2006. *Thermal storage commercial*
plant design study for a 2-tank indirect molten salt system. NREL, provided by the United States National Renewable Energy Laboratory. This document provides steam and heat transfer fluid (Therminol VP-1) parameters (temperature, pressure, enthalpy and thermal power equivalent) according to a indirect thermal storage and 50MW of nominal output parabolic trough model for United States locations. Due to the similarity with the parabolic trough power plant in Gibraleón, these values will be considered as representative for its Rankine Cycle Model and will be taken as a reference in order to obtain the efficiency of the system manually. However, the main purpose of this exercise is to validate the mathematical procedure and at any case the efficiency value obtained through this system will be taken for the simulation of the parabolic trough power plant in Gibraleón, as it would answer to reference conditions that may differ in a great mode from the real values of the plant. It is necessary, then, to characterise these values in order to ensure the complete comprehension of the calculating process, and so, some of the different power block stages will be related to specific numbers according to the following table:

**Table 38. Numerical equivalence of different steam cycle stages.**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Reference number</th>
<th>Field output HTF</th>
<th>Reheater output HTF</th>
<th>Superheater output HTF</th>
<th>Evaporator output HTF</th>
<th>Preheater output HTF</th>
<th>Solar Field input HTF</th>
<th>Preheater input water</th>
<th>Evaporator input water</th>
<th>Superheater input steam</th>
<th>HP turbine input steam</th>
<th>Reheater input steam</th>
<th>LP input steam</th>
<th>Condenser input steam</th>
<th>Condenser output water</th>
<th>LP Preheater input steam</th>
<th>LP Preheater input water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>
These numbers can easily be identified in the following figure:

![Diagram of a Solar Thermal Power Plant]

**Figure 120. Reference stages of the Rankine cycle.**  
[Source.-Own elaboration\(^{174}\)]

Please notice that not all the stages of this cycle have been considered, as only those with available reference data have been provided. This feature, however, is not a real limitation, as the different reference values provided in the mentioned source are largely enough to obtain the efficiency of the steam cycle. Now that the main stages of the process have been identified and located in the diagram, it is the time to introduce the different parameters provided by the mentioned source in order to act as reference data for further calculations. It is obvious that, as these values have been obtained for power plants located in the United States and answer to the very specific operating condition of each power plant, the results obtained cannot be understood as real and definitive ones, as they are just an estimation of approximated operating values. As it has been shown along this project, the different parameters obtained both with SAM and manual calculation are very similar to real operating values and it is possible to affirm that these estimations are reliable enough and can surely be accepted according to the objectives established in initial stages. The reference steam cycle parameters that will be used in this project are specified in the following table. It is important to consider that, as two different fluids are being considered for this system, some parameters are specific for one of them, such as density of the heat transfer fluid and must not be considered for water and steam. Taking this into account:

\(^{174}\) Ibid. [5]
Table 39. Steam cycle reference parameters.
[Source.- Own elaboration\textsuperscript{175}]

\begin{tabular}{|c|c|c|c|}
\hline
 & T [°C] & P [bar] & H [kJ/kg] & \(\rho_{HTF}\) [kg/m\textsuperscript{3}] \\
\hline
1 & 391,00\textsuperscript{176} & 6,20 & 989,4 & 35,00 \\
2 & 225,20 & 1,10 & 699,4 & 1,95 \\
3 & 380,00 & 4,80 & 969,5 & 30,50 \\
4 & 319,00 & 3,00 & 859,3 & 12,21 \\
5 & 301,70 & 1,10 & 828,88 & 9,13 \\
6 & 290,00\textsuperscript{177} & 1,10 & 808,4 & 7,42 \\
7 & 235,01 & 100,67 & 1015,0 & - \\
8 & 311,46 & 100,67 & 1408,1 & - \\
9 & 311,46 & 100,67 & 2726,6 & - \\
10 & 373,00 & 100,01 & 3011,7 & - \\
11 & 290,00 & 54,04 & 2712,4 & - \\
12 & 373,00 & 54,04 & 3195,8 & - \\
13 & 41,55 & 0,08 & 2352,9 & - \\
14 & 41,55 & 0,08 & 163,1 & - \\
15 & 183,34 & 3,04 & 2830,7 & - \\
16 & 41,55 & 9,31 & 163,9 & - \\
17 & 225,01 & 100,67 & 1003,5 & - \\
\hline
\end{tabular}

Please notice that no information is provided in the consulted source for heat transfer fluid enthalpy and density, and values have been obtained by interpolating data from the physical properties brochure of the Therminol VP-1 provided in Annex II. (except for those values related to integer temperatures such as 290°C and 380°C, which can be directly found in tables).

Now that the main reference values have been established, it is the time to begin with the calculating procedure. The steam cycle of the parabolic trough power plant in Gibraleón is based on two fluids. On one hand, the heat transfer fluid

\textsuperscript{175} Ibid. [36]

\textsuperscript{176} Although the value provided is 393°C, the selected HTF outlet temperature, according to previous explanations of this project is 390°C.

\textsuperscript{177} Although the value provided is 293°C, the selected HTF inlet temperature, according to previous explanations of this project is 290°C.
that collects the thermal energy provided by the solar field in order to transfer it to the steam cycle. On the other hand, water is responsible for the functioning of the steam turbine thanks to the thermal energy provided by the heat transfer fluid. It is necessary, then, to determine the mass flow rate of both fluids in the steam cycle of the plant in order to obtain the different works and heat exchanges required to obtain the efficiency of the steam cycle, which is given by the following expression:

$$\eta_{\text{STEAM CYCLE}} = \frac{\sum W_{\text{TURBINE}} - \sum W_{\text{PUMPS}}}{\sum Q_{\text{STEAM GENERATING ISLAND}}}$$ (128)

According to previous stages, the total heat transfer fluid mass flow rate in the parabolic trough power plant in Gibraleón is 1.122 kg/s. However, this value was calculated depending the thermal energy required to ensure the gross turbine output under a Solar Multiple of 2 and 7.5 hours of Equivalent Full Load Hours of TES ($Q_{\text{SOLAR FIELD}}$), which was 275 MWt. No matter which the solar multiple and thermal storage capacity are, the thermal energy provided to the steam cycle is the one related to a nominal output power of 50 MW (55MW under a 10% of parasitic and self consumption losses). This thermal energy is the design turbine thermal input ($Q_{\text{DESIGN TURBINE THERMAL INPUT}}$) previously established, with a value of 137.5 MWt. Taking all these features into account, and using expression (37) again, the mass flow rate of the heat transfer fluid in the steam cycle is:

$$m_{\text{HTC (STEAM CYCLE)}} = \frac{137.5 \times 10^6 \text{Wt}}{774.3761 \times 10^3 \text{J/kg} - 529.2757 \times 10^3 \text{J/kg}} = 561 \text{ kg/s}$$ (129)

Please notice that the heat transfer fluid inlet and outlet temperature enthalpies do not vary, as they are still established in 290°C and 391°C. The heat transfer fluid mass flow rate required to supply enough energy to the steam cycle is 561 kg/s, which is logically half the value obtained under a Solar Multiple of 2. The next step is to determine the mass flow rate of water required to interact with the heat transfer fluid. It is necessary, then, to perform a energy balance in the system:

$$\begin{align*}
\left( m_{\text{HTC (STEAM CYCLE)}} \right) \cdot \left( H_1 - H_6 \right) &= \left( m_{\text{WATER (STEAM CYCLE)}} \right) \cdot \left( H_{10} - H_7 \right)
\end{align*}$$ (130)

Expression (130) shows the energy balance between heat transfer fluid and water in the preheater, steam generator and superheater of the parabolic trough power plant in Gibraleón. This equation, in addition to the reference values introduced in Table (39), will allow to obtain the value of water mass flow rate required to ensure the steam cycle.
Isolating the mass flow rate of water from the expression above:

\[
m_{\text{WATER}}^{\text{(STEAM CYCLE)}} = \frac{m_{\text{HTC}}^{\text{(STEAM CYCLE)}} \cdot (H_1 - H_6)}{(H_{10} - H_7)}
\]  \hspace{1cm} (131)

The different reference values are introduced, obtaining:

\[
m_{\text{WATER}}^{\text{(STEAM CYCLE)}} = \frac{561 \text{ kg/s} \cdot (989.4 - 808.4)}{(3011.7 - 1015.0)} \text{ kJ/kg}
\]  \hspace{1cm} (132)

And finally:

\[
m_{\text{WATER}}^{\text{(STEAM CYCLE)}} = 50.85 \text{ kg/s}
\]  \hspace{1cm} (133)

As a result, the water mass flow rate required to ensure the 50MW Rankine steam cycle is 50.85kg/s. It is the time now to study the main parameters required to obtain the total efficiency of the steam cycle (128). First of all, regarding to the heat exchange between the heat transfer fluid and water in the preheater, it is possible to establish the following energy balance:

\[
\dot{Q}_{\text{PREHEATER}} = - \left( m_{\text{WATER}}^{\text{(STEAM CYCLE)}} \right) \cdot (H_7 - H_8)
\]  \hspace{1cm} (134)

And introducing the different reference values, the total heat provided by the heat transfer fluid to water in the preheater is:

\[
\dot{Q}_{\text{PREHEATER}} = -(50.85 \text{ kg/s} \cdot (1015.0 - 1408.1)\text{kJ/kg}) = 19.989.14\text{kWt}
\]  \hspace{1cm} (135)

According to the heat exchange in the steam generator, a new energy balance is introduced, repeating the procedure above in order to obtain the total heat provided by the heat transfer fluid to the water in the steam generator:

\[
\dot{Q}_{\text{STEAM GENERATOR}} = - \left( m_{\text{WATER}}^{\text{(STEAM CYCLE)}} \right) \cdot (H_8 - H_9)
\]  \hspace{1cm} (136)

\[
\dot{Q}_{\text{STEAM GENERATOR}} = -(50.85 \text{ kg/s} \cdot (1408.1 - 2726.7)\text{kJ/kg}) = 67.050.81\text{kWt}
\]  \hspace{1cm} (137)

And the same procedure is repeated again in order to obtain the total amount of heat exchanged in the superheater of the parabolic trough power plant in Gibraleón.
\[
\dot{Q}_{\text{SUPERHEATER}} = - \left( m_{\text{WATER}} \right)_{\text{(STEAM CYCLE)}} \cdot (H_9 - H_{10})
\]

(138)

\[
\dot{Q}_{\text{SUPERHEATER}} = -(50.85 \text{kg} / \text{s} \cdot (2726.7 - 3011.7) \text{kJ} / \text{kg}) = 14.492,25kWt
\]

Now that the main heat exchanges in the parabolic trough power plant in Gibraleón (preheater, steam generator and superheater) have been determined, it is the time to discuss this issue in the reheater. The main reason for not having applied the same procedure used for the other devices is the fact that the reheater depends on a steam extraction for the turbine, and it is necessary to select a reference value for the plant. According to the values provided in Kelly, B. and D. Kearney. 2006. Thermal storage commercial plant design study for a 2-tank indirect molten salt system. NREL, the selected extraction reference value for the parabolic trough power plant in Gibraleón is Y=30%. As a result, the energy balance for the reheater is given by the following expression:

\[
\dot{Q}_{\text{REHEATER}} = - \left( m_{\text{WATER}} \right)_{\text{(STEAM CYCLE)}} \cdot (H_{11} - H_{12}) \cdot (1 - Y)
\]

(140)

And introducing the different values in the expression above:

\[
\dot{Q}_{\text{REHEATER}} = -(50.85 \text{kg} / \text{s} \cdot (2712.4 - 3195.8) \text{kJ} / \text{kg} \cdot (1 - 0.3))
\]

(141)

Please notice that the turbine extraction factor plays an essential role in the total amount of thermal energy provided by the heat transfer fluid to this extraction steam. The higher is the steam extraction from the turbine, the smaller is the heat exchange in the reheater. Solving (141), it is possible to obtain a value of:

\[
\dot{Q}_{\text{REHEATER}} = 17.206,62kWt
\]

(142)

Once that the thermal energy provided by the heat transfer fluid to the extraction steam from the turbine is known, the only parameters that remain unknown are the ones related to the different absorbed works in the pumps and the generated work of the high pressure and low pressure steam turbine. Regarding to the pumping system, two main pumps will be considered: the feed water pump located after the deaerator and the condensate water pump. Please notice that the circulating cooling water pump has not been considered in these balances, as it has been considered non relevant due to its minor size. Regarding to the feed water pump, the following energy balance is described:

\[
\dot{W}_{\text{FEEDWATER PUMP}} = \left( m_{\text{WATER}} \right)_{\text{(STEAM CYCLE)}} \cdot (H_1 - H_{17})
\]

(143)

\[
\dot{W}_{\text{FEEDWATER PUMP}} = 50,85\text{kg} / \text{s} \cdot (1015,0 - 1003,5)\text{kJ} / \text{kg} = 584,78kW
\]

(144)
And, regarding to the condensate water pump:

\[
\dot{W}_{\text{CONDENSATE PUMP}} = \left( m_{\text{WATER}} \right)_{\text{(STEAM CYCLE)}} \cdot (1 - Y) \cdot (H_{16} - H_{14})
\]  

(145)

\[
\dot{W}_{\text{CONDENSATE PUMP}} = 50,85\,\text{kg} / \text{s} \cdot (1 - 0,3) \cdot (163,9 - 163,1)\,\text{kJ} / \text{kg} = 28,48\,\text{kW}
\]  

(146)

Finally, the produced work in both HP and LP steam turbine are given by the following expressions:

\[
\dot{W}_{\text{HP TURBINE}} = \left( m_{\text{WATER}} \right)_{\text{(STEAM CYCLE)}} \cdot (H_{10} - H_{11})
\]  

(147)

\[
\dot{W}_{\text{HP TURBINE}} = (50,85\,\text{kg} / \text{s}) \cdot (3011,7 - 2712,4)\,\text{kJ} / \text{kg} = 15.219.4\,\text{kW}
\]  

(148)

\[
\dot{W}_{\text{LP TURBINE}} = \left( m_{\text{WATER}} \right)_{\text{(STEAM CYCLE)}} \cdot (1 - Y) \cdot ((H_{12} - H_{15}) + (H_{15} - H_{13}))
\]  

(149)

\[
\dot{W}_{\text{LP TURBINE}} = (50,85\,\text{kg} / \text{s}) \cdot (1 - 0,3) \cdot ((3159,8 - 2830,7) + (2830,7 - 2352,9))
\]  

(150)

\[
\dot{W}_{\text{LP TURBINE}} = 28.721.61\,\text{kW}
\]  

(151)

To this point, the main parameters required to obtain the efficiency of the steam cycle have been determined, and so, it is possible to obtain an estimation of the performance of the Rankine cycle by introducing them in the original expression of (128):

\[
\eta_{\text{STEAM CYCLE}} = \frac{(15.219.4 + 28.721.61)\,\text{kW} - (584.78 + 28.48)\,\text{kW}}{(19.989.14 + 67.050.81 + 17.206.62 + 14.492.25)\,\text{kW}} = 0,3649
\]  

(152)

As a result, the efficiency of the steam turbine of the parabolic trough power plant in Gibraleón, according to the reference parameters, is 36,39%. This value is different from the 40% of steam turbine efficiency used in SAM. Such a great difference is responsible for great performance variations in the final output of the plant, and although the most restrictive option has been chosen in previous stages, this time the selected turbine efficiency for the parabolic trough power plant is 40%. It is necessary to explain the reason for this choice. The different reference values for steam cycle shown in Table 39. have been determined from the different parabolic trough power plants developed in the United States from 1985 to 2007. The main features of these plants are introduced in the following figure:
Figure 121. Reference United States parabolic trough power plants.  

As it can be seen, none of the reference projects has a nominal design output of 50MW and some of them have even been hybridized with fossil fuel boilers, so the reference values for the Rankine 50MW steam cycle in the pure solar thermal plant model carried out in Kelly, B. and D. Kearney. 2006. Thermal storage commercial plant design study for a 2-tank indirect molten salt system. NREL have been extrapolated from the experiences above and do not answer to real operating conditions under those specific features. This does not mean that the calculating procedure carried out in previous lines is useless, because it is not.

The main reason for carrying out this manual solving of the steam cycle efficiency is to ensure the validity of the different formulas, although the 36.49% value obtained cannot be taken as a reliable one for the simulation in SAM. Under the specific reference conditions provided in Table 39., the value obtained is very similar to the reference United States parabolic trough plants, which introduce efficiencies around 37.5% - 37.6%. In order to obtain a good value it would be necessary to discuss actual reference conditions, as Figure 121. shows that most of the reference projects were carried in the first 90s.

The chosen 40% of steam cycle efficiency used in SAM is more representative of the actual Rankine cycles in parabolic trough power plants, as several improvements have been developed in the last years. In order to reaffirm the chosen value, some steam cycle efficiencies for similar power plants in Southern Spain are provided in the following table:
Table 40. Conventional steam cycle efficiencies in some Southern Spanish operational parabolic trough power plants
[Source: Own elaboration\textsuperscript{178}]

<table>
<thead>
<tr>
<th></th>
<th>Steam turbine efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I</td>
<td>38,13</td>
</tr>
<tr>
<td>Andasol II</td>
<td>38,13</td>
</tr>
<tr>
<td>Andasol III</td>
<td>40,2</td>
</tr>
<tr>
<td>Extresol I</td>
<td>38,1</td>
</tr>
</tbody>
</table>

As a result, the chosen value of 40% is among the maximum steam cycle efficiencies currently available for actual parabolic trough power plants and is a very good value for the parabolic trough power plant in Gibraleón. It is important to mention that these different efficiencies are related to peak values, and lower efficiencies may appear during real operation of the plant. This is also another reason for selecting a 40% value, as this input parameter in SAM is related to the maximum efficiency value that is expected in the system, under full load of the steam turbine, and not to the average efficiency of the steam cycle. Once that the main parameters of the steam cycle in the parabolic trough power plant of Gibraleón have been discussed, determined and validated, they are introduced in SAM’s Power Cycle module, whose final layout is provided in Annex V. In this layout some new parameters have been introduced.

First of all, the maximum and minimum turbine operation values are related to the maximum and minimum loads of the steam turbine. This means that this device is able to work properly up to a 105% of the design gross nominal output (55MW) and must not be exceeded in order to avoid damages. At the same time, the turbine is must not work under a 25% of load and, if this occur due to very small solar resource, must also be switched off in order to prevent damages. Several cycle part load thermal to electric and cycle part load electric to thermal factors. The cycle part load thermal to electric is used to obtain the design gross point output of the plant (55MW, before losses), and defect values have been maintained in order to account for this. However, the cycle part load thermal to electric factors are related to the equivalent gas kWh of energy that must provide the backup fossil boiler. As the parabolic trough power plant in Gibraleón is purely solar and no backup boiler is used, the boiler LHV Efficiency (which is related to the efficiency of this device) has been established at zero. The evaporative water cooling tower must be considered too and so, the different cooling tower correction values (which are related to the amount of thermal losses in the cooling system) have been activated by introducing a number 1 in the different correction factors. Finally, a 20% of thermal energy required to increase the temperature of the system to nominal conditions after a non-operative period of time.

\textsuperscript{178} Some data has been provided in the different plant promoter’s websites, and others have been provided by NREL in http://www.nrel.gov. (accessed May 28\textsuperscript{th} 2012)
4.4.5. **Performance and annual energy production of the plant.**

To this point, the main parameters of the solar field, thermal storage system and steam cycle of the parabolic trough power plant in Gibraleón have been selected, and as a result, it is possible to obtain the global performance and annual energy production of the plant through SAM simulation software. Please notice that SAM is also a powerful tool for economical power plant simulation, but due to the specific objectives of this project (where only a general approach to the economical feasibility of the plant will be performed) only technical features will be considered for this simulation and only technical outputs will be discussed. In order to begin with SAM’s results, it is necessary to characterise a last module, and it is the one related to Parasitic Losses. As they answer to very specific features of each project and require a very complex solving procedure in order to determine them, the selected reference for the simulation is based on the SEGS VIII power plant experience. Due to the fact that SEGS VIII has a nominal output power of 80MW, reference parasitic losses are considered to be surely bigger than the real ones in the parabolic trough power plant in Gibraleón. However, taking this feature into account and considering that this simulation provides estimated values and not real results, this is the final choice. The final layout of SAM’s Parasitic module is provided in **Annex V.** Under this assumption, simulation has been performed, obtaining the following results:

![Monthly Output (Base Case)](image)

**Figure 122.** Monthly output bar graph distribution [kWh] for the parabolic trough power plant in Gibraleón.

[Source.-Own elaboration]

**Figure 122.** shows the monthly output of the parabolic trough power plant in Gibraleón, according to the selected input variables that have previously been explained. As it could be expected, the highest values are related to summer months, as this is when the solar resource is at its maximum availability. The output of the plant decreases as winter comes, reaching its lowest value in December, and intermediate seasons of spring and autumn are related to output positive and negative gradients, respectively. Once that this first qualitative result has been introduced, it is necessary to quantify the amount of output energy in terms of power units:
Figura 123 Monthly output [kWh] for the parabolic trough power plant in Gibraleón.
[Source:- Own elaboration]

As it was mentioned above, the maximum output power is provided in July, with a total amount of 26,815,200 MWh, and the lowest value is given in December, established in 3,926,94 MWh. If all the different monthly values are summed up, the total annual net output of the plant is 179.534MWh, which can be assumed to be a very reasonable value as other similar power plants located in Southern Spain provide very similar values:

Table 41. Approximated annual net output in some Southern Spanish operational parabolic trough power plants
[Source.- Own elaboration179]

<table>
<thead>
<tr>
<th>Annual output [MWh]</th>
</tr>
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<tbody>
<tr>
<td>Andasol I</td>
</tr>
<tr>
<td>Andasol II</td>
</tr>
<tr>
<td>Andasol III</td>
</tr>
<tr>
<td>Extresol I</td>
</tr>
<tr>
<td>Extresol II</td>
</tr>
<tr>
<td>Manchasol I</td>
</tr>
<tr>
<td>Manchasol II</td>
</tr>
</tbody>
</table>

As it can be seen, the annual output of the parabolic trough power plant in Gibraleón can be equaled to the average values for similar applications in Southern Spain and, consequently, can be assumed to be a reliable value. Now that the annual output of the plant has been determined, it is the time to focus on its performance, determining the different efficiencies of the plant (although some of them have been already found in previous stages of the project) and

179 Some data has been provided in the different plant promoter’s websites, and others have been provided by NREL and others in http://www.estelasolar.eu. (accessed May 28th 2012)
discussing the energy flow in the parabolic trough power plant in Gibraleón. Taking these considerations into account, Figure 124. Shows the annual energy flow of the plant:

![Annual Energy Flow (Base Case)](image)

**Figure 124.** Annual energy flow [kWh] for the parabolic trough power plant in Gibraleón.
[Source.-Own elaboration]

The dark green bar is related to the available direct normal irradiation in the selected location, which according the weather file that was chosen in SAM, has a value of 928.381 MWh. It is necessary to remember, however, that the real available solar resource is bigger to this value, as no specific information of the chosen parcel could be found in an accepted SAM file extension (1.965,6 kWh/m² according to the chosen weather file, and 2.069,01kWh according to on-site climate stations). From this 928.381 MWh, only 493.034 MWh are collected by the solar field and converted into profitable thermal energy. From this 493.034 MWh, the final thermal energy provided to the steam turbine is 457.653 MWh, as it has been mentioned before, thermal losses are occurred in the steam cycle. Finally, according to the thermal energy provided to the steam turbine, the final annual gross electric output of the parabolic trough power plant in Gibraleón is 201.548 MWh. This annual gross electric output needs to be reduced due to self consumption of the plant and parasitic losses, with final net annual energy output of 179.534 MWh injected to the Grid. It is possible to observe that the biggest energy loss is related to the collected solar resource in the solar field according to the available direct normal irradiation for the selected location, as for a annual solar resource of 928.381 MWh only 493.034 are collected and converted into useful thermal energy.

