# Analysis of a 50MWe CSP plant water consumption and an economic comparison

Department of Energy

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Executive Summary

Concentrated Solar Power (CSP) plants are attractive in sun-belt countries, such as Morocco in North Africa. The biggest CSP project accepted so far is the Moroccan Noor project (near Ouarzazate), which will produce up to 500 MW of electricity by 2020. CSP plants are mainly built in desert areas, where water is usually scarce. Project plans can be aborted because of the difficulty and cost of water and the reduction in plant efficiency if the plant is operated with limited water supplies. In order to improve the feasibility of such projects, the European project WASCOP (Water Saving for Concentrated Solar Power) has been launched to focus on reducing water consumption in CSP plants by 2020.

The project aim is to understand the water requirements for different (wet, dry and hybrid) cooling technologies and different mirror cleaning systems applied to a typical 50MW parabolic trough CSP plant under different climate conditions. In addition, it requires us to build an accessible technical and financial model to support a CSP plant project. We worked both from a literature review and the CSP System Advisor Model (SAM) to gather knowledge and a detailed technical background. The model has been built using MATLAB with a user friendly interface to be reused easily in any new CSP project. It takes into consideration data from handbooks and equations from the SAM. As the code is written from scratch, every step is well explained for new users. The hybrid cooling system is built from the scripts that correspond to both the wet and dry cooling system. Different cleaning methods can be chosen by the user through the interface.

If wet cooling is used, it is responsible for 90% of the water consumption in the plant (~105 $m^3$/year). In a hot desert environment, where daytime summer temperatures can reach 40°C, the plant efficiency with wet cooling is maintained whereas it could drop by 8% with dry cooling. This shows the importance of finding the best compromise to reduce water requirements while ensuring a satisfactory efficiency. The main feature of this project is that the model built can be used in any standard 50 MWe CSP plant enabling changes in the input variables. This consulting device can guide the user's

choices to the best solution responding to the project’s requirements (budget, geographic location, water consumption).

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## 1.1 Energy context and renewable energies

### 1.1.1 Energy context

The plunge in oil prices that has occurred over the past year could have been detrimental to renewable energy development.. But investments in clean-energy generation increased by 17% in 2014, after two years of decline in this sector. There are many reasons explaining why this link between renewables and oil has apparently less importance. Two of the main explanations would be that they clearly operate in distinct markets; oil for transportation and renewables for pure electricity production and that the costs of renewables are reducing. The moment for effective renewable energies has finally come, and this time the sector is experiencing significant investments and governmental incentives [1].

### 1.1.2 Energy in the MENA region

The Middle East and North Africa Region (MENA) has about 57% of the world's known oil reserves and 41% of proven natural gas resources. In addition to that, this region has outstanding solar resources. Nevertheless, there are huge gaps between countries rich in natural resources and other countries dependent on these resources. Most of the countries in the MENA region have full access to electricity, but energy is still a dream for about 30 million people, mostly off-grid in rural areas. In average, carbon intensity is higher than in industrialized countries, and the potential for renewable energies is clearly under-exploited. One of the major problems in the Middle East is the truancy of reforms in energy sectors around each country such as privatization of energy generation and the lack of private investments.

MENA countries are extremely vulnerable to the risk of climate change because of water scarcity in most of the regions and because of the high concentration of economic activities in the regions close to the coasts. However, significant progress is being made overall in the MENA region as the scope for improving energy supply and its efficiency, as well as the expansion of renewable energy generation, is substantially increasing. [2]

Commonly, MENA countries are split into two groups: the Net Oil-Importing Countries (NOIC) and the Net Oil-Exporting Countries (NOEC). Like most of the European and other countries, the governments in the MENA region have set up Renewable Energy targets and dates that go with these targets. In the majority of the states; the first target dates are around 2020 similarly to the EU countries. Figure 1 shows the renewable energy targets for the different countries in the MENA region.

| | | Renewable Energy Targets and Target Dates |
|---|---|---|
| NOEC | Algeria | 6% of electricity generation by 2015; 15% by 2020; 40% by 2030, of which 37% is solar (PV and CSP) and 3% is wind |
| | Bahrain | 5% by 2020 |
| | Egypt | 20% of electricity generation by 2020, of which 12% is wind |
| | Iran | — |
| | Iraq | 2% of electricity generation by 2016 |
| | Kuwait | 5% of electricity generation by 2020; 10% by 2030 |
| | Libya | 3% of electricity generation by 2015; 7% by 2020; 10% by 2025 |
| | Oman | 10% by 2020 |
| | Qatar | At least 2% of electricity generation from solar by 2020 |
| | Saudi Arabia | — |
| | Syria | — |
| | UAE | Dubai: 5% of electricity by 2030; Abu Dhabi: 7% of electricity generation capacity by 2020 |
| | Yemen | 15% of electricity by 2025 |
| NOIC | Djibouti | 30% of rural electrification from solar PV by 2017<br>100% renewable energy by 2020 |
| | Israel | 5% of electricity generation from renewables by 2014; 10% by 2020 |
| | Jordan | 7% of primary energy by 2015; 10% by 2020 |
| | Lebanon | 12% of electrical and thermal energy by 2020 |
| | Malta | 10% of final energy from renewables by 2020; 14% of electricity by 2020; 6% of heating and cooling by 2020; 11% of transport by 2020 |
| | Morocco | 42% of installed power capacity by 2020 |
| | Palestinian Territories | 25% of energy from renewables by 2020; 10% (or at least 240 GWh) of electricity generation by 2020 |
| | Tunisia | 11% of electricity generation by 2016; 25% by 2030; 16% of installed power capacity by 2016; 40% by 2030. |

**Figure 1: Overall Renewable Energy share Targets in the MENA countries** [2]

**1.1**

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**Figure 2: Noor 1 plant (160MW) (Akdim, 2016)** [28]

King of Morocco, Hassan II. This is the Noor I plant with half a million parabolic mirrors on the equivalent of almost 700 football pitches. This first part of the plant has an installed capacity of 160 MW with 3 hours of thermal storage equivalent to three hours of high production. Noor I is the proof that Morocco is effectively starting to take advantage of its abundant solar resources. This first unit of the Noor project had a capital cost worth more than 600 million euros, and was made possible thanks to the African Bank of Development, the German Public Bank, the World Bank, the French Agency for Development, the European Bank of Investment and the European Commission. Noor II and III are expected to be operational starting 2018, adding an installed capacity of 350 MW to the Ouarzazate compound of thermal solar plants [3].

Morocco’s supply in energy is based on conventional, non-renewable sources. Around 90% of its power generation comes from oil, coal and natural gas. The Kingdom’s dependence on imports for energy supply is worth 91%, especially for oil which is widely dominating the country’s energy mix. Saudi Arabia, Iraq, and Russia are the main oil exporters of crude oil to Morocco. In 2013, all energy imports (Crude oil and oil products, coal, natural gas and electricity) reached a total of 27% of all Morocco’s imports thanks to the new energy policy Morocco has adopted, the Government says they hope to be able to export electricity to Europe from renewables over the medium to the long term (by 2030) [4]. Figure 3 clearly demonstrates the forecast of energy mix in Europe and the MENA region for the coming 35 years.

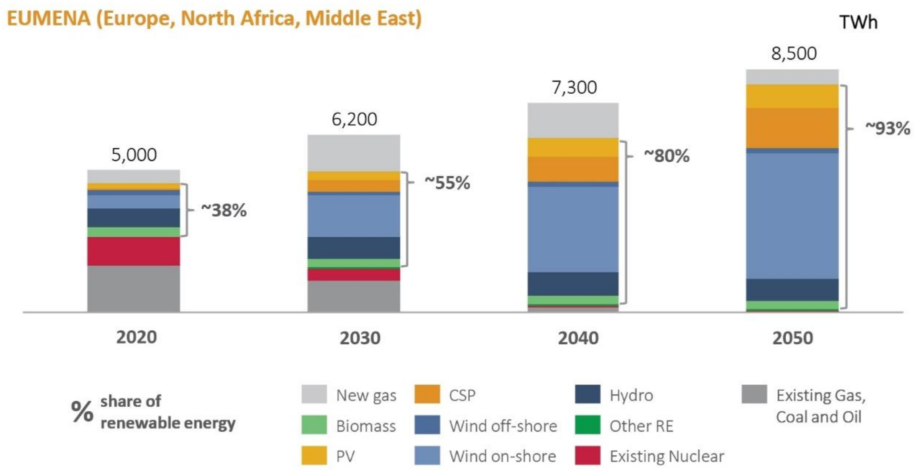



**Figure 3: Development of electricity mix in EUMENA (IRENA, 2013)** [2]

## 1.2 Solar Energy

### 1.2.1 Solar potential in the world

One hour of insolation corresponds to more than the planet's energy consumption for the whole year. By far, solar energy represents the largest energy resource on the Earth. Many interesting comparisons are made in order to truly understand what the massive potential solar energy is. To have an idea about how big the potential of solar power is, and by solar power we mean the power output obtained after converting solar energy into electricity, the selection of factors is an extremely important step. In some regions of the world, low-cost energy puts an end to the competitiveness with solar power, and

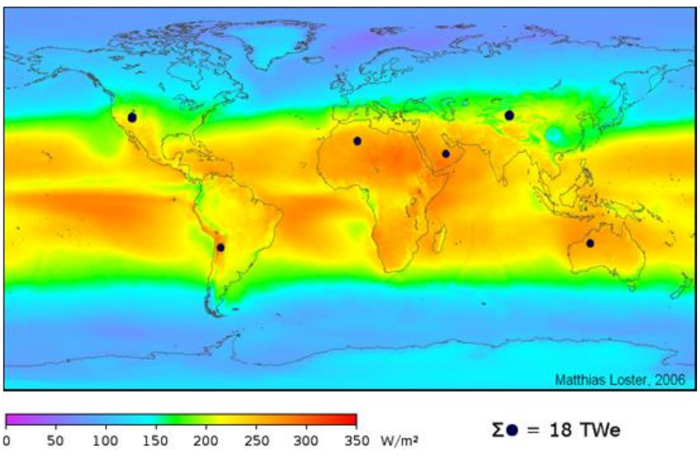



**Figure 4: World solar power potential (Loster, 2010)** [29]

makes it unfeasible in these respective areas.

The only option that might make solar power projects achievable in that countries is help from the government, such as incentives. Assuming that the electricity conversion rate is 8%, this map shows how much area has to be covered in photovoltaic panels to respond to the world’s energy demand. Nowadays, the PV panels’ efficiency is around 14%.[5]

If someday researchers and engineers develop photovoltaic panels capable of converting the power of photons into electricity with 20% efficiency, a surface area as big as Spain (500,000 km$^2$) would be enough to supply energy to the entire planet.

### 1.2.2 Solar potential in MENA region

As it has been said before, the Middle East is better known to the world as a dominant oil and gas supplier than as a promoter for renewable energy. However, last years have shown that many governments in the region are determined to achieve the ambitious renewable energy shares they have set. Indeed, many countries of the MENA region are oil importers and energy bills are getting bigger and bigger, and thus representing a more substantial part of their GDP. Moreover, the demand in electricity is surging at round 7% per year over the next 10 years as the population of the oil importer countries are growing constantly. According to the World Energy Outlook 2012, published by the International Energy Agency, the share of renewables in total electricity generation in the MENA region is set rise from the 2% obtained in 2010, to 12% by 2035. According to a study released by the World Bank, the MENA region receives between 22 and 26 percent of all solar energy hitting the Earth. Per square kilometre of solar energy potential, it is equivalent to the energy produced from up to 2 million barrels of oil. Moreover, the region’s solar potential is estimated to be considerably higher than that of all the other renewable resources combined, and could possibly meet the prevailing worldwide demand for electricity.[6]

### 1.2.3 Moroccan Agency for Solar Energy (MASEN)

The Moroccan Agency for Solar Energy was officially set up in 2010 to be in charge of the solar plan, part of the Moroccan National Energy Strategy (NES). Furthermore, it has created strong links and partnerships with numerous European agencies.

## 1.3 CSP plants

Concentrated Solar Power (CSP) plants use mirrors to focus the sunlight onto a collector before transferring this solar energy further to a heat transfer fluid that will serve electricity generation through a traditional steam turbine cycle. When used for large scale, CSP builders usually equip it with a storage system to allow the plant to produce electricity in the evening when the energy demand is generally at its peak, and also during the night. There are four types of CSP plants, namely: Solar Dish, Solar Tower, Fresnel Reflector and Parabolic Trough. These CSP variants differ on the mirror configuration and design, but heat transfer fluid is used in any case even if the plant is not designed to have a thermal storage system. CSP plants demand high direct solar irradiance in order to work effectively, and therefore the Sun Belt region is the best location for their installation. The USA and Spain are the world leaders in CSP, in terms of installed capacity. The total installed capacity in CSP plants connected to the grid and operational all over the world is 4,500 MW. [7]

### 1.3.1 Influence of the climate

Gathering climate data is crucial in order to be able to design a CSP plant. After choosing the plant's location, it is necessary to have some important weather data such as wet and dry bulb temperatures, humidity, wind speed, rainfall, and Direct Normal Irradiation (DNI). Data with a frequency of 10 minutes over an entire year is usually used as an input into the Software needed for the plant's design. System Advisor Model (SAM) is the most common program employed by engineers for plant design. The goal of this work was to build a model similar to SAM, able to determine the annual water consumption, and electricity production, depending on the inputs chosen by the user.

### 1.3.2 Water issues

CSP plants are usually built in deserts or areas where water usage can represent a real issue. Water is mostly used in the cooling towers in CSP technology, but also for cleaning the mirrors. The cleaning process requires demineralized water, whereas the water used for cooling doesn't require high quality specifications.. In addition to that, the cost of water and its transportation are key factors that have to be taken in account in order to establish a correct economic assessment during the design of a plant.

