SCHOOL OF SCIENCE AND ENGINEERING

Capstone Final Report

OPTIMIZATION OF CLEANING STRATEGY PROJECT NOORI

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Contents

Acknowledgment ......................................................................................................................... 6

I. Introduction ................................................................................................................................. 2
   1.1 Context .................................................................................................................................. 3
      i. Solar Energy context .............................................................................................................. 3
      ii. Solar Energy in the MENA region (and focus on Moroccan’s energy situation) .......... 3
   1.2 Aims and Objectives .............................................................................................................. 6
   1.3 STEEPLE Analysis {A STEEPLE analysis follows to describe the influence of this project
       on many levels such as Ecological, Economical....} ............................................................... 6

II. Theoretical Background ............................................................................................................. 8
   1.1 Surface Energy ....................................................................................................................... 8
      1.1.1 DELVO Theory ............................................................................................................... 9
      1.1.2 Van Oss and Polar (The Lifshitz-van der Waals (LW) and Apolar (Acid-Base)
           interactions approaches for determination of Surface Free Energy).............................. 10
      1.1.3 Work of Adhesion .......................................................................................................... 12
   1.2 CSP Plants ............................................................................................................................ 13
      1.2.1 Types of CSP reflectors ................................................................................................. 15
      1.2.2 CSP Mirrors under desert conditions ........................................................................... 17
   1.3 Cleaning Methods of CSP Reflectors .................................................................................... 18
      1.3.1 Current cleaning situation ............................................................................................... 18
      1.3.2 Dust mitigation (Prevention and Restoration) ................................................................. 21
      1.3.3 Wet Cleaning .................................................................................................................. 23
      1.3.4 Electrodynamical Screen (EDS) ..................................................................................... 23
      1.3.5 Coating for CSP Mirrors (Super hydrophobic and hydrophilic coating) ...................... 25

III. Methodology ............................................................................................................................. 26
   3.1 Surface tension of: ................................................................................................................ 26
      i. Distilled water ....................................................................................................................... 26
      ii. Additives .............................................................................................................................. 28
      iii. Sample of CSP Mirrors .................................................................................................... 29
   3.2 Work Adhesion of the Sample Mirrors with water ............................................................. 30
   3.3 Adhesion work of the Sample Mirrors with mixture of water additive ......................... 31
      i. Hydrophilic repulsion .......................................................................................................... 33
      ii. Hydrophobic attraction ...................................................................................................... 34

IV. Discussion ................................................................................................................................. 34

V. Cost analysis ............................................................................................................................... 35
VI. Conclusion ........................................................................................................................................... 36
VII. References .......................................................................................................................................... 37

List of figures:

Figure 1: the significant potential of renewable energy in Morocco .................................................. 3
Figure 2: Overall Renewable Energy share Targets in the MENA region........................................... 4
Figure 3: NOOR I Concentrated Solar Power Plant (160 MW) .............................................................. 6
Figure 4: schematic demonstrating the DELVO theory ........................................................................ 9
Figure 5: table of the values of surface tension components ............................................................... 11
Figure 6: picture of dew drops adhering to a spider web ................................................................. 12
Figure 7: illustration of a number of cases of cleavage, with each sort labeled ......................... 13
Figure 8: schematic of the CSP Plant process .................................................................................. 14
Figure 9: A characteristic of hourly load demand ............................................................................. 14
Figure 10: Parabolic Trough CSP technology (schematic and in real operation) ......................... 16
Figure 11: Linear Fresnel CSP Technology (schematic and in real operation) ............................... 16
Figure 12: Central Receiver CSP technology (schematic and in real operation) ....................... 17
Figure 13: Parabolic Dish CSP Technology (schematic and in real operation) ............................... 17
Figure 14: Daily area cleanliness factor calculation in NOORI ..................................................... 20
Figure 15: graph shows the better behavior of anti-soiling coating (Flabeg mirrors) .................... 22
Figure 16: schematic diagram of the travelling wave transporting a dust particle ...................... 24
Figure 17: water droplet on superhydrophobic coating ............................................................... 25
Figure 18: Subsequent steps of the detaching drop .......................................................................... 28
Figure 19: Stalagmometer and the stalagmometer tip ................................................................. 28
Figure 20: table of Components of Surface free energy of distilled water ................................. 28
Figure 21: Components of Surface free energy of the additives tested in the project ............ 29
Figure 22: Contact angle value of water, Formamide and Diiodomethane ................................ 29
Figure 23: The values of the components of the surface free energy of mirror sample ........... 30
Figure 24: table: Components of Surface free energy of water and surface (Mj/m²) .............. 31
Figure 25: table Components of Surface free energy water, surface and additives (Mj/m²) ... 32
Figure 26: work of adhesion of all the polymers when in contact with the surface .................. 33
Figure 27: table, sorted negative work of adhesion ...................................................................... 33
Figure 28: table, sorted positive work of adhesion ...................................................................... 34
Acronyms

MASEN: Moroccan Agency of Solar Energy
CSP: Concentrating Solar Power
SF: Solar Field
HTP: Heat Transfer Fluid
SGS: Steam Generation System
TES: Thermal Energy Storage
PB: Power Block
PTR: Parabolic Trough Reflector
HCE: Heat Collector Elements
NOMAC: The First National Operation and Maintenance Company
CSPP: Concentrated solar power plants
PEO: Polyethylene oxide
PVOH: Polyvinyl alcohol
CA: Cellulose acetate
MENA: Middle East and North Africa Region
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Abstract:

Solar energy is one of the most abundant and cleanest energy source known to mankind. It provides a high potential and energy source. Therefore, developed countries have made it possible to cover their energetic needs in terms of electricity through developing different energy stations that convert solar energy onto thermal or electrical energy. Concentrated solar power plants (CSPP) are one of the developed technologies used all over the world for that purpose. However, since CSP systems require an important use of water and generally located in regions that lack water resources, their functioning may be problematic. Since the amount of the water used in this technology is highly noticeable and prevent it from being fully green energy system. Hence, the aim of this research is to reduce water consumption used in the cleaning process of CSP mirrors in Moroccan project NOOR1 at Ouarzazate. Our main approach to solve this problem is the use of additives in the cleaning process. Several additives can be added to modify the surface tension characteristics of water for better water distribution when in contact with CSP mirrors. Our approach was proved and analyzed in two steps. The first step was the calculation of the surface tension of the three main factors (water, additives, and CSP mirrors). The second step was the calculation of the work of adhesion of the current situation and compare it the proposed situation; the calculations had been done with the use of the Van Oss theorem. This comparison, leads as to suggest adding additives that have the same properties as Polyethylene oxide (PEO), ethylene glycol, Polyvinyl alcohol (PVOH), ghassoul/10⁻² M NA (clay), natural ghassoul and Cellulose acetate (CA), since those additive are the ones that decrease the surface tension water, decrease the work of adhesion and as a result insure a high and spontaneous spreading of water when in contact with CSP mirrors. Throughout this method, we estimated a decrease of water by 20% to 30% when added with a small amount of clay; since, clay (ghassoul) is a highly safe, cheap and Moroccan product. This estimation we will insure a good cleaning, an efficient use of water, a
limited number of cleaning cycles, and promotion of a national product that can be used in many other processes that procedures water and not just in the cleaning process.

I. Introduction

Recently, the renewable energies market has been the cause of emergence of several technologies, including solar energy, which has been developing in a very high rate. Researchers nowadays have many sustainable opportunities thanks to the multiple offers made by different solar power plants, and, thus bringing more interest to this field. The economic advantage of those new Substituting energy resources is of great importance thanks to the decrease in the cost bill.

Currently, developed countries have made it possible to cover their energetic needs in terms of electricity through developing different energy stations with different capacities, ranging from kilowatts to megawatts. Thanks to its progressive research and development opportunities in areas of efficiency reliability, solar power plants, provide a wide range of opportunities for energy production and use.