**Figure 125.** shows a line plot graph of the available solar resource and the monthly output of the plant, allowing to observe the variability of the solar resource along the year. It is curious to see that the incident solar radiation along the year follows a very steep distribution, while the collected energy introduces smooth slopes and not great variations are noticed. This feature is
related to the fact that despite the great availability of the solar resource in summer periods, this huge increase in the direct normal radiation is not related to a very significant increase in the output of the plant, as higher temperatures reduce thermal exchange efficiencies and thermal losses are increased.

![Figure 125. Monthly Energy vs. Incident Solar Radiation [kWh].](source)

[Source.-Own elaboration]

Finally, SAM also provides an estimated value for the LCOE (nominal-w/o incentives) under the final values selected for the plant, established in 18,22 c$/kWh (14,30 c€/kWh\(^{180}\)).

![Figure 126. LOEC values [c$/kWh] for the parabolic trough power plant in Gibraleón.](source)

[Source.-Own elaboration]

This is a very good LCOE value, as it is similar to conventional LOCE (nom-w/o incentive) found in other plants, as it has been mentioned before. As it has

\(^{180}\) At a conversion rate of 1$=0,7851€
already been explained, this value can be considered as a very reliable one. Despite the fact that SAM provides economic data according to specific United States legislation, by selecting the nominal without incentive value of the LCOE it is ensured that this output is affected at the minimum expression by specific American economical concepts and it is possible to extrapolate this value to applications in other regions of the globe. Again, despite being a very reliable value, it still has to be considered as an estimation of the real value, as SAM does not answer to all the specific conditions that may be found in the parabolic trough power plant in Gibraleón and several assumptions have been made during the design stage. Now that a qualitative approach has been made on the performance of the plant, it is the time to quantify these efficiencies, in order to validate previous results and to characterize the plant at its maximum exponent. Under this consideration, the first performance output that will be determined is the Capacity Factor (CF), which is the amount energy from the theoretical maximum output power of the plant that is converted in net energy. This theoretical maximum output power can easily be found by multiplying the design net nominal power of the plant (50MW) and the number of hours in a year (8760 hours) and as a result, the capacity factor gives an idea of the global performance of the plant and should consequently be as higher as possible.

\[
CF = \frac{Annual \ Net \ Energy}{Design \ Net \ Power \cdot 8760} \times 100
\] (153)

\[
CF = \frac{179.534 \text{MWh}}{50 \text{MW} \cdot 8760 \text{h}} \times 100 = 40.989\%
\] (154)

During the steam cycle sizing stage, it had been determined that the final efficiency of the steam cycle in the parabolic trough power plant in Gibraleón was 40%. The efficiency of the solar field was also calculated in previous stages of this project, establishing minimum, average and maximum values in 35,16%, 44,29% and 50,12%, respectively. Finally, the only performance parameter that is left undetermined is the one related to the global performance of the plant, which is given by the following expression:

\[
\eta_{GLOBAL \ PLANT} = \frac{Annual \ Net \ Energy}{Annual \ Incident \ Solar \ Radiation} \times 100
\] (155)

\[
\eta_{GLOBAL \ PLANT} = \frac{179.534 \text{MWh}}{928.381 \text{MWh}} \times 100 = 19.33\%
\] (156)

The global performance of the parabolic trough power plant in Gibraleón is 19.33%, which is a very reasonable value if compared to similar power plants in Southern Spain (16% in Andasol I&II, 16% in Extresol, 18% in Andasol III\(^{181}\)). Once that this value has been found, the main parameters of the parabolic trough power plant in Gibraleón have been determined, and the sizing stage is concluded.

\(^{181}\) http://www.estelasolar.eu (accessed May 28th 2012)
4.5. Technology improvements

Now that the main objectives of this project have been accomplished, it has considered to be interesting to discuss and introduce some other relevant issues. Among them, the one related to the available and future technology improvements requires a necessary stop, as they will be responsible for an enhancing of parabolic trough power systems. The parabolic trough power plant in Gibráleón has been designed and sized according to current available technology, taking into account actual operational power plants in order to ensure its success, both technical and economical (which will be treated in next stages of this project). As a result, most of the selected solutions answer to reliable and previously proved systems, as they ensure that the output of the plant is the expected. However, different improvements and new investigation lines are carried out in parallel, in order to increase the efficiency of these kind of power plants as a way to consolidate their position in a power market that, little by little, is depending less on conventional fossil-fuel based generating systems and more on renewable technologies. During the following lines, the main R&D lines and ingenious solutions that promise great advantages in solar thermal power plants will be discussed, in an exercise that is aimed to establish a general view on the expected improvements that will surely appear in the next years.

4.5.1. Direct Steam Generation (DSG).

One of the main R&D lines is the one related to direct steam generation in parabolic trough power plants, due to the great advantages that this technology provides which result in a great cost reduction and a very important increase in the efficiency of the plant. According to what has been previously explained, in conventional parabolic trough power plants different heat transfer fluids (synthetic oils for indirect storage systems and molten salt mixture for direct storage systems) collect the thermal energy from the sun in order to generate steam in the steam generating island. However, what would it happen if steam was directly generated in the solar collectors? From a first view, an important cost reduction would appear for the fact that the steam generating island would automatically be unnecessary, at the same time that thermal efficiency would be increased as the heat losses occurred in the oil-to-water heat exchangers would be smaller. On the other hand, direct steam generation would require stronger piping system and better insulation in order to face the high pressures that would be necessary in the system. These and other topics will be discussed in the following lines, introducing the main features of this innovative technology that will surely bring great improvements in a future.

First of all, it is necessary to introduce the different research projects developed on this issue, in order to establish a time frame:

- **DISS Project:** the Direct Solar Steam Project was developed during 1996 and 2001 by a conjunction of different companies (CIEMAT, IBERDROLA, PILKINGTON, SIEMENS, PSA, INABENSA, ENDESA, etc.).

- **INDITEP Project:** the Integration of the Direct Steam Generation Technology for Electricity Production, which continued with de DISS experiences from 2002 to 2005 and was carried out by practically the totality of the companies that promoted that previous project.
The DISS Project proved the viability of high temperature DSG (400°C, 100 bar) in the linear receivers of the parabolic trough collectors by experimental simulations and first prototypes. The next step was obvious: once that DSG had been proved to be feasible, it was necessary to improve and enhance the different elements of this technology, in order to reduce costs and to ensure the success of commercial power plants. This second step was performed by the INDITEP Project, which established its main objective in designing a first 3MW DSG commercial plant once that the main technology issues were solved. Let’s now introduce the main features of DSG.

According with the experiences performed in the Almeria Solar Platform (PSA), there are three main configurations for direct steam generation: Once-through design, Recirculation design and Injection design.

![Diagram of Direct Steam Generation Designs](image)

**Figure 127.** Main parabolic trough Direct Steam Generation designs.

[Source.- Eck, M. and W.D. Steinmann. 2001. Direct Steam Generation in parabolic troughs: first results of the DISS Project. German Aerospace Center (DLR)]

The once-through configuration is largely the most simple of the three, but has shown to be difficult to control which may introduce some advantage for other concepts. The Recirculation design is based on a conventional recirculation boiler and requires a separator and a recirculation pump. As a result, this option is more expensive, but it is largely the most secure one. Finally, the Injection Design has provided great advantages in terms of control. This system is based on different collector modules with their own injection and measuring systems which are assembled in series. Several tests (more than 1500 hours of testing) have been performed at different temperature and pressure modes, introducing a clear advantage for recirculation design over once-through mode in terms of thermohydraulic behaviour and absorber tube strain. However, recirculation systems are not feasible for 100 bar cycles as several problems were noticed at that pressure, limiting their operation to 30 bar and 60 bar configurations. The maximum tested cycle pressure is 100 bar, as despite higher pressures would introduce better thermodynamic conditions, this would result in stronger and thicker systems and, consequently, much higher costs.
Despite the great improvements that are still required, direct steam generation in parabolic trough collectors has been proved to be feasible in all of the tested designs, and it is a matter of technology improvement to determine which one is the best option. Among the most common maintenance problems, pump failures, high electronic board replacement and temperature measurement errors at the absorber tubes due to solar resource are the most important ones. According to some of the advantages of DSG when compared to conventional parabolic trough systems, it is possible to highlight smaller pressure drops, smaller temperature gradients in absorber tubes, a reduction of investment cost (up to a 15%) and Levelized Cost of Energy (up to 25%) and an increase in annual output of the plant (up to 15%), as it is shown in the following figure:

![25% Levelized Electricity Cost (LEC) reduction](image)

**Figure 128. Main advantages of DSG in parabolic trough power plants.**
[Source.- Zarza, E et. al. 2001. The DISS Project: Direct Steam Generation in parabolic troughs: operation and maintenance experience. Update on project Status. CIEMAT]

As it has been mentioned before, the main objective of the INDITEP Project was to design a first 3MW Direct Steam Generation parabolic trough power plant. This objective was reached, establishing the facts for the next step in DSG evolution, which was to build that plant in order to discuss the commercial feasibility of direct steam generation in parabolic trough technology. This plant was the *Puertollano GDV 5MW Power plant*, constructed by *IBERDROLA, SENER, IDAE, CIEMAT* and *PSA* in *Ciudad Real, Spain*.

The *Puertollano GDV* project was developed between 2006 and 2011, with an investment of 20.000.000€, including different parabolic trough collector rows and a steam based power block connected to a generator. The main objective was to study the performance of the plant in a commercial environment and to determine the main operation modes that may appear. To this point the DSG plant of Puertollano is completely constructed and under operation, and final results may appear a near future.
Finally, there is one final issue that must be discussed, and it is the one related to thermal storage systems in DSG power plants. It is necessary then, to introduce the DISTOR Project (Energy Storage for Direct Steam Solar Power Plants) developed by DLR, CIEMAT, PSA, Flagsol GmbH and IBERINCO, among many others, between 2004 and 2007. The innovative DSG technology will require a thermal storage system, and it was nonsense to introduce conventional molten salt heat storage systems due to the specific new conditions introduced by this technology.

It was necessary, then, to investigate and develop new storage systems to answer to the special requirements of these innovative plants, as sensible heat storage systems are not feasible, introducing phase-change materials as the solution for this issue. This fact is related to the maximum energy provided by the steam, which is given in the condensation process. As condensation is a phase change, there is no temperature variation during this process and conventional sensible heat systems (which are based on a temperature variation of the material) are worthless. It is necessary a thermal storage system which is able to absorb energy at a constant temperature, and this is why the phase-change materials (which have been previously explained) become the optimal solution.

The DISTRO project developed a new storage system and introduced it in the Almeria Solar Platform DSG system in a 580x596x4310 mm (100 kWt) metallic module at 25 bar and 220°C.\textsuperscript{182} Several tests were performed and the feasibility of the system was proved, highlighting the critical impact of the piping system in the final performance of the thermal storage and determining the main improvement requirements of the system.

\textsuperscript{182} Almeria Solar Platform (PSA).
To this point, the main features of the innovative DSG technology have been introduced, highlighting the great possibilities of this concept and introducing this system a sure candidate for future parabolic trough power plants due to the great advantages provided. However, several problems have still to be solved, and this could be responsible for a delay in commercial DSG systems.

4.5.2. **Molten salt as heat transfer fluid.**

Although DSG is still in a development stage, it is the time to introduce one improvement that is little by little gaining positions in commercial parabolic trough applications, and it is the use of molten salt mixtures as both heat transfer fluids and thermal storage systems. This feature, known as direct thermal storage system, has been previously explained in previous stages of this project. Although initial direct storage technology was dismissed due to the necessity of very expensive pressurized storage tanks required to store the Caloria mineral oil, this technology has recently returned back to stage with the new trend in using molten salt for both heat transfer fluid and storage fluid in parabolic trough power plants.

By using the same molten salt mixture, there is no need for a heat exchanger between the solar field and the storage system, higher operating temperatures can be reached (450°C-500°C\textsuperscript{183}), which in turn results in higher steam cycle efficiencies, and no pressurized storage tanks are required, reducing dramatically its cost. What is more, solar salt is even cheaper than other synthetic oils (\textit{Therminol VP-1}) currently used. However, as it has been explained, the high freezing temperatures of these molten salt mixtures (120°C-220°C\textsuperscript{184}) require specific auxiliary warming systems (especially at night) that may introduce some extra costs. This is unfortunately not the only issue that molten salt heat transfer fluids face. Higher operating temperatures require improved heat collecting

\textsuperscript{183} D. Kearney et. al. 2002. Assessment of a molten salt heat transfer fluid in a parabolic trough solar field.

\textsuperscript{184} Ibid. [183]
elements able to stand them, resulting in higher thermal losses caused by
radiation. In fact, every element of the plant in contact with the solar salt must
be properly insulated from temperature and corrosion in order to avoid
malfunctioning and failures in the system. At the same time, the higher densities
introduced by these fluids require stronger pumping systems, increasing self
consumption of the plant. The customizing effort is specially noticed in the
different valve units along the plant, as they are typically very affected by molten
salt corrosion, although several materials are already available.

![Table of recommended materials for molten salt HTF depending on temperature](image)

**Figure 131.** Recommended materials for molten salt HTF depending on temperature

[Source.- D. Kearney et. al. 2002. Assessment of a molten
salt heat transfer fluid in a parabolic trough solar field.]

However, despite these small limitations, molten salt heat transfer fluids require
much less mass flow rates than synthetic oil applications and, as a result, smaller
pressures drops and parasitic losses are occurred along the piping system. This
feature, added to a simpler solar field layout with only one heat exchanger
located in the steam cycle, becomes very attractive for new parabolic trough
applications due to minor maintenance needs and a very important cost
reduction as fewer elements are required.

![Simplified schematics of a parabolic trough power plant with molten salt as heat transfer fluid and two-tank direct thermal storage technology](image)

**Figure 132.** Simplified schematics of a parabolic trough power plant with
molten salt as heat transfer fluid and two-tank direct thermal storage technology.

salt Heat Transfer Fluid Technology for Parabolic Trough Solar Power Plants. ]
Among the different molten salt mixtures for heat transfer fluid applications, it is necessary to highlight HITEC XL solar salt, manufactured by Coastal Chemical Co., with a composition of 48% Ca(NO$_3$)$_2$, 7% NaNO$_3$ and a 45% KNO$_3$, with a melting temperature of 140°C and a maximum operating temperature of 500°C.

### 4.5.3. New storage systems.

Thermal storage has proved to play an essential role in the performance and success of parabolic trough power plants, as they allow to increase the annual output of the plant as energy generation can continue even when there is not enough solar resource. It is not necessary to shut down the plant every night and so, start-up times are minimal and efficiency is notably increased. There are several R&D lines for new storage systems, highlighting the single-tank thermocline storage systems, solid storage systems and phase-change materials storage systems. These different solutions have already been introduced and discussed in Chapter 4.2 Thermal Storage and so, it is not necessary to carry out a new approach on them.

### 4.5.4. Plant size.

It is possible to reduce notably the cost of electricity increasing the size of the plant, highlighting a decrease of 12-14% by only doubling the size of the plant$^{185}$. This important reduction in the final cost of the plant is given by: smaller manufacturing costs (the more pieces are manufactured and supplied, the smaller is the cost per square meter), the non linear increase of the total cost of the plant (if the size of a plant is doubled, its cost is not doubled) and the non linear increase in organization and management needs (if the size of a plant is doubled, the total amount of employees required to control it is not doubled)$^{186}$. Among the disadvantages of this solution, the most significant issue is related to the increase in parasitic losses and pumping requirements due to bigger piping systems.

![Figure 133. Effect of power plant size on Levelized Cost of Energy (LCOE).](image)

http://www.solarpaces.org (accessed March 2$^{nd}$, 2012)

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$^{185}$ Ibid. [5]

$^{186}$ As according to [5] the total number of employees required to control operation of a parabolic trough is practically the same for both 10MW and 400MW applications.
According to Figure 133., if a 10MW reference plant is considered, the Levelized Cost of Energy can be reduced in a 61% by increasing the size of the plant to 400MW. Please notice that these big sizes can be achieved with a single big power plant or through the combination of different small size connected power plants, although the importance of manufacturing cost reduction will be much smaller for the second option.

One of the main issues that are limiting bigger plants is legislation. The Spanish Government has established a 50MW limit for solar thermal power plants in order to be subjected to the Special Regime and, consequently, to their favourable economic conditions. Although the subjection to Special Regime and their energy selling prices is favourable and results in higher benefits when compared to bigger not Special Regime solar thermal applications, it would be very positive to increase the limits of Special Regime nominal power, as this would provide double benefits for solar thermal applications: the favourable economic regime and the cost reduction related to size increase. As it can be seen, by just increasing the Special Regime from 50MW to 100MW, the Levelized Cost of Energy (LCOE) of the plant could be reduced in a 19%, which for the parabolic trough power plant in Gibraleón with a LCOE (nom-w/o incentives) of 14,30c€/kWh would become 11,58c€/kWh, according to Figure 133.

4.5.5. Improvement of the steam cycle.

As it has been previously mentioned, current steam cycles in parabolic trough power plants do are based on pure steam Rankine cycles with superheating and regeneration modules. However, numerous solutions are being studied and discussed, providing great possibilities for future applications. Among them, it is necessary to highlight two innovative steam cycles for solar thermal applications:

- **Organic Rankine Cycles (ORC):** largely used from 1980 in numerous geothermal, waste heat recovery and combined heat-power applications, introduce hydrocarbon fluids instead of traditional steam. By doing so, wet cooling is not necessary and can be cooled with a dry cooling method, reducing water consumption in a very important grade. In addition, it is possible to adjust the hydrocarbon fluid to the specific conditions of each project, simplifying the system and reducing maintenance needs and costs. The main advantage of the ORC is the fact that, by operating at lower temperature and pressures (304°C instead of actual 390°C\textsuperscript{187}), it is possible to substitute the current expensive heat transfer fluids like synthetic oils in indirect thermal storage systems and molten salt mixtures in direct thermal storage systems, introducing cheaper working fluids such as the Caloria heat transfer fluid used in initial direct thermal storage systems, as has been previously explained. By reducing the operating temperature of the system, smaller thermal losses due to radiation are occurred, and cheaper materials and devices can be used.

Organic Rankine Cycles are based on hydrocarbon fluids and, as a result, virtually no water is required (except the one related to maintenance operations such as mirror cleaning or similar), allowing solar thermal applications to be located in deserted locations were the solar resource is maximum. This feature is related to the possibility of using dry cooling

systems in this kind of power cycles. However, not all are good news for ORC. Due to the dry cooling system that has been mentioned above, this cycle is very affected by high ambient temperatures and this can be responsible for unfeasibility in deserted locations. At the same time, due to the lower operating temperatures and pressures, the efficiency of the cycle tends to be smaller than other conventional steam Rankine cycles, at around 35%[^188].

![Figure 134. Basic Organic Rankine Cycle Schematics.](source)


As a result, ORC must be carefully discussed depending on the specific conditions of each project, and it is mainly recommended for relative small applications located in deserted locations and those applications were cost reduction is the main objective despite minor annual outputs.

- **Combined Rankine/Kalina Cycle:** The Kalina Cycle is based on a water/ammonia solution that has been largely used in low temperature waste heat recovery and geothermal applications since 1960. By itself, the Kalina Cycle does not represent a feasible solution for the power block of commercial solar thermal power plants, as it is typically used in small size applications with small operating temperatures and pressures. However, this technology has recently become a topic in solar thermal applications by its combination with traditional Rankine steam cycles in back pressure turbines, as it allows to maintain power production even in low solar resource periods. Due to the specific features of steam, huge and expensive condensator units were required in conventional Rankine cycles, but the Rankine/Kalina combination introduces much smaller elements due to higher efficiencies related to the chemical features of the water/ammonia combination. In addition, this innovative system reduces the cost of dry cooling methods applications in deserted regions, and contrary to the ORC, these technology is available for big size power

[^188]: Ibid. [187]
plants (as it has been proved in the Negev Desert 50MW parabolic trough power plant, in Israel, with a global efficiency of 14.7%\textsuperscript{189}).