### 1.3.3 Aims and Objectives

WAter Saving for Concentrated solar Power (WASCOP) is a EC funded project aiming "to develop a revolutionary innovation in water management of CSP plants - flexible integrated solution comprising different innovative technologies and optimized strategies for the cooling of the power-block and the cleaning of the solar field optical surfaces". As this report forms part of WASCOP, water consumption has been the major subject analysed and discussed. The team's objectives were to evaluate precisely water consumption for a 50 MWe CSP plant, while building an accessible technical and financial model to forecast the water demand and electricity production .[8]

# 2 Cleaning methods

## 2.1 Importance of cleaning

### 2.1.1 Situation

CSP plants usually require a large area of mirrors in a desert region. It is the best location to benefit from the high DNI. However it implies that the mirrors will be subjected to dust and sand deposition. Only 10% of the overall mirror surface covered can lead to a loss higher than 50% in power. As desert regions do not record many rainy days over the year, additional manual cleaning is required to recover a satisfactory efficiency of the mirrors. Depending on the time of exposure without cleaning, mirror

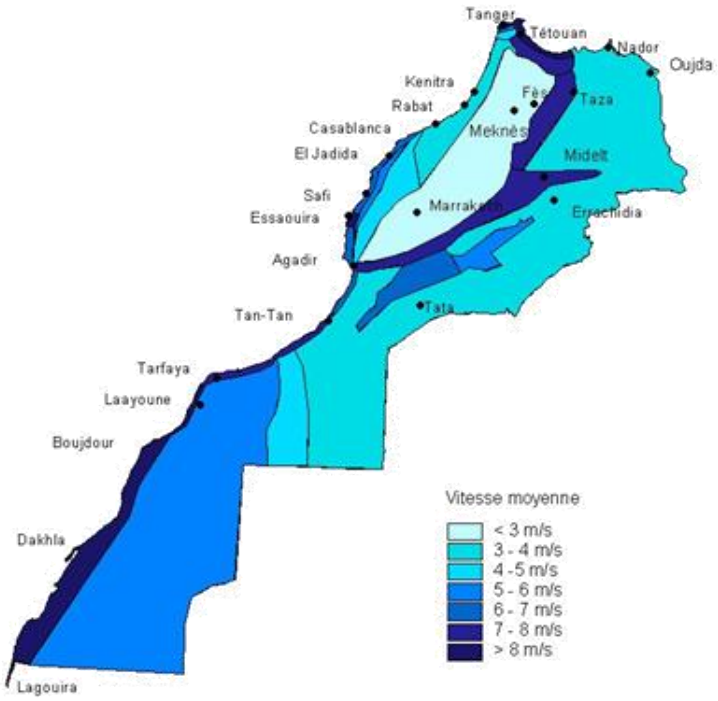



**Figure 5: Wind map of Morocco**

reflectance losses range from 5% to 25% [9].

Especially in Middle East and North Africa, where our project is focused (Morocco), dust and sand are driven by wind and local storms [10]. Studies and research are focussed on the dust deposition rate, to understand the deposition mechanism and the impacts on mirrors..

### 2.1.2 Dust and sand deposition

Sand is defined as a composition of different materials and particles. “Dust” is used for particles with a diameter lower than 500 μm (around 10 times a hair diameter)[11]. Its main characteristics involved in the CSP context are size, distribution and density;

composition, chemistry and charge. Then, its impact mostly depends on the weather conditions. For instance, density and distribution vary with wind variation, humidity and moisture will influence the chemistry on the coating surface. Travis Sarver et al. relate in their [11] results from deep studies led on environmental effects, characterization of dust and its issues and mitigation technique (mainly cleaning and washing methods), based on Mani and Pilai [12].

Dust deposition is the result of environmental and physical factors. Once a particle is carried to the mirrors, gravity pull its down to the surface where it can stick by electrostatic bonding. In addition to these forces, capillary and surface energy effects help to maintain the particle on the glass. Moreover, alternative sequences of high and low humidity can significantly damage mirrors. It is the case with morning dews, but it could happen during winter as well. As shown on Figure 6, salt particles can create strong bonding and become water-insoluble particles, which are harder to remove, even mechanically. It could require hard brushing which could scratch the mirrors, so lower

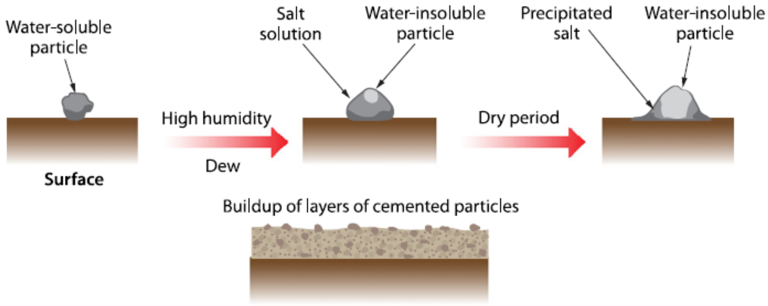



**Figure 6: Cementation of solid particles due to humidity**

its reflectance.

Besides, high velocity wind can damage the mirrors when carrying sand particles to collision. Figure 7 highlights different types of impact according to the impact velocity and the particle diameter. It shows four main kind of impacts. The most damageable one is the hypervelocity shock. Whatever the size of the particle, a very high speed would result in shock waves and heat generation through the collector. Repeated impact from intermediate velocity and particle diameter would result in a “deformation and destruction of the surface causing a loss of mass” (Erosion). Ballistics impacts dissipate kinetic energy of macro-particles into the collector material. Strain pressures and heat speed up the wear and tear of the surface. Then, sticking impacts represent the ordinary dust deposition of small particle carried by light wind.

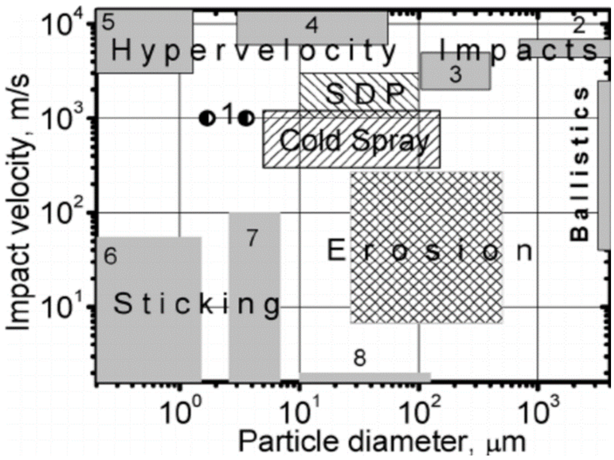



**Figure 7: Categories of impacts depending on particle diameters and impact velocity**

## 2.2 Dust mitigation methods

Cleaning and washing the mirrors are the main used dust mitigation methods. . These procedures produce either  prevention or restoration.

### 2.2.1 Prevention

Firstly, basic obstruction processes have to stop dust before it arrives too close to the mirror to be deposited. To do so, it is possible to build walls and barriers around the plant to protect the mirrors. Also, the stow position (turn the surface to the ground) is the easiest effective dust mitigation process to set up every day, when mirrors cannot be used (night, storms). Other prevention method are based on new types of coating. Vibrative coating aim to prevent dust deposition avoiding accumulation of particles via mechanical-electrical appliances. Then, the thermally induced air current is mainly used for telescope and aerospace. For a matter of cost, it cannot be applied on CSP collectors. In the end, the most promising coating, however still subject to further research, is the ElectroDynamic Screen (EDS). It is based on electrostatic repulsion along the collector surface to pull particles out of the mirror (cf. 2.3). These methods are useful to reduce significantly the number of washes (e.g. the water consumption) per year but again require a higher installation cost [11].

### 2.2.2 Restoration

Restorative methods are inevitable in soiling situations. It allows to one to recover up to 98% of the mirror reflectance. Efficient washing and cleaning involve significant water consumption. To minimise this amount, high water quality is essential. Demineralised water is usually used for cleaning solar plant collectors. Researchers are working on dry washing, which could use a mechanical brush to sweep the surface or possibly an air blower. However, air blowers cannot remove salt cemented particles; and brushes must be as soft as possible so as not to damage the mirrors after repeated contact cleaning cycles.

## 2.3 Wet cleaning

Most common cleaning methods of CSP mirrors use demineralised water (high quality cleaning but also high cost), brushes and manual labour to drive the cleaning truck (Appendix A.1). The overall process has then a significant cost over the year, as cleaning is regularly repeated in desert regions where water is scarce. A compromise is needed between cleaning mirrors to improve the effectiveness and scrubbing and scratching these mirror surfaces because of the frequency of brush cleaning.

As wet cleaning is essential and cannot be replaced by any efficient dry cleaning thus far, optimization of such cleaning cycle is an area for current research.. Researchers from the NREL [11] studied the correlation between reflectance losses and its recovery, for a number of cleaning cycles per week. They arrived at the conclusion that a 2-day-cycle is the best compromise with  annual average reflectance losses of 0.85%. More cleaning within two days does not recover significantly more specular reflectance whereas less cleaning would lead to an annual average loss of reflectance of 18% in the case of a 6-day-cycle and 31% in a 12-day-cycle. In a review written for the System Advisor Model developed by the NREL [13], the cleaning water consumption is estimated to be of 0.20 $m^3$/MWh, which gives a range between 10,000 and 15,000

$m^3$/year, for a 2-day-cycle cleaning of a 50 MWe plant. These values will be the benchmark for the validation of our cleaning model part. Then, SAM's inputs require a water consumption rate per unit area. To keep the same basis both for the calculations and comparisons, we reached a consumption into a range of 0.10 and 0.20 L/$m^2$/wash.

## 2.4 Electrodynamic Screen (EDS)

Water often represents a high share in the Operational costs of running a CSP plant, that's why researchers have been looking to find a new way to clean the mirrors of CSP facilities more efficiently and by reducing costs. Large-scale CSP plants are best suited for arid and desert regions which are extremely dusty. As we want to keep the mirrors clean for maximum reflectance and thus electricity output, an automated process seems to be the optimal solution (SunShot, 2012). [14]

Boston University together with Sandia National Laboratories and Abengoa Solar developed a transparent electrodynamic screen (EDS) as the future device for self-cleaning solar concentrators (Appendix A.2). Basically, this electrodynamic screen operates travelling-wave electric fields to move away particles of dust from the mirrors. In 2012, when EDS still was an R&D project, the technology won the Sunshot (U.S. Department of Energy) CSP R&D award. Current EDS coatings are able to eliminate 95% of the dust deposited in a very small amount of time, using only a very small fraction of the electricity produced by the plant. EDS systems use neither water nor manual labour. This innovative technology shows a strong potential for mirror cleaning for large-scale CSP plants [14].

## 2.5 SuperHydrophobic (SH) coating

The EDS system enables us to remove dust particles before its amount is too high on the mirrors. However, when only few particles are deposited in the morning, a SuperHydrophobic Coating (SHC) could change the negative effects of the dew (creation of bondings between the mirror and particles) into a free natural water cleaning. SHC is an anti-soiling coating which completely repels water. That's why even if it requires water cleaning, the amount of water per wash is significantly lowered. Water drops roll over the surface, catching dust particles to flow them out of the mirror, while drops would not be able to pull out dirt particles bonded on usual coatings (Appendix A.3).

The contact angle $\theta_0$ of water droplet is higher than 150° and the rolling angle $\theta_r$ lower than 5°, which means that the surface actually does not get wet (Figure 8). Coupling this coating with EDS is a promising area of CSP coating development. In such cases, the EDS would maintain an average efficiency when required while light rain and morning dews would remove small particles. As the EDS is controlled by operators, when there are free natural washing it can remain on a standby mode so as not to waste energy. It is important to keep in mind that during strong winds or storms, wet cleaning remains the best solution to remove large numbers of particles to restore the mirror reflectance.

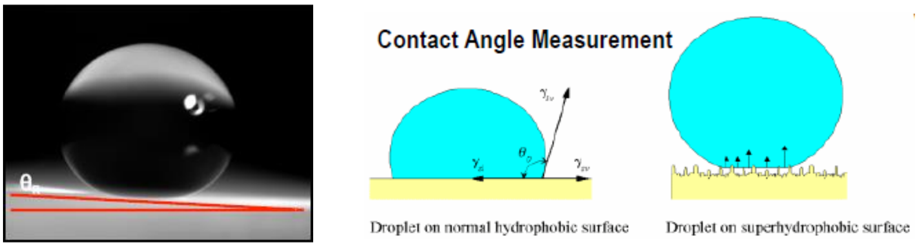



**Figure 8: Rolling angle and contact angle measurements** [30]

# 3 Cooling systems

Concentrated Solar Plants (CSP) require cooling through a condenser to reject heat from the steam. Cooling the water in the turbine closed loop makes the Rankine Cycle be more effective, what is more: a lower condensing temperature is obtained, the cycle is

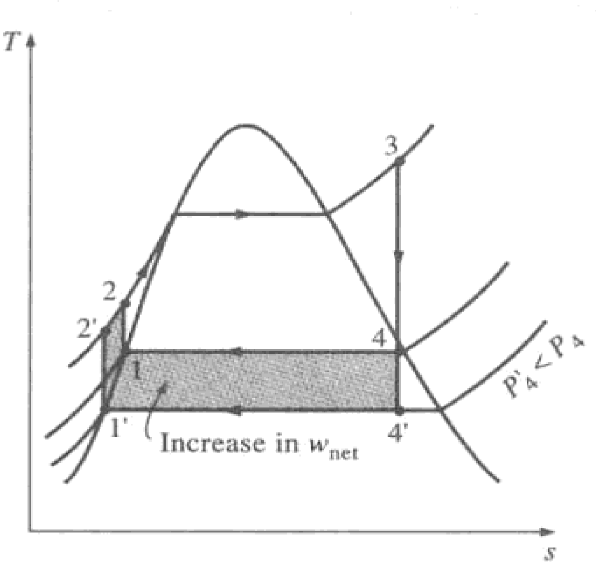



**Figure 9: Rankine cycle for different cooling level** [31]

improved as shown Figure 9.

Therefore, the plant efficiency is related to the effectiveness of the cooling system. Heat rejection is usually performed through evaporative processes in cooling towers, which use great amounts of water. Furthermore, dry cooling is dependent on dry bulb temperature, but evaporative cooling on wet bulb temperature, which is always lower due to thermodynamic reasons. This makes it more appropriate for the cooling and lets the turbine re-circulating water (the water used to move the turbine, not the cooling water) go to lower temperatures than with other cooling systems. Apart from the efficiency, another advantage of wet cooling systems is its usefulness in hot environments, where hot air makes dry cooling less efficient. Moreover, its small size along with the reduced equipment make initial capital costs cheaper [15]

However, wet cooling is not always the most suitable option for a power plant. Despite consuming less power than dry cooling systems, it involves great volumes of water which could be saved in a dry cooling (between 95%-100%), making operational costs lower. So, even if the capital cost for a dry cooling is 4%-9% higher, capital costs are made back in 20 years [16] . Additionally, the importance of water availability and evaporation ease must be kept in mind. On the one hand, hot environments are often arid, so water costs are increased considerably. On the other hand, warm areas can be more humid, affecting water-evaporation [15]. Hence, higher humidity leads to more water in the air, thus, less water can be evaporated and heat rejection is reduced (in wet cooling systems) [17].

Nonetheless, the equipment used in dry cooling is larger and fans are needed to move the air. These fans have a higher power consumption than wet cooling and it is taken from the electricity produced. Hence, the overall efficiency of the plant decreases significantly (near 5%). In the end, there is a possibility of mixing both systems, using the wet cooling for the hottest days of the year, or at least during summer, and dry cooling for the rest of the year. Hybrid cooling system needs both dry and wet cooling equipment, but smaller sizes. Although it involves different water volumes, water savings are about 60% compared to wet cooling. Capital costs are 3%-5% higher while overall efficiency is lessened by 4.5% (always compared to wet cooling). Nevertheless, its versatility gives it the possibility of improving efficiency in hot, cold and wet environments [15]. A good design of cooling systems requires understanding of different approaches and their capabilities. This section will explain the wet, dry and hybrid cooling systems and the associated thermodynamic equations (which will be used to build the MATLAB program).

## 3.1 Wet cooling

### 3.1.1 Water usage

In cooling towers or evaporative condensers, significant volumes of water are lost or must be replaced.  These water amounts are called drift, blowdown (or purge) and losses associated with evaporation and the summation of these contributes is called ‘make-up’ water.