One of the latest and most efficient technologies is known under the name of ‘concentrating solar power plants (CSPP). The advantage that CSPP has over other renewable energy technologies resides in the fact that CSPP are able to assimilate profitable energy storage systems and thus furnish manageable power demanded. CSP systems represent a very important potential in the renewable energies’ sector. However, since CSP systems require an important use of water and generally located in regions that lack water resources, their functioning may be problematic. In CSP systems, power is generated by the use of important amount of water creating steam in order to make the turbines turn. They are considered as thermal power plants. In addition to steam production, water is also used in the cleaning process of the mirrors as to maintain their maximal reflectivity.

This project addresses the issue of water use and aims to simultaneously reduce water consumption used in the cleaning process of CSP mirrors in Moroccan project NOOR1 at Ouarzazate. Concerning efficient water use in the cleaning process, several additives can be added to modify the surface tension characteristics of water for better water distribution when in contact with CSP mirrors. These additives can be polymers, clays or solutions. Throughout
this method, we will insure a good cleaning, an efficient use of water, and a limited number of cleaning cycles.

1.1 Context

i. Solar Energy context

The energy coming from the sun and converted into thermal or electrical energy is called solar power. It is the most abundant and cleanest renewable energy resource known to mankind. The planet has many rich solar resources. The contemporizing technologies provide a variety of uses, from generating electricity to providing light and heating water for both domestic and industrial uses. Technologies of the solar sector can be either active or passive. It depends on the manner by which solar energy is captured, converted and distributed. When energy is captured using photovoltaic panels and solar thermal collector, we are referring to active solar. Whereas, passive solar is more about orienting a whole building directly to the sun. the figure below demonstrates the big potential of renewable energy in our country.

![Significant Potential In Renewable Energy](image)

**Figure 1:** the significant potential of renewable energy in Morocco

ii. Solar Energy in the MENA region (and focus on Moroccan’s energy situation)

The Middle East and North Africa Region (MENA) contains over 57% of oil reserves in the whole world, 41% of proven natural gas resources, and benefits from rich solar resources.
However, there are outstanding discrepancies between the countries that thrive with those natural resources and the countries that depend on these resources. Actually, the majority of MENA countries have limited access to energy, and electricity is scarce in many rural areas. Still, the potential for renewable energies is undoubtedly under-exploited.

Since MENA countries suffer from water scarcity and economic activities are concentrated in coastal regions, they are extremely vulnerable to the risk of climate change. Fortunately, an important progress is taking place in the MENA region regarding the improvement of energy resources, in parallel with the increasing expansion of renewable energies.

In general, MENA countries can be divided into two groups: the Net Oil-Importing Countries (NOIC) and the Net Oil-Exporting Countries (NOEC). Similarly to the majority of the other countries especially European ones, MENA governments have put in place Renewable Energy targets and their agendas. In most states, the first target dates are around 2020 like their EU counterparts.

![Figure 2: Overall Renewable Energy share Targets in the MENA region](image-url)
The Middle East, as mentioned before, is not a leader in terms of promoting renewable energy, despite it being the world dominant oil and gas supplier. But lately, most governments of the region have showed a different behavior by shifting their plans to include renewable energy. In fact, oil import constitutes a sizeable part of the GDP of many countries in the MENA region. Additionally, and in correlation with the constant growth of their population, the demand in electricity will increase over the upcoming years at an annual rate of 7%. With regards to renewables energy percentage ratio to total electricity generation, the World Energy Outlook 2012 issued by the International Energy Agency claims that this ratio is supposed to reach 12% by 2035 as opposed to 2% in 2010. Along the same lines, a World Bank study showed that the MENA region alone was a recipient of 22% to 26% of the solar energy hitting the earth. In other words, a square kilometer of solar energy potential is equivalent to the energy produced from up to 2 million barrels of oil. This demonstrates a very promising future of the region in terms of renewable energy resource because its solar potential appears to be higher that all the other renewable resources combined. Therefore, the solar energy in the MENA region could even cover the global demand for electricity.

- **Morocco’s energy situation**

On the 4th of February 2016, the first step of the future largest Concentrated Solar Power (CSP) plant was initiated by his Royal Highness Mohamed VI: Noor I plant. It has half million parabolic mirrors which represent the equivalent of about 700 football pitches. Noor I offers an installed capacity of 160 MW with 3 hours of thermal storage which equates to 3 full hours of high production after sunset. This plant is the tangible and undeniable proof that the Moroccan Kingdom is effectively and efficiently beginning to take advantage of its outstanding solar resources. This huge project, which costs more than 600 million euros, saw the light of day thanks to many international banks such as the African Bank of Development, the German Public Bank, the World Bank, and the French Agency for Development, the European Bank of Investment and the European Commission. As for Noor II and III, they are projected to be functioning in 2018; these two plants will be adding an installed capacity of 350 MW to the Ouarzazate complex of concentrated solar power plants.

So far, Morocco’s supply from energy has been based on conventional, non-renewable sources. Indeed, about 90% of its power generation comes from oil, coal and natural gas, and is largely imported from Saudi Arabia, Iraq, and Russia mainly. Thanks to the country’s continuous efforts, in 2013, all energy imports including crude oil, oil products, coal, natural
gas, and electricity counted for only 27% of all Morocco’s imports. This was achieved thanks to the country’s new energy policy of depending on other alternatives, such as solar energy. The Moroccan government hopes that by 2030, it will be able to export electricity to Europe using renewables over the medium.

![Figure 3: NOOR I Concentrated Solar Power Plant (160 MW)](image)

1.2 Aims and Objectives

Water Saving for Concentrated solar Power piqued the interest of many researchers all over the world, it is in fact one of the R&D projects that they are willing to change and develop. The project’s main mission is to accurately assess cleaning water consumption for NOOR I CSP plant. Additionally, it aims at decreasing the water consumption at solar plant by changing the characteristics of the water and as a result changing its spreading when it touches the surfaces (CSP’s reflectors).

1.3 STEEPLE Analysis {A STEEPLE analysis follows to describe the influence of this project on many levels such as Ecological, Economical...}

In order to start any business, be it big or small, some analysis must be done so as to investigate the factors affecting the firm and check the effect on the environment in the short and the long term. To do this, The STEEPLE analysis is used in this project to assess all the factors affecting the ‘business’ of solar energy in Morocco and its direct effect on water efficient use in plant facilities. By STEEPLE, we are referring the political, societal, legal,
environmental, ethical, economic, and technological factors that affect each business strategic decision-making.

**Social factor:**

- The population growth represent one of the biggest problems not just in Morocco but worldwide, especially if we are talking about its relationship with the consumption of the earth’s non-renewable energy resources. Therefore, demographical growth leads to a higher energy’ demand, that leads to a higher electricity consumption.

**Technological factors:**

- The continuous improvement of technology makes analyzing and changing the microscopic characteristic of substances easier (such as water), and therefore improving many operations as the production of electricity.
- The use of technology has become more noticeable and easier and has given escalation to more origination and creativity.

**Environmental factors:**

- The optimization of the use of water in the wet cooling solar power plants is a key aim that leads the project to meet its environmental objectives and as a result be the maximum environmentally safe.
- Reduce the chemical marks of energy power plants on the environment.
- Encourage the use of renewable energies and sustainability to safeguard our environment.

**Ethical factors:**

- Encourage thinking about the next generation.
- Preserve earth’ natural sources and encourage responsibility toward the environment.

**Political factors:**

- Encourage the local electricity production of morocco and as a result decreasing the dependency of our country.
• orient the use of renewable energy to meet the new objective set by his majesty the king Mohamed VI (52% of the Moroccan electricity will be locally produced by renewable energies by 2030)

Legal factors:

• The Moroccan government sets a whole agency that takes care of all the new sustainable energy projects in the Moroccan sector (MASEN).
• New guidelines, laws, policies and projects were lanced last years to protect the environment and encourage the environmentally safe projects.
• The Moroccan 58-15 law project gives the opportunity of vending the surplus of energy from renewable sources to the ONEE; the case of complex NOOR.