![Diagram of a Solar Thermal Power Plant](image)

**Figure 135. Combined Rankine/Kalina cycle for parabolic trough applications.**

[Source.- Mittleman, G. and M. Epstein. 2010. A novel power block for CSP systems.]

As it can be seen in **Figure 135.**, the Kalina side of the power block uses a steam extraction from the high pressure side of the Rankine steam turbine to increase the temperature of the water/ammonia solution to 160°C and 50 bar in order to be converted in the Kalina turbine into mechanical energy. This extra power provided by the Kalina side of the power block helps to provide the nominal output even when the solar resource is insufficient. As a result, the Rankine/Kalina cycle is able to reduce the total installed cost between 12% and 16%, with a LCOE reduction of 0.5%\textsuperscript{190}, but at a minor efficiencies, so it is still necessary to work in order to be able to compete with actual steam Rankine cycles.

The main possibilities for steam cycle efficiency improvement in parabolic trough power plants are related to an increase of the temperature and pressure of the steam provided to the turbine, and this is why so many efforts are focused on innovative working fluids and, especially, in direct steam generation, as their implementation in commercial scale solar thermal applications will be closely related to an improve in thermal efficiency of the steam turbine and, consequently, in the final output of the plant.

\textsuperscript{189} Ibid. [106]

\textsuperscript{190} Ibid. [106]
4.5.6. Development of new systems and improvement of actual solutions.

The experience acquired in commercial solar thermal power plants allows to maintain a continuous feedback with suppliers and manufacturers in order to improve the different elements of the system and to find new useful solutions. Although is very difficult to mention all of them, it has been considered interesting to highlight the main improvements currently in development.

- **Collector structure:** Including improvement of actual designs by introducing bigger concentrators and implementation of new systems such as tilted single axis parabolic trough collectors. The structure cost reduction related to size increase is not very significant, but it is when interconnection, electronics, hydraulic drives and linear receiver costs are studied. At a same length, a higher aperture area will result in minor amount of heat collecting elements, and this may be critical when it has been proved that the 50MW parabolic trough power plant in Gibraleón requires 720 solar collector assemblies. However, bigger concentrators will result in bigger reflecting surfaces too, so it is necessary to discuss this point carefully when designing new collectors.

![Collector structure diagram]

**Figure 136. Effect of collector size in different parameters**


Experimentally, there is a clear tendency in increasing collector size, as new designs are providing bigger and bigger aperture areas. On the other hand, tilted single axis collectors are a very hot topic due to the great possibilities that they introduce, estimating solar field efficiency increases up to 9% with only a 8° tilt in the collector.

![Tilted parabolic trough collectors]

**Figure 137. Tilted parabolic trough collectors**

[Source.- García, A.F. et. al. 2010. Parabolic trough solar collectors and their application.]

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191 Ibid. [5]
• **Reflective surfaces:** main efforts are focused on developing more reflective and resistant surfaces at a minor cost. Different innovative materials are introducing themselves little by little in a marked largely dominated by reflective mirrors, such as the *ReflecTech* reflective surface that has been chosen for the parabolic trough power plant in Gibraleón.

• **Ball joints:** since ball joints appeared to substitute the problematic flexible hoses in parabolic trough solar fields, they have consolidated in the market due to their fantastic features. However, efforts are still to be made concerning pressure drops and maintenance facilities.

• **Heat collection elements:** this is probably one of the main R&D lines in components for parabolic trough power plants, due to the great possibilities that improvements may introduce. The main efforts are focused on reducing thermal emissivity, increasing glass transmittance and tube absorbance and to develop new resistance units in order to ensure that no vacuum is lost in any element of the solar field. In this objective, innovative coatings (like the ones studied in the *CIEMAT*) play an essential role, such as the previously mentioned *cermet* material. At the same time, there is a clear tendency in increasing the diameter of the linear receivers in order to allow higher mass flow rates and, consequently, higher thermal energy.

Parallel to this wish of higher thermal efficiencies, several efforts are made on developing cheaper devices. To this date, there are only a few manufacturers that provide linear receivers for parabolic trough commercial scale applications (vacuum based) and, as a result, prices are high and shipping times are expanded. It is necessary to develop new cost reduced linear receiver designs without compromising thermal efficiencies, in order to increase the offer of this kind of elements and, consequently, result in smaller operating costs for parabolic trough power plants that will help to ensure their commercial success.

4.5.7. **Hybridization.**

Hybridization of solar thermal power plants with other power generating systems is a reality, as it is shown in the previously explained *Integrated Solar Combined Cycle System (ISCCS)* plants where parabolic trough power plant is integrated in a conventional combined gas turbine cycle. The energy provided by the parabolic trough system is used to increase the thermal energy of the exceeding heat from the gas turbine. By doing so, the efficiency of the process is higher and operating costs are reduced. This hybridization, as it has been previously explained, is not restricted to combined gas turbine cycles, as it is possible to implement it in conventional coal-based power plants, reducing the amount of coal and improving the performance of the plant.

Thanks to this hybridization, initial solar thermal experiences were able to enter the energy market, and are still a key point in order to consolidate this technology. Several plants prove the feasibility and success of combined solar/fuel power plants, although the development of pure solar thermal applications during the last years are gaining positions little by little.
However, this hybridization with conventional power plants is not the only possibility. In fact, main efforts are focused on hybridization with other renewable technologies, in order to reduce environmental impact to the minimal expression and to prove the feasibility of renewable systems against fossil fuel based plants. Among this kind of hybridization, the most important is the one related to a biomass/solar thermal hybrid power plant. Although CSP and biomass power plants are cheaper by themselves than when combined in a single application, but the total amount of operating hours and the final output of the plant can be increased up to 2,77192 times. Thanks to this hybridization, it is not necessary to introduce expensive storage systems, as those periods with insufficient solar resource are covered by the biomass module of the plant. This feature implies the need for a very dynamic biomass boiler that must be able to adapt quickly to the specific needs of the plant and, as a result, it is typical to include a backup natural gas system in order to increase the flexibility of the device against punctual requirements.

It has been previously mentioned that, the bigger the plant is, the higher is its efficiency and the lower is its Levelized Cost of Energy. However, the main problem to apply this improvement to biomass/solar hybrid plants is the fact that large plants require large amounts of biomass for the boiler, and this may become a problem when a continuous supply is essential. In addition, the biomass boiler needs heat exchangers to supply thermal energy to the heat transfer fluid and, consequently, small efficiency losses are introduced. There are different configurations for hybrid biomass/solar power plants, although the most
common introduces a biomass boiler in order to increase the thermal energy of the heat transfer fluid before this reaches the steam generating train.

![Solar Thermal Power Plant Diagram]

**Figure 139. Main elements of a biomass/parabolic trough hybrid power plant**


To sum it up, when solar resource is available, the plant will be operating in CSP mode, collecting energy from the sun and converting it into electricity. During punctual decreases of the solar resource, the backup natural gas module of the biomass boiler will act, supplying the extra energy to maintain the power block at its nominal output. During large periods without solar radiation (at night, for example), the output of the plant is maintained thanks to the thermal energy provided by the biomass boiler.

Small experimental 10MW biomass/solar hybrid power plants have been built in Ribera del Duero (Spain) by the R&D department of Magtel Renovables Group\(^{193}\) in order to study the possibility of feasible commercial scale power plants. This experience has highlighted LCOE values around 19,48cC/kWh\(^{194}\) at the reference biomass marked price. This reference plant was built next to two 10MW parabolic trough power plants with and without thermal storage, in order to compare and contrast the values obtained. Although LCOE of the hybrid plant is still higher than the one found in the power plant with storage, it is surprisingly smaller to the one introduced by those plants without thermal storage, which introduces great possibilities for biomass/solar hybrid power plants in those regions with moderate solar resource and small sunlight hours.

Biomass/solar hybrid power plants introduce great possibilities for future power plants, thanks to the combination of two different renewable technologies. Despite that initial results are very positive, it is still necessary to develop new systems and to solve specific problems in order to ensure the complete consolidation of this technology in the market. Among these required improvements, the most critical aspect is the one related to the dynamism of the biomass boiler, as the natural gas currently used to ensure this feature reduces the renewable character of this technology. As well, other relevant problems related to integration of these two different systems still need to be solved.

\(^{193}\) [http://www.magtelrenovables.com](http://www.magtelrenovables.com)

\(^{194}\) [http://www.energias-renovables.com](http://www.energias-renovables.com)
CHAPTER 5: MAINTENANCE AND USE

Now that the main features of the parabolic trough have been introduced, discussed and chosen, it is the time to focus on a critical aspect of parabolic trough power plants, and it is the one related to maintenance requirements and use. Maintenance plays an essential role in the final output and performance of the plant, being necessary to establish an appropriate maintenance plan in order to ensure that the plant is operating at its maximum capacity. Small problems such as punctual leakages, insulation problems, device failures and dust accumulation may not seem very important by themselves. However, the combination of different issues may result in critical performance reduction and can surely be responsible for the success or failure of a project.

Different maintenance operations can be highlighted, although it is possible to classify them in three main types:

- **Predictive maintenance operations**: they are related to the monitoring of different parameters of the solar field in order to identify failure modes and to establish references for noticing when a device is proximal to failure. When some of the characteristic parameters of a device exceeds normal operating ranges, it can be assumed that this device is susceptible of failure and, as a result, it is substituted for a new element. Thanks to this, failure is avoided before it even happens, maximizing the performance of the plant as no shut downs are required.

- **Preventive maintenance operations**: based on the same idea as the predictive maintenance, failures are avoided before they come to reality. However, contrary predictive maintenance, there is no continuous monitoring of different parameters, and operating life of the different elements are estimated according to previous test developed by the
manufacturer or according to previous experience with similar devices in the plant. As a result, preventive maintenance is based on experience, and requires systematic and periodic inspection and element substitution.

- **Corrective maintenance operations**: they are related to the substitution of a damaged element once that failure has been produced. This is the most basic maintenance system, and cannot be applied without combining it with predictive or preventive maintenance due to the small effectiveness of the same.

As a result, the best option for the parabolic trough power plant in Gibraleón is a combination of the three maintenance disciplines. The most critical elements of the plant will be continuously monitored and other less relevant devices will be periodically substituted according to previous experience. At the same time, any failure will be rapidly solved thanks to a corrective maintenance plan carried out through a material stock that will be stored in the plant.

It is necessary, then, to indentify the main maintenance requirements of the parabolic trough power plant in Gibraleón in order to establish an appropriated maintenance plan, introducing the most common failures and providing some use recommendations in order to increase the operating life of the equipment. The importance of maintenance in solar thermal applications has largely been considered, although very little documentation is versed on this issue. In order to develop this maintenance and use stage, four main modules will be considered:

- **Maintenance of the solar field.**
- **Maintenance of the steam cycle.**
- **Maintenance of general systems.**
- **Fire protection.**

### 5.1. Maintenance of the solar field

If maintenance has been introduced as a critical aspect in the performance of the parabolic trough power plant in Gibraleón, this feature becomes even more important when regarding to the solar field. Due to the high operating temperatures typically reached in this module, combined to the fact that the different elements of the solar field are exposed to outside climate conditions, it is very important to ensure that everything works properly in order to collect the maximum solar resource and, consequently, improve the output of the plant. As a result, it is possible to highlight different issues according to the following elements:

#### 5.1.1. Collector alignment.

During previous stages of the project, a North-South orientation has been chosen for the parabolic trough power plant in Gibraleón due to the great advantages introduced by it. However, during normal operation of the plant, wind impact and vibrations can be responsible for minor misalignments and, as a result, solar collectors should be periodically checked in order to ensure correct alignment. It
is recommended to install automatic alignment systems in order to allow this operation from the main control system, although due to the great cost of this kind of solution, collector alignment is typically performed manually. Taking this feature into account, manual alignment must be simple and fast in order to reduce maintenance times and to ensure that misalignments are rapidly solved.

5.1.2. **Damages in collector structures.**

During normal operation of the plant, the different collector structures may be affected by vibrations, thermal stress and mechanical efforts due to wind action. This issue is not restricted to the metallic structure of the collector design, but to all different auxiliary structures such as collector supporter arms and linear receiver subjection structures. The different efforts applied on these elements can be responsible for deformations, as well as oxidation due to climatologic conditions if the galvanic coating is damaged by dust or suspended particles in air.

5.1.3. **Reflecting surface reflectivity and cleanliness.**

Due to the suspended particles in the wind, the reflective surface of the different solar collectors of the solar field can be scratched and dust is accumulated in it surface, reducing the reflectivity of the surface and resulting in a minor solar efficiency. As a result, it is critical that the different collectors of the solar field are periodically cleaned and that the maximum care is kept during this operation, as abrasive tools such as conventional metallic brushes can damage the surface of the reflector. During summer months, when the ambient temperature is higher, soiling rates of up to 0.5%/day\(^{195}\) can be found in the solar field. Soiling rates are closely related to moisture levels, wind presence, precipitations and proximal sources of dust. However, with good cleaning, the reflectivity of the collector can be returned to initial values, so it is important to establish a convenient maintenance plan for reflective surface washing in order to ensure that efficiency is maximized. It is important to make a deeper approach on rainfall. Although rain can be used to wash the reflective surface through an appropriate orientation of the collectors, it typically introduces more disadvantages than advantages. Rain may have lots of suspended particles and corrosive chemicals that could be responsible for decrease in the reflectivity. When rain dries, the suspended particles are left on the reflective surface on a circular shape (the same spots can be easily noticed in domestic mirrors and surfaces) and chemicals suspended in acid rain can damage the protective coating of the reflective surface. As a result, the most common washing method is carried out by a combination of pressurized demineralised water and brushing. By using demineralised water, no spots are left on the surface and reflectivity is recovered. Parallel to collector washing, it is essential to perform a periodic reflectivity measuring with specific devices (known as reflectometers, and manufactured by companies such as AZ Technology Co.\(^{196}\)) in order to ensure that this does not decrease under acceptable levels and, if this happens, the reflective surface must be substituted.

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\(^{195}\) Ibid. [5]

\(^{196}\) [http://www.aztechnologies.com](http://www.aztechnologies.com)
Figure 140. Reflectivity test in a parabolic trough collector

According to the most common demineralised water-based washing systems, it is possible to highlight four main procedures:

- **Traditional high-pressure/low-water-volume method**: this cleaning method is largely the most common system in initial solar thermal applications, and it is based on high-pressure demineralised water that it is sprayed over the reflective surface with hand-held nozzles operated by employees. However, due to the increase of solar field sizes and the variability of the result related to human fatigue, this method has little by little been overcome by other innovative cleaning procedures with less human requirement and more effectiveness.

Figure 141. Traditional high-pressure/low-water-volume cleaning method

- **Rotating head high-pressure method**: this new cleaning method, created by the O&PMP developed in SANDIA Laboratories in 1999 (which is, in fact, the source of the different Figure 140, and Figure 141. introduced), is based on high pressure rotating nozzles that are installed in a vehicle
that is driven by an operator. Thanks to this invention, the operation does not have to operate the nozzle manually, as this can be controlled through an automatic control panel located in the maintenance vehicle. These innovative rotating nozzles are also known as Twister nozzles.

![Image](image1.jpg)

**Figure 142. Rotating head high-pressure cleaning method**

Despite providing great results, each cleaning unit can only wash a single row of collector assemblies at a time, while other cleaning methods such as the deluge-type system can clean two rows at a time, reducing maintenance operation.

- Deluge-type low-pressure/high-water-volume method: this system is based on a simultaneous two parallel row cleaning performed with a conventional truck with incorporated nozzles at both sides. When the truck is driven between two collector assembly rows, these must be oriented in a convenient facing position in order to allow simultaneous washing. Due to the bigger size of trucks when compared to other maintenance vehicles such as the ones used in traditional and O&MIP systems, it is important to ensure that sufficient space is left between different collector rows. Taking into account that the minimum row-to-row distance established in previous stages of the project was 17,4m in order to avoid mutual shading, this is not a problem.

![Image](image2.jpg)

**Figure 143. Deluge-type low-pressure cleaning method**
**Special acid gel/high-pressure method:** not all the different collectors of the solar field are subjected to equal soiling rates. For example, during the O&MIP experience developed in SANDIA Laboratories, it was proved that those collectors located near the cooling tower were susceptible of higher soiling rates due to the presence of higher moisture levels. The evaporated water of the cooling tower can reach some of the collector rows which, in combination with suspended particles carried by wind, can be responsible for mud accumulation over the reflective surfaces.

Due to the criticality of these devices, special cleaning methods were developed. Generally, these innovative systems were based on a previous acid gel appliance followed by a high-pressure demineralised water spraying. Thanks to this, very dirty collectors with reduced reflectivity values under 40% could be restored to initial 88% of reflectivity, according to the experiences developed by SANDIA Laboratories. However, this system has been little by little substituted due to the environmental danger related to these acid gels, introducing new systems such as anti-soiling chemical coatings for these susceptible elements of the solar field.

Although all of the previously mentioned cleaning methods have been proved to be valuable, current parabolic trough power plants are typically based on deluge-type and rotating-head demineralised water cleaning methods, although there is a clear tendency in using truck-based deluge-type systems as cleaning rates do not differ in a great mode from rotating head results, and cleaning times are driven to practically half the time required in rotating head systems (which in turn is related to lower maintenance costs). As a result, the selected cleaning method for the parabolic trough power plant in Gibraleón must be the deluge-type low-pressure/high-water-volume system, regarding to the great advantages mentioned above.

### 5.1.4. Hydraulic drives.

The hydraulic drive is responsible for the alignment of the solar collector assemblies according to the position of the sun, increasing this way the total amount of solar energy collected by the solar field. This positioning must be smooth, accurate and continuous, being necessary to carry out periodical maintenance operations such as lubrication of the mobile parts. Again, a good maintenance plan is essential to ensure that the drive system is at its best condition. These periodical maintenance operations must be focused on hydraulic fluid levels, leakage detection, cleaning of the different sensors of the drive (heat transfer temperature, radiation, position, etc.) and substitution of elements over their operating life in order to avoid failures (preventive maintenance).

### 5.1.5. Damaged linear receivers.

Due to the importance of the different heat collecting elements of the solar field, as they are the ones that collect the thermal energy provided by the sun and, consequently, are responsible for the final output of the plant, it is critical to ensure that not a single element is damaged in the plant. Although this is very difficult to the great size of the solar field (composed by 720 solar collector assemblies), it is important to keep failure rates under very strict limits in order to ensure that the efficiency of the solar field is as maximum as possible.
The most typical problems related to linear receivers are vacuum loss, breakage of the glass enclosure, degradation of the absorber coating and deformation of the metallic absorber tube\textsuperscript{197}. Please notice that many of this failure modes are closely related, such as the degradation of the absorber coating, which is given by a glass enclosure breakage and, consequently, by a vacuum loss in the element, as well as deformation of the different absorber tubes that may result in glass breakage, with identical results. It is important to check periodically the different linear receivers in the solar field in order to ensure that the maximum thermal efficiency is reached.

![Image](image_url)

**Figure 144. Substitution of a damaged glass enclosure**


In the maintenance of linear receivers under good operating conditions, manufacturers play an essential role. The innovative expansion bellow introduced in previous stages of this project has reduced in a great mode the amount of glass breakages due to thermal expansion and contraction of the heat exchanger elements connections due to temperature variations. At the same time, stronger and more flexible materials need to be developed without compromising the efficiency of the linear receivers, as well as to develop new devices that can be replaced on site by manufacturers of the same power plant. This is just the case of the SCHOTT PTR70 linear receiver, chosen for this project, which allows to substitute damaged elements from the solar field on site, being only necessary to store some extra units in the plant to be used in case of failure in the solar field.

### 5.1.6. Leakages and pressure drops in ball joints.

Due to the high operating temperatures reached in the solar field, as well as to the expansion and contraction related to them, the different ball joints that connect consecutive solar collector assemblies can be damaged, resulting in heat transfer fluid leakages and, consequently, in pressure drops along the system. As a result, it is necessary to check periodically the different ball joints of the solar field, and this is when preventive maintenance plays an essential role. Due to the simplicity of these elements, it is very difficult to develop a constant monitoring as no specific failure parameters can be associated (apart from the ones related to

\textsuperscript{197} Ibid. [5]
pressure drops in the circuit due to leakages, but the variations introduced by the failure of a few ball joints along the solar field are small and can easily be unnoticed. It is necessary, then, to establish a periodical substitution calendar according to the average operating life of these devices, obtained from different manufacturer testing and, once that the plant is under operation, from the average failure rates of the different ball joints located between the different collector).

![Figure 145](image)

**Figure 145.** Ball joint insulation at the end of a solar collector assembly

By the combination of a good preventive maintenance and a good corrective maintenance (with backup units stored in the power plant in order to reduce substitution times in case that a device fails), the problems related to leakages and pressure drops in ball joints can be reduced to the minimum expression. At the same time, it is important to verify that thermal insulation is properly performed, as it can be responsible for great improvements in the thermal efficiency of the solar field.

### 5.1.7. Adjustment of solar tracking system.

According to the selected Skytrakker system, which is based on a complex solar position algorithm that sends real-time information in order to act on the drive system or to monitor the performance of the solar field, this may require to be updated in order to maximize solar collection and punctual damages may appear, being necessary to check periodically the functioning and accuracy of the system. Taking this feature into account, the Skytrakker control system introduces a great advantage related to the fact that it allows to carry out easy and quick on-site maintenance in order to change damaged devices.