#### 3.1.1.1 Drift

Drift losses happen in cooling towers, when water droplets are lost leaving cooling towers due to the airflow. Drift losses, also called mist, are limited by drift eliminators, which goal is to, as its own name says, eliminate drift. Water lost through drift in evaporative condensers and cooling towers is usually dependant on eliminators. Even if nowadays could be lower, usual losses are between are between 0.05%-0.2% of water flow through the tower.[18]

#### 3.1.1.2 Blowdown

The water used for cooling comes from various sources (rivers, ground waters…), and in every case contains dissolved solids. In a closed-loop system, water is evaporated in evaporative condensers or cooling towers while these solids remain within the cooling cycle. Hence, the concentration of total dissolved solids (TDS) in the water remaining increases and must be maintained below 2,000-3,000 mg/l, because the system could suffer from corrosion or scaling [18] .

Consequently, using the blowdown or purge, part of the water is removed and the cycle is filled again with new cooling water (also taking into account evaporative and drift losses). In order to control the blowdown, cooling water conductivity is measured, as it is proportional to concentration of TDS. These methods work automatically and TDS concentration is monitored continuously. Therefore, small volumes of water are purged more frequently to maintain the concentration in the desired level. Thus, the amount of water discharged is minimised [18] .

When blowdown water is released, environment must be bear in mind, as water with high concentration of solids can damage rivers and affect wildlife. Hence, law regulate its emissions. What is more, water discharge legislation varies from one country to another, so concentration limits are different in each.

#### 3.1.1.3 Losses associated with evaporation

When cooling water passes through evaporative condenser or cooling tower, part of it is evaporated and sent to the atmosphere. This water is taken into account as a loss and must be replaced [18].

#### 3.1.1.4 Other losses

Other losses as leaks can also happen. Faulty pumps or pipeline joints can suffer leakages, but this leads to insignificant losses, so they are not taking into account in the calculations. Nevertheless, in order to prevent that, pipelines and other items are routinely checked and corrective actions taken[18].

### 3.1.2 Wet evaporative cooling system

An important aspect to take into account is the inlet/outlet temperature of the cooling condenser, which should be the lowest possible in order to improve the plant efficiency ($\Delta T$<10-15ºC) [15]. In our interface this temperature has been set as 10ºC. Figure 10 shows a diagram in which the steam from the turbine is rejected by a conventional wet

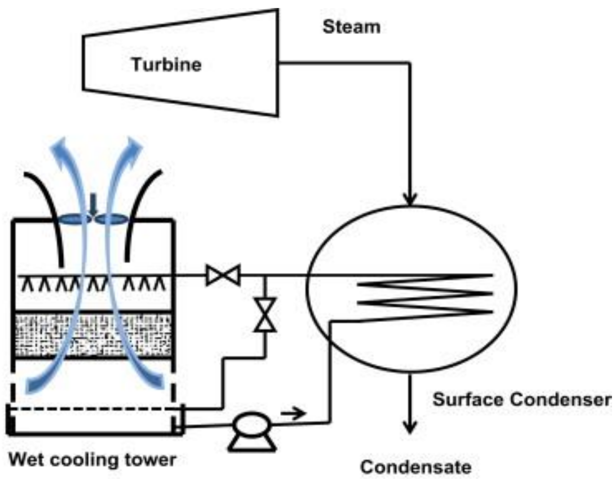



**Figure 10: Wet cooling system diagram** [15]

cooling tower:

Heat exchange occurs as heat loss and latent heat of vaporisation. Being the last one 85%-90% of the heat removed, the previously mentioned air humidity takes real importance now. Anyway, the heat transference is performed by circulating water through the condenser and using it to remove heat from the steam flow. Then, heated water goes to the cooling tower, where heat is released by direct evaporation. Heat rejected in the condenser is calculated as the heat transferred to cooling water, thus, heat capacity of water (specific heat) must be taken into account: [19]

$$Q_{rejected}[kW] = \Delta T_{cw}[K] * \dot{m}_{cw}\left[\frac{kg}{s}\right] * cp_{cw}\ \left[\frac{kJ}{kg\ K}\right]$$

Where $cp_{cw}$ is the heat capacity of water, $m_{cw}$ is the mass flow of the cooling water and $\Delta T_{cw}$ is the inlet-outlet condenser temperature difference. As the plant has a certain amount of heat to reject in each cycle in order to accomplish an effective plant performance, and $cp_{cw}$ remains also quite constant, the mass flow of water will vary and depend on $\Delta T_{cw}$.

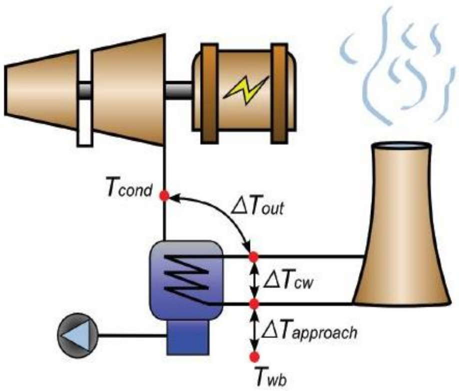


**Figure 11: Temperatures in a wet cooling system** [19]

Actual temperature rise is also necessary for calculating $T_{cond}$ (condensation temperature) and, with it, $P_{cond}$ (condensation pressure). $P_{cond}$ is used for the calculation of efficiency, which is the better as long as $T_{cond}$ and $P_{cond}$ are the lower. $T_{cond}$ is calculated as follow [19] :

$$T_{cond} = T_{wb} + \Delta T_{approach} + \Delta T_{cw} + \Delta T_{out}$$

Where $T_{wb}$ is the wet bulb temperature, $\Delta T_{cw}$ inlet-outlet condenser temperature difference (set as 10°C in the interface), $\Delta T_{out}$ (set as 2°C in the interface) is the difference between temperature of the outlet cooling water and $T_{cond}$, $\Delta T_{approach}$ (set as 3°C in the interface) is the temperature difference between the circulating water at the condenser inlet and the wet bulb ambient temperature, used with the ref. condenser water temperature difference value to determine the condenser saturation temperature and thus the turbine back pressure. All the temperature relations can be seen graphically in Figure 11. By contrast, in Figure 12 the efficiency flow chart for both wet and dry cooling systems is displayed, where temperatures are the input.

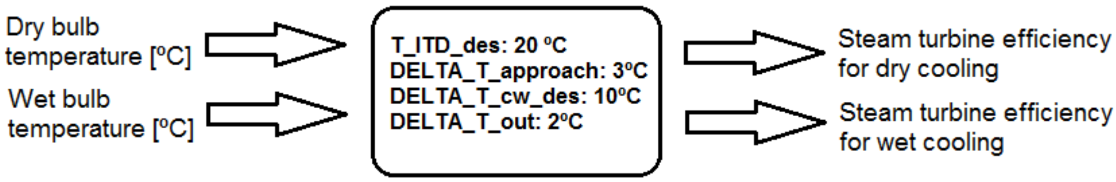



**Figure 12: Efficiency Flow Chart**

Finally, 'make-up' water must be calculated, which is the volume of water which has to be refilled, calculated as the sum of blowdown, drift and evaporation losses everything in $m^3/h$ [19]:

$$\dot{m}_{make-up} = \dot{m}_{blowdown} + \dot{m}_{evaporation} + \dot{m}_{drift}$$

Where drift are calculated as a small fraction of cooling water mass flow ($f_{drift} = 0.01$):

$$\dot{m}_{drift} = f_{drift}\, \dot{m}_{cw}$$

However, evaporative losses are calculated according to the heat rejected, using evaporation enthalpy:

$$\dot{m}_{evaporation} = \frac{\dot{q}_{rej}}{\Delta h_{evap}}$$

Blowdown calculation is achieved with cycles of concentration (C), parameter which can be introduced manually in the MATLAB interface, and which is defined as the ratio of make-up water over blowdown water. Then:

$$\dot{m}_{blowdown} = \frac{\dot{m}_{evaporation}}{C - 1}$$

## 3.2 Dry cooling

Dry heat exchanger is used to cool down the exhaust steam which comes from the turbine. For that, air is pushed by fans as shown in Figure 13, consuming great amounts of power. Heat dissipation will depend, in part, on air properties (humidity, specific heat, etc), but mainly on the air mass flow. In spite of saving 95% of water comparing to wet cooling, power consumption in fans make it quite less efficiency. 5% of produced power is used forcing the air through the cooling tower.[15]

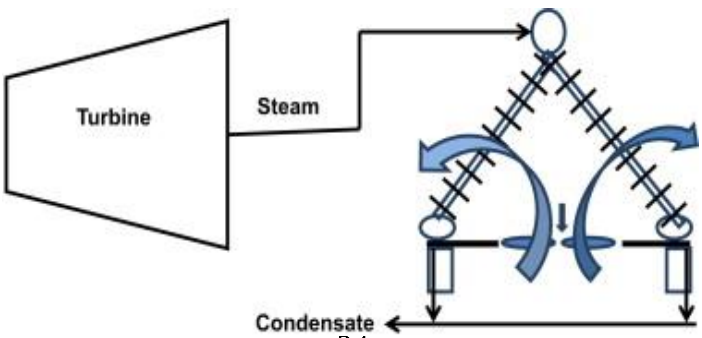





**Figure 13: Dry cooling system diagram** [15]

However, parameters calculated in dry cooling are similar to wet cooling. Heat rejected is calculated as the heat transferred to air, thus, heat capacity of air (specific heat) must be taken into account:[19]

$$\dot{Q}_{rejected}[kW] = (T_{ITD} - \Delta T_{out})[K] * \dot{m}_{air}\left[\frac{kg}{s}\right] * cp_{air}\ \left[\frac{kJ}{kg\ K}\right]$$

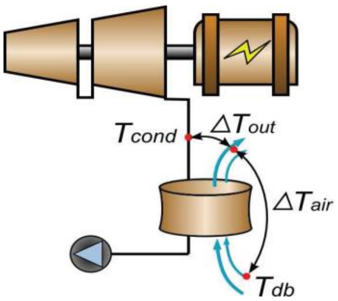


**Figure 14: Temperatures in a dry cooling system [19]**

Where $cp_{air}$ is the heat capacity of air, $m_{air}$ is the mass flow of the air and $\Delta T_{out}$ is the average outlet temperature and the air inlet temperature difference. $T_{ITD}$ Initial temperature difference (ITD), difference between the temperature of steam at the turbine outlet (condenser inlet) and the ambient dry-bulb temperature. Temperature relations are graphically explained in Figure 14. As the plant a certain amount of heat to reject in each cycle in order to accomplish an effective plant performance, and $cp_{air}$ remains constant (1005 $J.kg^{-1}.K^{-1}$), the mass flow of air will vary depending on the temperatures.

Initial temperature difference is also necessary for calculating $T_{cond}$ (condensation temperature) and, with it, $P_{cond}$ (condensation pressure). $P_{cond}$ is used for the calculation of efficiency, which is the better as long as $T_{cond}$ and $P_{cond}$ are the lower. $T_{cond}$ is then calculated, with $T_{db}$ dry-bulb temperature and $T_{ITD}$, set as 20°C in the interface: $T_{cond} = T_{db} + T_{ITD}$ [19].

## 3.3 Hybrid cooling

A hybrid cooling system works with both dry and wet cooling systems in parallel or serial configuration as shown in Figure 15. This allows the plant use the most effective cooling depending on the environment. Therefore, cooling type can vary depending on the ambient temperature and, consequently, save more than 60% of water consumed in a wet cooling configuration. On warm days, as the air cannot cool the steam enough, dry cooling is avoided and water is used instead. During winter, cold weather enhances the performance of the dry cooling configuration. In this way, large volumes of water can be saved [15].

The percentage of water cooling used according to ambient temperature can be introduced manually. However, MATLAB script uses a linear relation based on the dry bulb temperature (cf. subsection 5.1.4).

# 4 Economic Analysis

## 4.1 Introduction

The economic feasibility of a CSP plant depends on solar resources on site and on the prices of water, electricity, or cost of labor for instance. Costs of the plant can be divided into two groups: investment costs including cost of financing (CAPEX) and operational and maintenance costs (OPEX). An access to the reliable cost database remains limited because it is a relatively immature technology. Because of the high CAPEX, incentives or soft loans can cover the cost gap between the power cost and the available tariff. The Moroccan government have not implemented renewable energy certificates yet, a factor that could be an additional source of income [18].

## 4.2 Input parameters

The calculation of the economics for a CSP plant is primarily based on the work of J. Hernandez-Moro and J. Martinez-Duart [20]. Several assumptions and their equivalent values have been collected and presented in Appendix C.1.

## 4.3 Equation explanation (wet cooling only)

The total cost of fresh water for a reference year takes into consideration the total consumption of water in the power plant and the price of water:

$$water\_cost\_wet[\$] = m\_water\_year\_wet[m3] * water\_cost[\frac{\$}{m3}] \qquad (1)$$

The total water transportation cost comprises both distance and transportation costs:

$$trans\_water\_cost\_wet[\$] = m\_water\_year\_wet[m3] * transportation\_cost[\$/(m3 \cdot km) * distance \qquad (2)$$

The total cost of water demineralization depends on the amount of water needed for cleaning the mirrors and on the cost of treatment per unit:

$$water\_treatment\_wet[\$] = cleaning\_ww\_wet[m3] * water\_treatment[\frac{\$}{m3}] \quad (3)$$

The annual cost of water is gradually increasing because of inflation and in respect to i-year:

$$annual\_cost\_water\_wet[\$] = (Eq(1) + Eq(2) + Eq(3)) * \left(1 + \frac{inflation[\frac{\%}{yr}]}{100}\right)^{(i-1)} \quad (4)$$

The total fresh water cost (1) with respect to the increase in water price for i-year is shown as:

$$water\_cost\_i\_wet[\$] = Eq(1) * \left(1 + \frac{inflation}{100}\right)^{(i-1)} \quad (5)$$

Similarly, the transportation expenditures growth is reflected in:

$$trans\_water\_cost\_i\_wet[\$] = Eq(2) * \left(1 + \frac{inflation}{100}\right)^{(i-1)} \quad (6)$$

The increase in demineralization cost is given by:

$$water\_treatment\_i\_wet[\$] = Eq(3) * \left(1 + \frac{inflation}{100}\right)^{(i-1)} \quad (7)$$

Consequently, labor cost in i-year is represented by:

$$annual\_labour\_cost[\$] = staff\_number * 12 * average\_salary * labour\_multiplication\_factor * \left(1 + \frac{salary\_increase}{100}\right)^{(i-1)} \quad (8)$$

Value of the electricity sold to the grid in i-year:

$$electricity\_sold\_wet[\$] = total\_electricity\_delivered\_wet * \left(1 + \frac{degradation\_{factor}}{100}\right)^{(i-1)} * electricity\_cost * \left(1 + \frac{inflation}{100}\right)^{(i-1)} \quad (9)$$

Capital cost of investment including incentives:

$$investment\_wet[\$] = cc\_wet * 10^6 \left(\frac{1-incentives}{100}\right) \qquad (10)$$