Economic factors:

• The suggested solutions will reduce the water used in the cleaning operation and as a result reduce one of the biggest expenses of the power plant.
• Proposed methodologies can be used also in other fields.

II. Theoretical Background

For the seek of finding a solution to our problem, we opt to use the following theorems:

I.1 Surface Energy

A material, which resists stress and rigid is defined as a solid. A solid surface is characterized by its surface energy and surface free energy.

There are two categories of surfaces of solid materials which are:

- High surface energy material, which contains metals and inorganic compounds like oxides, silica, silicates, nitride and diamond.

- These surfaces form low energy interfaces under water.

- Low surface energy materials like oils, and Teflon. The high-energy surfaces spontaneously absorb them because the free surface energy of the system is reduced. Mostly, there have a very elevated rate of hydrophobicity, high dispersion or hydrophobic forces, and very low polar forces.
• These surfaces form high energy interfaces under water

I.1.1 DELVO Theory

The DLVO theory explains the stability of colloidal suspension. It also holds a description of the balance between two forces, van der Waals attraction and electrostatic repulsion. When two colloids get approached by each other and show the beginning of interference between their electrical doubles layers, here the electrostatic repulsion gets more significant. To overcome this repulsive force, some energy is required. The repulsion curve represented in the figure shows the amount of energy to be overcame if the particles are both forced. It has a maximum value that is linked to the surface potential once they begin to touch. Outside the double layer, it decreases to zero. In each colloidal particle, the forces between molecules cause van der Waals attraction to take place. Each molecule of the colloid is connected to one molecule in the other colloid particle through van der Waals attraction. This is additive force. The variation in van der Waals force between colloidal particles is indicated by an attractive energy represented in the curve.

Colloids tend to agglomerate or separate by the combination of the two curves, those of electrostatic repulsion and van der Waals attraction. This tendency is explained in the DLVO theory. To obtain the net energy, the smaller value is deduced from the larger one, at each distance. Energy can be mistaken for an energy barrier when there is repulsion. The energy barrier might be increased or decreased through modifying the ionic or pH environment or through increasing the amount of surfactants in order to have an effect on the surface charge of the colloid.

Figure 4: schematic demonstrating the DELVO theory
Van Oss and Polar (The Lifshitz-van der Waals (LW) and Apolar (Acid-Base) interactions approaches for determination of Surface Free Energy

In the Acid-Base approach, the interactions contained in the dispersive component are from dipole $\gamma^{LW}$, and the polar component $\gamma^{AB}$ is separated into an electron acceptor as an acid component, and electron donor as a basic one.

\[
\begin{align*}
\gamma_S &= \gamma_{SL}^{LW} + \gamma_{SL}^{AB} \\
\gamma_L &= \gamma_{SL}^{LW} + \gamma_{SL}^{AB}
\end{align*}
\]

or: $\gamma^{AB}_L = 2\sqrt{\gamma_{SL}^{LW}\gamma_{SL}^{AB}}$ and $\gamma^{AB}_S = 2\sqrt{\gamma_{SL}^{AB}\gamma_{SL}^{LW}}$

Where $\gamma^{LW}$ is caused by the interactions which resulted from induced dipoles (Lifshitz–Van Der Waals (LW)), $\gamma^+_S$ is the Lewis-acid component and $\gamma^-_S$ is the Lewis-base component.

Young’s equation:

\[
\gamma_{SV} = \gamma_{LG} \cos \theta_Y + \gamma_{LS}
\]

Using Good-van Oss approach:

\[
\begin{align*}
\gamma_{SV} &= \gamma_S - \pi_e \approx \gamma_S \\
\gamma_{LV} &= \gamma_L - \pi_e \approx \gamma_L
\end{align*}
\]

$\pi_e$: pression vapor.

\[
\Rightarrow \gamma_S = \gamma_L \cos \theta_Y + \gamma_{LS}
\]

\[
\gamma_{SL} = \gamma_S - \gamma_L \cos \theta_Y
\]
\[
\gamma_{S\text{LW}}^L + \gamma_{L\text{LW}}^S - 2\sqrt{\gamma_{L\text{LW}}^L \gamma_{S\text{LW}}^L} + 2(\sqrt{\gamma_{S\text{LW}}^L \gamma_{S\text{LW}}^L} + \sqrt{\gamma_{L\text{LW}}^L \gamma_{L\text{LW}}^L} - \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} - \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L}) = \gamma_S - \gamma_L \cos \theta_Y
\]

\[
2\left\{\sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} - \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{L\text{LW}}^L \gamma_{L\text{LW}}^L}\right\} = \gamma_L(1 + \cos \theta_Y)
\]

We have 3 unknowns; we must utilize 3 equations with three unknowns.

\[
\begin{align*}
2\left\{\sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L}\right\} &= \gamma_{L1}(1 + \cos \theta_1) \\
2\left\{\sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L}\right\} &= \gamma_{L2}(1 + \cos \theta_2) \\
2\left\{\sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L} + \sqrt{\gamma_{S\text{LW}}^L \gamma_{L\text{LW}}^L}\right\} &= \gamma_{L3}(1 + \cos \theta_3)
\end{align*}
\]

In order to solve the equation, we use 3 different liquids: Neutral liquid, Polar liquids and non-Polar liquids, generally we often used distilled water, Diiodomethane, and Ethylene Glycol (or Formamide) liquids.

Three different liquids are used which are neutral, polar and non-polar liquids. Generally, distilled water is used, diiodomethane, and ethylene glycol or Fromamide liquids.

| Liquids            | \(\gamma_{L\text{LW}}^L\) (mJ/m\(^2\)) | \(\gamma_L^+(mJ/m^2)\) | \(\gamma_L^-(mJ/m^2)\) |
|--------------------|-----------------------------------|----------------|
| Water H\(_2\)O     | 21.6                              | 25.4 | 25.4 |
| Formamide (CH\(_3\)NO) | 38.7                             | 2.3  | 39.4 |
| Ethylen Glycol     | 29                                | 1.92 | 47   |
| Diiodomethane (CH\(_2\)I\(_2\)) | 50.5                             | 0.7  | 0.0  |

Figure 5: table of the values of surface tension components
I.1.3  Work of Adhesion

When dissimilar particles or surfaces tend to cling to each other, this is called adhesion. When similar or identical particles or surfaces tend to cling to each other, this is called cohesion. The forces behind these two phenomena can be categorized in several ways. Chemical adhesion, dispersive adhesion and diffusive adhesion hold the examples of the intermolecular forces causing the function of multiple kinds of stickers and sticky tape.

![Image of dew drops adhering to a spider web](image)

**Figure 6: picture of dew drops adhering to a spider web**

The work that is required to build an area of a surface is conventionally defined to be surface energy. Surface energy can be viewed in another way when related to the necessary work to cleave a bulk sample. This creates two surfaces. In case the new syrfaces are similar, the surface energy $\gamma$ of each surface is set to be half the work of the cleavage as show in the following equation:

$$W: \gamma = (1/2)W_{11}.$$  

In case the surfaces are not equal, we need to apply the equation of Young-Dupré:

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12},$$

Where $\gamma_1$ and $\gamma_2$ are the surface energies of the two new surfaces, and $\gamma_{12}$ is the interfacial energy.

The same logic is carried on in case of a system of three species:

$$\gamma_{13} + \gamma_{23} - \gamma_{12} = W_{12} + W_{33} - W_{13} - W_{23} = W_{132},$$

Where $W_{132}$ is the energy of cleaving species 1 from species 2 in a medium of species 3.
Figure 7: illustration of a number of cases of cleavage, with each sort labeled

A: $\gamma = (1/2) W_{11}$

B: $W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}$

C: $\gamma_{12} = (1/2) W_{121} = (1/2) W_{212}$

D: $W_{12} + W_{33} - W_{13} - W_{23} = W_{132}$.