### 5.2. Maintenance of the steam cycle.

#### 5.2.1. Steam turbines.

The high and low pressure steam turbines are the heart of the power block in a parabolic trough power plant, as they are responsible of the conversion of
thermal energy provided by the solar field or the thermal storage system into mechanical energy. Due to their criticity, periodical maintenance operations must be carried out, including leakage identification (oil, steam or water), required drains and purges and lubrication fluid level control, mainly. Parallel to these conventional and daily maintenance operations, both high pressure and low pressure steam turbines are generally inspected once a year by manufacturer maintenance teams in order to verify the correct functioning of the device.

5.2.2. Generator.

With the steam turbine, the electricity generator is probably the most important element in the power block of the plant, as it is responsible of the conversion of the mechanical energy provided by the turbine into electrical energy. As it happened with the turbine, periodical maintenance must be performed in order to control lubrication fluid levels and to identify hot spots along the different parts of the device (generally through thermographic measuring systems). Again, a yearly inspection is generally carried out by a maintenance team from the manufacturer of the generator in order to complement daily maintenance carried out by plant operators.

5.2.3. Legionella control in cooling tower.

In order to avoid Legionella generation in the water cycle of the cooling tower, periodical inspection and disinfection with specific chemical substances must be performed in the cooling tower system.

5.2.4. Oxigen control in the deaerator.

The most common failure in preheaters is caused by suspended oxygen in the water provided by the deaerator. As it has been mentioned in previous stages of this project, by introducing chemical scavengers in the water it is possible to reduce oxygen presence to the minimal expression. The selected chemical scavenger for the parabolic trough power plant in Gibraleón was is the sodium sulphite, due to its high efficiency and low cost. The amount of sodium sulphite introduced in the system must be carefully selected and specified in the maintenance plant, in order to avoid that this chemical substance reaches the steam turbine mixed with the steam.

The most common deaerator failures are specified in Figure 96, and are related to high levels of oxygen in the water provided to the preheater due to air leakage, insufficient scavenger or malfunctioning, pressure fluctuations due to temperature variations and incorrectly sized valves, low outlet temperature due to insufficient steam supply and malfunctioning and high level of CO₂ in the water provided to the preheater due to too high water PH. It is necessary, then, to periodically check the deaerator in order to avoid this common problems, as well as to develop a good predictive and preventive maintenance plan, including monitoring the amount of dissolve oxygen of the water or other interesting parameters.
5.3. Maintenance of general systems.

5.3.1. Leakages in control and security valves.
According to the criticity of the different control and security valves, different maintenance operations must be performed, although regarding to a common maintenance plan, periodical temperature measures, leakage detection and regulation procedures must be carried out in order to ensure the best operating conditions. Other issues such as water proofing of the electrical actuators and functioning of the communication lines with critical valves must equally be taken into account in these periodical maintenance operations, as they play an essential role in the final performance of the plant too.

5.3.2. Transformers.
The maintenance operations in the different transformers of the plant is mainly the same that the one performed in other applications, with special attention to hot spots, cooling oil leakage and degradation and winding insulation. In addition, and answering to the Spanish legislation, periodic inspections must be carried out by an authorised company. The criticity of the transformer will be closely related to the periodicity and intensity of maintenance operations, as it happened in control and security valves.

5.3.3. Temperature and pressure sensors.
Due to the great importance of monitoring devices such as temperature and pressure sensors for the final output of the plant, it is important to check periodically that all the different measuring systems and devices are correctly adjusted in order to ensure the maximum reliability of the control and maintenance operations. Again, the intensity and periodicity of the different maintenance operations will be closely related to the criticity of the sensor.

5.3.4. Pumping systems.
As it has been previously mentioned, the periodicity and intensity of maintenance operations in pumping systems of the plant will depend on the criticity of the pump, although some general operations can be easily highlighted, and they are the ones related to closing liquid levels, impulsion and absorption pressure values, bearing temperatures, vibration and noise levels and leakages due to damaged junctures, mainly. This last issue is a very common failure in commercial parabolic trough power plants\(^\text{198}\) and, consequently, junctures must be checked with greater intensity and smaller periodicity than other elements of the pump in order to avoid failures.

\(^{198}\) According to Cohen, G., D. W. Kearney and G. J. Kolb. 1999. Final Report on Operation and Maintenance Improvement Program for Concentrating Solar Power Plants. For example, the feedwater pump of the SEGS V power plant failed 42 times in a year due to defective junctures.
5.4. Fire protection.

The parabolic trough power plant in Gibraleón contains a great amount of Therminol VP-1 diphenyl oxide/biphenyl synthetic oil and molten salt mixture for heat transfer fluid and heat storage fluid, respectively. During normal operation, up to 1%\(^{199}\) of these fluids can be volatilized into the air each year, becoming an explosive mixture that must be carefully treated. The ATEX Normative, adapted to the Spanish legislation as R.D. 681-2003, *Health and security protection for those workers exposed to the intrinsic risks of explosive atmospheres*, and under application since 30\(^{th}\) June 2006, is required due to the fire and explosion risk related to these volatile mixtures that may occur in solar thermal power plants. As a result, several modules of the plant, such as the heat transfer fluid pumping system and thermal storage module are subjected to its requirements.

In the second article of the R.D. 681/2003, an explosive atmosphere is defined as *the mixture with air, under atmospheric conditions, of different inflammable substances in the form of gas, vapour, fog or dust in which, after an ignition, combustion occurs on the totality of the unburned mixture*. This document establishes the main obligations of the employer regarding to explosive atmospheres, different classification regarding to specific features of the system and minimal dispositions related to the protection of health and security of employees in those atmospheres.

*Figure 146. Fire in Andasol II Power Plant (12/03/12)*

[Source.- http://www.ideal.es (accessed May 28\(^{th}\) 2012)]

Typically, parabolic trough power plants introduce an automatic fire extinguishing system that is permanently receiving information of several detection systems located in critical modules of the plant. If there is a positive detection, the automatic system will shut the alarm off, initiating the different automatic fire extinguishing systems (water sprinklers, gas injection systems, etc.) As a result, it is critical to ensure that all the different elements of the fire extinguishing system work perfectly through a periodical maintenance plan. Among the different elements that must be checked, it is possible to highlight temperature sensors, water sprinklers, control pad, extinguishing water pumping system, water storage system, portable fire extinguishers emergency signing, illumination and acoustical alarms, among many others. Depending on the size

\(^{199}\) Ibid. [198]
of the plant, this may require permanent contact with proximal fire fighter’s station and even a fire extinguishing truck that must be permanently located in the plant.

The most critical modules of the plant are the heat transfer fluid expansion tank, the heat transfer system pumping system, the administration and control building, the warehouse and maintenance building, the water treatment building, the generator area and the different transformers of the plant, among others. All these modules are typically equipped with fixed fire extinguishing systems and complemented with portable systems such as manual fire extinguishers for punctual fires. The biggest fixed fire system is located in the heat transfer fluid expansion tank area, which introduces firewalls between the different expansion tanks in order to avoid propagation in case of fire in some of the elements. According to the United States National Fire Protection Association (NFPA), a minimum firewater supply of 2 hours is required for the heat transfer fluid expansion tank area, which results in 1363 m$^2$ of water that must be stored until its supply is needed. This firewater system includes different hydrants, monitors, valves, pumps and sensors in order to ensure that it is always ready to face a fire in the plant.

The parabolic trough power plant in Gibraleón will consequently need a fire risk evaluation performed by an authorised company and validated by the nearest fire brigade, as well as an emergency plan to establish the main actuating lines in case that a fire is started in any area of the plant. Among these actuating lines, danger can be easily reduced by only sectorizing the different areas of the plant, especially in the solar field, although a heat transfer fluid fire in the heat transfer fluid of the solar field will surely be extinguished by itself due to the big separation between collector assembly rows and the fact that the different collector materials do not have a significant intrinsic fire power. However, sectorizing of the solar field was proved to be very useful in the fire started in the solar field of Andasol I power plant on the 15$^{th}$ December 2009. The fire started in the middle of the solar field, but as this was conveniently sectorized, the fire fighters were able to close the heat transfer valve manually. As no heat transfer fluid reached the fire, this could be rapidly extinguished and less than an hour was required for the whole process. In this case, sectorizing was critical in the success of the fire brigade, although fires in much more critical modules of the plant could be much more dangerous, as it was effectively demonstrated in the fire started in the power block of Andasol II power plant of the 13$^{th}$ March 2012 (Figure 146.), where almost three hours were required to extinguish it (the fire started at 5:00AM and could finally be extinguished by 8:00AM, approximately).

To this point, the main maintenance needs of the parabolic trough power plant in Gibraleón have been introduced. However, this is just a general approach based on previous parabolic trough experiences and so, the final maintenance plant must be developed according to the specific features of the project and taking into reference the requirements established by local administrations, European councils or any other official organism of application.

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200 http://www.nfpa.org

201 http://www.ideal.es
CHAPTER 6: ENVIRONMENTAL IMPACT

The different construction, operation and maintenance stages of the parabolic trough power plant project are related to a great amount of environmental impacts. As any other big project, it is important to identify, quantify and, as far as possible, reduce those impacts. Due to the special features of the solar thermal technology, this environmental concern becomes even more important. The parabolic trough power plant in Gibraleón is a renewable environmental friendly project due to the fact that no fossil fuel is needed for electrical generation. The whole energy required for the generating process is provided by the sun. No backup fossil fuel boiler has been chosen for this project, resulting in a pure solar thermal system with no significant polluting emissions.

During the following lines, a brief environmental assessment will be performed, highlighting the main impacts and determining the total amount of emission savings related to this project. Please notice that this is not only a voluntary initiative, as according to the AUTONOMIC LAW 7/2007, July 9th, of the Integrated Management of the Environmental Quality in Andalusia, the parabolic trough power plant in Gibraleón is included in the Category 2.6 – Electrical energy generation systems based on solar and photovoltaic technology, constructed in undeveloped land and with a total surface over 2 ha of the Annex I – Actuation categories subjected to environmental prevention and control instruments. As a consequence, the parabolic trough power plant in Gibraleón is subjected to a Unified Environmental Authorization (AAU) developed by the Andalusian Autonomic State, and will require a Environmental Impact Assessment (EIA). This document identifies and quantifies the main environmental impacts that the project may introduce, according to the requirements established by the LEGISLATIVE ROYAL DECREE 1/2008, January 11th, which approves the revised text of the Environmental Impact Evaluation Law. The Environmental Impact Assessment must be handed in to the
Andalusian Environmental Department, which will be responsible for the approval of the project. It is important to mention that this approval may be immediate or may be subjected to some conditions.

**Figure 147. General stages for the development of an EIA**

[Source.- http://www.tecnun.es (accessed June 1st 2012)]

**Figure 147.** shows the general stages for the development of an Environmental Impact Assessment. As it can be seen, this is not a simple process, as several organisms are includes. As a result, the EIA must be developed in the very first initial stages of the project, in order to ensure that the time required to obtain the correspondent authorisation is as small as possible. According to the **AUTONOMICA LAW 7/2007**, the EIA must include at least the following requirements:

- Main features of the project.
- Considered alternatives and justification of the chosen solution.
- Identification of the main environmental impacts, with special attention to human beings, flora, fauna, air, weather, cultural treasures and their interaction.
- Preventive and corrective measures.
- Environmental control program.
- Summary.
Due to the extension of the Environmental Impact Assessment, which would constitute a single project by itself, only a general approach will be performed in the following lines, highlighting the main impacts and providing different preventive and corrective measures in order to reduce them. This general approach will be performed without compromising the rigour and accuracy required by such a critical topic.

6.1. Main environmental impacts and corrective measures.

6.1.1. Material processing and manufacture.

The main elements of the parabolic trough power plant in Gibraleón have been introduced in previous stages of the project. A conventional solar thermal power plant requires a huge number of devices and systems in order to ensure its functioning. Each device has its own supplier, its own manufacturing process and its own material choice, so the different elements required to ensure the success of the plant will necessarily introduce an environmental impact related to their manufacture. If the plant needs solar collectors, these need to be fabricated, generating different emissions (commonly CO₂, SO₂ and NOₓ products from combustion processes) that will be consequently related to the environmental impact of the plant.

Due to the specific characterisation of this impact, as it answers to the manufacturing procedures carried out by each manufacturer, it is very difficult to reduce them in a very significant way. Each manufacturer must establish their own environmental policies and plans, answering to legal requirements (regulations and legislations of the country) or just to a self responsible behaviour towards the environment. However, it is possible to enhance this reduction by prioritizing those manufacturers committed to environmental protection and by demanding recycled elements and substitution of toxic elements during manufacturing processes for other less harming products. If non-toxic elements are demanded, the different manufacturers will have to adapt their production procedures in order to answer to that demand. The main problem for this corrective measure is that these less harming elements are usually more expensive than their polluting homonyms, reducing their implantation in commercial scale power plants. It is necessary an enhancing policy, carried out by local, national and continental Authorities, in order to reduce the cost of eco-friendly materials and manufacturing costs, by introducing economical incentives, subsidies and other measures in order to ensure that these are little by little introduced in the market.

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6.1.2. **Construction stage.**

The main environmental impacts related to the construction stage of solar thermal power plants are not very different from those that can be usually found on other similar power plant operations. Due to the huge amount of different impacts, only the most important ones will be discussed. First of all, in order to supply the different materials and parts, and to allow the different workers to accede the location, it will be necessary to construct access roads, resulting in a traffic increase (and consequently, a temporal increase in polluting emissions) and the introduction of toxic substances (petrol and hydrocarbon compounds of the asphalt, mainly). However, due to the great communications of the selected location, with direct access through road **N-431** and **Quinto Centenario Highway** (exits number 99 and 94), only small access roads will be needed.

It is important to ensure that the machinery does not exceed the limits of the parcel, in order to avoid unnecessary land impact. Taking this feature into account, the limits of the project will be delimited in the very first moment, by introducing reference signs such as posts that, once that construction stage is finished, will be removed. In case that any tree is left in this delimitation, this will be extracted and planted in a proximal region, but in any case will be cut down (especially in case of protected species). The different land adjustment operations will be the least as possible, in order to reduce land impact to the minimal expression, selecting materials and colours according to the specific features of the region.

In order to avoid acoustic impact, the noisiest procedures will be performed outside of resting hours, using adequate equipment and avoiding unnecessary noise. It is important to ensure that, during construction stage, water is applied to the ground in order to avoid dust emission. If any maintenance operation is needed in the machinery, this will be carried out in special facilities in order to avoid accidental leakages. Once that construction stage has been finished, all the different equipment will be removed and the parcel will be conveniently cleaned up, carrying out recuperation processes for the most affected features, as far as possible. It is important to ensure that the different workers are familiarized with the Environmental Impact Assessment in order to ensure the best results. Finally, as a curiosity, an archaeological team must be controlling construction operations in order to ensure that no historical treasure is damaged. In case that any relevant historical discovery was found, the construction operations would immediately be stopped.

6.1.3. **Land use.**

In previous stages of the project, an average estimation of 2 ha/MWe was introduced. Taking into account the nominal output of the plant, 50MW, the total area would be 100 ha. However, after the sizing stage of the parabolic trough power plant in Gibraleón, a total amount of 204,77 ha was obtained, which practically is related to 4 ha/MWe ratio, which is considered to be the correct one. It is easy to see that this is quite a big area and that most of it is used to contain the solar field (131,78 ha), but it is important to remember that parabolic trough technology is among the less land-using solar thermal technologies, as it was mentioned in the initial stages of the project. This 204,77 ha of land must be deforested and occupied, decreasing the total amount of available land for agriculture and other profitable purposes. At the same time,
extra land will be required to construct access roads to the plant, as it has been mentioned above.

### 6.1.4. Ecosystem, flora and fauna.

A very sensitive selection of the plant location is critical, as it has a direct impact on ecosystem, flora and fauna. The selected location for the parabolic trough power plant in Gibraleón is classified as **rustic soil** (Figure 33.), with agriculture established as the main use for the parcel. As a result, no special flora and fauna impact will be noticed, as no deforestation will be required and only conventional vegetation will be removed. What is more, despite initial land adjustment operations that will remove vegetation and will leave the parcel at the same level, flora will be lately favoured by the effect of collector shade in the creation of a microclimate\(^\text{204}\).

Other solar thermal technologies may introduce specific risks, such as the effect of central tower power plants on birds. If any bird flies through the concentrating beam line of the solar field, this is immediately inflamed, which in fact is very common for this kind of technology. Due to the small height of the parabolic trough collector assemblies and their special geometry that focuses the solar radiation on the absorber tube, no impact is estimated to be caused on birds. However, what it is necessary to ensure is that illumination systems during night periods are conveniently chosen and installed, in order to avoid behaviour alterations in the fauna of the region, especially in nocturnal animals.

### 6.1.5. Visual impact.

Again, it is very important to select carefully the location of the solar thermal power plant, as this will be closely related to the visual impact. Due to the specific operating requirements of these kinds of systems, solar thermal power plants are typically located in regions with small demographic density and very small visual impact may be introduced as far as natural reserves are avoided. Again, as it happened in with fauna impact, solar tower seem to introduce higher visual impact than other technologies such as parabolic trough, dish Stirling and linear Fresnel, due to the height of the central tower. For the parabolic trough power plant in Gibraleón, no area of special interest is located in the nearby of the plant, and due to the height of the different parabolic trough collector assemblies (which rarely exceed 5 m), visual impact will only be noticed from very proximal observers. In fact, due to the orography of the selected region (land is not totally plain), the parabolic trough power plant in Gibraleón is not expected to be observed from the town of Gibraleón, which the most proximal population nucleus.

### 6.1.6. Noise.

Due to the fact that the most proximal population nucleus (Gibraleón) is located 11,2 km away from the parabolic trough power plant, no special noise impact is expected to be caused on the town’s inhabitants. However, due to the fact that it introduces a 7,5 equivalent full load hours TES value, a 24 hour continuous operation will be maintained and this could be responsible for disturbance in

\(^{204}\) Ibid. [202]
proximal house. At the same time, this feature will introduce a relevant impact on fauna, as continuous noise can affect the different animals of the region, modifying their behaviours. It is important, then, to ensure that the maximum acoustic insulation is performed in the power block module, as well as to select those elements (steam turbine, pumps, hydraulic drives, etc.) carefully in order to reduce noise impact. Operation is not the only noise focus of the plant, as other indirect causes such as traffic and constructing operations in initial stages of the project must also be taken into consideration when designing an actuation plant.

6.1.7. Water use.

Due to the chosen cooling system (evaporative water cooling) an average water consumption between 3030 and 3785 litres/MWh\(^{205}\) is expected. Taking into account that the net annual output of the plant, obtained with SAM, is 179.534 MWh, it is possible to estimate that annual water consumption of the parabolic trough power plant in Gibraleón can be estimated to be between 543.988 and 679.536 tons. This such a great amount of water can easily be supplied as, according to previous stages of this project, the selected location is 7km away from the water supply channel of the industrial zone of Huelva and very near to the water reservoirs of Piedras (28 km), El Sancho (20 km) and Los Machos (14 km). It must be said that, in order to obtain water from this water reservoirs, the appropriate authorisation must be obtained, and the special conditions established in it must be strictly followed.

Despite the fact that there is enough water resource in the area, this does not mean that it can be wasted. Due to the criticity of the resource, it is important to ensure that only the necessary water is used, reinforcing this supply with other systems such as rain collecting ponds and water depuration systems, in order to ensure a constant supply in case of a decrease in the water storage levels (due to droughts, for example). At the same time, the different chemical substances introduced in process water during operation (oxygen scavengers and biological treatment chemicals, mainly) must be filtered in order to avoid soil contamination and ecosystem impact.

6.1.8. Leakages and spillages of chemical substances.

The power plant in Gibraleón is a two-tank indirect storage parabolic trough power plant and, as a result, introduces a difference between the heat transfer fluid and the heat storage fluid. The selected heat transfer fluid was the Therminol VP-1 diphenyl oxide/biphenyl synthetic oil, and the chosen heat storage fluid was the HITEC Solar Salt (60% NaNO\(_3\), 40% KNO\(_3\)). As it has been previously mentioned, small leakages (due to volatilization, mainly) and accidental spillages can occur in the plant, and so, it is essential to establish an accurate maintenance plan in order to ensure that no fluid is spilled, as well as to establish adequate chemical continence procedures in order to establish the main operating recommendations in case this occurs (hydrocarbon digestive bacteria). A leakage can be environmentally dangerous but, at the same time, can be responsible for injuries and health impact when regarding to operators. It is

\(^{205}\) Ibid. [8]
critical, then, to ensure that no leakages are produced in order to minimize ecological disasters and to avoid any kind of danger for the workers of the plant (by applying job security regulations and normative and providing special equipment to the operators of the plant).

As it has been previously mentioned, special attention may be paid to critical parts of the system, such as pipes, valves and joints. Regarding to the Therminol VP-1 properties, this is slightly toxic by punctual ingestion and non-toxic by dermal contact. The rest of Therminol VP1 physical and chemical properties can be found in Annex II. On the other hand, despite being a relatively stable, non-flammable mixture, the HITEC Solar Salt can be responsible for explosions and fires when being in contact with organic materials at high temperatures. The main features of the HITEC Solar Salt are provided in Annex III.

Taking all these considerations into account, it can be concluded that a great ecological impact reduction can be easily obtained by introducing innovative systems that avoid synthetic oils and molten salt mixtures in the plant, introducing DSG technology as a great possibility for future applications. Do to the fact that they are a dangerous residue, once that the different heat transfer and heat storage fluids have finished their operating life, they will be stored in the plant until an Authorised Organism removes them.