Annual depreciation of the plant is expressed as:

$$depreciation\_wet[\$] = \frac{Eq(10)}{lifetime} \qquad (11)$$

Corporate tax payable for i-year is:

$$tax\_cost\_wet[\$] = \frac{tax}{100} * (Eq(9) - Eq(11) - Eq(8) - Eq(5)) \qquad (12)$$

Profit after tax for i-year

$$profit\_wet[\$] = Eq(9) - Eq(12) - Eq(11) - Eq(8) - Eq(5) \qquad (13)$$

i-year levelized discounted rate (decrease in the value of money):

$$LDR = \frac{1}{\left(\frac{1+discounted\_rate[\%]}{100}\right)^i} \qquad (14)$$

i-year profit after tax expressed in current (first year) value of money:

$$discounted\_profit\_wet[\$] = Eq(14) * Eq(13) \qquad (15)$$

i-year operational cost expressed in current (first year) value of money:

$$opex\_discounted\_wet[\$] = (Eq(8) + Eq(4) + Eq(12)) * Eq(13) \qquad (16)$$

“Artificial” production of the electricity during the plant’s lifetime expressed in the current price of the electricity:

$$discounted\_electricity\_wet[\$] = \frac{Eq(9) * Eq(14)}{electricity\_cost} \qquad (17)$$

The net present value of the investment represents the sum of all profits minus the investment cost. The total profitability of the investment over the plant’s lifetime in the current value of money is expressed as:

$$NPV\_wet[\$] = (\sum Eq(15)) - Eq(10)) \qquad (18)$$

The total operational spending over the plant's lifetime in the current value of money:

$$opex\_wet[\$] = \sum Eq(16) \qquad (19)$$

The total electricity production over the plant's lifetime expressed in the current price of the electricity:

$$discounted\_wet[\$] = \sum Eq(17) \qquad (20)$$

Leveled cost of electricity (LCOE):

$$LCOE\_wet[USD¢/kWh] = \frac{Eq10*(Eq(10)+Eq(19))}{Eq(20)} \qquad (21)$$

## 4.4 Value of money

Figure 15 represents the value of a $1 investment over a period of 30 years, representing a CSP plant's lifetime (discounted rate 10%). This graph shows that $1 spent today is comparable to $2 spent in 10 years, or even to $3 spent in 15 years. According to these numbers, it is cheaper to invest in affordable technologies right now and improve the system later rather than spending massive amounts in service solutions from the beginning. In order to better understand the affordability of any technology, it is necessary to investigate in inflation reducing the value of money (increase the price of the products), and technical development that causes reduction in price.

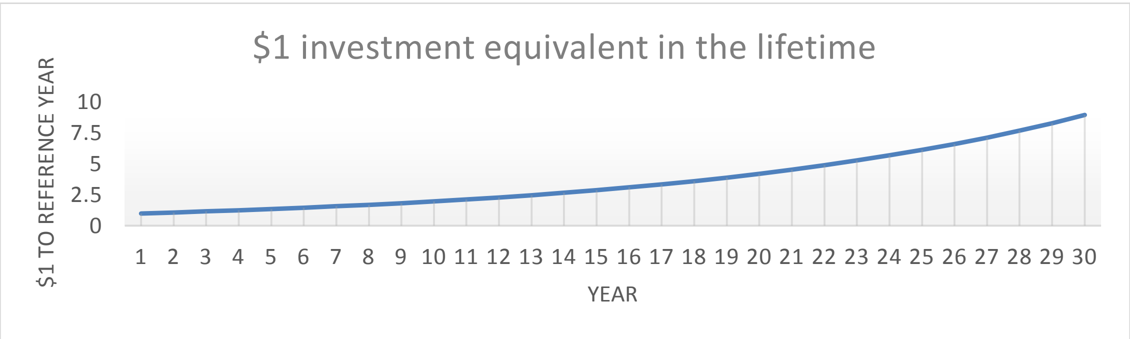



**Figure 15: Value of money through the lifetime**

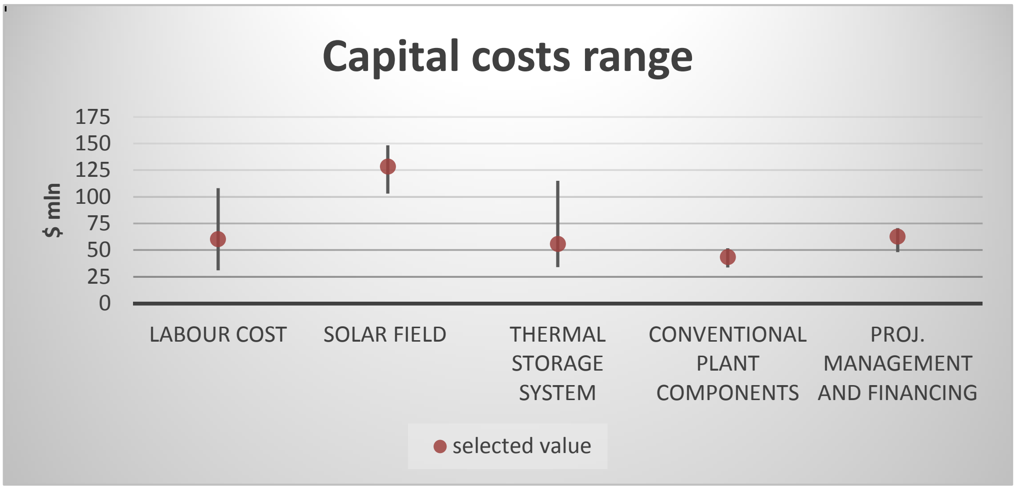
## 4.5 Capital costs

The estimation of the capital cost for CSP plants is crucial in economic evaluation, because the building and construction represent an important part of the required funds. The estimation of the required financing has been achieved thanks to the analysis and comparison of four existing installations and one predicted plant where the data was extracted from existing CSP plant and adjusted according to the forecast change in the cost. As there was no available data about investment costs, a proper estimation has been made to determine the results. A comparison of different CAPEX's is limited because different sources aggregate cost categories differently. For example, in one case labour cost is included in "solar field cost" category whereas in the other is excluded. To create approximated CAPEX model, in this case for CSP plant with unknown labour costs, its value has been assumed as a similar share/similar value in the CAPEX like in the plant where data are available. The most detailed breakdown of CSP capital costs is provided by Ernst & Young and Fraunhofer (2011) for a 50 MW PT Andasol plant in Spain, with a storage capacity of 7.5 hours and an estimated cost of $364 million (i.e. USD 7280/kWe). This reference has been used as a background to create cost categories in Appendix C.2 [21].

**Table 1: CAPEX estimation example – in this case cost approximation based on $ million instead of % CAPEX**

| | Plant I | Plant II | Plant III | Plant IV | Plant V (approximation) | Average = model cost assumption |
|---|---|---|---|---|---|---|
| $ million | 70.9 | 62.8 | 68.2 | 48.3 | 62.1 | 62.8 |
| percentage of the total capital expenditures [%] | 19 | 19 | 24 | 17 | 13 | 18 |

The capital cost evaluation methodology gives very rough information about investment cost, rather than a multi-factor tool of cost estimation and may be used only as CAPEX




range indicator.

**Figure 15: CAPEX range**

The wide variation is driven by different cost structures in different locations. These variations depend mostly on energy storage and labour cost as displayed in Figure 16. The value of modelled CSP plant is in the typical range that is shown in Table 2 [22]. Proportion of the capital cost has been presented in Figure 18.

**Table 2: Typical cost of CSP plants**

| Typical range | Model (7h storage) |
|---|---|
| 3550-10552 $/kWe | 7000 $/kWe |

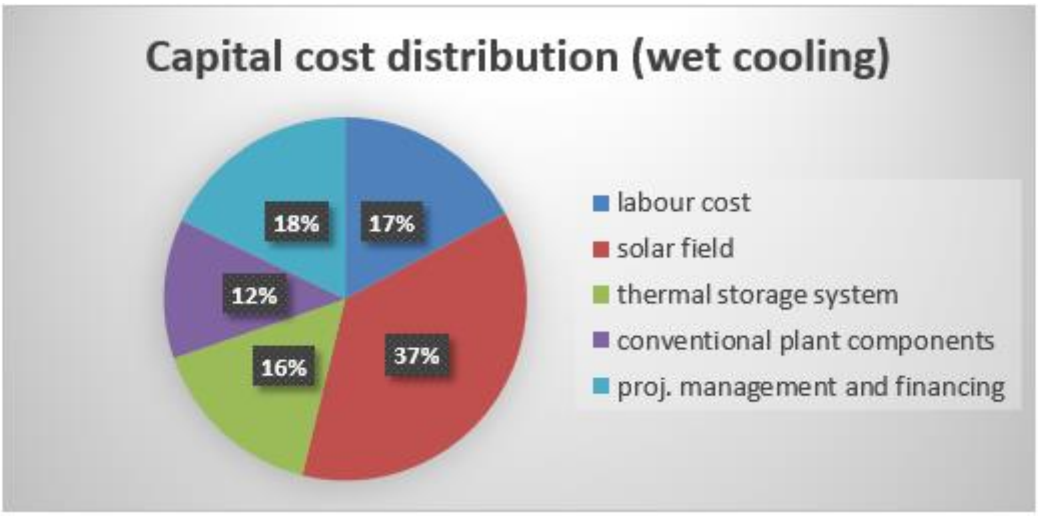


**Figure 16: Capital cost distribution**

### 4.5.1 Cooling system capital cost

The wet cooling systems cost is based on the Approach temperature (explained in the subsection 3.1.2) has been shown. This dependence is shown (in Fahrenheit) in Figure

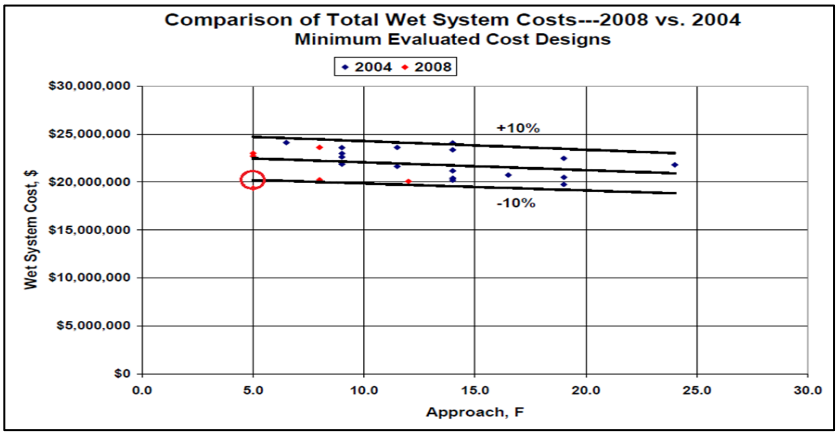



**Figure 17: Wet cooling system**

19. According to that, the variation of the cost is in range of $370-500/kWe.

As for dry cooling, the variation in investment cost is strongly related to ITD and to the intermediate temperature difference, as explained in subsection 3.2. Cost variations are much more significant ($50-110m) compared to the ones related to the wet cooling system. This is the reason why the dry cooling system is definitively more cost sensitive.

In Figure 20 this larger variation is clearly presented. For the designed parameters, the cost is relatively low (bottom part of the range). A system operated under lower ITD costs more and, as a result, the difference in the capital cost of wet and dry cooling systems is even greater. The typical cost of dry cooling system is $500-1000/kWe.

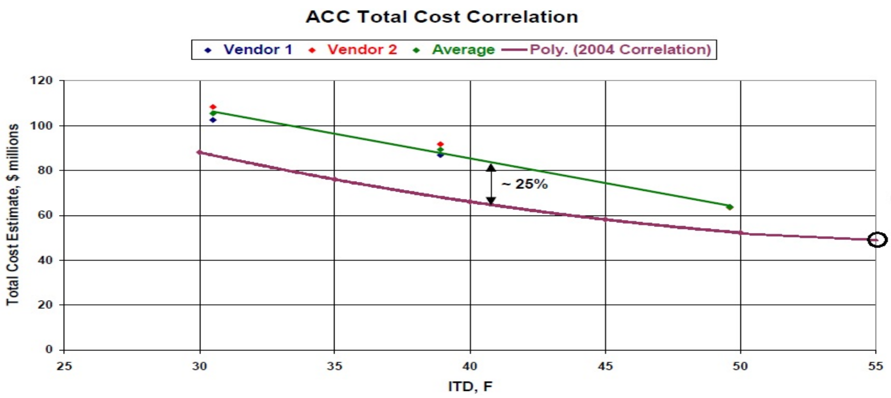



**Figure 18: Dry cooling system cost**

## 4.6 Operational cost

In this analysis, operational and maintenance costs comprise water cost (pure water, transportation, and demineralization) and labour cost only. Those factors are only dependent on the location and may vary significantly across the globe. Inflation is affecting the costs of water and electricity generated, water treatment and transportation. Other OPEX include replacements and repairs, but those details have not been taken into consideration in this analysis.

### 4.6.1 Water delivery cost

The water transportation can be managed by road tanker or pipelines. If the latter, the approximate capital cost is \$17,700 per km (in California) [23]. Assuming the construction of a pipeline which covers the wet cooling CSP plant demands of about 492 000 $m^3$/year of water, with a design of 250% of average nominal flow (reduce the cost of on-plant water reservoir which accumulates water during night hours) with a velocity of 1.5 m/s, the required inlet water pipe diameter is 0.2m. In this case each km of pipeline costs over \$132 000 in the US. In Morocco pipeline construction cost is assumed to be about 40% lower. As a result, every 42km of water pipeline, the investment is increased by 1%. It represents a \$3.3 million investment cost and a total water consumption of $14.76 \times 10^6$ $m^3$ through its lifetime. The cost of the pipeline per each cubic meter transported in 30 years is \$0.224 which is almost 60% of the water cost and has a value of \$0.0054/(km*$m^3$). In this calculation, cost of pumping of the water has been excluded from the total transportation cost. In fact, it strongly depends on altitude differences (pumping against gravitational force) and pipeline material (shear stress forces). In conclusion, in this case, considering a distance of 65km between the water source and the CSP plant, the transportation cost exceeds the cost of water. For desert regions an extremely long distance between the water sources and CSP plant reduces the profit of the wet cooling system. In addition, a long water pipeline creates a risk of leakages and illegal connections in water scarce regions that might cause additional costs. In this case, dry cooling system seem to be the most reliable solution. In Table 3 the typical range in operational cost is presented [15].

**Table 3: General OPEX comparison**

| Model (6h storage) | Source (6h storage) |
|---|---|
| 0.014-0.038 $/kWh | 0.02-0.035 $/kWh |

## 4.7 LCOE

The Levelized Cost of Electricity (LCOE) is the price of electricity required for a project where lifetime revenues would equal costs, including a return on the capital invested equal to the discount rate. The LCOE is widely used in renewable energy technology comparisons. In this case the LCOE includes financial aspects such as CAPEX, OPEX, incentives, taxation, inflation, salary increase, discount rate and technical factors (lifetime, degradation of the plant). A typical range in LCOE for this technology is displayed in Table 4 [15]:

**Table 4: General LCOE comparison**

| Model (6h storage) | Source (6h storage) |
|---|---|
| 0.24-0.29 $/kWh | 0.20-0.33 $/kWh |

# 5 Model construction

## 5.1 Performance model

### 5.1.1 Development of the code

The aim of the project is to develop a software which incorporates a performance and financial model to assist decision making for those users involved in CSP plant projects, specifically those based on parabolic through technology. Nowadays, the most used open source software for people involved in the renewable energy industry is the System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL). SAM incorporates many different options in order to be able to characterize any kind of renewable energy project. It has a large number of financial and performance inputs to be given by the user and also a huge variety of different output values which can be plotted.

