
REPORT

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Abstract

In this project the innovative technology of solar ponds is deeply analyzed. A solar pond can be described as a water pond that through a salinity gradient is capable to store part of the incident solar radiation during long periods of time. This heat can be extracted using a heat exchanger to supply an external application. The salinity gradient is the most important part of the system to ensure a successful operation.

This work is based on the study of the first industrial solar pond constructed in Europe, located in Granada. Frist, the technology is deeply presented and thanks to the sensors installed in the system the parameters used to control its operation are identified and assessed.

Then, the technology is analyzed from energy and exergy point of view. This solar pond is the first industrial solar pond evaluated through an exergy analysis. In order to complement this information and to analyze the state of development and the maturity of the technology a thermoeconomic analysis, based on exergy results and economic parameters, is also included.

In the Granada solar pond after a long period of successful operation some problems in the salinity gradient were detected, put differently, the salinity gradient started to deteriorate. In literature no references were found related to this problem. In that context, this work also includes a stability analysis to identify where and when the salinity gradient deterioration started and how it can be prevented.
Index

ABSTRACT ........................................................................................................ 1

INDEX .............................................................................................................. 2

1. GLOSSARY ..................................................................................................... 5

2. PREFACE ........................................................................................................ 10
   2.1. Origin of the project ............................................................................... 11
   2.2. Motivation .............................................................................................. 11

3. STATE OF THE ART ..................................................................................... 13
   3.1. Scope of the project ............................................................................... 18

4. METHODOLOGY ............................................................................................ 20
   4.1. Operation principles ............................................................................. 20
   4.2. Environmental benefits and sustainability ............................................ 21
   4.3. System description ................................................................................. 22
   4.4. Filling process ......................................................................................... 26
   4.5. Operation and maintenance .................................................................... 28
   4.6. Evolution of the salinity gradient ............................................................ 30
   4.7. Salinity of the solar pond ........................................................................ 32
   4.8. Economic parameters of the system ....................................................... 37
       4.8.1. CAPEX .............................................................................................. 37
       4.8.2. OPEX .............................................................................................. 39
   4.9. Energy and exergy analysis .................................................................... 39
       4.9.1. Energy ............................................................................................ 41
           4.9.1.1. Energy flows ........................................................................... 41
           4.9.1.2. Energy efficiency .................................................................... 44
       4.9.2. Exergy ............................................................................................ 45
           4.9.2.1. Exergy flows ........................................................................... 45
           4.9.2.2. Exergy efficiency .................................................................... 47
       4.9.3. Thermoeconomic analysis ............................................................... 48
   4.10. Stability ................................................................................................... 50
       4.10.1. Thermal and expansion coefficients ............................................. 52
       4.10.2. Stability analysis methodology ..................................................... 56

5. RESULTS ......................................................................................................... 58
   5.1. Energy and exergy analysis .................................................................... 58
5.1.1. Thermoeconomic analysis ................................................................. 63
5.1.1. Minimum price for the exergy stored .............................................. 66
5.1.2. Minimum surface to ensure the thermoeconomic feasibility under different scenarios .......................................................................................... 68
5.2. Stability .............................................................................................. 69
5.2.1. First operation period ......................................................................... 70
5.2.2. Second operation period ...................................................................... 75

6. MATURITY OF THE TECHNOLOGY ......................................................... 81

7. CONCLUSIONS ..................................................................................... 83

8. ACKNOWLEDGEMENTS ....................................................................... 85

9. BIBLIOGRAPHY ................................................................................... 86
1. Glossary

In this section the meaning of the different signs, abbreviations and symbols and elements used along the project is specified.

**Abbreviations**

\[\begin{align*}
SGSP & \text{ Salinity Gradient Solar Pond} \\
SP & \text{ Solar Pond} \\
UCZ & \text{ Upper convective zone} \\
NCZ & \text{ None convective zone} \\
LCZ & \text{ Lower convective zone} \\
Fr & \text{ Froude number} \\
CAPEX & \text{ Capital expenditures} \\
OPEX & \text{ Operating expense} \\
LSTM & \text{ Local Standard Time Meridian} \\
LT & \text{ Local Time} \\
GMT & \text{ Greenwich Mean Time} \\
EoT & \text{ Equation of Time} \\
TCF & \text{ Time correction factor} \\
LST & \text{ Local Solar Time} \\
SMN & \text{ Stability Margin Number}
\end{align*}\]

**Subscripts**

\[i \quad \text{Layer}\]
\( t \)  Time
\( x \)  Depth
\( B \)  Bottom
\( T \)  Net
\( CI \)  Investment cost
\( OM \)  Operation and maintenance cost
\( ch \)  Chemical
\( ph \)  Physical