Special attention must be paid to operators in this stage. By ensuring a good knowledge of the different systems of the plant, introducing specializing courses and enhancing worker’s collaboration trough training investment, it is possible to reduce environmental impacts in a relevant grade. This feature is related to the fact that, the more the operator knows, the quicker this will notice a failure in the system, and the better the solution applied by it will be. At the same time, by introducing sensible operational practices from the very first stages of a worker’s formation (sensible water use, safety measures, use of adequate equipment, etc.), great improvements can be achieved.

6.2. Estimation of environmental impact.

There are several procedures for estimating the environmental impact of a system. The best option will depend on the specific features of each project but, however, these can only be considered as an approximation of the real environmental impact, as most of the different parameters answer to subjective criteria. According to the mentioned features, the main environmental impact estimation procedures are:

- **Check list procedure**: this estimation method is based on pre established lists that summarize the main impacts of specific stages and projects. These are typically filled with ticks and crosses, introducing quite a simple binary qualification procedure that may sometimes be incomplete as a huge amount of lists would be required for the most complex projects. At the same time, the subjectivity of environmental impact estimation procedures is easily noticed in this procedure, being critical to ensure that all the different check lists of a project are filled by a single evaluator. As a result, this procedure must only be applied in small size and simple projects and, as a result, they cannot be used in the environmental impact assessment of the parabolic trough power plant in Gibraleón.
• **Simple Matrix procedure**: the single matrix procedure increases the complexity of the method, relating those processes susceptible of causing environmental impact with the different environmental components that may be affected by these processes. Thanks to this feature, it is possible to identify the main impacts of a project with less subjective criteria. Despite being a quite simple method, it is possible to increase the extent of this procedure through a combination with other graphic and more complex components, although these combinations end to be substituted by complex matrix procedures. The most common single matrix procedure is the *Cause-Effect Matrix*.

• **Complex Matrix procedure**: the complex matrix procedures increase the complexity of single matrix methods in order to obtain a more complete evaluation of the environmental impact of a project depending on the different processes developed in it. The most common complex matrix procedure is the *Importance Matrix*. Once that the main environmental effects have been identified, the Importance Matrix allows to quantify those impacts and to obtain a final importance qualification in a scale which varies from 13 to 100. This is a great advantage when compared to other complex matrix methods, such as the *Leopold Matrix* procedure, where the values obtained cannot be considered by themselves and require to be compared to other similar projects in order to obtain an estimation of the environmental character of the system. As a result, different parameters will be introduced, relating a numerical value to specific importance ranges in order to obtain the global characterisation of the project. The general procedure of the Importance Matrix will be developed in the next stages of the project.

According to the mentioned features, it is necessary to select the environmental impact estimation procedure for the parabolic trough power plant in Gibraleón. In order to ensure the maximum rigour and accuracy, a combination of two estimation methods will be performed: a general identification of the different environmental impacts will be carried out through a Cause-Effect Matrix procedure and, once that these impacts have been identified, a more complex approach will be performed with an Importance Matrix procedure.

### 6.2.1. **Cause-Effect Matrix procedure for the power plant in Gibraleón**

In order to apply the Cause-Effect Matrix procedure in the parabolic trough power plant, the different environmental components will be related with the different processes of the project, identifying the environmental impacts with a cross. As a way to give a more global approach to the project, three stages will be studied: *construction*, *operation* and *dismantling*. 
Table 42. Cause-Effect Matrix for the construction stage of the parabolic trough power plant in Gibraleón.  
[Source.- Own elaboration\textsuperscript{206}]

<table>
<thead>
<tr>
<th></th>
<th>Land acquisition (A)</th>
<th>Land Adjustment (B)</th>
<th>Construction of Access Roads (C)</th>
<th>Construction of Accessory Facilities (D)</th>
<th>Transport of Materials (E)</th>
<th>Use and Reparation of Machinery (F)</th>
<th>Construction of Main Facilities (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Quality (1)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Acoustic Impact (2)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Suspended Particles (3)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Ground Pollution (4)</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Water Quality (5)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Amount (6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fauna (7)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Flora (8)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Land Use (9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscape (10)</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to Table 42, there is a clear predominance of some environmental impacts among the totality of the discussed elements. As it can be seen, Air Quality, Acoustic Impact, Suspended Particles and Fauna and Flora impacts are largely the most common issues in the parabolic trough power plant in Gibraleón, as they are introduced by several processes during the construction stage of the plant. It is necessary, then, to apply the corrective and preventive measures introduced in previous stages of the project in order to minimize the environmental impact on these parameters. Please notice that no impact has been noticed in Water Quality and Water Amount. This may seem untrue, as water is required in several processes during the construction stage (ground moisturising, cleaning operations, concrete production, etc.). However, it has been considered that water quality is related to the chemical composition of the selected water reservoir, and the different construction stages do not have any

impact on it. On the other hand, water amount is related to the quantity of water supplied by the water reservoir. All the different construction processes previously mentioned can easily be solved by supplying water with trucks to the plant. This water can be stored in the rain collecting pond in order to be used in those minor operations, as the required amount of water for these is insignificant compared to the estimated water consumption of the plant during operation. Once that the different environmental impacts of the construction stage, it is the time to discuss those during operation of the plant.

Table 43. Cause-Effect Matrix for the operation stage of the parabolic trough power plant in Gibraleón.

[Source.- Own elaboration\textsuperscript{207}]

<table>
<thead>
<tr>
<th>Air Quality (1)</th>
<th>Plant Facilities (H)</th>
<th>Solar Collection (I)</th>
<th>Thermal storage (J)</th>
<th>Power block (K)</th>
<th>Maintenance Operations (L)</th>
<th>Electrical Injection to the Grid (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Impact (2)</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suspended Particles (3)</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground Pollution (4)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Quality (5)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Water Amount (6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fauna (7)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Flora (8)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Land Use (9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Landscape (10)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

As it can be seen, it is not possible to observe a general pattern in the different environmental impact distribution during operation of the plant. However, by direct comparison with Table 42., it is possible to affirm that the environmental impact associated to the operation stage of the parabolic trough power plant in Gibraleón is largely smaller than the one introduced during construction stages. This feature could have been expected, according to the different issues introduced in previous lines. Finally, it is necessary to repeat this process for the

\textsuperscript{207} Ibid. [206]
dismantling stage of the project, which is related to the removal of the different elements of the plant once that its operating life has been concluded.

**Table 44. Cause-Effect Matrix for the dismantling stage of the parabolic trough power plant in Gibraleón.**

[Source: Own elaboration\(^{208}\)]

<table>
<thead>
<tr>
<th></th>
<th>Dismantling of the plant (N)</th>
<th>Residue Removal Operations (O)</th>
<th>Restoration (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Quality (1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic Impact (2)</td>
<td>(x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suspended Particles (3)</td>
<td>(x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground Pollution (4)</td>
<td></td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>Water Quality (5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Amount (6)</td>
<td></td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>Fauna (7)</td>
<td>(x)</td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>Flora (8)</td>
<td>(x)</td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>Land Use (9)</td>
<td>(x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscape (10)</td>
<td>(x)</td>
<td>(x)</td>
<td></td>
</tr>
</tbody>
</table>

It could have been easily expected that the dismantling stage of the parabolic trough power plant in Gibraleón would introduce the least environmental impact of the different considered stages, as it is shown in **Table 44**. To this point, a general identification of the main environmental impacts associated to the different stages of the parabolic trough power plant in Gibraleón has been performed. Although it has been previously mentioned, it is important to remember that this Cause-Effect procedure introduces a very subjective approach the EIA, as most of the parameters introduced above answer to personal considerations. As a result, the different impacts shown in the tables above will be considered as an estimation and, in any case, as a definitive solution.

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\(^{208}\) Ibid. [206]
6.2.2. **Importance Matrix procedure for the power plant in Gibraleón.**

As it has been previously mentioned, the Importance Matrix procedure is based on 11 different parameters related to a determined numerical value, and through the combination of them it is possible to obtain the *Global Impact Index (GII)* of a project. Taking all these features into account, the different categories of the Importance Matrix are:

- **Nature of the impact**: it is used to differentiate those positive impacts (+) and those negative ones (-), through the introduction of a sign.

- **Intensity (IN)**: this category varies from 1 to 12 and it is related to the intensity of the considered impact.

- **Extension (EX)**: it is related to the dispersion of the impact along the project.

- **Moment (MO)**: the moment parameter represents the time between the start of a process and the apparition of its correspondent environmental impact.

- **Persistence (PE)**: it is related to the time required to remove an impact once that this has been produced.

- **Reversibility (RV)**: the reversibility shows the possibility of naturally restoring the environmental impacts after they have been produced.

- **Synergy (SY)**: it represents the ability of an impact to combine with others increasing their hazard. Some impacts may be relatively unimportant by themselves, but can be critically dangerous when combined with other environmental impacts.

- **Accumulation (AC)**: this parameter reflects the increase of an impact while it is being produced. This can easily be explained with dust emissions: once that construction processes begin, if no measure is applied, there will be a great amount of dust removed and carried by the wind. After several months of operation, the total amount of accumulated dust on, for example, local vegetation, increases in a very significant way and, despite in an initial moment this was not a problem, the accumulation of the impact can be harming for the environment.

- **Effect (EF)**: depending on the impacts are direct or indirect.

- **Periodicity (PR)**: the periodicity represents the regularity in the production of an impact, which can be regular, irregular, punctual, etc.

- **Restorability (RT)**: this parameter must not be confused with the reversibility, as the first one is related to a natural recovering process, and restorability is carried out through human operations.
Through the combination of these 11 different parameters, it is possible to obtain a GII for the project, through the following expression:

\[ GII = +/- (3 \cdot IN + 2 \cdot EX + MO + PE + RV + SY + AC + EF + PR + RT) \]  \hspace{1cm} (157)

This is, again, a very subjective procedure, as most of the different parameters answer to personal considerations. However, in order to ensure a bigger accuracy, it is possible to relate the different numerical values to tangible references, as it is shown in the following figure:

![Design of a Solar Thermal Power Plant](image)

**Figure 148. Numerical values for the Environmental Impact Assessment through a Importance Matrix procedure.**

[Source. - Instructive for the assessment of environmental impacts, Environmental Quality Assessment Direction (DIGECA), http://www.digeca.go.cr (accessed June 1\textsuperscript{st} 2012)]

Now that the main bases of this procedure have been explained, it is the time to proceed with the quantifying process for the environmental impact introduced by the parabolic trough power plant in Gibraleón. Once that this assessment is finished, it is possible to compare the obtained GII value with the reference parameters. Taking this feature into account, a GII value under 25 is related to an irrelevant impact. Moderate impacts are comprised between 25 and 50, and followed by severe impacts between 50 and 75. As a result, those GII values over 75 are considered critical impacts and cannot be implemented at any cost.

\[209\] Instructive for the assessment of environmental impacts, Environmental Quality Assessment Direction (DIGECA), http://www.digeca.go.cr (accessed June 1\textsuperscript{st} 2012).
During the Cause-Effect Matrix procedure, the reader may have noticed an alphanumerical code in the different construction, operation and dismantling matrixes: Table 42., Table 43. and Table 44., respectively. To this point, no comment has been made on this issue, and it is the time to justify their introduction. Through a very simple line/column positioning system, it is possible to locate a specific impact just in a similar way than a conventional Battleship Game. As a result, an environmental impact over the fauna caused by construction of access roads during the construction stage of the project will be codified as C7, a water consumption produced in the power block during operation will be codified as K6, and the same procedure would be applied to the different identified impacts. Thanks to this codification, it is possible to develop the following Importance Matrix for the parabolic trough power plant in Gibraleón:

**Table 45. Importance Matrix for the parabolic trough power plant in Gibraleón.**

[Source.- Own elaboration\(^{210}\)]

<table>
<thead>
<tr>
<th>+/-</th>
<th>IN</th>
<th>EX</th>
<th>MO</th>
<th>PE</th>
<th>RV</th>
<th>SY</th>
<th>AC</th>
<th>EF</th>
<th>PR</th>
<th>RT</th>
<th>GII</th>
</tr>
</thead>
<tbody>
<tr>
<td>A9</td>
<td>-</td>
<td>12</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>B1</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B2</td>
<td>-</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B3</td>
<td>-</td>
<td>4</td>
<td>4</td>
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<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>-41</td>
</tr>
<tr>
<td>B7</td>
<td>-</td>
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<td>4</td>
<td>2</td>
<td>2</td>
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<td>1</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>B8</td>
<td>-</td>
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<td>4</td>
<td>2</td>
<td>2</td>
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<tr>
<td>B10</td>
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<td>4</td>
<td>4</td>
</tr>
<tr>
<td>C1</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
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<tr>
<td>C2</td>
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<td>4</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>C3</td>
<td>-</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<td>4</td>
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<td>1</td>
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<td>C4</td>
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<td>4</td>
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<td>4</td>
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<tr>
<td>C7</td>
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<td>4</td>
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</tr>
<tr>
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<td>4</td>
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\(^{210}\) Ibid. [206]
### Design of a Solar Thermal Power Plant

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As it can be seen, there are several relevant environmental impacts in the different stages of the parabolic trough power plant in Gibraleón. It is curious to see that, during the dismantling stage of the project, some positive impacts are produced, and they are the ones related to the removal of all the facilities of the plant and the restoration of the different natural resources, especially in terms of water use. It is very difficult to understand the results of the Importance Matrix procedure, as they are represented by a huge amount of numerical values. As a result, applying the qualifying criteria previously mentioned (irrelevant, moderate, severe and critical), it is possible to obtain the following table:
### Table 46.

**Final results of the Importance Matrix for the parabolic trough power plant in Gibraleón.**

[Source: - Own elaboration\textsuperscript{211}]

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<th>GII</th>
<th>Impact Classification</th>
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<tbody>
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<td>B1</td>
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<tr>
<td>B2</td>
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\textsuperscript{211} Irrelevant (GII <25), Moderate (25≤GII<50), Severe (50≤GII<75), Critical (GII ≥75)
<p>| | | |</p>
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<tr>
<td>M7</td>
<td>-30</td>
<td>MODERATE</td>
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</table>
And, summarizing the total amount of impacts depending on their classification:

**Table 47. Classification results of the Importance Matrix for the parabolic trough power plant in Gibraleón.**

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>IRRELEVANT</th>
<th>MODERATE</th>
<th>SEVERE</th>
<th>CRITICAL</th>
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<tbody>
<tr>
<td>11</td>
<td>55</td>
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It can easily be observed that there is a clear predominance of moderate impacts and, as a result, the convenient preventive and corrective measure previously mentioned must be applied in order to ensure that the environmental impact is reduced to the minimal expression. There are two severe impacts related to *land use* during land acquisition in the construction stage of the plant, and *water consumption* in the power block during operation. This fact is related to the great amount of land required to build the power plant, which according to previous stages was estimated in 204.77 ha, and the chosen evaporative wet cooling method, whose consumption has been established between 543.988 and
679.536 tons of water per year. According to the determined values, it can be concluded that this brief Environmental Impact Assessment for the parabolic trough power plant in Gibraleón is positive, although the subjectivity of the chosen evaluating methods only allows to consider this results as estimations and, in any case, as definitive values.

6.3. Determination of CO₂ savings.

The parabolic trough power plant in Gibraleón is based on a pure solar thermal technology and, consequently, no fossil-fuel emissions are produced. It has been considered as interesting to determine the total amount of CO₂ saved when compared to other available power generating technologies in Spain. First of all, it is necessary to determine the different existing power generation systems and to quantify the total amount of energy provided by each of them.

![Graph of installed power in Spain by technology](image)

**Figure 149. Installed power in Spain depending on technology (31/12/2011)**


According to Figure 149, the most installed power technology is the *combined cycle power*, followed by *wind power* and *hydraulic power*. It is curious to see that solar thermal technology is also noticed, with a total amount of 1% of the 100.576 installed MW. Once that the different generation technologies have been defined, it is the time to determine the total amount of CO₂ emissions related to these systems. Since the 5th of June 2009, REE provides real-time CO₂ emissions depending on the different technologies of the Spanish Electricity Sector.²¹² Thanks to this feature, it is possible to obtain an average value of CO₂ emissions per generated power unit (tons of CO₂ per MWh, mainly) depending on the selected technology. Taking this feature into account, these values are introduced in the following figure:

²¹² [http://www.demanda.ree.es/demanda.html](http://www.demanda.ree.es/demanda.html)
Figure 150. Average emissions [tons of CO₂ per MWh] depending on technology

To this point, the main distribution of the generating technologies in Spain and the total amount of CO₂ related to these systems are known. Please notice that, contrary to Figure 149., the different Cogeneration, Solar Photovoltaic, Solar Thermal and Renewable Thermal are combined in Figure 150., with an average global value of 0.25 tons of CO₂ per MWh. It is important to mention that Solar Photovoltaic, Solar Thermal and Renewable Thermal are considered to introduce no CO₂ emissions, so the average value provided for renewable energies can be assumed to be related to Cogeneration. Taking all this features into account, the average emission rate for the global Spanish Energy Sector is given by the following expression:

\[
\frac{CO_2 \text{ tons}}{MWh} = \sum_{i=1}^{n} (\text{System}_i \cdot \text{Average emissions}_i)
\]

\[
\frac{CO_2 \text{ tons}}{MWh}_{AVG} = \left(25\%_{\text{COAL}} \cdot \frac{0,7}{MWh} CO_2 \text{ tons} \right) + \left(12\%_{\text{NUCLEAR}} \cdot \frac{0,95}{MWh} CO_2 \text{ tons} \right) + \\
+ \left(8\%_{\text{WIND}} \cdot \frac{0}{MWh} CO_2 \text{ tons} \right) + \left(19\%_{\text{HYDRAULIC}} \cdot \frac{0}{MWh} CO_2 \text{ tons} \right) + \\
+ \left(21\%_{\text{RENEWABLES}} \cdot \frac{0}{MWh} CO_2 \text{ tons} \right) + \left(15\%_{\text{OTHER}} \cdot \frac{0.25}{MWh} CO_2 \text{ tons} \right)
\]
As a result:

\[
\left( \frac{CO_2 \text{ tons}}{MWh} \right)_{AVG} = 0,3265
\]  

(160)

The value obtained is the average CO\(_2\) emission ration for the whole energy sector in Spain. According to Table 15., the total amount of sunlight for the selected location is 2754 hours of sun per year, so the total amount of saved CO\(_2\) can easily be found through the following expression:

\[
Saved \, CO_2 = \left( \frac{CO_2 \text{ tons}}{MWh} \right)_{AVG} \cdot \text{Annual Net Output}
\]

(161)

\[
Saved \, CO_2 = 0,3265 \frac{CO_2 \text{tons}}{MWh} \cdot 179.534 \frac{MWh}{\text{year}}
\]

(162)

\[
Saved \, CO_2 = 58.617.851 \frac{\text{tons}}{\text{year}}
\]

(163)

According to (163), the total amount of CO\(_2\) saved by the parabolic trough power plant in Gibraleón is approximately 58.617,851 tons per year, which is a great value regarding to the total amount of emissions of the Spanish Electric Sector during 2011, which reached the 73.000.000 tons of CO\(_2\).213. Trough a simple operation:

\[
\% \, Saved \, CO_2 = \frac{58.617.851 \text{ tons}}{73.000.000 \text{ tons}} \times 100 = 0,08\% 
\]

(164)

The parabolic trough power plant in Gibraleón would introduce a 0,08\% reduction in the total amount of CO\(_2\) emissions of the Spanish Electric Sector, which can be considered as a great advance in order to achieve the different emission objectives established by the European Community for the next years. To this point, the environmental impact assessment of the parabolic trough power plant in Gibraleón is concluded, introducing this technology as a great allied in the protection of the environment. It must be said, however, that all the different values obtained in this stage can only be considered as estimations due to the subjectivity of the selected procedures.

---

CHAPTER 7:
GRID CONNECTION
PROCEDURE

The main objective of the parabolic trough power plant is to produce electrical energy. However, this effort is worthless without an appropriate distribution system which allows to provide this energy to consumers. Taking this feature into account, it has been considered essential to perform a general approach to the different processes required to ensure this connection, in order to provide a global view to the project. As a result, the Grid Connection Procedure is based on the following stages:

1. **Draw up of the basic documentation**: first of all, it is necessary to elaborate a draft of the project in order to obtain the connecting point authorisation. This draft may contain the more relevant features of the project, including technical features, location and owner, among many others.

2. **Authorisation for land use application**: in order to begin with construction operations, it is necessary to apply for the land use authorisation in the Town Hall of Gibraleón.


4. **Connecting point application**: in order to obtain the connection authorisation, different documentation is required. Among it, it is possible to highlight the **general application, project owner, project location, selected connection point, main technical features** (voltages, short circuit power, etc.) and the **authorisation for land use** of the Town Hall of Gibraleón. Some extra documentation may be required by the Electrical Company, but in any case, this has only 10 days after the application has been sent to demand it. This procedure lasts typically a month, approximately, and authorisation can be
given directly or under some conditions. If those conditions were considered to be abusive, it is possible to inform the correspondent Administration which will have to make a decision in less than 3 months. In any case, all the economical expenses related to this procedure, as well as any other related to the connection process (wires, devices, etc.), will be assumed by the owner of the project.

5. **Final project:** once that the connecting point has been authorised, it is necessary to elaborate the definitive project of the parabolic trough power plant in Gibraleón, which must be written by a competent technician, include all the basic elements of the project and signed by an authorised Engineering College.

6. **Administrative Authorisation of the Autonomic Government:** in order to obtain this document, it is necessary the correspondent application, which must be signed by the owner of the plant, the definitive project signed by an authorised Engineering College and the accreditation of the purchase or rent of the land where the project will be located.

7. **Connecting Point Statement,** elaborated by a competent Organism of the Autonomic Government or the State Government, depending on the specific features of the project. This public communication process is typically 3 months, although for big projects (such as the parabolic trough power plant in Gibraleón) this time period can be substantially increased.