I.2 CSP Plants

Concentrating Solar Power (CSP) technology is based on collecting solar energy and concentrating it in order to generate an elevated temperature heat source. It can be employed to generate heat for industrial processes, or as a final product as electricity. In a CSP plant specifically, solar collectors which are a field or mirrors, collect the solar direct irradiations. The solar collectors concentrate the energy into receivers where the energy is absorbed to provide high temperature heat. Conventional power cycles are driven by the use of this heat, and eventually generate electricity.

CSP plants include cost effective thermal energy storage (TES) systems thanks to the high temperature heat that is generated as a midway step. TES system makes the plant able to stock the energy in order to be used in the future. In a similar manner, the technology gets flexible
enough to permit the hybridization with other more conventional fossil-fuel fired heat sources. This flexibility is due to the coupling of the conventional power generation cycles. The following schematics shown in the figure below roughly summarize the process.

![Figure 8: schematic of the CSP Plant process](image)

One of the main competitive advantages of CSP plants and makes them “dispatchable” is the possibility to present manageable power on demand through one of the process which are TES integration or hybridization. Biomass being apart, CSP is among the very few renewable dispatchable alternatives which already have a success in the large power generation market.

The dispatchable attribute of a CSP plants enable the plant to be developed in order to complete several different roles in electrical systems. A characteristic of hourly load demand is shown in figure below, for a sub-tropical region. It shows the power demands in MW for each hour of the day. We can identify three different demand loads which are: the base load, the peak load and the intermediate load.

![Figure 9: A characteristic of hourly load demand](image)
The base load is the least level of demand in an electrical supply system in twenty four hours range. Their plants have lower generation costs and high capacity factors, such as coal, nuclear, and hydropower.

The peak load is the period during which the demand is higher than the average periods of the day. The variations of peak load can be shown on a daily, monthly or even seasonally basis. Power plants cover peak loads, often mentioned as mid-merit plants and “peakers”. Mostly, peaker plants need to be very flexible when it comes to start up times and abilities for load regulation.

Finally, the intermediate load which is the load band between the predicted demand and the base load. It is also covered by mid-merit power plants. However, in their operations, they experience fewer variations. The following paragraphs provide a general understating of the main components in a CSP plant, the major technologies known for each, and the modern CSP plant layouts.

I.2.1 Types of CSP reflectors

The block of SF or solar field is made for concentrating solar radiations to produce the high temperature heat. Three main components form the SF which are the collector field, the heat transfer fluid HTF and the receiver.

Parabolic Trough CSP technology

The most efficient SF technology which is used in the NOOR1 project case study is of type Parabolic Trough or PT. Its collectors are to be linear-focus mobile collectors, made of parabolicaly shaped mirrors focusing onto a tubular receiver. It is the most efficient among all CSP technologies and cover around 85% of the general CSP installations up to now. Figure below presents this technology in both schematics and under real operation. The HTF in PT concentrators which is usually oil, passes into the receiver. The latter is often a metal pipe enclosed by a vacuumed tube, in order to decrease convection losses to the least. The collector can track the path that the sun takes longitudinally. Up to now, conventional systems are crapped to 390°C because of the property limitations of HTF. For example in a steam-cycle, the steam is commonly generated by the heat carried by the HTF.
Linear Fresnel CSP Technology

Linear Fresnel reflectors or what is called LF, are equivalent to PT collectors. LF reflectors are formed by several long row flat mirror likes which focus on a linearly fixed receiver. Figure below shows the model. To maintain the focus on the receiver, the flat mirrors rotate in a simultaneous manner. This gives an important rate in freedom of design.

Central Receiver CSP technology

Central receiver or CR systems are made of an array of tracking mirrors. There tracking mirrors can be referred to as heliostats. They concentrate the direct radiations onto a central receiver generally in an elevated support .It is usually called the tower as show on the left of figure 6. This kind of systems can also be named “solar tower power plants” or STPP.
Parabolic Dish CSP Technology

Parabolic dish systems or PDs are made of a sequence of mirrors that have a form similar to that of a circular paraboloid section. The energy is concentrated into the focus point on which the receiver is mounted. PDs use a 2-axis tracking system which enables it to have the most optical efficiency between, all the rest of the commercial concentrators. Therefore, it enables it to attain higher temperature. The receiver collects the heat and makes it ready to use locally by any engine, or can be relocated to a ground based plant.

I.2.2 CSP Mirrors under desert conditions

i. Influence of the Climate (Desert conditions and impact of sand deposition)

In order to design a CSP plant, the climate of the region and its impact is a very important variable to be taken into consideration and climate data should be collected beforehand. Therefore, and following the choice of the plant’s location, information about the weather is
crucial for the following step of the project. The weather data could reveal if the location is wet, dry, humid or rainy. It could also reveal information about the wind speed and the Direct Normal Irradiation (DNI). Then, a specialized software of the plant’s design analyzes the data with a frequency of 10 minutes over an entire year. System Advisor Model (SAM) is the most common program employed by engineers for plant design. These initial data collection and analysis allow a better understanding on the interaction of water with the CSP reflectors. I should point out that there is cooperation between NOOR I and a website specialized in energy; the website helps the project in its high forecasting methodological analysis, and it especially allows the plant to have a clear prediction and to plan accurately its future production. (www.meteoforenergy.com).

ii. Water issues

What makes CSP plants work a challenge, is the fact that it should be built in a desert where water can represent an issue, but still needing water for many other tasks. In fact, water is necessary for the functioning of the plants as it is used for the cooling tower in CSP technology (wet cooling Rankine cycle), as well as for cleaning the mirrors. The use of water becomes very expensive in such power plants because the cooling and the cleaning processes need water that is demineralized and treated. And that is why the cost of water and the cost of its transportation are to be added to economic assessment during the designing phase of a plant. Moreover, the company that takes care of this operation is NOMAC (First National Operation & Maintenance Co. Ltd). NOMAC has five water reservoirs dams in the surroundings of the plant that keeps the water reserves in its maximum.

I.3 Cleaning Methods of CSP Reflectors

I.3.1 Current cleaning situation

CSP plants normally require a huge area of mirrors in a desert area. It is the most suitable location to profit from the high DNI. Nonetheless it infers that the mirrors will be exposed to dust and sand deposition. A loss higher than 50% in power can be provoked by only 10% of the complete mirror surface covered. As desert areas do not experiment many rainy days over the year (for natural cleaning), additional manual cleaning is needed to obtain a good effectiveness of the mirrors. Mirror reflectance losses range 5% to 25%, depending on the time of exposure without cleaning.
Especially in the MENA region (Middle East and North Africa), where our project is centered (Ouarzazate, Morocco), dust and sand are constantly propelled by regional storms and winds. Inquiries and Research are concentrated on the dust deposition level, to try to grasp the deposition apparatus and the effects on mirrors.

We have an estimation of the water consumption of 1.7 million m$^3$ per year, for the first wet-cooling project (Noor I) in our Ouarzazate one. The water supply reserve for the solar complex is the Mansour Eddabhi dam (located 12 km from the central infrastructure of our project). No well or groundwater resource is developed. The current water needs (for Noor I) are satisfied using direct supply from the stock of the Mansour Eddabhi dam, at first transported by tank trucks for storage in a temporary pond, and then through a impermanent pipeline. In addition to that, we have the water storage stocks (with a total capacity of 300,000 m$^3$) that have been put in place in the construction of the site to guarantee the security of the cooling apparatus and cleaning. MASEN bought the required amount of raw water from ONEP (Office National de l'Eau Potable), then does a basic water filtration and treatments and then sell it to NOMAC. This later does a more advanced and developed filtration and chemical treatment that gives as a result a demineralized water with specific characteristics and purity that meets the requirements for running the steam turbine, heat exchanger, cooling tower, and mirrors cleaning process.