The CSP model is a tool similar to SAM but with the following modifications:

• All inputs and outputs used by the model are clearly located in the same interface.

• In order to create a simple and rapid decision making tool, the number of inputs which can be modified by the user has been reduced to the essential ones.

• The model is programmed as a MATLAB script, which is a well-known engineering and science software. This allows the user to modify the main code in order to meet their needs or improve the model.

• The weather data used by the model uses 8760 component vectors (one component for every hour of the year), this allows the user to get weather data from SAM and implemented in the code.

• The CSP interface allows the user to plot up to 37 different graphs in order to rapidly evaluate results and easily determine possible relations between different outputs.

Some of the equations and assumptions used in the performance model are taken from the SAM technical manual [19], although most of them are taken from specialized references and implemented by the authors, also including the financial model. SAM has been used to verify that the equations and assumptions used in the CSP model provide coherent results. The CSP plant’s performance is closely related to the weather conditions of the region where the plant is located [24]. This is the reason why in this technology a deep knowledge of the statistical metrological year is essential. The development of the interface was first based on the performance model and then the financial model was added. In the forthcoming sections, the equations which define the performance model are explained.

### 5.1.2 Heat input and storage

The solar radiation received by the mirrors and the heat is transferred to the receiver tube, is given by:

$$q_{input\ field}[W] = field\ collector\ dni[W/m^2] * \ mirror\ area\ [\mathrm{m}^2]$$

Due to the complexity of the solar field modelling, the turbine heat input is defined only by a single coefficient: field efficiency $\eta_{field}$.

$$q\ input\ turbine[W] = q_{input\ field} * \eta_{field}$$

$$\eta_{field} = 0.52 \quad \text{[13] [24]}$$

The Heat transfer fluid is heated by the solar radiation and either passes directly to the water/steam heat exchangers that feed steam to the turbine or to molten salt heat exchangers to heat molten salt being pumped from the cold storage tank (around 300°C) to the hot storage tank (around 390°C). When using thermal energy from the tanks the processes reversed; the molten salt heating the HTF to about 380°C where it is fed into the water/steam heat exchangers that generate the steam for the turbine. The storage system is fundamental as regard to the CSP performances. This is around the 30% of the capital cost, and by increasing the number of hours of storage, the system is able to work on cloudy or rainy days, and even during the night. Mirror defocusing is only required if the hot molten salt tank reaches its storage limit [24]. The storage system is able to absorb any excess solar energy when the amount of heat exceeds the heat design input of around 135 MW. The addition of a thermal storage system leads to an increase of the availability given by the following expression:

$$Availability\ [\%] = \frac{year\ operating\ hours}{8760\ h/year}$$

The availability represents the fraction of time the plant is available to operate (usually>85%). This is strictly related to the weather conditions in that particular location, the size of the solar field and the amount of energy it captures and to the size of the thermal storage system [24]. The main problem of the CSP technology is that this ratio rarely overtakes 30-40% [24], whereas fossil fuel power plants may reach up to 95 %; operating at full load with infrequent stoppages due to maintenance. The number of hours of storage at full capacity is an input to the MATLAB interface. The storage limit is calculated as:

$$storage\ limit[MWh] = q_{input\ design}\ \ [135\ MW_t] *\ storage\ capacity[h]$$

The tanks are massive constructions, usually up to 20 m high and up to 40 m in diameter. In order to simplify the model the tank's thermal losses are approximated to be a constant, even if it depends on the size of the storage and the tanks:

$$Tank\ losses = 0.45 MW_t\ \ per\ hour\ \ [24]$$

### 5.1.3 Power Cycle and Efficiency calculation

The turbine's nominal gross power output is 50 MWe. The turbine's heat input depends on the Rankine cycle efficiency. The turbine efficiency is calculated referring to the inlet steam and outlet turbine conditions: steam pressure and temperature. At the approximately 390-400 ºC temperatures for CSP trough plant, the boiler usually operates at a pressure of 100 bar with steam superheated close to the maximum HTF temperature of about 395 ºC. For this reason plant efficiency is mainly affected by turbine load (part-load operation is less efficient) and the outlet steam conditions, effectively the condensing pressure. In this case condensing pressure is related to the condensing temperature since the steam is saturated at the outlet from the turbine.

The condensing temperature, for the dry, hybrid and wet cooling are evaluated and explained in section 3.2. The steam condensing pressure is different for the three ways of heat rejection: wet, dry and hybrid. By knowing the condensing temperature, the condensing pressure can be evaluated:

$$p_{cond}[Pa] = 1123.1 - 19.64\ T_{cond} + 4.426\ T_{cond}^2 - 0.039\ T_{cond}^3 + 9.655 * 10^{-4}\ T_{cond}^3$$

Moreover, as regard to the hybrid cooling, simultaneously we are having two ways of heat rejection (wet and dry), and therefore two different results for the condensing pressure. We chose to select the highest from both [19].

According to the Rankine cycle displayed in Figure 19, at the turbine inlet the steam is saturated. By implementing polynomial equation based on saturated steam tables [25], specific entropy and enthalpy of the points on the curve (A, B, C, and F) can be inferred.

$$P_{vaporization\ boiler} = 100\ bar = constant$$
$$T_{vaporization} = 311\ °C$$
$$s_b, s_c, h_b, h_{turbine\ inlet} = f(p\ vaporization) = known\ values$$
$$s_a, s_f, h_a, h_f = f(p\ condensation) = known\ values$$

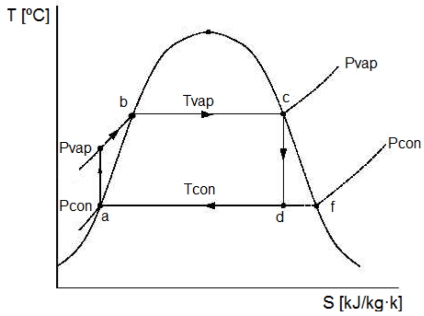


**Figure 19: Rankine Cycle**

As first approach, the expansion in the turbine is supposed as isentropic; and by knowing the isentropic efficiency, the steam quality at turbine outlet can be evaluated.

$$s\ turbine\ inlet = s\ turbine\ outlet \quad (isentropic\ expansion)$$
$$x_{turbine\ OUTLET_s} = \frac{s_c - s_a}{s_f - s_a}$$
$$h\ turbine\ outlet_s \left[\frac{J}{Kg}\right] = h_a + x_{turbine\ OUTLET_s} * (h_f - h_a)$$
$$\eta_{turbine\ isentropic} = \frac{h_{turbine\ inlet} - h_{turbine\ outlet}}{h_{turbine\ inlet} - h_{turbine\ outlet\_s}} = 0.9$$

Once the quality and the enthalpy of the output's water and saturated steam are known, the enthalpy at turbine outlet is calculated. Subsequently, the enthalpy drop, as well as the heat input are calculated; therefore the efficiency of the steam turbine is:

$$h_{turbine\ outlet} = h_{turbine\ inlet} - (h_{turbine\ inlet} - h_{turbine\ outlet_s}) *\ \eta_{turbine\ isentropic}$$
$$\eta_{cycle} = \frac{h_c - h_e}{h_c - h_a} = \frac{work}{heat\ input}$$

Figure 20 shows the efficiency of the turbine, which is presented as a vector of 8760 columns, one for every hour, as the efficiency depends on dry and wet bulb temperatures.

This is the behaviour of turbine efficiency during the year, as a function of time. Moreover the dependency on the efficiency and the turbine is presented in Figure 21. The temperatures are presented for Aswan (Egypt). Aswan desert climate is characterized by dry weather, so the difference between the dry and wet bulb temperature is relevant. Dry bulb temperature is involved in the calculation of the condenser pressure for dry cooling as the heat is mainly rejected as sensible heat [19]. Whereas the wet bulb temperature is used for wet cooling, as it is an evaporative process with the rejected latent heat depending also on relative ambient humidity [19]. For this reason the efficiency is significantly lower for dry cooling compared to a wet cooling system [19].

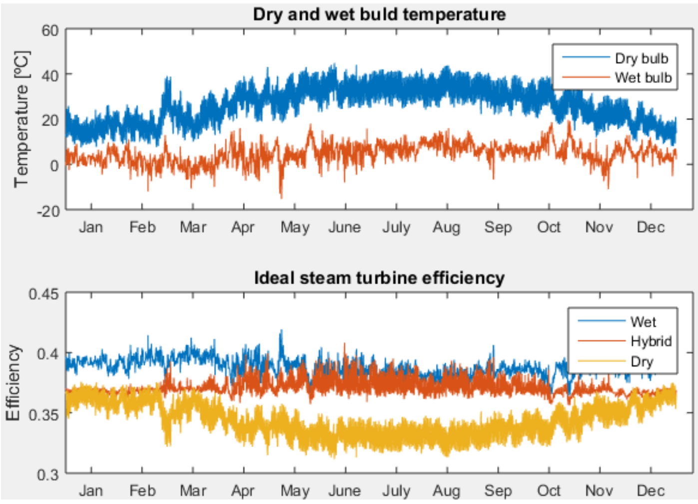



**Figure 20: Temperature and turbine efficiency as a function of time**

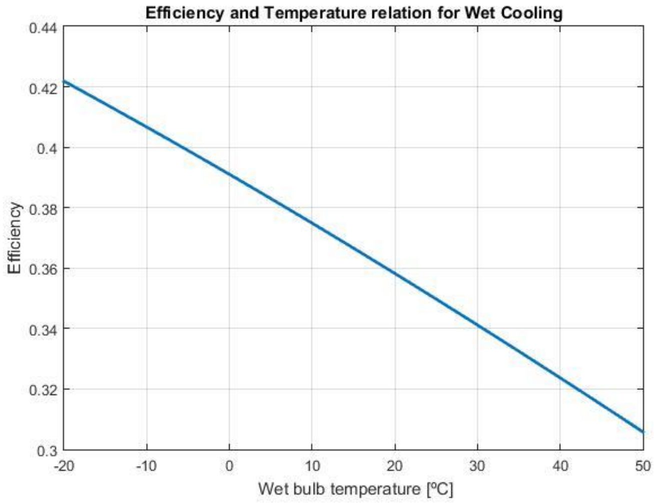



**Figure 21: Turbine efficiency with respect to wet bulb temperature for wet cooling**

Knowing the efficiency of the turbine, the gross electricity production can be estimated. The gross production does not take into account the parasitic losses. Electricity produced by the steam turbine every hour is the power input to the turbine multiplied by the actual efficiency of the turbine depending on the cooling method.

$$electricity\ produced\ [MW] = heat\ turbine\ input[MW] * \eta_{cycle}$$

The heat that must be rejected in the condenser or by the fan is calculated as:

$$q\ rejected[MW] = q\ input - electricity\ produced$$

### 5.1.4 Wet cooling fraction in hybrid cooling

In order to define the amount of heat rejected by the wet and dry cooling methods in the hybrid system, a wet cooling fraction $wcf$ is defined in a range from 0 to 1:

$$q_{rejected}wet = wcf * q\ rejected$$

$$q_{rejected}dry = (1 - wcf) * q\ rejected$$

For the hybrid cooling system, the wet cooling fraction is assumed to be constant every hour. The wet cooling fraction depends on the dry bulb temperature following the next relation which is implemented as a linear function within a range between 40ºC and 10ºC. According to this the curve trend is presented in Figure 22:

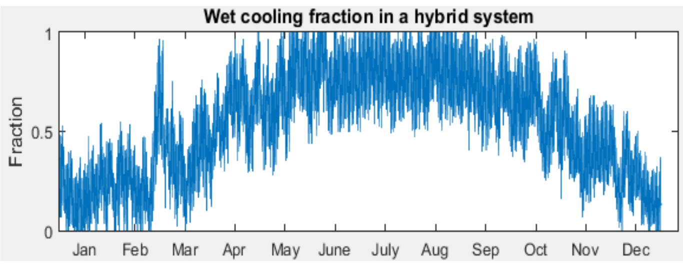



**Figure 22: Wet cooling fraction in Casablanca (MOROCCO)**

$$wcf = 1 \qquad when\, Tdry \geq 40°C$$

$$wcf = 0 \quad when\, Tdry \ \leq 10°C$$

### 5.1.5 Water Consumption

As regard the water calculation; different sources of water consumption are involved. The amount of cleaning water is calculated as:

$$m_{cleaning}\left[\frac{m^3}{year}\right] = frequency * solar\ field\ area[m^2] * f_{cleaning}\left[\frac{m^3}{m^2}\right]$$

Where frequency states for the number of cleaning per year and f_cleaning for the specific amount of water required for cleaning. The blowdown and the mass of water evaporated represent the two main contributions of water consumption. The blowdown water depends on the number of concentration cycles. We consider C as being the number of cycles.

$$m_{blowdown}\left[\frac{m^3}{s}\right] = m_{evap} * \frac{1}{(C-1)} \qquad C = concentration\ cycles$$

The mass of evaporated water is calculated from the heat rejected in the steam turbine and the enthalpy of evaporation of water, which is a function of ambient pressure and relative humidity:

$$h\ evap\left[\frac{\mathrm{J}}{\mathrm{kg}}\right] = f(p_{amb}) = +2.362 * 10^{-6} * p_{amb} + 3.085 * 10^{-10} * p_{amb}^2$$

$$m_{evap}\left[\frac{m^3}{s}\right] = \frac{heat\ rejected\ [kW]}{h\ evap\ [kJ/kg] * \rho_{water}[kg/m^3]}$$

The mass of drift water is assumed to be a small fraction of the mass-flow of water pumped into and tumbling down within the cooling tower. However, this contribution is less than 1-2% of the total water consumption. The formula used is:

$$m_{drift}\left[\frac{m^3}{s}\right] = f_{drift} * m_{cw} \qquad f_{drift} = 1\%$$

The total water consumption of the CSP plant is the sum of the four sources of water explained.

$$m_{makeup}\left[\frac{m^3}{s}\right] = m_{drift} + m_{blowdown} + m_{evap} + m_{cleaning}$$

Table 5 displays different contributions of annual water consumption for the next inputs:

- Location: Casablanca (Morocco)
- Cycles of concentration: 5
- Solar mirror area: 500000 m2
- Cleaning factor: 0.0005 m3/m2
- Cleaning frequency: 2 week-cycle
- Thermal storage: 7 hours

| | Wet Cooling | Hybrid Cooling | Dry Cooling |
|---|---|---|---|
| Cooling Water [m3/year] | 19693802 | 8116825 | 0 |
| Evaportated Water [m3/year] | 367188 | 151396 | 0 |
| Drift losses [m3/year] | 19694 | 8117 | 0 |
| Blowdown [m3/year] | 91797 | 37849 | 0 |
| Cleaning [m3/year] | 6500 | 6500 | 6500 |
| Water Consumption [m3/year] | 485179 | 203862 | 6500 |
| Water Consumption [m3/MWh] | 3.807 | 1.691 | 0.056 |