8. **Local Planning Permission:** once that the previously mentioned stages have been finished, it is the time to begin the construction of the power plant. In order to do so, it is necessary to apply for the local planning permission in the Town Hall of Gibraleón, which will at least require the following documentation: national identification number of the owner, definitive project signed by an authorised Engineering College, selected Project Manager, Autonomic Administrative Authorisation and, depending on the specific features of the project, an Environmental Impact Assessment (which is, as it has been previously mentioned, necessary for the parabolic trough power plant in Gibraleón). The local planning permission introduces some taxes, which will vary depending on each Town Hall, and lasts typically 3 months.


10. **Construction operations:** once that the previous requirements have been accomplished, it is the time to begin with the construction operations of the parabolic trough power plant in Gibraleón.

11. **Emission of the Feature Newsletter of the project,** including the main technical features of the project and the different construction certifications.

12. **Autonomic Start Up Authorisation:** once that the plant has been built up and it is ready to start operation, it is necessary to apply for the Autonomic Start Up Authorisation, which will require the different construction certifications in order to ensure that all the different systems of the project have been properly installed.
13. **Application of the Electrical Company Agreement:** once that the autonomic start up authorisation has been delivered, the owner of the plant must sign the contract with the Electrical Company within the next month. In order to sign the contract, several documentation will be needed, highlighting the Code of Activity and Establishment provided by the Tax Agency. This contract must include the main operational, economical and technical features of the project as well as the rights and obligations of both the owner and the Electrical Company.

14. **Previous Administrative Record in the National Renewable Production Listing:** according to the ROYAL DECREE 661/2007, May 25th, which regulates the electrical energy production activity in Special Regime, all the different producers subjected to the Special Regime must be recorded in the National Renewable Production List. In order to do so, it is necessary to provide the following documentation: owner data, social capital of the project, shareholders with participation over 5%, main energy efficiency, technical and security features of the project, other projects subjected to the Special Regime owned by the holder of the project and economical exercise of the previous year, among many others. The application for this record must be handed in the competent Organism of the Autonomic Government, including the Electrical Company Agreement and the connecting point authorisation. Once that the previous administrative record in the National Renewable Production List has been done, the project will obtain a specific registration number.

15. **Review of the Measuring Systems of the plant by the Electrical Company:** in order to ensure that the maximum accuracy is performed, the Electrical Company has a month to verify that the different measuring systems of the parabolic trough power plant in Gibraleón are adequate, sufficient and work properly. In case of conflict between the Electrical Company and the owner, it is possible to inform the correspondent Administration which will have to make a decision in less than a month. It is possible that, in order to ensure this review, the power plant requires to be connected to the Grid. If this happens, this connection will only have a provisional character and, once that the different measures are concluded, must be disconnected from it. If everything is correct, and all the different taxes are paid, the Electrical Company or the System operator will elaborate a Compliance Certificate.

16. **Definitive Administrative Record in the National Renewable Production Listing:** the definitive record in the National Renewable Production Listing will require the selected selling option, certification of the payment of the correspondent Administrative Taxes, Compliance certificate of the Electrical Company or System Operator, application signed by the own and a certified copy of the Electrical Company Agreement. Once that this documentation has been handed in and the correspondent processing time is concluded, the definitive record in the National Renewable Production Listing is done and the registration number is fully valid.

17. **Connection to the Electrical Grid:** once that the previous statements have been concluded, it is the time to apply for the definitive connection to the Electrical Grid, which the Electrical Company must answer in less than a month. If the Electrical Company did not answer within this month, the
authorisation would be presumed and the parabolic trough power plant in Gibraleón connection to the Grid would be performed. On the other hand, in case of conflict, it would be necessary to inform the correspondent Administration. In addition to the application, some documentation may be necessary, highlighting the Compliance certificate of the Electrical Company or System Operator, Low Voltage Installation Certification, manufacture certifications for the different elements and devices of the connection system (transformers, wiring, measuring devices, etc.) or the definitive project of the connection system signed by an authorised Engineering College, among others. Once that the main documentation has been handed in, and a positive answer has been received from the Electrical Company (or the process time has exceeded a month), the parabolic trough power plant in Gibraleón is ready to be connected to the Grid.

The different grid connection procedures are summarized in the following figure:

![Diagram summarizing grid connection procedures](image_url)

**Figure 151.** Summary of the different stages of the Grid Connection Procedure

[Source.- Own elaboration]
CHAPTER 8:
ECONOMIC ANALYSIS
OF THE PROJECT

IMPORTANT NOTE: According to the ROYAL DECREE-LAW 1/2012, January 27th, which removes the retribution preassignment procedures and economic incentives for new cogeneration, renewable energies and waste electrical energy power plants, all the new power plants subjected to the Special Regime that to date 28th of February 2012 were not included in the Retribution Pre-assignment Register established by the ROYAL DECREE-LAW 6/2009, April 30th, which approves determined measures in the energetic sector and social bonus, will not enjoy any kind of economical incentive and the Retribution Pre-assignment Register procedure is removed. This measure affects to the following incentives:

- All the Regulated Tariffs, Primes and Economical Limits, as well as the Economical Complements due to Reactive Energy and Efficiency established in the ROYAL DECREE 661/2007, May 25th, which regulates the electrical energy production activity in Special Regime.

This measure can be explained by the current convulse economic situation and the overwhelming consecution of the renewable energy objectives established for the period 2005-2010, where excessive incentives and primes resulted in a huge increment of renewable energy producers, even over the desired rate, and a consequent increase of the Spanish Tariff Deficit. As a result, according to these limitations, the parabolic trough power plant in Gibraleón would not enjoy any kind of incentive nor prime and, consequently, its economical regime and retribution procedure will be equal to other conventional fossil-fuel based plants. So, why has the entire project been designed for the 50MW power limit in order to be subjected to the Special Regime, if there are not any kinds of advantages? Well, the main reason is the temporary condition of this measure, as it has been introduced taking into account the difficult economical situation of the country and the huge tariff deficit introduced by the previous renewable boom that has
being produced during the last years. What this means is that, presumably, once that this complicated situation finishes (this is quite a difficult thing to determine, indeed), the special retribution regime will be restored. By designing the parabolic trough power plant in Gibraleón to the specific requirements established in order to access the Special Regime, once that the different economical incentives and primes are restored (and who knows, maybe new ones will be introduced), the plant will be able to become part of this Special Regime as only bureaucratic processes will be needed.

Finally, the removal of the special economical regime can even affect the economic analysis stage of this educational project, especially taking into account that during the Engineering Studies in the University College of Technical Industrial Engineering of Barcelona (EUETIB) all the different subjects involving economical assessments and analysis for renewable energies have been based on this special retributive system. However, in order to ensure the maximum accuracy and rigour, as it has been done in all the previous stages of the project, the parabolic trough power plant in Gibraleón will be studied according to real social, technical and economical situation, and this prime removal must be considered. A general approach will be made on this issue, in order to determine the estimated selling price of the electricity and the investment cost of the project. Although the definitive economic analysis of the parabolic trough power plant in Gibraleón would involve a huge amount of variables the specific objectives of this project introduce these two parameters as sufficiently representative for this general approach and so these will be the discussed topics.

8.1. Introduction to the Spanish Electricity Market.

In order to estimate the selling price of the electrical energy produced in the parabolic trough power plant in Gibraleón, it is essential to understand how does the Spanish Electricity Market work. First of all, it is necessary to introduce the main actors and to explain how the different demands and offers are related.


According to what it is established at the Article 34 of the Law 54/1997, November 27th, of the Spanish Electrical Sector, the System Operator is responsible for the guarantee of the continuity and security of the supply, as well as for the coordination of the production and distribution systems, working with the different operators and elements of the Spanish Electricity Market and ensuring the maximum transparency, objectivity and independence. To put it into a nutshell, the System Operator is responsible for the management of the electrical transport grid. The Spanish System Operator is Red Eléctrica de España (REE)\textsuperscript{214}. Among the different functions of the Spanish System Operator, it is possible to highlight the following:

\textsuperscript{214} http://www.ree.es
To guarantee the supply at short and medium term.

To estimate the use of the different production system, with special regards to hydroelectric power plants, according to the estimated demand, electrical equipment availability and any other relevant conditions.

To receive and manage different information related to maintenance operations, failures and any other exceptional conditions in order to communicate them to the Market Operator.

To coordinate and modify the different maintenance plans in order to ensure that the transmission system is compatible with the different generation plants.

To implement the different recommendations and impositions established by the Spanish Government.

To estimate the capacity of the international supply in order to ensure energy exchange in short-term, managing the different required operations.

To program the operation of the different systems according to the offers and demands provided by the Market Operator, solving any technical problem and considering exceptional conditions in order to minimize impacts when they occur.

To collaborate with the different operators of the Spanish Electricity System, as well as with the Spanish Ministry of Industry, Tourism and Commerce\(^{215}\) in order to evaluate and verify the different accorded plans.

To ensure the development and increase of the Spanish Transport Grid under principles of homogeny, security and coherence.

To provide the sufficient information to other interconnected grid operator in order to ensure an efficient and safe operation.

To ensure that no user is discriminated, providing the sufficient information in order to allow that they can join the system efficiently.

To liquidate and communicate the different payments related to peninsular and extra peninsular systems.

At the same time, the System Operator is responsible for any other function as far as this is conveniently established by an authorised organism. During the different functions previously mentioned, a new player has been introduced: the Spanish Market Operator, which needs to be introduced too.


According to what it is established at the Article 33 of the LAW 54/1997, November 27\(^{th}\), of the Spanish Electrical Sector, the Market Operator is responsible for the management of the different electricity trading offers in the Daily Market under the principles of transparency, objectivity and independence.

\(^{215}\) http://www.mityc.es
The Spanish Market Operator used to be OMEL\textsuperscript{216}, although according to the Mibel Agreement, since July 1\textsuperscript{st} 2011 all its functions are developed by OMIE\textsuperscript{217} and OMEL is left as the stock owner company. Among the different functions developed by the Market Operator, it is possible to highlight the following:

- To receive the different selling offers related to each programmed period provided by the different elements of the Daily Market, as well as the different purchase offers related to each programmed period.

- To obtain the sufficient information from the different elements of the Spanish Electricity Market, in order to take into account the energy demanded by these.

- To obtain economic guarantees, both directly and indirectly.

- To join the different purchase and selling offers, from the lowest offer until the demand is covered in each programmed period, informing all the different producers, distributors, qualified consumers and authorised external agents of the Spanish Electricity Market.

- To communicate to the System Operator the different electricity selling and purchase offers provided by the different elements of the Spanish Electricity Market for each programmed period.

- To inform publicly and periodically about the development of the Spanish Electricity Market.

At it happened with the System Operator, the Market Operator is responsible for any other function as far as this is conveniently established by an authorised organism.

8.1.3. Daily Market.

The Daily Market plays an essential role in the Spanish Electricity Market, as it is responsible for the management of the different electricity trading offers in order to find an offer/demand balance at the lowest cost. For example, the different electricity producers introduce their offers for each programmed period of the day (for example, 300MW from 8:00h to 9:00h, 400MW from 9:00h to 10:00h, etc.), which are sent to the Market Operator (OMIE) according to the different grid connecting points. The different distributors, qualified consumers and authorised external agents are the ones that will introduce the purchase offers for each programmed period of the day (for example, 50MW at 5:00h in the grid connecting point number 8 and at a price of 52€/MW). These are known as simple offers, and those which introduce extra technical or economical requirements are known as complex offers.

Once that the different trading offers have been done, the Market Operator will join them as far as they have been received sooner than 10:00h the considered day. Once that the different balances are finished, the Market Operator established the input programming and the total amount of electrical energy

\textsuperscript{216} http://www.omelholding.es

\textsuperscript{217} http://www.omie.es
required to cover the demand of each considered period. At 12:00h, the daily
*Base Functioning Programming* is published, including the final balances of the
different trading offers for the day and, by 14:00h, any other required
modification in order to ensure the security of the system has been introduced
and published in the *Definitive Daily Viable Programming*. Thanks to this clever
system, the problem related to the impossibility of storing electrical energy is
solved and all the demand is covered.

### 8.1.4. Intra-Daily Market.

The Intra-Daily Market is responsible for the regulation of the Definitive Daily
Viable Programming by introducing electricity trading offers, which as happened
in the Daily Market, can be both simple and complex.

### 8.1.5. National Commission of the Electricity Sector.

The National Commission of the Electricity Sector is responsible for the regulation
of the Spanish Electricity System under the principles of transparency and
objectivity and ensuring a fair competition. This commission is composed by 8
members and 1 President, which are selected according to proved and
recognised experience, and eventually other punctual members such as the
Minister of Industry, Tourism and Commerce or any other authorised person may
be included, although this temporary member will not have any authority in the
Commission and will only play an advisory role. Among the different functions of
the National Commission of the Electricity Sector, it is possible to highlight:

- To play an advisory role for the Government in terms of electrical topics,
collaborating with it in the development and modification of the *LAW 54/1997, November 27th*, of the Spanish Electrical Sector.

- To help in the electrical planning and in the elaboration of retribution and
tariff establishments for the Spanish Electrical Sector, elaborating the
assessments required by the different Autonomic Governments.

- To liquidate the transport and distribution costs of the electrical energy, as
well as any other established by an authorised organism, informing every
6 months about this exercises to the Spanish Ministry of Industry, Tourism
and Commerce.

- To verify, according to the requirements of the Government or different
Autonomic Governments, the accomplishing of the technical and
economical conditions as well as the juridical separation of the different
electrical activities. In order to do so, the National Commission of the
Electricity Sector will be able to require all the information that it considers
as important, publishing it in the *National State Newsletter* (BOE). At the
same time, the National Commission of the Electricity Sector is able to
develop any process in order to ensure that the information provided is
ture, although this information is classified and can only be remitted to the
Spanish Ministry of Industry, Tourism and Commerce and the different
Autonomic Governments.
• To solve any conflict between electrical producers, Market Operator, System Operator, transporters, distributors and consumers. This function is voluntary, private and free.

• To determine responsibilities related to failures and retribution decreases in the system, informing, developing and managing the different punishments related to them.

• To ensure that fair competition is real, informing about any suspicious activity and the main evidences that reinforce this belief.

• To establish its own organisation and functioning, as well as to hire their own employees.

• To elaborate an annual assessment of the different activities developed by the National Commission of the Electricity Sector that must be sent to the Senate and the Congress of Deputies.

Again, the National Commission of the Electricity Sector may be responsible for any other function as far as this is conveniently established by an authorised organism.

8.2. Estimated selling price.

Now that the main actors of the Spanish Electricity Market have been introduced, it is the time to estimate the selling price of the electricity generated in the parabolic trough power plant in Gibraleón. In order to do so, it is necessary to introduce the different selling prices of previous dates, which are provided in the Market Operator website.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>January</td>
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<tr>
<td>January</td>
</tr>
<tr>
<td>February</td>
</tr>
<tr>
<td>March</td>
</tr>
<tr>
<td>April</td>
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<tr>
<td>May</td>
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<tr>
<td>June</td>
</tr>
<tr>
<td>July</td>
</tr>
<tr>
<td>August</td>
</tr>
<tr>
<td>September</td>
</tr>
</tbody>
</table>
### Table 48.

<table>
<thead>
<tr>
<th>Month</th>
<th>Value1</th>
<th>Value2</th>
<th>Value3</th>
<th>Value4</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>35,78</td>
<td>42,63</td>
<td>57,46</td>
<td>-</td>
</tr>
<tr>
<td>November</td>
<td>32,39</td>
<td>40,93</td>
<td>48,38</td>
<td>-</td>
</tr>
<tr>
<td>December</td>
<td>30,43</td>
<td>46,34</td>
<td>50,07</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>36,98</td>
<td>36,95</td>
<td>49,92</td>
<td>47,38</td>
</tr>
</tbody>
</table>

As it can be seen in **Table 48.**, there has been a clear increase in the average annual electricity selling price in Spain and so, regarding the values obtained during the first months of 2012, it is possible to conclude that the 2009 and 2010 prices are not representative. It is, then, a matter of selecting the reference value from the average 2011 and 2012 prices.

According to the monthly average, it is not possible to observe any tendency in the electricity prices of 2012, as despite the fact that they are higher than their homonyms for the first three months of the year, they suddenly decrease in April, reaching values which are lower than those in 2011. In order to ensure the validity of the choice, the selected estimated selling price for the parabolic trough power plant in Gibraleón is the most restrictive one among the considered. As a result, the selected value is 47,38€/MWh. Taking into account the fact that the annual output of the parabolic trough power plant in Gibraleón is 179,534 MWh, it is possible to obtain a first estimation of the benefits from the first year of operation through the following expression:

\[
1st \ year \ benefits = 47,38 \frac{\text{€}}{\text{MWh}} \cdot 179,534 = 8,506,320,92€
\]

Please notice that this value is worthless without the possibility of comparing it to other references. A real economic analysis of the project would estimate the different incomes in a 30 years horizon, taking into account the different IPC variations and any other relevant conditions. However, due to the specific objectives of this project, and the intrinsic problematic related to the possibility of returning to a Special Regime retribution in the following years, only a brief approach on the economic performance of the plant will be developed and these first year benefits have been calculated in order to estimate an approximated returning period once that the initial investment has been determined.

### 8.3. Required investment.

Due to the great amount of parameters related to the economic cost of the parabolic trough power plant in Gibraleón and, consequently, its required initial investment, the estimation of this sum will be performed through a cost ratio system. A reliable source has been selected, obtaining an estimation for the different elements of the plant in [€/parameter] and, as a result, the obtained value cannot be considered as a definitive establishment, but as an estimation of the real value according to the different cost ratios.
Figure 152. Cost ratios in a commercial parabolic trough power plant with synthetic oil as heat transfer fluid and no thermal storage.


Now that the different cost ratios have been introduced and all the different technical parameters are known, it is possible to obtain an estimation the required investment for the parabolic trough power plant in Gibraleón:

Table 49. Estimation of the Investment required for the parabolic trough power plant in Gibraleón.

[Source.- Own elaboration]

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Cost Ratio</th>
<th>ACUMULATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Field</td>
<td>1,367.843 m²</td>
<td>190 €/m²</td>
<td>259,890,170 €</td>
</tr>
<tr>
<td>Thermal Storage</td>
<td>1,031.250 kWt</td>
<td>31,6 €/KWh</td>
<td>32,587,500 €</td>
</tr>
<tr>
<td>Steam Cycle</td>
<td>50.000 kWe</td>
<td>700€/kWe</td>
<td>35,000,000 €</td>
</tr>
<tr>
<td>Land</td>
<td>2,047.717,23 m²</td>
<td>2 €/m²</td>
<td>4,095,434,46 €</td>
</tr>
<tr>
<td>Employees</td>
<td>40 un.</td>
<td>48,000€/un.</td>
<td>1,920,000 €</td>
</tr>
<tr>
<td><strong>PARCIAL SUM</strong></td>
<td>-</td>
<td>-</td>
<td>333,493,104 €</td>
</tr>
<tr>
<td>Insurance</td>
<td>PARCIAL SUM</td>
<td>1%</td>
<td>3,334,931,04 €</td>
</tr>
<tr>
<td>Maintenance</td>
<td>PARCIAL SUM</td>
<td>1%</td>
<td>3,334,931,04 €</td>
</tr>
<tr>
<td>C&amp;E</td>
<td>PARCIAL SUM</td>
<td>10%</td>
<td>33,349,310,4 €</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>-</td>
<td>-</td>
<td>373,512,275,68 €</td>
</tr>
</tbody>
</table>
As it can be seen in **Table 49.**, the required investment for the parabolic trough power plant in Gibraleón is 373.512.275,68€. As it can be seen, most this cost is related to the solar field. The distribution of the different costs of the parabolic trough power plant can be easily shown in the following graphic:

**Figure 153. Cost distribution in the parabolic trough power plant in Gibraleón**
[Source.-Own elaboration]

As it can be seen, the cost associated to the solar field represents the 69,58% of the total cost of the plant, followed by the steam cycle, the different organisation and maintenance operations and the thermal storage system. In order to verify the total required investment for the parabolic trough power plant in Gibraleón, other similar parabolic trough power plants in Southern Spain have been considered:

**Table 50. Approximated initial investment in other similar Southern Spanish operational parabolic trough power plants**
[Source.- Own elaboration²¹⁸]

<table>
<thead>
<tr>
<th></th>
<th>Investment cost [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andasol I</td>
<td>300.000.000</td>
</tr>
<tr>
<td>Andasol II</td>
<td>300.000.000</td>
</tr>
<tr>
<td>Andasol III</td>
<td>300.000.000</td>
</tr>
<tr>
<td>Extresol I</td>
<td>300.000.000</td>
</tr>
<tr>
<td>Extresol II</td>
<td>300.000.000</td>
</tr>
</tbody>
</table>

²¹⁸ Some data has been provided in the different plant promoter’s websites, others have been provided by NREL in [http://www.nrel.gov](http://www.nrel.gov) and others in [http://www.estelasolar.eu](http://www.estelasolar.eu). (accessed May 30th 2012)
According to Table 50., the required investment in the parabolic trough power plant in Gibraleón is approximately a 20% more expensive than the average cost for other similar parabolic trough power plants located in Southern Spain. This difference may be explained by the use of the different cost ratios introduced in Figure 152. that, despite being perfectly suitable for a first estimation of the required investment, may result a bit inaccurate when compared to the reference values for other similar plants, as these answer to a much deeper approach. Taking all this features into account, it can be concluded that the obtained initial investment of 373.512.275,68€ is a good value, although due to the applied cost ratios, this value can only be considered as an estimation and never as the definitive value.