NOOR I cleaning current situation is based on the mirrors reflectivity factor that is measured manually every morning with a reflectometer (Reflectometer R15) before sunrise in 12 mirrors in each area (8 areas) of the plant. The collected data is gathered and averaged in an excel table that gives as a result the percentage of cleanliness in each area. Thus, the area with the least percentage is the one that get cleaned that day. So the current strategy of cleaning is not scheduled or organized, it depends on the cleanliness percentage of each day (figure below).
NOMAC have three cleaning trucks with curved rotation brushes that rotate along the collectors' curved axes; normally just two cleaning trucks who operate (the third one is stand by) each day. The trucks drivers have a formation and allow them to adapt the soft brushes to the mirror's shape and remain them in full contact with the reflecting surface at all times without damaging them or scratching them; the mirrors are at the cleaning position (20°, 160°). This process is usually accompanied with demineralized high pressured water that assures the total cleanliness of mirrors. Moreover, there are seven truck drivers and two cleaning shifts per day; the first shift starts at sunset 18:30 and finished at 22:00, and the second shift starts at 22:00 and finishes at sunrise. This process cleans at maximum 60 loops per day (out of 400 loops) and it takes seven days to clean all the plant.

So to summarize the cleaning process, in order to maintain the efficiency, reflector mirrors are washed once every seven days at NOOR 1, and more than 36500000 litters of demineralized water are utilized every year without further recovery. The cleaning is performed in two stages. The cleaning trucks have water sprayers which first spray the dirty mirrors with demineralized water to make them wet. This is directly followed by cleaning brushes that rotate and clean the dirt off the mirrors. Then there is another row of sprayers at the back that rinse the cleaned mirrors off. At present, there is no water recovery plant associated with the NOOR 1, and this large amount of water is directly disposed to the ground.

**Figure 14: Daily area cleanliness factor calculation in NOORI**

<table>
<thead>
<tr>
<th>AREA</th>
<th># Collectors</th>
<th>Bi</th>
<th>Partial Clenliness</th>
<th>Area Clenliness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93.00</td>
<td>33.7%</td>
<td>0.30153714</td>
<td>93%</td>
</tr>
<tr>
<td>2</td>
<td>183.00</td>
<td>66.3%</td>
<td>0.624400114</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>74.00</td>
<td>42.0%</td>
<td>0.406571661</td>
<td>97%</td>
</tr>
<tr>
<td>4</td>
<td>102.00</td>
<td>58.0%</td>
<td>0.562082515</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>89.00</td>
<td>33.7%</td>
<td>0.318909287</td>
<td>95%</td>
</tr>
<tr>
<td>6</td>
<td>175.00</td>
<td>66.3%</td>
<td>0.533499741</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>79.00</td>
<td>42.9%</td>
<td>0.415471043</td>
<td>96%</td>
</tr>
<tr>
<td>8</td>
<td>105.00</td>
<td>57.1%</td>
<td>0.546818717</td>
<td></td>
</tr>
</tbody>
</table>
To be solved, the “dust mitigation challenge” needs alternatives customized based on the intensity if the soiling operations and the size/application of the solar system. For the soiling spectrum, in global regions where it often rains and snows, negligible losses might be observed in residential and small commercial systems due to the dust in those regions. When dust is accumulated, it can significantly decrease the system capacity. This is when the problem of mitigating or cleaning the dust gets necessary and cost-effective sequence of operations. Sometimes, skeptics use coatings or active electronic elements to write off any of the prevention approaches. It is because of initial added costs to the solar panels or heliostats. For large installations however, cleaning can be in the range of multimillion dollars t=yearly for 200- MW fields.

Restauratio

It is all about the post-soiling cleaning techniques. The cleaning techniques serve to deduct and return the surface to a near original condition or get as close to it as possible.

**Washing** uses water or detergent with low surface energy to wash off the dirt, prior the development of strong chemical or mechanical bonding.

Description: it frequently washes with detergent solutions, labor intensive, impacts on the environment like water usage, quality and getting rid of wastewater. It is labor intensive as it allows possible automation. Timewise, its scale is of short-term and immediate. It is primarily based on already existing products, operation and maintenance.

**Cleaning**: uses chemical or mechanically cleaning techniques, active and is able to break the mechanical and chemical bonds.

Description: chemical or mechanical supplements to washings. Its design is intensive as in automated high pressure washers. It is concerned about damage and is labor intensive. Its timescale goes from short term and immediate.

**Prevention**

- Anti-soiling coatings for solar mirrors
Anti-soiling coating by FLABEG shows better behavior than standard mirror surfaces.

Figure 15: graph shows the better behavior of anti-soiling coating (FLABEG mirrors)

- Wind fences in the surroundings of the power plant, that decreases the velocity and the mass of sand and wind reaching the plant.
- Paved roads, not dirt roads in power plants.
- Stowing the array causing prevention. A movable array (CPV array) can be inverted or stowed to avoid that the dusts gets accumulation at night and during storms. As the stowing process is usually time consuming, there would be a problem in case the dust storm starts quickly or unexpectedly.
- Electrostatic repulsion of the incident dust is used for prevention. The laboratory scale has conducted investigations with the help of a microscope slide coated with a conducting tin oxide SnO2 film and biased up to 1000 v not to attract the positively charged dust particles. This alternative was examined in Sandia in a wind tunnel with Arizona dust in speeds varying between 0 and 25 m/s. This simulation shows the accumulation of 5-6 weeks of dust in ten minutes. This test has shown that dust accumulation significantly decreases in comparison with non-treated glass.
- Using turbidity spoilers for prevention. The aerodynamic spoilers are specially designed and positioned. They induced a turbulent-flow boundary layer to start the sweeping of the dust from the surface. The primer results present some minor improvement in dust accumulation but this approach as innovative as it is, was reported to be more in need of extensive advancement.
Using vibrating the surface for prevention. Special mechanical electrical instruments provide vibrations for the device and activates it in periods of highly accumulated dust, like in storms in order to forbid the surface accumulations. It has the potential of freeing the particles from the surface after accumulation. (Williams et al. [159])

I.3.3 Wet Cleaning

Water is a quite powerful medium for surface cleaning. Nature has been an excellent companion of sun installations in a great part of the world, presenting periodic washing of the surfaces thru helpful climate styles (e.g., rain and snow). Nonetheless, for many areas, natural climate assistance has not been so prevalent; and there is a considerable need for human intervention. The modern cleaning scenario involves an elevated utilization of demineralized water and brush cleaning without any necessity to apply a detergent. Still, our first suggested solution is the usage of additives that will simplify the cleaning process and make the use of water and time of cleaning considerably minimal; many investigators have argued, in these last years, that the usage of chemical marketers can be very useful in carrying the solution cleaning to the next degree—with added and active potential to eliminate particulates by considering the chemical bonding that would clench the soiling. An inherent gain is that it requires less water and less aggressive spraying/brushing, which may possibly be a damage constraint. This solution approximates the reflectivity of mirrors to boom up until 98%.

Cleaning solutions: Efficient cleaning solutions commonly employ chemical substances (e.g., detergents) that have the following characteristics:

- Capable of decreasing surface tension (surface energy)
- Low-price (in their solution volume)
- Able to be easily handled and blended in automated equipment, and
- Non-toxic, secure, and biodegradable.

I.3.4 Electrodynamic Screen (EDS)

For the aim of decreasing the water usage in the CSP plant and correspondingly decreasing the operational costs of running the plant, many researches was done in furtherance of innovating a new technology that will ameliorate the cleaning efficiency with less price and
water; the technology won the SunShot (U.S. Department of Energy) CSP R&D award in 2012.

Furthermore, big CSP plants are in most cases located in dry, dusty, arid, and rough regions. Their locations always create big challenges to the operations and maintenance department of the power plant because they have to keep the mirrors clean for maximum reflectance and thus electricity output. Hence, the proposed solution is a transparent electrodynamic screen (EDS) that was developed after collaboration between Boston University, Sandia National Laboratories and Abengoa Solar. (SunShot, 2012).