**Table 5: Model table results for water consumption**

### 5.1.6 Parasitic losses

In a power plant the turbine is asked to drive many auxiliaries. The main parasitic loss in wet cooling is the power required by the pump for circulating water through the cooling system. Whereas, as regard the dry cooling system, the main parasitic loss is due to the electricity required for the fan which drives the cooling air in the air-cooled condenser. For the hybrid cooling the fan and the pump are working in parallel and so the parasitic loads will be the sum of the two contributes [24]. In this section the equations are presented to calculate these two parasitic losses. As regard the wet cooling system, water is pumped to the top of the cooling tower. This water is then sprayed onto layers of packing within the cooling tower that breaks the water into droplets as it falls down so that the water can lose temperature through evaporation. The pump has to drive this water flow. The CSP plant contains other pumps to move the heat transfer fluid and the condensed water from the condenser to the boiler. However because of the huge mass of cooling water only the contribution of this pump becomes relevant [24]. The water inlet enthalpy is calculated as:

$$h_{water\ pump\ inlet}\left[\frac{J}{Kg}\right] = 2.296 * 10^5 + 2.785P_{amb} - 1.112 * 10^{-5}P_{amb}^2 + 2.12 * 10^{-11}p_{amb}^3$$

The outlet enthalpy is given by the increasing pressure and the density of the water. The increase in pressure is around 1 bar for 10 m height. The cooling tower is assumed 50 m high, therefore the increase in pressure is 5 bar.

$$h_{water\ pump\ outlet_s}\left[\frac{J}{Kg}\right] = h\ water\ pump\ inlet + \frac{\Delta P_{water}}{\rho_{water}}$$

$$\Delta P_{water} = 5\ bar$$

Considering an isentropic efficiency of the pump equal to 0.8 [19], the power required for driving the pump, assuming an efficiency of 75% [19] is calculated as:

$$h_{water\ pump\ outlet}\left[\frac{J}{Kg}\right] = h_{water\ pump\ inlet} + \frac{h_{water\ pump\ outlet_s} - h_{water\ pump\ inlet}}{\eta_{pump_s}}$$

$$W_{absorbed\ pump}[W] = \left[\frac{h_{water\ outlet} - h_{water\ inlet\ pump}}{\eta_{pump}}\right] * m_{water}$$

$$\eta_{pump} = 0.75$$

$$W_{parasitic\ \ losses}[W] = W_{absorbed\ pump}$$

As regard parasitic losses in the dry cooling, a pressure fan ratio has been defined. Then, air temperature is calculated (with $cp_{air}$ = 1005 $J.kg^{-1}.K^{-1}$ and $R_{air}$ = 286.7 $J.kg^{-1}.K^{-1}$):

$$pressure\ fan\ ratio = \frac{pressure\ fan\ oulet[bar]}{pressure\ fan\ inlet[bar]} = 1.005$$

$$T_{fan\_out} = fan\ outlet\ temperature[K] = T_{dry}[K] * pressure\ fan\ ratio^{\frac{R_{air}}{cp_{air}}}$$

After computing the air temperature, the enthalpy is calculated as:

$$h_{fan\ inlet}\left[\frac{J}{kg}\right] = f(T_{dry}) = 2.735 * 10^5 + 1002.9 * T_{dry} + 0.0327 * T_{dry}^2$$

$$h_{fan\ outlet\ s}\left[\frac{J}{kg}\right] = f(T_{fan\_out}) = 2.735 * 10^5 + 1002.9 * +0.0327 * T_{fan\_out}^2$$

Considering an efficiency of 0.75 and an isentropic efficiency of 0.80, the power absorbed by the fan is calculated as:

$$h_{fan\ outlet}\left[\frac{J}{kg}\right] = h_{fan\ inlet} + \frac{h_{fan\ outlet\ s} - h_{fan\ inlet}}{\eta_{pump_s}}$$

$$W_{absorbed\ fan}[W] = \left[\frac{h_{air\ outlet} - h_{air\ inlet}}{\eta_{fan}}\right] * m_{air}$$

$$W_{parasitic\ \ losses}[W] = W_{absorbed\ fan}$$

For the hybrid cooling the fan and the pump are working in parallel and so the parasitic loads will be the sum of the two contributes.

$$W_{parasitic\ \ losses}[W] = W_{absorbed\ fan} + W_{absorbed\ pump}$$

$$electricity\ delivered = electricity\ produced - parasitic\ losses$$

In the end when we have calculate the electricity delivered to the grid the total CSP plant efficiency can be defined, based on the parasitic losses and the power cycle.

## 5.2 Interface and its functions

### 5.2.1 Main structure script

The physical and the financial model are combined and programmed as a MATLAB script. In order to improve the usability of this tool, the code is supported by a user-friendly interface where the user can easily modify key parameters that affect the operation of the plant. The interface is created with the GUI (Graphical User Interface) MATLAB tool and then converted to an executable file (.exe) in order to allow the user to use the program without the need of having MATLAB installed. Figure 23 illustrates the CSP interface. In order to present the main features of the program, all elements

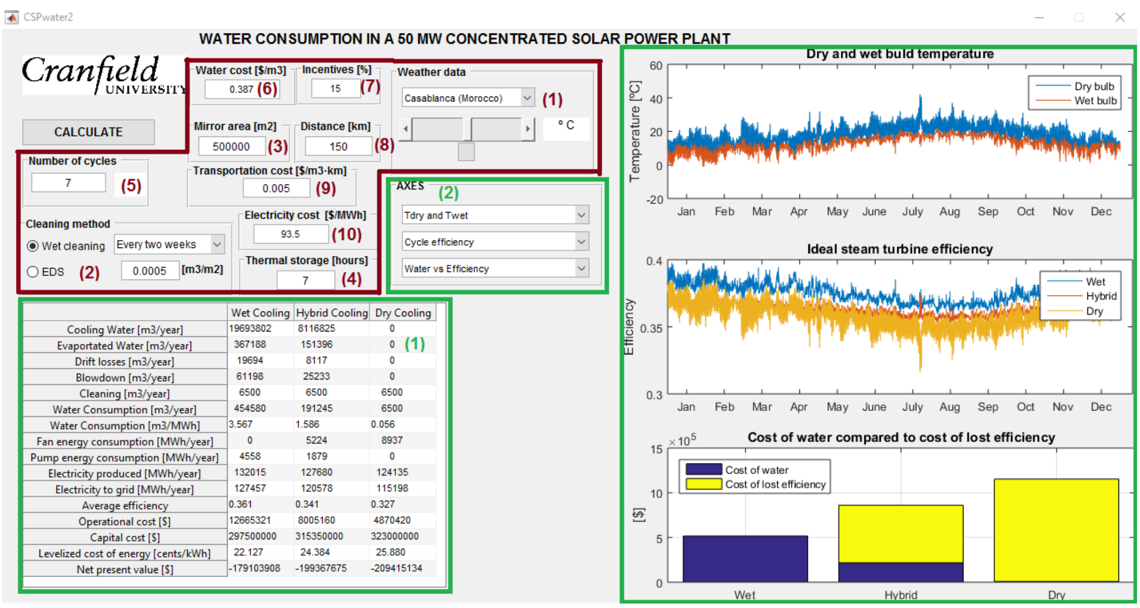



**Figure 23: MATLAB interface**

have been enumerated. The outputs are marked with green squares and the inputs are located into the red zone.

### 5.2.2 Inputs and user's choices

1) As stated previously, the input of the model are four vectors which characterize the weather conditions of the region where the plant is located:

   - Location Direct Normal Irradiation (DNI) [W/m2];
   - Ambient pressure [Pa];
   - Wet bulb temperature [°C];
   - Dry bulb temperature [°C];

   These vectors are automatically assigned to the model by selecting a location in the weather data section. The location already prefixed in the system are: Casablanca (Morocco), Aswan (Egypt), Cairo (Egypt), Key West (USA), New York (USA), Phoenix (USA), Villanueva (Spain) and Seville (Spain). In case the user wants to fix a new location, the weather vectors should be implemented in the MATLAB code. In order to appreciate the output's variation with respect to temperature changes, the user can increase or decrease dry and wet bulb temperatures by adjusting the slider located below the location menu. Maximum and minimum position of the slider corresponds to +10ºC and -10ºC addition to every component of the dry and wet bulb temperature vectors.

2) There are two main options for cleaning the reflectors, electrodynamic screen (EDS) or the ordinary wet cleaning. As stated in subsection 2.4, the EDS cleaning technology has no associated water consumption. For wet cleaning there's a default value of 0.2 $l/m^2$ [13] which can be modified by the user. The cleaning frequency can also be selected from three possible options; cleaning every two weeks, once a week or twice a week.

3) The total effective reflector's area of the CSP plant can be fixed by the user in m2.

4) The maximum thermal storage capacity, considered as the maximum amount of time that the steam turbine can be delivering nominal power using only energy from the thermal storage, is defined by the user in hours.

5) The number of concentration cycles represents the amount of dissolved minerals in the recirculating cooling water. In most cooling towers the concertation cycles ranges from 3 to 7. For those plants which use well water which has a major level of dissolved minerals, it is required a low number of cycles. Those plants which use rainwater, with a low quantity of minerals dissolved, are allowed to concentrate to 7 or more cycles of concentration [19](J.Wagner & Gilman, 2011).

6) Water cost represents market price of the clean “tap” water in the location closest to the proposed CSP plant. The value is taken from national water supplier and varies in a typical range 0.4 - 1.9 $\$/m^3$. [26]

7) Incentives are defined as percentage reduction in capital cost and are a common way of promoting CSP plant depending on local regulations.

8) Distance between the water source and the CSP plant in km.

9) Transportation cost express the price of transportation of the water from the source to the CSP plant in $\$/m^3$*km.

10) The electricity cost corresponds to the local electricity price which is delivered to the grid including VAT in $/MWh. Its typical range is 75-340 $/MWh [27]**.**

### 5.2.3 Outputs

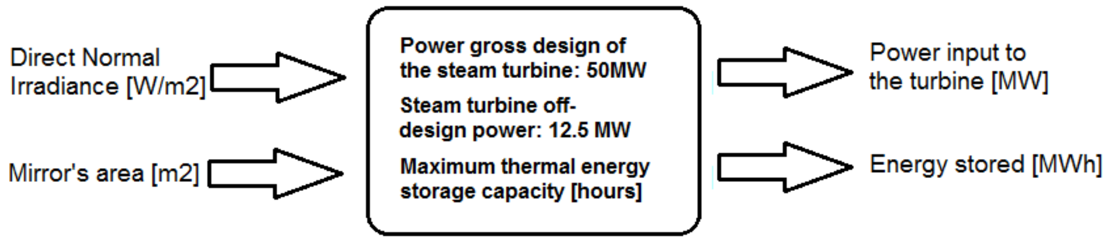
Once all parameters are defined, the algorithm will run by pressing the CALCULATE push button. When the calculation is done, the following results are displayed in the main output table.

- Cooling Water [$m^3$/year]: Total amount of cooling water circulating through the condenser in order to absorb the steam turbine rejected heat.
- Evaporated Water [$m^3$/year]: Total amount of evaporated water in the cooling tower.

- Drift losses [$m^3$/year]: Total amount of cooling tower drift.
- Blowdown [$m^3$/year]: Total water drained from the cooling system in order to remove mineral build-up.
- Cleaning [$m^3$/year]: Annual water consumed for cleaning the reflectors.
- Water Consumption [$m^3$/year]: Total annual water consumed by the CSP plant.
- Water Consumption [$m^3$/MWh]: Water consumption per MWh produced.
- Fan energy consumption [MWh/year]: Annual energy consumption of the parasitic losses associated to the dry cooling.
- Pump energy consumption [MWh/year]: Annual energy consumption of the parasitic losses associated to the wet cooling.
- Electricity produced [MWh/year]: Total annual gross energy output of the CSP plant.
- Electricity to grid [MWh/year]: Total annual electricity delivered to the grid.
- Average efficiency: Annual average efficiency of the steam turbine.
- Operational cost [$]: Total operational cost of the CSP plant during the lifetime.
- Capital cost [$]: Total initial investment reduced by the value of incentives.
- Levelized cost of energy [c$/kWh]: Average cost of the production of the electricity during the lifetime.
- Net present value [$]: Difference between total profit generated through the lifetime of the CSP reduced by total operational cost.

Additionally, 37 different graphs (Appendix B.1) can be displayed in any of the three available axes. This facilitates the process of evaluating the results and determining relationships between different parameters.

Every time any input is modified it is necessary to undertake a recalculation by pressing the "calculate" button. The script that represents the physical model of the CSP plant is divided into three parts, one for each cooling method. Every time the user presses the CALCULATE button, all parts are executed in series one after the other, as the program provides the results for each cooling method. Despite the fact that the model is separated in three differentiate parts, corresponding to different cooling methods, there are two main scripts which appear in all parts. The CSP script (see Appendix) emulates the normal operation of a CSP plant with a thermal energy storage. The code's input is the DNI vector and the total mirror area. The CSP script considers as a default a nominal power of the steam turbine 50MW and an off-design power of 25% the nominal power [19]. The main inputs are the power delivered to the turbine and the energy stored in the tank every hour. In the flow chart below the logical process that has driven the MatLab calculation is presented.




# 6 Results and Findings

## 6.1 Parametric results

The CSP program is a useful tool to illustrate important relations between different variables in a process. In the following section, a parametric analysis is developed in order to show how different parameters affect the water consumption and the electricity produced in a 50MW wet cooling CSP plant. The study has been done modifying one of the inputs while leaving the rest at a fixed value. The default values used in the analysis are:

Location: Casablanca (Morocco)

- Cycles of concentration: 5
- Solar mirror area: 500000 $m^2$
- Cleaning frequency: Once a week (52 times per year)
- Cleaning factor: 0.0005 $m^3/m^2$
- Thermal storage: 7 hours

## 6.2 Water Consumption

As shown in Table 6, the chosen location really influences the water consumption of the plant. There are two main factors which affect the water consumption in a wet cooling system, the DNI and the dry and wet bulb temperatures of the selected region. The DNI of the selected location determines the amount of electricity produced, which is directly related with the amount of circulating water needed for cooling the steam turbine. As the average DNI of the location increases, total annual electricity produces increases as does the total annual water consumption.

The other parameter which indirectly affect the water consumption are the wet and dry bulb temperatures of the selected location. Considering two desert regions with similar DNI during the year as Aswan in Egypt and Phoenix in USA, it can be inferred that the annual electricity produced in Aswan is higher than in Phoenix, but as the relative humidity in Aswan is considerably lower (important difference between dry and wet bulb temperatures), the efficiency of the Rankine cycle is higher and this leads to a lower water consumption compared to a similar plant in Phoenix (cf. Appendix B). The final result with respect to electricity produced and water consumption for different locations are presented in Table 6.