Finally, in order to finish the economic analysis of the parabolic trough power plant in Gibraleón it is necessary to focus on the problematic related to the removal of the Special Regime retribution system. A gross estimation of the investment recovery period can easily be obtained by dividing the initial investment of the project by the annual benefits of the plant. Please notice that, by doing so, a great amount of variables are obviated (such as the price actualisation, among many others) and a great error related to supposing this annual income as constant is introduced. However, accuracy is not needed in order to validate this establishment:

\[ \text{Investment recovery period} = \frac{373.512.275,68\€}{8.506.320,92\€ / \text{year}} = 43,9 \equiv 44 \text{ years} \quad (166) \]

According to (166), under the established selling price of the electrical energy (47,38€/MWh), 44 years would be needed to recover the initial investment. This fact, taking into account that according to Figure 152. the average operating life of parabolic trough power plants is 30 years, is disastrous, as the total time required to recover the initial investment is higher than the operating life of the plant: a huge amount of money will be lost. As a result, the removal of the economical incentives and primes for those power plants subjected to the Special Regime is a condemnation for these kinds of technologies, as their higher electricity generation cost when compared to other conventional fossil-fuel based power plants makes them economically unfeasible. It would be interesting to compare this value to the investment recovery period with investments. Let's suppose a determined value for Complements due to Reactive Energy and Efficiency established in the ROYAL DECREE 661/2007, May 25th, which regulates the electrical energy production activity in Special Regime. According to its Article 29., if the Complement due to Reactive was still established, this would be of 78,441 €/MWh, which for the annual net output of the parabolic trough power plant in Gibraleón, would result in:

\[ \text{Complement per reactive} = 78,441\€ / \text{MWh} \cdot 8\% = 6,275\€ / \text{MWh} \quad (167) \]

Please notice that the 8% value is related to a bonus established depending on the power factor of the generated electricity. According to the Annex V. of the ROYAL DECREE 661/2007, May 25th, which regulates the electrical energy production activity in Special Regime, the selected value is related to a inductive power factor under 0,95, which has been considered as a very reasonable value.
Figure 154. Estimation of the Complement per Reactive in Special Regime. 
[Source.- Annex V. of the ROYAL DECREES 661/2007, May 25th which regulates the electrical energy production activity in Special Regime]

On the other hand, remembering that, according to the **ROYAL DECREES 661/2007, May 25th**, which regulates the electrical energy production activity in Special Regime, the parabolic trough power plant in Gibraleón was classified as **Category b, Group b.1, Subgroup b.1.2**, the reference prime for the first 25 years is 281,894€/MWh.

Figure 155. Estimation of the Complement per Reactive in Special Regime. 
[Source.- 2012 Tariffs, Primes and Limits from those systems classified as Category b in the Article 2. of the ROYAL DECREES 661/2007, May 25th ]

Taking all this features into account, the estimated selling price of the electricity generated in the parabolic trough power plant in Gibraleón if the Special Regime retributive system was still established would be:

\[
\text{Estimated selling price with incentives} \quad = 47,38 + 6,275 + 281,894 = 335,549€ / \text{MWh} \quad (168)
\]

The estimated selling price with incentives is approximately 7 times bigger that the estimated selling price without them. Under this acknowledge, the annual net output of the parabolic trough power plant in Gibraleón would generate much higher benefits, as it is shown in the following expression:


\[ 1st \ year \ benefits_{\text{WITH INCENTIVES}} = \frac{335,549}{MWh} \cdot 179.534 = 60.242,454.17€ \] (169)

And consequently, the estimated investment recovery period with incentives would be:

\[ Investment \ recovery \ period_{\text{WITH INCENTIVES}} = \frac{373.512,275,68€}{60.242,454,17€ / year} = 6.2 \text{ years} \] (170)

The estimated recovery period without incentives was established around 44 years, whereas with incentives is only of 6.2 years. As a result, the economic viability of the parabolic trough power plant in Gibraleón depends on the reestablishment of the Special Regime retribution system. Due to the fact that the generating costs of these kinds of systems is still high when compared to traditional power plants, they do need some to be reinforced through different primes and incentives. Thanks to this, the parabolic trough power plants will be able to consolidate in the power market and, once that the natural development of the technology and the new discoveries (direct steam generation) reach a commercial feasibility, these incentives will not be necessary anymore.

In order to conclude, it is important to mention that a small hope can be found in the third point of the Article 3. of the ROYAL DECREE-LAW 1/2012, January 27th, which removes the retribution preassignment procedures and economic incentives for new cogeneration, renewable energies and waste electrical energy power plants. According to this point, the Spanish Government, despite the removal of general incentives and primes for Special Regime plants, is able to establish specific economic retribution regimes for specific plants, according to the following statements:

- Installed power of the plant.
- Output voltage of the plant.
- Proved environmental benefits introduced by the plant.
- Primary energy savings related to its implantation.
- Energy efficiency of the plant.
- Investment and operational costs of the plant.
- Production of useful heat at a reasonable cost.
- Chosen technology of the plant.
- Economical situation of the country.

As a result, in case that the parabolic trough power plant in Gibraleón was to be constructed now, it could obtain a special retribution regime if all the previous statements are properly demonstrated and the Spanish Government agrees. However, the current economical situation (which is, in fact, one of the conditions of this special specific retribution) and the huge tariff deficit related to renewable energies will surely be responsible for the denial of this application.
CHAPTER 9: CONCLUSIONS

To this point, the main features of the parabolic trough power plant in Gibraleón have been introduced, discussed and chosen, in order to validate the technical and economical viability of the project. A general introduction to the solar thermal power production technology was developed in the very first stages, followed by the selection of the different elements of the solar field, thermal storage system and steam cycle of the plant, ensuring the maximum rigour and accuracy in order to choose the best options. After this selection process, the sizing stage of the parabolic trough power plant in Gibraleón was performed, determining the main parameters and validating them through computer simulation. Finally, a small introduction to the main currently active R&D lines, a general environmental assessment, an explanation of the main grid connection procedures and a brief economic analysis were developed. The project is concluded and all the tools are provided, so it is the time to extract its main conclusions.


The main conclusions extracted from the development of this project are:

- The parabolic trough power plant in Gibraleón is technically viable, as their performance parameters are slightly better than the ones commonly found in similar currently operational 50MW parabolic trough power plants in Southern Spain.

- Regarding to the ROYAL DECREE-LAW 1/2012, January 27th, which removes the retribution preassignment procedures and economic incentives for new cogeneration, renewable energies and waste electrical energy power plants, the parabolic trough power plant in Gibraleón is not economically viable, as the generation cost of its electricity is notably bigger than the estimated selling price. If it is not possible to obtain a specific retribution regime (according to the third point of the
Article 3. of the mentioned decree), it is unadvisable to implement this project. In order to ensure the economical viability of the parabolic trough power plant in Gibraleón, it will be necessary to wait until the different primes and incentives are re-established.

- As a temporary measure, the re-establishment of the Special Regime retribution must be accompanied by an increase in the nominal output power limit that allows to be subjected to this classification, as the actual 50MW value is too small. The bigger the size of the plant is, the lower the costs are.

- This current unfavourable situation must be understood as an opportunity to invest in R&D and not as a disastrous situation regarding to sales. The Spanish solar thermal market will surely be temporary frozen, so the different manufacturers should reduce their production levels and invest in the development of new systems and solutions. When the different incentives and primes are re-established, the new improvements will reduce the cost of solar thermal power plants, reducing consequently the amount of incentives that must be provided to ensure their commercial viability and ensuring this way that this situation is not produced again.

- The parabolic trough solar thermal technology as an energy production system is commercially available today, as well as the central tower technology. Stirling and Linear Fresnel systems have demonstrated to be viable in small size applications, but they are still in an experimental stage when regarding to commercial-scale systems.

- Thermal storage is the answer to the intermittent operation in current solar thermal plants, increasing its final output and efficiency and reducing the final cost related to them, despite a higher initial investment.

- Several R&D operations are currently being made on parabolic trough technology, introducing great possibilities for the future. Among these, direct thermal storage systems are a commercial reality nowadays, although the biggest expectations are placed on direct steam generation, due to the great efficiency increase related to this technology. As well, several improvements of actual designs are being discussed, highlighting a tendency in the increase of the diameter of the linear receiver, the introduction of new storage systems and the substitution of glass reflectors by reflective mirror films, mainly.

- Southern Spain is a great location for solar thermal applications, due to high annual direct normal irradiation values, big water availability, and their favourable meteorological, topographical and infrastructural conditions. These features are the region, with more than 30 solar thermal plants implemented in the last years.

- Huelva is a key location, as it provides exceptional conditions and no solar thermal project has been developed there yet.

- Maintenance operations are critical in order to ensure the maximum efficiency of the plant, and special attention must be paid on this issue.
• **Solar thermal power plants are a great allied regarding to environmental preservation**, as a huge amount of CO₂ emissions can be avoided. This feature can be responsible for a cost decrease related to CO₂ emission rights and can help in the consecution of the emission objectives established in international environmental agreements. The main environmental impacts are regarded to land use and water consumption, being necessary to improve the efficiency of alternative cooling methods and the efficiency of the solar field (as this represents the majority of the required surface of the plant). However, these are notably inferior to the ones introduced by conventional fossil-fuel systems and other renewable energies, as well.

• **The main cost in parabolic trough power plants is introduced by the solar field** and so, it would be necessary to develop new cheaper solar collectors and solar field devices, in order to decrease the initial investment required to begin the project, without compromising the global efficiency of the plant.

To conclude, these are very difficult times due to the global economic crisis that is changing the world as we know it, but in order to ensure the environmental preservation of our planet, it is essential to invest in renewable technologies as they represent a new clean and sustainable future. Among these, solar thermal power plants may become a great tool in the consecution of these objectives, as it is a successfully proved technology and many advances are expected in the following years.
9.2. Factsheet of the plant.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site</strong></td>
<td>Parcel 26th of the Estate number 11 in Tojalillo, Gibraleón (Huelva)</td>
</tr>
<tr>
<td><strong>Available solar radiation</strong></td>
<td>2.069,01 kWh/m²·year (5,67 kWh/m²·day)</td>
</tr>
<tr>
<td><strong>Sunlight</strong></td>
<td>2754 hours of sun/year</td>
</tr>
<tr>
<td><strong>Average wind Speed</strong></td>
<td>3 m/s</td>
</tr>
<tr>
<td><strong>Average temperature</strong></td>
<td>19°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SOLAR FIELD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chosen Technology</strong></td>
<td>Parabolic trough</td>
</tr>
<tr>
<td><strong>Concentrator</strong></td>
<td>Skytrough space-frame collector, manufactured by Skyfuel Ltd.</td>
</tr>
<tr>
<td><strong>Reflector</strong></td>
<td>ReflecTech PLUS mirror film, manufactured by Reflectech Inc.</td>
</tr>
<tr>
<td><strong>Linear Receiver</strong></td>
<td>SCHOTT PTR70, manufactured by Schott Solar A.G.</td>
</tr>
<tr>
<td><strong>Heat Transfer Fluid</strong></td>
<td>Therminol VP-1 diphenyl oxide/biphenyl synthetic oil, manufactured by Solutia</td>
</tr>
<tr>
<td><strong>HTF Pump</strong></td>
<td>RPH oil pump, manufactured by KSB A.G.</td>
</tr>
<tr>
<td><strong>Solar Tracking System</strong></td>
<td>North-South single-axis</td>
</tr>
<tr>
<td><strong>Drive Unit</strong></td>
<td>OnSun hydraulic drive, manufactured by Skyfuel Ltd.</td>
</tr>
<tr>
<td><strong>Control Unit</strong></td>
<td>Skytrakker electronic control, manufactured by Skyfuel Ltd.</td>
</tr>
<tr>
<td><strong>Layout</strong></td>
<td>H type distribution</td>
</tr>
<tr>
<td><strong>HTF Inlet Temperature</strong></td>
<td>290°C</td>
</tr>
<tr>
<td><strong>HTF Outlet Temperature</strong></td>
<td>391°C</td>
</tr>
<tr>
<td><strong>Solar Field Area</strong></td>
<td>131,78 m²</td>
</tr>
<tr>
<td><strong>Number of SCA</strong></td>
<td>720</td>
</tr>
<tr>
<td><strong>Number of Collector Loops</strong></td>
<td>120</td>
</tr>
<tr>
<td><strong>Collected Thermal Energy</strong></td>
<td>275 MWt</td>
</tr>
<tr>
<td><strong>HTF Loop Mass Flow Rate</strong></td>
<td>9,35 kg/s</td>
</tr>
</tbody>
</table>
# Design of a Solar Thermal Power Plant

## THERMAL STORAGE

<table>
<thead>
<tr>
<th>Chosen Technology</th>
<th>Two-tank indirect oil/salt thermal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Storage Fluid</td>
<td>Solar salt (60% NaNO₃, 40% KNO₃)</td>
</tr>
<tr>
<td>Storage tanks</td>
<td>28 meters high and 28 meters of diameter Carbon Steel Cylindrical Tanks.</td>
</tr>
<tr>
<td>Oil-to-salt Heat Exchanger</td>
<td>EMBaffle shell&amp;tube heat exchanger, manufactured by EMBaffle B.V and Talleres MAC S.A.</td>
</tr>
<tr>
<td>Molten Salt Pumps</td>
<td>VE-Y molten salt pump, manufactured by Ensival-Moret/A.R. Wilfley &amp; Sons</td>
</tr>
<tr>
<td>Cold Tank Temperature</td>
<td>293°C</td>
</tr>
<tr>
<td>Hot Tank Temperature</td>
<td>386°C</td>
</tr>
<tr>
<td>Equivalent Full Load TES</td>
<td>7.5 hours</td>
</tr>
<tr>
<td>Stored Thermal Energy</td>
<td>1.031,25 MWh</td>
</tr>
<tr>
<td>Molten Salt Mass</td>
<td>25,787,24 tons</td>
</tr>
</tbody>
</table>

## STEAM CYCLE

<table>
<thead>
<tr>
<th>Chosen Technology</th>
<th>Rankine 100bar and 373°C superheated/reheated steam cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Output</td>
<td>50MW</td>
</tr>
<tr>
<td>Cooling Method</td>
<td>Evaporative Wet Cooling</td>
</tr>
<tr>
<td>Steam generating train²¹⁹</td>
<td>FW 50MW Coil-Type steam generating island, manufactured by Foster Wheeler A.G.</td>
</tr>
<tr>
<td>Condenser</td>
<td>FW condenser, manufactured by Foster Wheeler A.G.</td>
</tr>
<tr>
<td>Low pressure reheater</td>
<td>FW LP U-Type Feed Water Horizontal Heater, manufactured by Foster Wheeler A.G.</td>
</tr>
<tr>
<td>Deaerator</td>
<td>Cochrane H-H Spray and Tray deaerator, manufactured by Frost Engineering Service Co.</td>
</tr>
<tr>
<td>Oxygen Scavenger</td>
<td>Sodium Sulphite (Na₂NO₃)</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>SST-700 Steam Turbine, manufactured by Siemens A.G.</td>
</tr>
<tr>
<td>Generator</td>
<td>Direct Air Cooled Gen-100A-4P (11kV), manufactured by Siemens A.G.</td>
</tr>
</tbody>
</table>

²¹⁹ Including Preheater, Superheater, Reheater and Evaporator.
<table>
<thead>
<tr>
<th>Feed water pump</th>
<th>HGC horizontal multi-stage ring-section pump, manufactured by KSB A.G.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensate pump</td>
<td>VLT condensate extraction pump, manufactured by Ruhrpumpen Group</td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>Omega single-stage axially-split volute casing pump, manufactured by KSB A.G.</td>
</tr>
<tr>
<td>Water mass flow rate</td>
<td>50,85 kg/s</td>
</tr>
<tr>
<td>HTF mass flow rate</td>
<td>561 kg/s</td>
</tr>
</tbody>
</table>

### ENVIRONMENTAL ASSESSMENT

<table>
<thead>
<tr>
<th>Identified Impacts</th>
<th>11 Irrelevant impacts, 55 moderate impacts and 2 Severe Impacts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saved CO₂</td>
<td>58.617,851 tons/year</td>
</tr>
<tr>
<td>Water consumption</td>
<td>611.762 tons/year(^{220})</td>
</tr>
<tr>
<td>Land Use</td>
<td>204,77 ha</td>
</tr>
</tbody>
</table>

### PERFORMANCE AND OUTPUT

| Global Efficiency of the Plant | 19,3% |
| Solar Field Efficiency | 44,29% |
| Steam Cycle Efficiency | 40% |
| Capacity Factor | 40,989% |
| Annual Net Output | 179.534 MWh |
| LCOE (w/o incentives) | 143 €/MWh |
| Estimated Selling Price\(^{221}\) | 47,38 €/MWh |
| Initial Investment | 373.512.275 € |
| First Year Benefits | 8.506.320,92 € |
| Investment Recovery Period\(^{222}\) | 44 years |

\(^{220}\) Average value obtained from the estimated water consumption upper (679.536 tons/year) and lower (543.988 tons/year) values.

\(^{221}\) Without Special Regime Primes and Complements per Reactive, according to the ROYAL DECREE-LAW 1/2012, January 27th.

\(^{222}\) Under the current removal of the Special Regime incentives and primes. An estimation of the Investment Recovery Period related to the reestablishment of this economic complements has been performed, obtaining a value of 6,2 years under an estimated electricity selling price of 335,549 €/MWh.
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http://www.boe.es
http://www.csptoday.com
http://www.abengoasolar.com
http://www.solel.com
http://www.flagbeg.com
http://www.flagsol-gmbh.com
http://www.samca.es
http://www.skyfuel.com
http://www.reflectechsolar.com
http://www.enea.it
http://www.schottsolar.com
http://www.therminol.com
http://www.dow.com
http://www.helac.com
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http://www.eurotecnia.it
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http://www.lointek.com
http://www.embaffle.com
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http://www.lavozdelebro.com
http://www.friatec.com
http://www.flowserve.com
http://www.ruhrpumpen.com
http://www.sulzerpumps.com
http://www.ensival-moret.com
http://www.wilfley.com
http://www.alborgcsp.com
http://www.asme.org
http://www.tema.org
http://www.aalborgcsp.com
http://www.fwc.com
http://www.thermaxindia.com
http://www.energy.siemens.com
http://www.ambassadorco.com
http://spxheattransfer.com
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http://www.cleanboiler.org
http://www.fapdec.org
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http://www.mityc.es
http://www.omelholding.es
http://www.omie.es
http://www.marquesadosolar.com
http://www.protermosolar.com
http://www.sciencedirect.com
http://books.google.es
http://www.bjwe.com
http://www.rankingsolar.com
http://andaluciainformacion.es
http://www.eleconomista.es
http://erenovable.com
http://www.radiogranada.es
http://www.granadahoy.com
http://www.appa.es
http://www.atean.es
http://www.apeh.org
http://www.ctaer.com
http://www.minetur.gob.es
http://www.diphuelva.es
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http://www.esiold.us.es
http://www.eolss.net
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http://www.fika.org
http://www.direc2010.gov.in
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http://www.jkearney.com
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http://wenku.baidu.com
http://www.friatecnca.net
http://www.balcke-duerr.de
http://energiza.org
http://www.asp-solar.com
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http://www.lepten.ufsc.br
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http://www.greenpeace.org
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11.4. Index of abbreviations

CNE ................................................................. Spanish National Energy Commission
IDAE .................................................. Spanish Diversification and Energy Saving Institute
DNI .......................................................... Direct Normal Irradiation
HTF .......................................................... Heat Transfer Fluid
SEGS ...................................................... Solar Electricity Generating Systems
ISCCS ....................................................... Integrated Solar Combined Cycle System
DIR .......................................................... Direct Illumination Receivers
IIR .......................................................... Indirect Illumination Receivers
SCADA ...................................................... Supervisory Control And Data Acquisition
CLFR ........................................................ Compact Linear Fresnel Receiver
CF .............................................................. Capacity Factor
NREL ......................................................... National Renewable Energy Laboratory
CIEMAT ........................................ Energetic, Environmental and Technological Investigation Centre
ADNI ........................................................ Annual Direct Normal Irradiation
DDNI ........................................................ Daily Direct Normal Irradiation
FEMA ...................................................... United States Federal Emergency Management Agency
AICIA ........................................................ Thermodynamics and Renewable Energy Group of the Industrial Cooperation and Investigation Association of Andalucía
RIA .......................................................... Andalusian Agroclimatic Information Network
INTA .......................................................... National Institute of Spatial Techniques
SPA .............................................................. Almería Solar Platform
ENEA ...................................................... Agency for New Technologies, Energy and Environment of Italy
DLR ............................................................ German Aerospace Centre
ASME ......................................................... American Society of Mechanical Engineers
TEMA ...................................................... Tubular Exchanger Manufacturers Association
TES .............................................................. Thermal Storage System
SCA .......................................................... Solar Collector Assembly
NFPA ........................................................ United States National Fire Protection Association
REE .......................................................... Red Eléctrica de España
EIA .......................................................... Environmental Impact Assessment
IN .............................................................. Intensity
EX .............................................................. Extension
MO .............................................................. Moment
PE .............................................................. Persistence
RV ................................................................. Reversibility
SY ................................................................. Synergy
AC ................................................................. Accumulation
EF ................................................................. Effect
PR ................................................................. Periodicity
RT ................................................................. Restorability
GII ................................................................. Global Impact Index
11.5. Index of symbols.