Electrodynamic screen is considered as a transparent coating that will be in the top of the CSP mirrors. This screen will move away the dust of the mirror surface by operating travelling-wave electric fields (the figure below shows schematic view of the travelling wave and how it transports a dust particle). The proposed technology is considered optimal; it doesn’t need manual labor or the use of water, it needs a very small amount of time, and it eliminates 95% of dust depositions. This innovation represents the future for mirror cleaning for large-scale CSP plants.

![Schematic diagram of the travelling wave transporting a dust particle](image)

**Figure 16: schematic diagram of the travelling wave transporting a dust particle**

Nonetheless, EDS has some important disadvantages that should be taken into consideration:

- It is highly expensive to be implemented in large-scale CSP plants
- For operating, it needs a high-voltage external power source
- If the EDS is implemented self-sustainable (with the power output from the solar cell), it may require a rate of power that cannot be supplied to
it in bad weather conditions or when the plant does not perform well. So the cleaning of the mirrors will depend on the plant’s performance.

I.3.5 Coating for CSP Mirrors (Super hydrophobic and hydrophilic coating)

**Superhydrophobic coating:**

In the morning, only a few particles are deposited. Then, the negative effects of the dew - creation of bonding between the mirror and the particles- could be changed into free natural water cleaning thanks to what is referred to as a SuperHydrophobic Coating (SHC). SHC is an anti-soiling coating that has the property of being a water-repellent. Indeed, thanks to this property, the amount of water needed per wash is notably reduced. Water drops just slide over the surface trapping dust particles on their way and getting them out of the mirror, while drops would not be capable of pulling out the dirt particles that are bonded on usual coatings.

Let the contact angle of water droplets be \( \theta_0 \), and the rolling angle be \( \theta_r \). We have that \( \theta_0 > 150^\circ \) and \( \theta_r < 5^\circ \). This shows that the surface really does not get wet. The combination of this coating and EDS is very promising in the scope of CSP coating development. The EDS’ role would be to keep an average efficiency and the morning dew and light rain would take care of getting rid of small particles. Since the EDS is actually controlled by operators, it can be put on standby mode to avoid wasting any energy when nature offers its free washing agents. In the case of strong winds and storms, however, the best solution is wet cleaning in order to remove the numerous and various particles that landed on the mirror in order to restore its reflectance.

![Figure 17: water droplet on superhydrophobic coating](image-url)
Example of superhydrophobic coating presented by FLABEG: duraGLARE - Anti-Soiling Coating

FLABEG is one of the leading companies in the manufacturing CSP’ mirrors industry; it is the main supplier of Complex NOOR. Their R&D department presented lately an innovative coating “duraGLARE”; a superhydrophobic anti-soiling coating that can reduce the deposition of dust’ particles on the CSP mirrors by up to 50%. This coating is expected to increase the overall efficiency of the plant, because it is expected to increase the reflectivity of the solar field by 1-2%. The persuasive advantages of this innovation will be: high repulsion of dust sand and other particles, high optical transparency, and it will facilitate the cleaning process.

III. Methodology

Because we believe that the topic of soiling of Concentrating Solar Power (CSP) mirrors is important since the reflectivity of the mirrors is directly relational to the overall efficiency of the power plant. The presented work gives a theoretical overview of how can we optimize the overall expenses of NOOR1 by minimizing the amount of water used in the cleaning process. Our work started by believing that controlling water drop deposition is the key factor to our research and analysis. The aim of our research is to propose all the feasible solutions that can be implemented in NOOR1 to decrease the water consumption in the washing operation, in addition to find the perfect additives (polymers, solutions, organic substances…) that will decrease the surface free energy of water and as a result increase the spreading and the wettability of water when in contact CSP mirrors.

3.1 Surface tension of:

As mentioned in the theoretical part one of the approaches to compute the surface tension of a liquid, a surface and a mixture of liquid-additive is by comparing their Adhesion work. Therefore in order to compare the behavior of only distilled water in contact with mirrors and a mixture of distilled water and an additive in contact with mirrors, we had to calculate the surface free energy and the work of adhesion of each part of the comparison’ elements.

i. Distilled water
Because of the lack of necessary equipment at the AUI ground, I was obliged to take the result of the surface tension of the distilled water from the latest research of Dr. Khaldoun; the calculation of the water’s surface free energy was done in ERESEN’s laboratory (INSTITUT DE RECHERCHE EN ENERGIE SOLAIRE ET ENERGIES NOUVELLES). The results was gotten using Drop volume method (stalagmometric method).

Steps of calculating the surface tension of a liquid using the drop volume method:

- Placing vertically the glass capillary, the drop will start to form slowly at its tip.
- Counting and weighting a quit few drops of a liquid dripped out of the glass capillary of the stalagometer
- The detachment of the pendent drop begins when the weight or the volume of the drop attains a magnitude that matches the surface tension of the liquid.
- Once the weight \( g \) of the drops equals the surface tension \( \gamma \) multiplied by the circumference \( (2\pi r) \) of the tube, the drop starts to fall down
- Note that, the weight of the falling drop \( W' \) is different (lower) than the real (expected) real weight of the drop \( W \). because an amount of the drop’s volume might be left on the tip of the stalagmometer (Up to 40%). The figure below shows Subsequent steps of the detaching drop
- The final equation of this method is stated as: \( W' = 2\pi r \gamma f \)

Where:

- \( f \) : the ratio of \( W' \)/ \( W \) (correction factor)
- \( W' \) : the weight of the falling drop
- \( r \) : the capillary radius
- \( \gamma \) : the surface tension of the liquid

\( \Rightarrow \) therefore, after the previous steps we can be able to solve the equation for the surface tension
Figure 18: Subsequent steps of the detaching drop

Figure 19: Stalagmometer and the stalagmometer tip

<table>
<thead>
<tr>
<th>Components of Surface free energy (Mj/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(LW)</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Water</td>
</tr>
</tbody>
</table>

Figure 20: table of Components of Surface free energy of distilled water

ii. Additives

The surface tension of all the additives used in my research was taken from a reliable source from internet (was approved by Dr. Khaldoun) because of the lack of the equipment at the AUI ground. The table below presents the components of all the additives tested.

<table>
<thead>
<tr>
<th>Components of Surface free energy (Mj/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(LW)</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (PTFE)</td>
</tr>
<tr>
<td>Cellulose acetate (CA)</td>
</tr>
<tr>
<td>Polyethylene oxide (PEO, PEG, polyethylene glycol)</td>
</tr>
<tr>
<td>Polyethylene (PE)</td>
</tr>
<tr>
<td>ethylene glycol</td>
</tr>
<tr>
<td>Polyvinyl alcohol (PVOH)</td>
</tr>
<tr>
<td>Additive</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**Figure 21: Components of Surface free energy of the additives tested in the project**

From the presented table we can notice that we choose to test a variety of elements that differs between kinds of clays and polymers.

iii. Sample of CSP Mirrors

Concerning the surface free energy of solid surfaces such as CSP mirrors, we used drop shape analyzer (DSA-100S) for the measurements of the contact angles of the glass mirrors and three different liquids including water, diiodomethane, and ethylene glycol liquids (Neutral liquid, polar liquid and non-Polar liquid).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample of the glass used in Noor I</td>
<td>45.56°</td>
<td>36.15°</td>
<td>48.80°</td>
</tr>
</tbody>
</table>

**Figure 22: Table: Contact angle value (value ± 2°) of water, Formamide and Diiodomethane on**

The values obtained and the values of the components of the three liquids (water, diiodomethane, and ethylene glycol) are then replaced in the final equation of Good Van Oss approach:

\[
2 \left\{ \sqrt{\gamma_S} \gamma_{L1} + \sqrt{\gamma_S} \gamma_{L1} + \sqrt{\gamma_S} \gamma_{L1} \right\} = \gamma_{L1} (1 + \cos \theta_1) \\
2 \left\{ \sqrt{\gamma_S} \gamma_{L2} + \sqrt{\gamma_S} \gamma_{L2} + \sqrt{\gamma_S} \gamma_{L2} \right\} = \gamma_{L2} (1 + \cos \theta_2) \\
2 \left\{ \sqrt{\gamma_S} \gamma_{L3} + \sqrt{\gamma_S} \gamma_{L3} + \sqrt{\gamma_S} \gamma_{L3} \right\} = \gamma_{L3} (1 + \cos \theta_3) 
\]
We got three equations with three unknowns $\gamma_S^{LW}, \gamma_S^-, \gamma_S^+$. Accordingly, we solve them to estimate the components and the parameters of SFE of the glass mirror used in the solar field. The results are presented in Table below.