**Table 6: Water consumption and electricity produced for different locations**

| **Location** | **Casablanca (Morocco)** | **Aswan (Egypt)** | **Cairo (Egypt)** | **Villanueva (Spain)** | **Key-West (USA)** | **Phoenix (USA)** |
|---|---|---|---|---|---|---|
| **Cooling Water [$m^3$/year]** | 19,693,802 | 30,823,697 | 21830,798 | 29,537,857 | 23,279,352 | 31,593,903 |
| **Evaporated Water [$m^3$/year]** | 367,188 | 575,449 | 407844 | 552,116 | 435,146 | 589,480 |
| **Water consumption [$m^3$/year]** | 491,679 | 763,135 | 544636 | 732683 | 580212 | 781,443 |
| **Water consumption [$m^3$/MWh]** | 3.858 | 3.604 | 3.823 | 3.861 | 4.106 | 3.856 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Electricity to grid [MWh/year]** | 127,457 | 211,719 | 142,455 | 189,778 | 141,303 | 202,632 |
| **Average efficiency** | 0.361 | 0.375 | 0.363 | 0.360 | 0.346 | 0.359 |

**Error! Reference source not found.** shows the total water consumption with respect to the solar mirror area. The trend is having this because there is an almost linear relation between the annual electricity delivered to the grid and the total mirror's area of the CSP plant. This also leads to an increase of the water consumed by the plant in order to cool the steam turbine. On the other hand, there is a minimum in the specific water consumption per MWh (Figure 25) when considering the cleaning water, as it shows the effect of cleaning a large area that does not produce proportionally more power that creates the up-turn at the end. The maximum capacity of the thermal storage is also related with the annual water consumption (Figure 26). As the thermal storage capacity increases, the annual electricity produced rises as the CSP plant is capable of storing more energy. This leads to an increase in the time that the steam turbine is delivering power. However, there is a maximum energy storage capacity which contributes to the increase in electricity produced, as the real limitation in electricity produced is fixed by the DNI of the selected region and the total mirror's area available for the CSP plant.

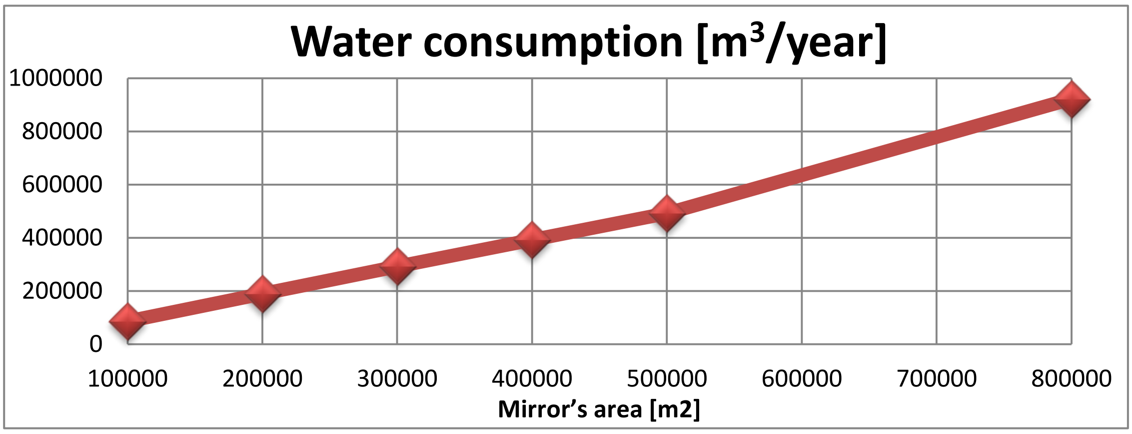



**Figure 24: Water consumption [$m^3$/year] function of mirror area**

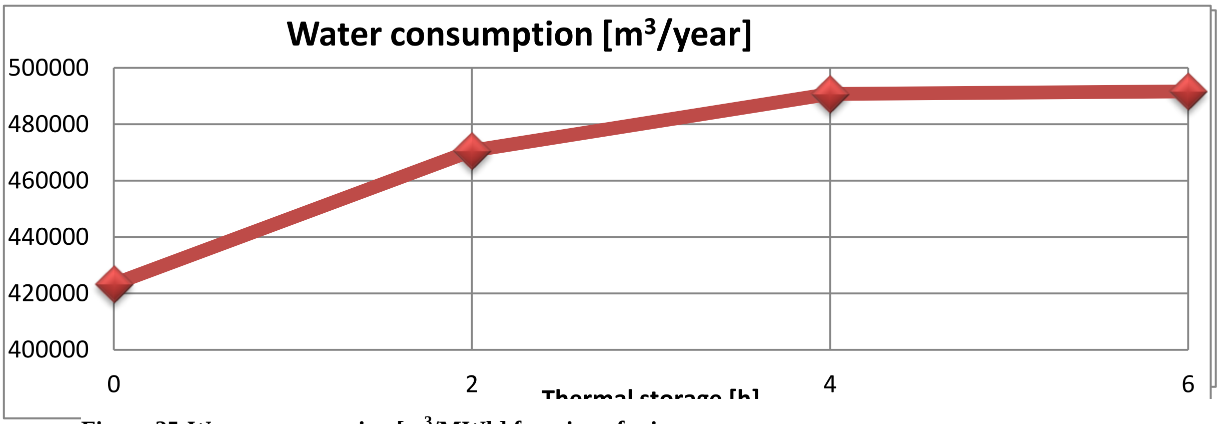


**Figure 25:Water consumption [m$^3$/MWh] function of mirror area**

Then, Table 7 illustrates how the total annual water consumption varies with the number of cycles of concentration. By increasing the cycles of concentration from 3 to 7, the total annual water consumption is reduced by 122,395 m$^3$. This proves the importance of selecting a proper source of water with low concentration of dissolved minerals in order to reduce the water consumption. Another option is to carry out a demineralisation water treatment to the cooling water, which may be economically non-viable.

**Table 7: Water consumption for different cycles of concentration**

| **Number of cycles** | **3** | **4** | **5** | **6** | **7** | **8** |
|---|---|---|---|---|---|---|
| **Water consumption [m$^3$/year]** | 583,475 | 522,278 | 491,679 | 473,319 | 461,080 | 452,337 |
| **Water consumption [m$^3$/MWh]** | 4.579 | 4.098 | 3.858 | 3.714 | 3.618 | 3.550 |

As stated previously, ambient temperature and relative humidity are an important factor which determines the water consumption and electricity production in the selected region. As temperature increases, the efficiency of the Rankine cycle decreases, which means a growth in rejected heat in the steam turbine when delivering nominal power. This translates into a rise in the cooling water usage and a reduction in electricity produced (cf. Appendixes). The interaction between the financial model and the physical model of the CSP plant allows us to obtain useful results in order to evaluate the economic viability of the project.

## 6.3 Financial Results

Economic evaluation of the CSP plant shows that the capital cost (CAPEX) is a critical factor, which makes the cost of electricity significantly higher compared to conventional power plants. Moreover any improvement in this area can firmly influence general affordability of the system, as about 90% of the LCOE depends on the CAPEX. For instance, an economic comparison of similar CSP plants built in Casablanca (Morocco) and Phoenix (California, USA) shows how the location affects CSP cost (Table 8).

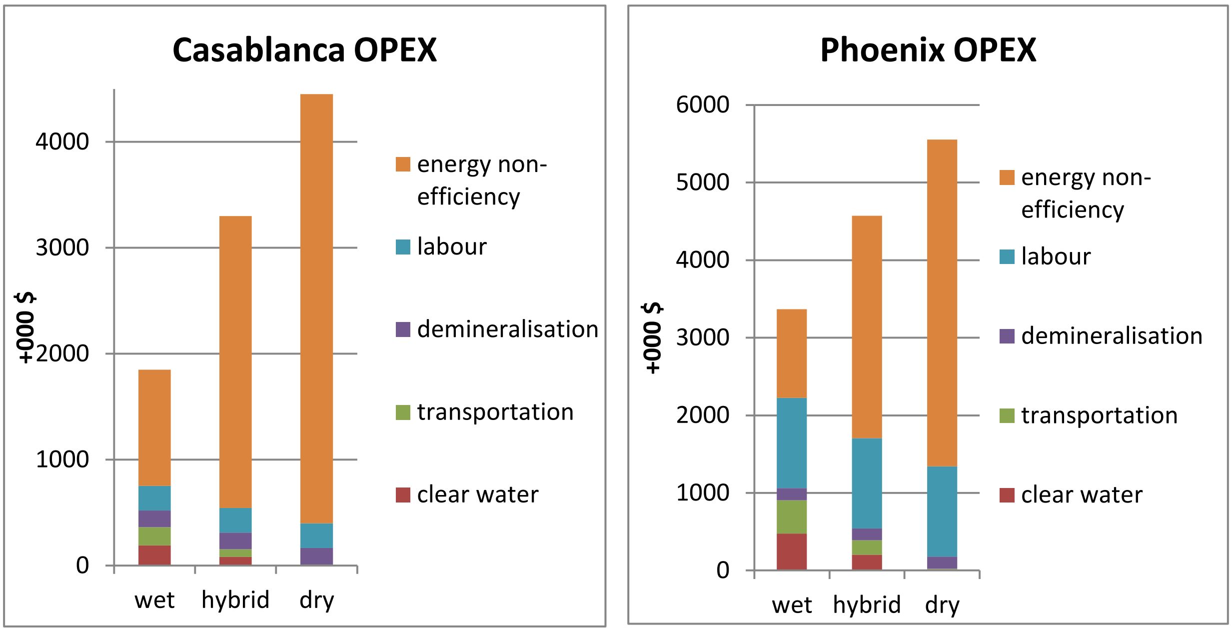



**Figure 27: Operational cost distribution**

**Table 8: Total CAPEX and OPEX comparison**

| Place | Casablanca, Morocco | Phoenix, US | Difference between MR and US |
|---|---|---|---|
| CAPEX without labour cost | 290.2 | 290.2 | - |
| CAPEX labour cost | 60.2 | 120.4 | 100% |
| CAPEX total | 350.2 | 410.4 | 17% |
| OPEX without labour cost | 1.61 | 2.21 | 37% |
| OPEX labour cost | 0.23 | 1.16 | 500% |
| **Total lifetime spending (levelled cost)** | **376.6** | **457.3** | **21%** |

Table 8 Presents results for two extreme OPEX situations (low and high cost country).

Table 9 highlights difference between minimum and maximum factors. For both system, the on-site electricity consumed which is not sold represents the main profit loss. In comparison, the water cost does have a wide impact on the OPEX. In addition, the cost of transportation of water is defined in $/(m$^3$.km).

**Table 9: Maximum and minimum inputs comparison**

| Location | Casablanca, Morocco | Phoenix, US | Difference |
|---|---|---|---|
| Distance from CSP to water source [km] | 65 | 150 | 130% |
| Cost of construction of pipeline [$/km] | 79 200 | 132 000 | 66% |
| Average gross salary ($/month) | 691 | 3456 | 500% |

| | | | |
|---|---|---|---|
| Water cost [$/m$^3$] | 0.387 | 1.000 | 158% |

Shortening the distance between the water source and the power plant from 65km to 1km would reduce the LCOE by 1%. Economically speaking, the feasibility of a new power plant mainly results in the LCOE value comparing to the usual cost of electricity where the plant is built.

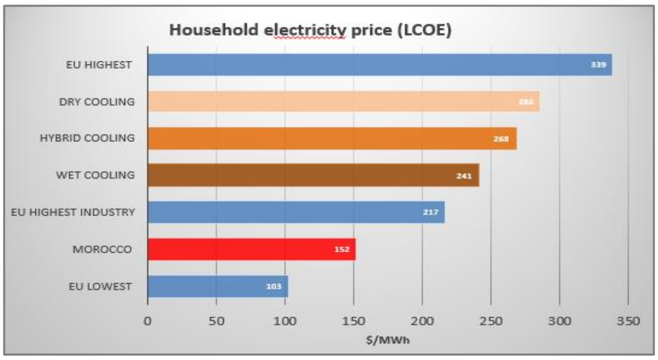



**Figure 28: Electricity price comparison**

As further research are still going on, both for the cooling systems or the cleaning methods, the economic feasibility of some systems, such as the EDS coating, is not achieved yet. Boston University and NASA researchers aim to work on this, to be able to confirm that such coatings might be the future of CSP plants.

# 7 Conclusions and Recommendations

The aim of the Project was to develop a performance and financial model of a 50 MWe CSP plant. MATLAB has been the chosen to implement the model, as it is a globally well-known programming language and software used by scientists and engineers. This leads to a greater amount of users who can modify and improve the code. The final consulting device is a MATLAB script supported by a user friendly interface which improves the usability of the program. Finally the program is compiled and delivered also as an executable file to allow a user the ability to use the software without the need of having MATLAB installed.

The development of that tool has allowed the authors to get a proper understanding on the parameters affecting the performance of a CSP plant. On the one hand, because of the nature of the power technology, a high DNI is needed in order to maximize the electricity produced by the plant. On the other hand, temperature and relative humidity determine the efficiency of the steam turbine. To sum up, as CSP plants are usually in desert regions characterized by a dry climate and high solar irradiation, an appropriate analysis of weather conditions is essential to forecast the viability of locating a CSP plant in the selected region.

The selection of a suitable cooling system will depend on economic factors associated to the chosen region. If there is a source of water nearby and the cost of transportation is affordable, the wet cooling system will be prioritized as it provides a higher efficiency of the thermal cycle compared to the other cooling methods. However, if the cost of water is comparatively high, hybrid or dry cooling may be a suitable option. Thus, the user should evaluate the difference between the cost of losing efficiency compared to a wet cooling system, and the cost of water.

Besides, there might be social or political factors affecting the selection of a suitable cooling system. The existence of a strongly water dependent industry, such as agriculture, or the presence of a local community can cause third parties to be affected by the CSP plant water consumption and make them reluctant to the idea of implementing such a plant nearby.

The reduced number of inputs as well as the fact that all the information are displayed in the same interface, simplifies the process of calculation and decision-making. Moreover, the code is commented and programmed in an understandable way to help the user implement new features or modify the script. Additionally, the program uses as inputs the same vector's size as SAM, which allows the addition of new locations directly from SAM.