\( \delta \) ....................................................... declination [°]

\( n \) ....................................................... ordinal number of the year

\( \psi \) ....................................................... latitude [°]

\( \lambda \) ....................................................... longitude [°]

\( \omega \) ....................................................... hour angle [°]

SH ....................................................... solar hour [h]

CH ....................................................... civil hour [h]

\( \varepsilon \) ....................................................... advancement [h]

TE ....................................................... time equation [h]

\( \alpha \) ....................................................... azimuth [°]

\( h \) ....................................................... height [°]

I ....................................................... irradiance [W/m²] or [MJ/m²] or [cal/cm².min]

\( i \) ....................................................... incident angle [°]

N ....................................................... normal to the aperture plane

S ....................................................... direction of the incident solar beams on the collector

\( \rho \) ....................................................... tracking angle [°]

EDesign Gross Output ........................................... gross turbine design energy [MW]

\( \eta_{\text{Design Turbine Gross Output}} \) ............................................ gross turbine efficiency [%]

QDesign Turbine Thermal Input ..................................... thermal energy required to produce E\text{Design Gross Output} [MWt]

Q\text{Piping Loss} ..................................................... thermal losses due to piping [W/m²]

Q\text{HCE Loss} ..................................................... thermal losses due to linear receivers [W/m²]

\( \eta_{\text{Peak Optical}} \) .......................................... peak efficiency of the solar field [%]

SM ....................................................... solar multiple

ASolar Field ..................................................... solar collecting area of the solar field [m²]

N\text{SCA} ..................................................... number of solar collector assemblies

d\text{SCA-ROW} .................................................... distance between SCAs in a row [m]

d\text{ROW-ROW} .................................................... distance between different rows in the solar field [m]

d\text{HORIZONTAL} .................................................... horizontal length of the solar field [m]

d\text{VERTICAL} .................................................... vertical length of the solar field [m]

m\text{HTF} ..................................................... mass flow rate of HTF in the solar field [kg/s]

m\text{HTF Loop} .................................................... mass flow rate of HTF in each loop of the solar field [kg/s]

Q\text{Solar Field} ..................................................... thermal energy provided by the solar field [MWt]

H\text{HTF Inlet} ..................................................... enthalpy of HTF at inlet temperature [kJ/kg]

H\text{HTF Outlet} ..................................................... enthalpy of HTF at outlet temperature [kJ/kg]
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\( T_{\text{INLET}} \) ........................................... Inlet temperature of the HTF in the solar field [°C]
\( T_{\text{OUTLET}} \) ........................................... Outlet temperature of the HTF in the solar field [°C]
\( T_{\text{REFERENCE}} \) ........................................... Average temperature of the selected location [°C]
\( \text{Re} \) .......................................................... Reynolds number
\( \Pi \) .......................................................... \( \Pi \) number
\( \rho_{\text{HTF}} \) .............................................. Density of the HTF [kg/m³]
\( \mu_{\text{HTF}} \) ................................................ Dynamic Viscosity [Pa·s]
\( \nu_{\text{HTF}} \) ................................................ Speed of the HTF [m/s]
\( C \) .......................................................... Concentrating Ratio
\( \theta_{\text{ACC}} \) ................................................ Acceptance angle [°C]
\( D_{\text{TUBE}} \) ........................................................ Diameter of the absorber tube [m]
\( L_{\text{TUBE}} \) ................................................ Length of the absorber tube [m]
\( A_{\text{TUBE}} \) ................................................ Area of the absorber tube [m²]
\( \Omega \) .......................................................... Aperture angle of the collector [°]
\( K(\theta_{\text{ACC}}) \) ............................................. Modifier per acceptance angle (insolation clearness index)
\( \eta_{\text{THERMAL}} \) ............................................ Thermal efficiency [%]
\( \eta_{\text{SOLAR FIELD (MIN)}} \) ................................ Minimum efficiency of the solar field [%]
\( \eta_{\text{SOLAR FIELD (MAX)}} \) ................................ Maximum efficiency of the solar field [%]
\( \eta_{\text{SOLAR FIELD (AVERAGE)}} \) ................................ Average efficiency of the solar field [%]
\( F_{\text{CLEANING}} \) ............................................ Cleanliness factor of the collector [%]
\( R_f \) .......................................................... Reflectivity of the reflective surface [%]
\( \sigma \) ....................................................... Linear receiver absorbance [%]
\( \gamma \) ........................................................ Interception factor [%]
\( \tau \) ........................................................ Solar transmittance [%]
\( C_p \) .......................................................... Calorific capacity of the molten salt mixture [J/kg]
\( Q_{\text{SALT}} \) .............................................. Thermal energy stored in the molten salt mixture [MJ] or [MWht]
\( m_{\text{SALT}} \) .................................................. Total mass of molten salt mixture [t]
\( T_{\text{HOT}} \) .................................................. Hot tank temperature [°C]
\( T_{\text{COLD}} \) ................................................ Cold tank temperature [°C]
\( \rho_{\text{HOT SALT}} \) ............................................. Density of the hot molten salt mixture [kg/m³]
\( V_{\text{HOT SALT}} \) ........................................... Volume of the hot molten salt mixture [m³]
\( \rho_{\text{COLD SALT}} \) ........................................ Density of the cold molten salt mixture [kg/m³]
\( V_{\text{HOT TANK}} \) ........................................... Volume of the hot storage tank [m³]
\( R_{\text{HOT TANK}} \) .......................................... Radius of the hot storage tank [m]
\( h_{\text{HOT TANK}} \) .......................................... Height of the hot storage tank [m]
\( A_{\text{HOT TANK}} \) .............................................. Surface of the hot storage tank [m²]
\( V_{\text{COLD TANK}} \) ............................................... Volume of the cold storage tank [m³]

\( R_{\text{COLD TANK}} \) ............................................. Radius of the cold storage tank [m]

\( h_{\text{COLD TANK}} \) ............................................... Height of the cold storage tank [m]

\( A_{\text{COLD TANK}} \) ............................................... Surface of the cold storage tank [m²]

\( E_{\text{MAX TO STORAGE}} \) .................. Maximum energy provided to the thermal storage system [MWt]

\( E_{\text{MAX FROM STORAGE}} \) ........... Maximum energy provided by the thermal storage system [MWt]

\( \eta_{\text{STEAM CYCLE}} \) ............................................ Efficiency of the steam cycle [%]

\( m_{\text{HTF (STEAM CYCLE)}} \) .......................... Mass flow rate of HTF in the steam cycle [kg/s]

\( m_{\text{WATER (STEAM CYCLE)}} \) .......................... Mass flow rate of water in the steam cycle [kg/s]

\( W_{\text{TURBINE}} \) .................................................. Work generated by the turbine [KWt]

\( Q_{\text{STEAM GENERATING ISLAND}} \) ................ Heat provided by the steam generating island [KWt]

\( Q_{\text{PREHEATER}} \) ............................... Heat provided by the HTF to the water in the preheater [KWt]

\( Q_{\text{STEAM GENERATOR}} \) .......................... Heat provided by the HTF to the water in the steam generator [KWt]

\( Q_{\text{SUPERHEATER}} \) .......................... Heat provided by the HTF to the water in the superheater [KWt]

\( Q_{\text{REHEATER}} \) ........................................ Heat provided by the HTF to the water in the re heater [KWt]

\( W_{\text{FEEDWATER PUMP}} \) ...................................... Work related to the feedwater pump [KW]

\( W_{\text{CONDENSATE PUMP}} \) ..................................... Work related to the condensate pump [KW]

\( W_{\text{HP TURBINE}} \) ......................... Work related to the high pressure side of the turbine [KW]

\( W_{\text{LP TURBINE}} \) ........................................ Work related to the low pressure side of the turbine [KW]

\( CF \) ......................................................... Capacity Factor of the plant [%]

\( \eta_{\text{GLOBAL}} \) ................................................. Global efficiency of the plant [%]
11.6. Visit to Andasol III parabolic trough power plant.

It has been four months now since this project started, and lots of hours have been spent on reading information and writing the different chapters of it. Due to the enormous size of this kind of technology when applied to a commercial scale, huge values have been determined during the different sizing stages of the projects, and this theoretical approach to solar thermal power plants sometimes made me forget the real size of the parameters, elements and devices that were being explained. Under this acknowledge, I considered interesting to see a real power plant, to get a more tangible approach to these systems, touching and watching real elements in order to realise the magnitude of the topics developed.

Due to the great possibilities that Southern Spain introduces, lots of solar thermal power plants are currently operative in the region. However, they are all owned and exploited by private companies and this is intrinsically related to a very strong confidentiality and lots of difficulties during information research, as has been proved during the development of the project. Despite these disadvantages, I decided to move on and send some e-mails to different solar thermal power plants and, if I were lucky, I could have the opportunity to visit one of them although this is known to be very rare and answer to very exceptional situations.

Luckily, I received an answer from Dr. Frank Dinter, manager of Marquesado Solar, which is promoting the Andasol III Thermo Solar Power Plant in Aldeire-La Calahorra, Granada (Spain). He put me in contact with Leopoldo Martínez González-Escalada, Site Director of the plant, who redirected me Pilar Huerta Arenas, arranging a meeting for the 7th of June of 2012. Through the following lines the main points of the visit will be introduced, highlighting some of the main aspects explained by Antonio Alemán Pérez, Process Engineer of the Plant, who was responsible for my visit. Most of the information introduced in the following lines is graphic, as it is related to the photographs that were taken during my visit, so this annex is intended to be stimulating and to fulfil the curiosity of the readers.

First of all, it is the time to explain the actual situation of Andasol Project. The next Andasol IV, Andasol V, Andasol VI, Andasol VII and Andasol VIII are currently stopped due to the removal of the Special Regime incentives previously explained. When I arrived to Andasol III, I was informed about the main aspects of the plant and I was given the correspondent safety equipment, consisting of helmet, protective glasses and reflective vest. After this, we got on a car and we drove to the Solar Field, where the visit started.

The very first thing that surprised me was the fact that all the three Andasol solar thermal power plants share their location with a wind power plant and a small photovoltaic generating system, which are located in the surroundings of the plant. This is quite curious, as in less than 400 ha three different renewable power plants are exploited, resulting in quite a promising experiment in terms of environmental sustainability. Despite being near La Calahorra, the land where Andasol III is located in the township of Aldeire. Regarding to our visit:
Image 1. End of row in the solar field of Andasol III power plant.

Image 2. Cavitation prevention system for solar field piping.
Image 3. Innovative flexible hose solution for shared pylons.

Image 4. Hot and cold HTF piping system.
As it can be seen in Image 4., when the HTF reaches its outlet temperature, this is driven through the hot header of the solar collector loop to the main cold HTF pipe, which can be seen on the right. This pipe will be responsible for carrying the heated HTF to the power block and thermal storage system, in order to perform all the different processes explained in the project. The cold HTF runs through the left pipe and it is distributed to the different loops of the solar field. Please notice that these two bigger pipes are covered with a thermal insulation (commonly, rock wool or similar) and an aluminum cover, in order to reduce thermal losses up to 5%, according to Antonio, and to avoid any injuries due to the high operating temperatures of the fluid.

Image 5. End pylon.
**Image 5.** shows an end pylon, please notice that these elements are reinforced with stronger structures in order to stand higher winds and mechanical efforts, according to what has been previously explained in the project. Although Antonio told me that double foundation systems are the best option, these are notably more expensive, and the simple foundation system used in Andasol III fulfills all the requirements at a lower cost.

![Image 5](image5.png)

**Image 6.** “Spring place” thermal expansion absorber system.

Each solar collector assembly introduces 3 linear receiver units. Surprisingly, I could notice that these elements can be touched without problem, as the external glass protective cover is cold, and only the absorber tube inside them reaches high temperatures. In order to absorb thermal expansion of the different metallic supporting structures of the absorber tubes, a metallic plate is assembled between the solar collector and the supporter. Thanks to this system, axial expansion and contraction movements are compensated, reducing linear receiver and reflective mirror breakages.

I wondered whether this nail supporting system introduced any kind of problems, so I asked Antonio about this issue. He told me that no maintenance had been done in nail strengthening since Andasol III started operation, so I could be concluded that initial mounting procedures can avoid these problems if they are properly performed. As a curiosity, Antonio commented that upper mirrors in each collector are slightly bigger (around 20 cm) and smoothly more curved in order to ensure the best optical efficiency of the device. Regarding to the total amount of elements, Andasol III is divided in 8 individual generating modules, with 19 loops per module, which results in a total amount of 152 collector loops.
Image 7. Detail of the torque-box collector structure in Andasol III.

Image 8. Wind barriers, reducing wind impact up to a 25%.

Image 10. Mirror supports based on an elastic juncture and a very stable glue.
A great amount of parameters need to be monitored (temperature, wind, light, etc.) and, as a result, a great amount of sensors and detectors are located all around the solar field. At the same time, electric tracing is required in order to avoid HTF solidification, because according to what Antonio said, temperatures of even -10°C were reached during winter in Andasol III. **Image 11.** shows a temperature sensor located in the drive pylon, which can be easily identified due to the two hydraulic pistons in white.
When I asked Antonio about the average rate of broken receivers in the solar field, he estimated them to be of around an 8,5% of the total amount of solar collecting elements of the plant. Every time a linear receiver breaks, the high pressures can impulse the tiny glass bits and break reflective mirrors in the surroundings. I could firmly confirm this as I personally took a small mirror bit from the ground. It is necessary to ensure that the minimum damaged devices are found in the solar field, in order to maximize production. The SCHOTT PTR70 linear receivers used in Andasol III introduce a clever indicator, according to Antonio. Under good operating temperatures, a small blue indicator is shown in the expansion bellow of the element. If vacuum started to degrade, this indicator will turn into white. However, Antonio highlights the difficulty of noticing the difference between both colours, and demands some kind of safer indicator in order to carry out a good preventive maintenance. As a way to confirm the value provided by the indicator, thermo graphic pistols are also used in order to study the state of the receiver.

As our visit to the solar field ended, I asked some other questions. It was very funny to know that the row-to-row distance in Andasol III is 17,4m, just the same value that was obtained in this project, although there is a tendency in reducing this distance up to values around 16m due to a land cost issue, mainly. The average speed of the HTF in the solar field is 3,5 m/s, maintaining a turbulent regime in order to maximize thermal exchange. Finally, regarding to mirror cleaning, this operation is carried out with osmotic water during night, involving a rotative brush head machine and a conventional parabolic cleaning machine. Antonio established that the best way of cleaning the different collectors is snow. When it snows (which is not rare in winter), the different Andasol III collectors are aimed to the sky, collecting as much snow as possible.
This snow is left until it begins to melt, when the collectors are pointed to the ground in order to allow this water to leave. To this point, the solar field had been explained, and it was the time to visit the thermal storage system.

Image 13. Molten salt storage tanks in Andasol III power plant.

Image 13. shows the different molten salt storage tanks of the thermal storage system in Andasol III. The cold tank is on the left, and the hot tank is on the right. This cannot be noticed directly by looking at the picture, and I was only able to distinguish them after Antonio told me which one was the cold one, and which one was the hot one.

It was amazing to hear that, contrary to what could be expected, these tanks were not build from the bottom to the top. Each tank was divided in some kind of ring sections: the first section was built on site and, once this was finished, the constructors elevated it and began building the second ring section. Another shock was suffered when Antonio told me that, initially, the molten salt mixture was not melted. They had to buy separately the NaNO₃ and KNO₃ in solid state, mixing them and melting them on site. There is only one company in Spain that is able to provide the sufficient infrastructure and experience: Chumillas & Tarongi (www.chumillas-tarongi.com), which have become very rich due to the boom of solar thermal power plants with thermal storage in Southern Spain. The estimated cost of all the molten salt mixture, including prime material and melting processes, was around 35 M€. Molten salt is injected through some eductors located in the bottom of each tank, which are nothing but injectors in a pentagonal shape. Thanks to this, a more uniform mixture is achieved.
Due to the criticity of the supporting structure of the thermal storage system in Andasol III, it is necessary to insulate the different pylons and structures. If this is not done, during a fire this would rapidly collapse, resulting in a disastrous molten salt spillage which could be very dangerous in terms of safety, environmental preservation and fire extinguish, among many others. By only applying an external thermal insulation, the total RF of the different structures is easily increased in a great way.

**Image 14. Structure thermal insulation.**
Image 15. Pneumatic valves in the thermal storage system.

**Image 16.** Shows the different cooling pipes introduced in the foundation of each molten salt tank. As it has been previously explained, these pipes can be used to inject cooling air (or any other kind of cooling fluid) in case of a critical increase of the temperature of the bottom concrete foundation. Concrete can be affected by the high temperatures introduced by the molten salt mixture in the different storage tanks, so it is critical to ensure that this is at its best condition in order to avoid structural damages in the system.

**Image 17.** Molten salt pump.
Andasol III power plant has 5 oil-to-salt heat exchangers in order to ensure a good thermal exchange between the heat transfer fluid and the thermal storage fluid. This are covered in aluminum, avoiding injuries due to the high temperatures reached inside them and to reduce thermal losses due to convection and radiation, mainly.

**Image 18.** Oil-to-salt heat exchangers.
Image 19. Oil-to-salt heat exchanger close view.

Image 21. Views from the top of the thermal storage system.

Image 22. Heat transfer fluid piping cavitation absorber system.
Image 23. Solar field terraces in Andasol III.

Image 24. Thermal storage system gas purging exit.
Image 25. *HTF and molten salt inlet pipes in the oil-to-salt heat exchanger*

Image 26. *Antonio showing the possibility of developing manual repairing operations inside the different oil-to-salt heat exchangers.*
Image 27. Water pond next to the thermal storage system.

Image 28. ABB transformer for auxiliary systems in the thermal storage side.
**Image 29.** Molten salt heater in the bottom of the cold storage tank.

**Image 30.** Stairs connecting the different oil-to-salt heat exchangers with the ground.
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Image 31. HTF piping indicator. Red colour is related to hot HTF and the different arrows show the direction of this fluid.

Image 32. Bottom 2x400 m³ expansion vessels.
Image 33. Top 1x200 m³ expansion vessel.

Image 34. Pumping maintenance operations.
Image 35. Detail of piping thermal insulation system.

Image 36. Oil-to-salt piping infrastructure.
Image 37. HTF recovery ponds.

Image 38. Steam cycle and BOP stages of Andasol III.

Image 40. MAN steam turbine.
Image 41. Low pressure side of the steam turbine.

Image 42. High pressure side of the steam turbine.
Image 43. Electrical generator.

Image 44. Data plate of the MAN steam turbine.
Maybe one of the most impressive things I saw was the steam turbine. When we got into the building, the temperature inside it was very high, as well as the noise due to the operation of the turbine. This device is huge, requiring sufficient space in order to ensure that all the different elements can be properly interconnected. As it happened with other systems in Andasol III, each pipe was indicated with the working fluid inside it and the direction of it.
Image 46. Connection of the low pressure side of the turbine and the condenser.

Image 47. Condensate pumps.
Image 48. Electrical tracing in the steam cycle piping system.

Image 49. Preheaters.
Image 50. Deaerator.

Image 51. Feedwater pumps in Andasol III power plant.
**Image 52.** Close view of a feedwater pump in Andasol III power plant.

**Image 53.** Andasol III cooling towers.
Image 54. View of the solar field and office building in Andasol III.

Image 56. Connection box for the electrical tracing system of the steam cycle.

Image 57. Underground water extraction point.
Design of a Solar Thermal Power Plant

**Image 58.** Rotative brush head cleaning machine.

**Image 59.** Water treatment. Sand filter.
The filtered water tank in Andasol III power plant has a capacity of 5,400 m³, from which 900 m³ are to be used for the fire extinguishing system. As a curiosity, Antonio told me that the neighbours of Aldeire had complaint about the green colour of this element, as they considered to be very noticeable from large distances. Despite this minor inconvenient, which Antonio agreed, he established that this was a very intuitive colour and allowed to perform a rapid identification. Colours play, then, a critical role in the different systems of the plant, as they allow to distinguish different systems according to their use in an intuitive way.
Image 61. Demineralised water tank.

Image 62. Filtering unit of Andasol III power plant.
Image 63. Sodium Sulphite (oxygen scavenger) injection system.

Image 64. Water treatment substances.
Image 65. PH regulation system, based on sulphuric acid.

Image 67. Main fire water pump.

Image 68. Auxiliary diesel fire water pump.
Image 69. Fire protection system control unit.

Image 70. Fire water supply from the filtered water tank.
Image 71. Pressurized air system.

Image 72. Close view of a pneumatic valve.
Image 73. 220kV electrical substation in Andasol III.

Image 74. Main transformer of the electrical substation (left).
Image 75. Transformer for auxiliary services in Andasol III power plant.

Image 76. Electric MV cells with extractable units on the right.
Image 77. Frequency variation units.

Image 78. Inside of a MV cell.
Image 80. Main output values for the precise moment when the picture was taken.

Image 81. Auxiliary diesel electrical generators.
Image 82. One of the 5 meteorological substations located all around Andasol III.

Image 83. Antonio Alemán Pérez, Process Engineer of Andasol III.
To this point, the visit to the Andasol III parabolic trough solar thermal power plant was concluded, and so is this brief summary of the main elements and systems of the plant. As the reader may have noticed during this annex, this is nothing but a relaxed approach to real solar thermal power plants, an opportunity to see real devices at a real scale. Personally, this has been an amazing experience, and has given me a more tangible view of the project. It is easy to write parameters in a $10^6$ scale, but when you are on site and you realise the real size of those huge elements, the power of engineering as a way to develop new technologies and change the world is clear.

I would like to thank again all the team of Marquesado Solar for allowing me to visit their facilities, as I know they are busy and this is a great favour, and especially to Antonio for being so kind and helpful during my visit. I hope that I have not forgotten anybody in the *Special Thanks* initial chapters, and under the sincere belief of considering this visit a very stimulating and interesting process, this small summary of the visit to Andasol III power plant is finished.
11.7. Plans.

01. Site plan.
02. Location plan.
03. Floor view of the plant.
04. Floor view of the storage and power blocks.
05. Collector loop piping detail.
06. Floor view of the main building.
07. Floor view of the thermal storage system.
08. Section of the thermal storage system.
09. General diagram of the plant.
11.10. Annex III. Thermal Storage System.
11.11. Annex IV. Steam Cycle.
11.12. Annex V. System Advisor Model