<table>
<thead>
<tr>
<th>Sample of the glass used in the CSP mirrors</th>
<th>$\gamma_S^{Tot}$ (mJ/m$^2$)</th>
<th>$\gamma_S^{LW}$ (mJ/m$^2$)</th>
<th>$\gamma_S^{AB}$ (mJ/m$^2$)</th>
<th>$\gamma_S^-$ (mJ/m$^2$)</th>
<th>$\gamma_S^+$ (mJ/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample of the glass used in the CSP mirrors</td>
<td>37.94</td>
<td>27.61</td>
<td>10.34</td>
<td>0.61</td>
<td>43.74</td>
</tr>
</tbody>
</table>

**Figure 23: Table: The values of the components of the surface free energy of mirror sample**

3.2 Work Adhesion of the Sample Mirrors with water

After finding all the necessary values, I start my analysis by first calculating the work of adhesion of the current situation; work of adhesion of distilled water when in contact with CSP mirror.

Well the work of adhesion of two elements in contact is defined as:

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}.$$  

In our case:

$$W_{SL} = \gamma_S + \gamma_L - \gamma_{SL} \quad \text{Eq (i)}$$

Where

- $\gamma_S$ is the surface energy of the surface (mirror)
- $\gamma_L$ is the surface energy of the liquid (distilled water)
- $\gamma_{SL}$ is the interfacial energy.

We use the Van Oss approach to calculate the interfacial energy $\gamma_{SL}^{Tot}$

$$\gamma_{SL}^{Tot} = \gamma_S^{LW} + \gamma_L^{LW} - 2\sqrt{\gamma_L^{LW}\gamma_S^{LW}} + 2(\sqrt{\gamma_L^{+}\gamma_S^{+}} + \sqrt{\gamma_L^{-}\gamma_S^{-}}) - \sqrt{\gamma_S^{+}\gamma_L^{+}} - \sqrt{\gamma_S^{-}\gamma_L^{-}}$$

Using the following information:

<table>
<thead>
<tr>
<th>Components of Surface free energy (Mj/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(LW)</td>
</tr>
</tbody>
</table>
Figure 24: Table: Components of Surface free energy of water and surface (MJ/m²)

We get:

$$\gamma_{\text{SL}}^{\text{Tot}} = 27.61 + 21.6 - 2\sqrt{27.61 \times 21.6} + 2(\sqrt{43.74 \times 0.61} + \sqrt{25.4 \times 25.4} - \sqrt{43.74 \times 25.4} - \sqrt{0.61 \times 25.4})$$

$$\gamma_{\text{SL}}^{\text{Tot}} = -13.0365$$

So we replace the gotten value in Eq (i), we obtain:

$$W_{\text{SL}} = \gamma_{S} + \gamma_{L} - \gamma_{\text{SL}} = 37.94 + 72.8 - (-13.0365)$$

$$W_{\text{SL}} = 123.7765$$

The positive value means that the surface energy of water when in contact with mirror is so high => the water does not spread very well on the surface of the CSP mirrors.

3.3 Adhesion work of the Sample Mirrors with mixture of water additive

Similarly, in order to calculate the work of adhesion of our proposed solution; the work of adhesion of sample mirrors with mixture of water additive, we opt for the use of Van Oss theorem and work of adhesion theorem but this time with three elements.

$$\gamma_{13} + \gamma_{23} - \gamma_{12} = W_{12} + W_{33} - W_{13} - W_{23} = W_{132}$$

$$\gamma_{\text{SP}} + \gamma_{\text{LP}} - \gamma_{\text{SL}} = W_{\text{SL}} + W_{\text{PP}} - W_{\text{SP}} - W_{\text{LP}} = W_{\text{SPL}}$$

The table below shows the surface tension components of all the additives chosen to be tested.

<table>
<thead>
<tr>
<th>Component of the surface free energy (MJ/m²)</th>
<th>Y(LW)</th>
<th>Y(+)</th>
<th>Y(-)</th>
<th>Y(TOT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>21.6</td>
<td>25.4</td>
<td>25.4</td>
<td>72.8</td>
</tr>
<tr>
<td>Surface (CSP mirror)</td>
<td>27.61</td>
<td>43.74</td>
<td>0.61</td>
<td>37.94</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (PTFE)</td>
<td>19.9</td>
<td>0.1</td>
<td>1.6</td>
<td>20.8</td>
</tr>
<tr>
<td>Cellulose acetate (CA)</td>
<td>39</td>
<td>0.3</td>
<td>22.2</td>
<td>43.5</td>
</tr>
<tr>
<td>Material</td>
<td>$\gamma_{12}$</td>
<td>$\gamma_{13}$</td>
<td>$\gamma_{23}$</td>
<td>$\Delta W$ (water/surface)</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Polyethylene oxide (PEO, PEG, polyethylene glycol)</td>
<td>44,3</td>
<td>0,02</td>
<td>58</td>
<td>45,1</td>
</tr>
<tr>
<td>Polyethylene (PE)</td>
<td>31,5</td>
<td>0,1</td>
<td>0,9</td>
<td>31,7</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>29</td>
<td>1,92</td>
<td>47</td>
<td>47,99</td>
</tr>
<tr>
<td>Polyvinyl alcohol (PVOH)</td>
<td>42</td>
<td>0</td>
<td>37</td>
<td>42</td>
</tr>
<tr>
<td>Polyvinyl acetate (PVA)</td>
<td>42,6</td>
<td>0,04</td>
<td>22,3</td>
<td>44,5</td>
</tr>
<tr>
<td>ghassoul/10⁻² M Na</td>
<td>29,07</td>
<td>4,51</td>
<td>48,77</td>
<td>58,76</td>
</tr>
<tr>
<td>ghassoul Naturel</td>
<td>31,23</td>
<td>4,57</td>
<td>32,1</td>
<td>55,47</td>
</tr>
</tbody>
</table>

**Figure 25: table Components of Surface free energy water, surface and additives (Mj/m²)**

In an excel file I computed the interfacial energy of water-additive, water-surface, and surface--additive of all the cases in the order to get to their adhesion work.

The table below show all the results obtained:

<table>
<thead>
<tr>
<th>$\Delta W$ (water/surface)</th>
<th>123,7765</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta W$ (water/PTFE/surface)</th>
<th>43,26929</th>
<th>$\Delta W$ (water/PVOH/surface)</th>
<th>-62,7391</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{13}$</td>
<td>35,69746</td>
<td>$\gamma_{13}$</td>
<td>-7,15184</td>
</tr>
<tr>
<td>$\gamma_{23}$</td>
<td>-5,46467</td>
<td>$\gamma_{23}$</td>
<td>-68,6238</td>
</tr>
<tr>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta W$ (water/CA/surface)</th>
<th>-28,1685</th>
<th>$\Delta W$ (water/PVA/surface)</th>
<th>-29,2946</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{13}$</td>
<td>5,499955</td>
<td>$\gamma_{13}$</td>
<td>6,605541</td>
</tr>
<tr>
<td>$\gamma_{23}$</td>
<td>-46,705</td>
<td>$\gamma_{23}$</td>
<td>-48,9367</td>
</tr>
<tr>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta W$ (water/PEO/surface)</th>
<th>-94,6745</th>
<th>$\Delta W$ (water/ghassoul Na/surface)</th>
<th>-53,4254</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{13}$</td>
<td>-21,2029</td>
<td>$\gamma_{13}$</td>
<td>-10,7827</td>
</tr>
<tr>
<td>$\gamma_{23}$</td>
<td>-86,5081</td>
<td>$\gamma_{23}$</td>
<td>-55,6792</td>
</tr>
<tr>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
<td>$\gamma_{12}$</td>
<td>-13,0365</td>
</tr>
</tbody>
</table>

| $\Delta W$ (water/PE/surface)   | 50,63416 | $\Delta W$ (water/ghassoul Ntl/surface) | -33,3256 |