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# APPENDICES

## Appendix A

### A.1 Wet cleaning

**Figure 29: Cleaning truck [32]**

### A.2 EDS diagram

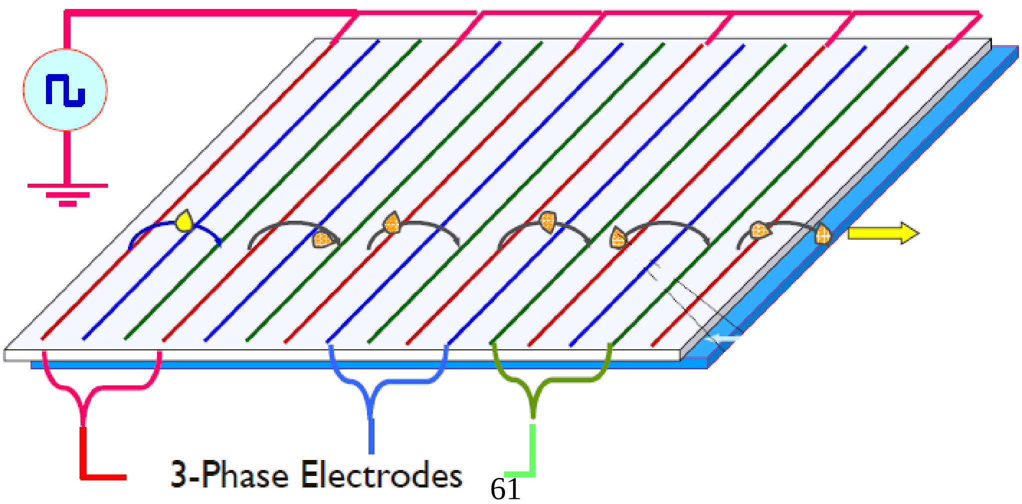




**Figure 30: EDS coating diagram**

## A.3 SuperHydrophobic coating

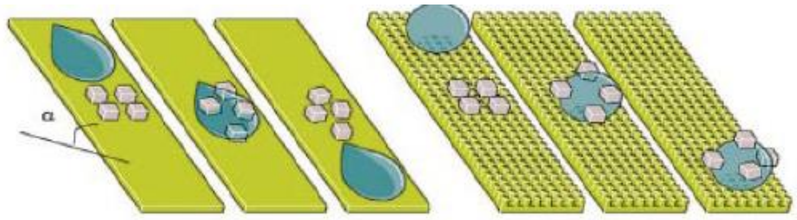


**Figure 31: Water drop rolling on mirrors [33]**

(Left: usual mirror – Right: SH coating)

# Appendix B

## B.1 Output's list (Graphs)

• Water consumption: Displays the vector corresponding to the total water consumption (cleaning and cooling water) every hour [m3/h].

• Tdry and Twet: Displays the two vectors of wet and dry bulb temperatures corresponding to the selected location for the analysis [ºC].

• DNI·Area: Vector corresponding to the direct normal irradiation of the selected location multiplied by the total mirror's area [MW].

• Total water consumption: Stacked bar chart which illustrates the quantity of water consumed for every cooling method as evaporated, drift and blowdown water. Cleaning water is also displayed in order to visualize the fraction of the total consumption which is spent in cleaning the reflectors [m3/year].

• Cycle efficiency: Displays the vectors corresponding to the steam turbine ideal efficiency for every cooling method. As explained in (=), the steam turbine efficiency varies for every hour as it depends on dry and wet bulb temperatures.

• Condenser pressure wet: The condensation pressure in the condenser for wet cooling system [Pa].

• Condenser pressure dry: The condensation pressure in the condenser for dry cooling system [Pa].

• Power input wet: Displays the vector corresponding to the power input to the steam turbine. The power input is calculated assuming as a power input design value the nominal power of the turbine (50MW) divided by the calculated efficiency for that hour [MW].

• Power input hybrid: Power input to the steam turbine considering the efficiency calculated for hybrid cooling [MW].

• Power input dry: Power input to the steam turbine for dry cooling [MW].

• Energy storage wet: Thermal energy stored considering that steam turbine's efficiency is calculated for wet cooling [MWh].

• Energy storage hybrid: Thermal energy stored considering a hybrid cooling system [MWh].

• Energy storage dry: Thermal energy stored assuming a dry cooling system [MWh].

• Electricity produced wet: Displays the vector corresponding to gross electrical output for wet cooling every hour [MW].

• Electricity produced hybrid: Gross electrical output for hybrid cooling [MW].

• Electricity produced dry: Gross electrical output for dry cooling [MW].

• Electricity to grid wet: Total electricity delivered to the grid every hour. Calculated as the gross electrical output minus the parasitic loads for wet cooling [MW].

• Electricity to grid hybrid: Total electricity delivered to the grid for hybrid cooling [MW].

• Electricity to grid dry: Total electricity delivered to the grid for dry cooling [MW].

• Parasitic losses wet (pump): Parasitic losses associated with the power delivered to the pump which pumps water to the cooling tower [MW].

• Parasitic losses hybrid (pump & fan): Parasitic losses associated to the power delivered to the pump which pumps water to the cooling tower and the fan which drives the air in the dry condenser [MW].

• Parasitic losses dry (fan): Parasitic losses associated to the power delivered to the fan which drives the air in the dry condenser [MW].

• Cooling water wet: Circulating cooling water in the condenser for wet cooling [m3/h].

• Cooling water hybrid: Circulating cooling water in the condenser for hybrid cooling [m3/h].

• Evaporated water wet: Evaporated water per hour in the cooling tower considering wet cooling [m3/h].

• Evaporated water hybrid: Evaporated water per hour in the cooling tower considering hybrid cooling [m3/h].

• Drift losses wet: amount of water directly dropped outside of the cooling tower, for wet cooling [m3/year]

• Drift losses hybrid: amount of water directly dropped outside of the cooling tower, for hybrid cooling [m3/year]

• Blowdown wet: amount of water removed in order to decrease the concentration of minerals for wet cooling [m3/year]

• Blowdown hybrid: amount of water removed in order to decrease the concentration of minerals for hybrid cooling [m3/year]

• Fraction (hybrid): wet cooling fraction in the hybrid cooling system [0,1]

• Electricity sold: electricity delivered to the grid [MWh/year]

• Final profit after tax: total discounted annual profit [$/year]

• Annual cost water (wet): annual water charge through the power plant lifetime considering transportation, water treatment and water cost for wet cooling [$].

• Annual cost water (hybrid): annual water charge through the power plant lifetime considering transportation, water treatment and water cost for hybrid cooling [$].

• Annual cost water (dry): annual water charge through the power plant lifetime considering transportation, water treatment and water cost for dry cooling [$].

• Water vs Efficiency: The water cost vs efficiency chart is a useful diagram where the user can compare the economic viability of a plant using different cooling methods and see how this dependence varies when modifying any of the inputs.

## B.2 Water consumption depending on Thermal storage

| **Thermal storage [h]** | **0** | **2** | **4** | **6** |
|---|---|---|---|---|
| **Cooling Water [m$^3$/year]** | 16,887,839 | 18,832,123 | 19,654,865 | 19,693,802 |
| **Evaporated Water [m$^3$/year]** | 314,791 | 351,097 | 366,461 | 367,188 |
| **Water consumption [m$^3$/year]** | 423,377 | 470,703 | 490,731 | 491,679 |
| **Water consumption [m$^3$/MWh]** | 3.867 | 3.861 | 3.859 | 3.858 |
| **Electricity to grid [MWh/year]** | 109,503 | 121,939 | 127,202 | 127,457 |
| **Average** | 0.362 | 0.362 | 0.361 | 0.361 |

| efficiency | | | | |
|---|---|---|---|---|

## B.3 Water consumption depending on Temperature variation

| Temperature variation [ºC] | -10 | -4 | 0 | +4 | +10 |
|---|---|---|---|---|---|
| Cooling Water [$m^3$/year] | 19,170,995 | 19,489,383 | 19,693,802 | 19,912,568 | 20,240,374 |
| Evaporated Water [$m^3$/year] | 357,440 | 363,377 | 367,188 | 371,267 | 377,379 |
| Water consumption [$m^3$/year] | 478,971 | 486,710 | 491679 | 496,996 | 504,964 |
| Water consumption [$m^3$/MWh] | 3.597 | 3.750 | 3.858 | 3.972 | 4.154 |
| Electricity to grid [MWh/year] | 133,184 | 129,816 | 127,457 | 125,144 | 1215,92 |
| Average efficiency | 0.378 | 0.368 | 0.361 | 0.355 | 0.344 |

## B.4 Water consumption depending on mirrors area

| Mirror's area [$m^2$] | 100,000 | 200,000 | 300,000 | 400,000 | 500,000 | 800,000 |
|---|---|---|---|---|---|---|
| **Cooling Water [$m^3$/year]** | 3,453,451 | 7,601,549 | 11,714,154 | 15,695,968 | 19,693,802 | 36,980,366 |
| **Evaporated Water [$m^3$/year]** | 64,392 | 141,714 | 218,420 | 292,646 | 367,188 | 691,230 |
| **Water consumption [$m^3$/year]** | 86,543 | 189,944 | 292,539 | 391,904 | 491,679 | 921,817 |
| **Water consumption [$m^3$/MWh]** | 3.879 | 3.862 | 3.859 | 3.858 | 3.858 | 3.867 |
| **Electricity to grid [MWh/year]** | 22,317 | 49,195 | 75,825 | 101,610 | 127,457 | 238,390 |
| **Average efficiency** | 0.360 | 0.361 | 0.362 | 0.362 | 0.361 | 0.360 |

# Appendix C

## C.1 Economic inputs

| Symbol | unit | Additional information |
|---|---|---|
| Lifetime | 30 years | Typical expected CSP plant lifetime [20]. |
| Water treatment | 12.0 $/m$^3$ | Cost of chemical demineralization of the water used for the cleaning of the mirrors, estimated on [26]. |
| Degradation factor | 0.2 %/annual | Annual degradation rate of the power plant expressed as a degradation in electricity generation due to drop of the efficiency caused by ageing of the system [20]. In SAM degradation factor is 0.5%. [24] |
| Average salary | 512 $/month | Arithmetical average salary in the particular region (southern Morocco) derived from four the closest location surrounding the place of the CSP plant (derived from www.numbeo.com) |
| Labor multiplication factor | 1.35 | Expected ratio between average salary in CSP power plant and average salary in the region. |
| Staff number | 28 persons | Number of employees in 50 MW power plant. (from comparison to Nevada CSP plant of 64MW, 28 full-employed staff) to 30-40 |
| Inflation | 2 % | 20-years average annual inflation in the country |
| Salary increase | 2.5 % | Annual increase in salary (assumed as 125% of inflation rate) |
| Tax | 14 % | Corporate profit tax in Morocco (varies between 10 to 30% depending on the branch) |
| Discounted rate | 10 % | Discount rate depends on the certainty of the investment in particular economic activity. The value refers to decrease of the money value within a year for CSP power plant. In general, low values are seen in very safe investments (property, art masterpieces), high values of discounted rate are common in new technologies (hi-tech equipment) which reduce in value rapidly |
| Cc cooling wet | $20 mln | Capital cost of wet cooling system in 50 MW power plant for given technical requirements |
| Cc cooling h | $41 mln | Capital cost of hybrid cooling system in 50 MW power plant for given technical requirements. Assumed as 70% of the cost difference between dry and wet cooling system |
| Cc cooling dry | $50 mln | Capital cost of dry cooling system in 50 MW power plant for given technical requirements |

## C.2 Capital cost comparison of existing CSP plant

| | AndaSol 50MW | | | | | US 100 MW | | US 100MW | | SAM 103MW | | Model | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2010 | | *2017 | | | 2004 | | 2005 | | 2009 | | 2017 | |
| | mln $ | % | ost reductior | mln $ | % | mln $ | % | mln $ | % | mln $ | % | mln $ | % |
| **Labour cost: site and solar field** | **62.4** | **17%** | | **59.0** | *18%* | **31.1** | *11%* | **41.6** | *15%* | **108.3** | *22%* | **60.3** | *17%* |
| site preparation and infrastructure | 21.2 | *6%* | no reduction | 21.2 | *6%* | 5.6 | *2%* | | | | | | |
| electric installations and others | 14.4 | *4%* | big | 12.5 | *4%* | 5.6 | *2%* | | | | | | |
| solar field | 11.3 | *3%* | small | 10.5 | *3%* | 7.0 | *3%* | | | | | | |
| steel construction | 9.1 | *3%* | small | 8.4 | *3%* | 8.6 | *4%* | | | | | | |
| piping | 6.4 | *2%* | no reduction | 6.4 | *2%* | 4.2 | *2%* | | | | | | |
| **Equipment: solar field and HTF system** | **140.3** | *39%* | | **126.8** | *38%* | **121.9** | *42%* | **103.2** | *36%* | **148.5** | *31%* | **128.1** | *37%* |
| steel construction | 39.0 | *11%* | small | 36.2 | *11%* | 32.3 | *13%* | | | | | | |
| receivers | 25.9 | *7%* | big | 22.5 | *7%* | 28.2 | *12%* | | | | | | |
| mirrors | 23.1 | *6%* | big | 20.1 | *6%* | 26.8 | *11%* | | | | | | |
| HTF system (piping, insulaton, Heat-Exs, pump | 19.5 | *5%* | small | 18.1 | *5%* | 15.7 | *5%* | 6.0 | *2%* | 30.2 | *6%* | | |
| electronics, controls & solar equipment | 9.1 | *3%* | small | 8.4 | *3%* | 4.2 | *2%* | | | | | | |
| pylons, swivel joints, trackers | 8.1 | *2%* | small | 7.5 | *2%* | 5.6 | *2%* | | | | | | |
| heat transfer fluid | 7.8 | *2%* | big | 6.8 | *2%* | 4.2 | *2%* | | | | | | |
| foundations | 7.8 | *2%* | small | 7.2 | *2%* | 4.9 | *2%* | | | | | | |
| **Thermal storage system** | **38.4** | **11%** | | **34.3** | *10%* | **55.8** | *19%* | **34.8** | *12%* | **115.1** | *24%* | **55.7** | *16%* |
| salt | 18.6 | *5%* | big | 16.1 | *5%* | | | | | | | | |
| storage tanks and fundations | 8.9 | *2%* | small | 8.3 | *3%* | | | | | | | | |
| heat exchangers, pumps, insulation | 7.4 | *2%* | small | 6.9 | *2%* | | | | | | | | |
| balance of system | 3.5 | *1%* | big | 3.0 | *1%* | | | | | | | | |
| **Conventional plant components and plant system** | **52.0** | **14%** | | **47.0** | *14%* | **34.0** | *12%* | **36.8** | *13%* | **47.7** | *10%* | **43.5** | *12%* |
| power block | 20.8 | *6%* | small | 19.3 | *6%* | | | 23.3 | *8%* | | | | |
| balance of plant | 20.7 | *6%* | big | 18.0 | *5%* | | | 13.5 | *5%* | | | | |
| grid connection | 10.5 | *3%* | small | 9.7 | *3%* | | | | | | | | |
| **Others** | **70.9** | **19%** | | **62.8** | *19%* | **48.3** | *17%* | **68.9** | *24%* | **62.2** | *13%* | **62.6** | *18%* |
| project management (EPC) | 28.1 | *8%* | big | 24.4 | *7%* | | | | | 17.4 | *4%* | | |
| financing | 21.8 | *6%* | small | 20.2 | *6%* | | | | | | | | |
| project development and allowances | 21.0 | *6%* | big | 18.2 | *6%* | | | 18.4 | *6%* | 44.8 | *9%* | | |
| Total cost | **364.0** | *100%* | 9% | **330.0** | *100%* | **291.1** | *100%* | **285.3** | *100%* | **481.7** | *100%* | **350.4** | *100%* |
| $ cost per kW installed | **7.3** | | | **6.6** | | **5.8** | | **5.7** | | **9.6** | | **7.0** | |