32
As I mentioned previously the work of adhesion helps us understand the spreading of one liquid on another liquid or on a surface. Its results help us predict if the liquid spreading would spread spontaneously or not. Therefore, if the reaction has a net loss in free energy it will be spontaneous; so, the more the adhesion of work is less than zero, the more the liquid is highly spreadable.

i. Hydrophilic repulsion

The surfactants, clay, and polymers that gave as a high work loss function by breaking down the interface between water and dirt. In addition to that they hold dirt in suspension, and thus allow their removal easily. They function this way because they hold both a hydrophilic (water loving) group, such as an acid anion, (-CO$_2$ or SO$_3$) and a hydrophobic (water hating) group, such as an alkyl chain.

Table below presents all water-additives result that represent a hydrophilic repulsion; the ones with the highest negative loss of adhesion work compared to water-surface.

<table>
<thead>
<tr>
<th>∆W (water/surface)</th>
<th>123,7765</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆W (water/PEO/surface)</td>
<td>-94,6745</td>
</tr>
<tr>
<td>∆W (water/ethylene glycol/surface)</td>
<td>-63,1892</td>
</tr>
<tr>
<td>∆W (water/PVOH/surface)</td>
<td>-62,7391</td>
</tr>
<tr>
<td>∆W (water/ghassoul Na/surface)</td>
<td>-53,4254</td>
</tr>
<tr>
<td>∆W (water/Natural ghassoul/surface)</td>
<td>-33,3256</td>
</tr>
<tr>
<td>∆W (water/PVA/surface)</td>
<td>-29,2946</td>
</tr>
<tr>
<td>∆W (water/CA/surface)</td>
<td>-28,1685</td>
</tr>
</tbody>
</table>

Figure 26: work of adhesion of all the polymers when in contact with the surface

Figure 27: table, sorted negative work of adhesion
ii. Hydrophobic attraction

The testes additives that represent a hydrophobic attraction and therefore cannot be used in our proposed cleaning process are

| ΔW (water/PTFE/surface) | 43,2692 |
| ΔW (water/PE/surface)   | 50,6341 |

**Figure 28: table, sorted positive work of adhesion**

IV. Discussion

The additives used in our testing vary between polymers, surfactants, and clay. From the gotten results we can notice that the values of the total work of adhesion of CSP water-additive-mirror vary between negative and positive magnitudes. These values can be interpreted by first understanding the meaning of their signs and then comparing them with the value of the work of adhesion of the current situation (ΔW (water/surface)=123.77). This comparison have the goal of understanding how spreadable will be our solution (water-additive) when in contact with the mirrors.

Firstly, we should remember that according to the energy of adhesion shows a good spreading when it is highly negative since energy is released when two compressed phase-vapor borders are destroyed and a liquid-solid or liquid-liquid boundary is created. Therefore the negative values obtained (e.g: ΔW(water/PEO/surface)=−94,6745, ΔW(water/ethylene glycol/surface)=−63.189, ΔW (water/ghassoul Na/surface)=−53.524, etc ) means that those additives are highly recommended to be used to decrease the surface tension of water, subsequently, to spread well the water. However, the positive obtained values (eg: ΔW(water/PTFE/surface)= 43,2692, and ΔW (water/PE/surface)= 50,6341) signifies that those additives will not spread well on the surface, therefore, there are nor recommended.

The decrease of the surface tension of water when mix with an additive is explained by Vander walls interactions, the surface of mirrors has a highly small base surface tension (Y(−)=0.61); this means that the surface has a high wellness to attract positive charges. However, all the chosen polymers and clay (ghassoul) that are recommended are characterized by the fact that they contain both a hydrophilic (water loving) side, such as an acid anion, (−CO_2^− or SO_3^−) and a hydrophobic (water hating) side; one side contains positive charges and the other
side contain negative charges. Therefore, once the water-additive solution gets in contact with the surface. Its hydrophilic side (that has a high wellness to give charges) gets easily and fast attracted by the surface (which leads the solution to spread well on the surface).

To conclude, we suggest adding additives that have the same properties as Polyethylene oxide (PEO), ethylene glycol, Polyvinyl alcohol (PVOH), ghassoul/10^{-2} M NA (clay), natural ghassoul and Cellulose acetate (CA), because those additive are the ones that decrease the surface tension water.

V. Cost analysis

According to many researches done lately, it is estimated that using a small amount of clay in water can decrease the contact angle of water when in contact with CSP mirrors from 45,56° to 3,5°; equivalent to a decrease of water by 20% to 30%. Therefore, according to our assumption we compared the water consumption in the current cleaning process with our proposed solution that will decrease the amount of water used by 20% to 30%. So, firstly we calculated the cost of water used yearly.

According to data providing by NOMAC the amount of water used per day is 600 m³ and it costs the company 100 MAD for 1 m³ of treated water.

- Water consumption in the cleaning process: $600 \text{ m}^3 \times 365 = 219,000 \text{ m}^3 \text{ per year}$
- Cost: $219,000 \text{ m}^3 \times 100 \text{ DH} = 21,900,000 \text{ MAD per year}$

Thus if we decrease the amount of water used by of 20% to 30 % we obtain:

$219,000 \text{ m}^3 \times 20 \% < \text{Water savings in m}^3 < 219,000 \text{ m}^3 \times 30 \%$

$43,800 < \text{Water savings in m}^3 < 65,700$

$4,380,000 < \text{Cost savings in DH} < 6,570,000$

So to conclude, we can notice that the amount of money saved is highly noticeable, this amount will cut the company’s expenses with an interesting amount. But most importantly it will save a highly important amount of water that makes project NOOR1 meet the aims of the national energy strategy.
VI. Conclusion

Concentrated solar power plants are one of the most advanced technologies in terms of generating electricity from solar energy. However, this technology is facing many issues; one of their main issues is their high consumption of water in their daily operations (especially if the power plant is using wet cooling in its Rankine cycle). Therefore, my project is addressing that issue; optimization of water in the cleaning process of CSP mirrors since the amount of water used in this process is highly conspicuous. My project’s case study was the solar power plant Noor 1 in Ouarzazate. In order to achieve that aim, a theoretical analysis was done using a variety of theorems such as Volvo theorem, Van der Waal’s theorem and Van Oss theorem. These theorems are used for calculating the surface tension of water in various cases where variety of additives was added to change the characteristics of the water when in contact with CSP mirrors. Therefore, decreasing the surface tension of water will increase the distribution of it on the surfaces of the mirrors. The additives used are polymers, detergents, and clay. Our suggested solution is explained by the energy of adhesion since it is a good measure for how easily a liquid wets another liquid or a solid. Therefore, we opt for comparing the work of adhesion of water when mix with an additive and in contact with CSP mirrors with the work of adhesion of just water in contact with CSP mirrors. This comparison, leads as to suggest adding additives that have the same properties as Polyethylene oxide (PEO), ethylene glycol, Polyvinyl alcohol (PVOH), ghassoul/10-²M NA (clay), natural ghassoul and Cellulose acetate (CA), since those additive are the ones that decrease the surface tension water. Then, a cost analysis was done, according to our assumption we compared the water consumption in the current cleaning process with our proposed solution that will decrease the amount of water used by 20% to 30%. The comparison was highly visible, and the amount water saved is a key factor that will push the project to meet its expectations for being fully a green energy system.
VII. References

- C.M. Chan, Polymer Surface Modification and Characterization, Hanser, Munich 1994, 35-76