**Parameters**

\( I \)  Solar radiation
\( Q \)  Energy flux
\( E / \dot{E} \)  Exergy flux
\( \dot{Z} \)  Annual capital cost
\( Q_{\text{stored layer}} \)  Energy stored in a certain layer
\( E_{\text{stored layer}} \)  Exergy stored in a certain layer
\( Q_{\text{in layer}} \)  Input energy in a certain layer
\( E_{\text{in layer}} \)  Input exergy in a certain layer
\( Q_{\text{out layer}} \)  Output energy in a certain layer
\( E_{\text{out layer}} \)  Output exergy in a certain layer
\( Q_{\text{sin}} \)  Inlet solar radiation inlet
$$Q_{s\text{out}}$$ Outlet solar radiation inlet

$$E_{s\text{in}}$$ Inlet solar radiation exergy

$$E_{s\text{out}}$$ Outlet solar radiation exergy

$$Q_{\text{abs layer}}$$ Energy absorbed by a layer

$$E_{\text{abs layer}}$$ Exergy absorbed by a layer

$$Q_{\text{in layer} \rightarrow \text{layer}}$$ Energy transmitted from one layer to another

$$E_{\text{in layer} \rightarrow \text{layer}}$$ Exergy transmitted from one layer to another

$$Q_{\text{ext}}$$ Energy extracted from the system

$$E_{\text{ext}}$$ Exergy extracted from the system

$$Q_{\text{loss layer}}$$ Energy lost from a certain layer

$$E_{\text{useless layer}}$$ Exergy lost and destroyed in a certain layer

$$c_{\text{ext}}$$ Cost of the extracted exergy flux

$$c_{\text{stored}}$$ Cost of the stored exergy

$$c_{\text{solar}}$$ Cost of the solar exergy

$$m_{\text{layer}}$$ Water mass of a certain layer

$$C_{\text{p layer}}$$ Heat capacity of a certain layer

$$T_{\text{layer}}$$ Temperature of a certain layer

$$\dot{m}_{\text{ext}}$$ Mass flow rate through the heat exchanger to extract heat

$$C_{\text{p}}$$ Heat capacity of water used to extract heat

$$T_{\text{in}}$$ Water temperature before the heat exchanger

$$T_{\text{ext}}$$ Water temperature after the heat exchanger
\( R \) Fraction of the solar radiation directly reflected to the environment

\( L \) Total depth of the solar pond

\( R_{\text{cond}} \) Conductive resistance

\( \Delta z \) Thickness of contact zone

\( A \) Area

\( K \) Thermal conductivity

\( E \) Static stability

\( i_r \) Economy inflation

\( n_y \) Lifetime of the solar pond

\( \text{Inv. Cost} \) Investment cost of the solar pond

\( x_i \) Molar fraction

\( e_{x,ch}^0 \) Standard molar chemical exergy

\( R \) Universal gas constant

**Greek symbols**

\( \theta_i \) Angle of incidence

\( \theta_r \) Refraction angle

\( \phi \) Latitude

\( \delta \) Declination angle of the sun

\( \omega \) Hour angle

\( \lambda \) Reflectivity of the bottom of the solar pond

\( \eta \) Energy efficiency
\[ \psi \] Exergy efficiency

\[ \alpha \] Thermal expansion coefficient

\[ \beta \] Salinity expansion coefficient

\[ \Pi \] Aggregated exergy fluxes
2. Preface

Since the middle of past century, the global energy consumption has significantly increased as a consequence of the development of an industry-based society and the increase in population and its associated energy consumptions. Since 1965, the global population increased from 3,339,593 thousands inhabitants to 7,383,009 in 2015, [1], at the same time the energy consumption increased from 3,730.7Mtoe to 12,105Mtoe, [2]. Thus, the global population was in 2015 2.21 times the global population in 1965 and the energy consumption 3.51 times. The energy consumption increased at a higher ratio than the energy population, consequently, the society has become more energy intensive.

The energy sector developed to sustain the growing demand is based on fossil fuels, resulting in important environmental impacts, such as the climate change.

Moreover, fossil fuels are finite on earth. Hence, the current situation cannot be indefinitely sustained. The large rate of consumptions is exhausting the reserves. Importantly, the reserves are not uniformly distributed along the different countries. Hence, some regions have nowadays an important dependence, almost completely, on different external providers. This situation results in political, geographic and military conflicts.

In that context, the necessity of new types of energy came on vanguard few years ago. The development of renewable energies occupies most of the attention both in terms of research and investment. Renewables were introduced to the society as a new type of energy that may overcame all problems associated to fossil fuels. Renewable energy, produced by renewable resources, is typically perceived by the society as infinite energy. However, some renewable resources are only infinite if the appropriate management is carried out, such as biomass.

Solar energy has been deeply investigated in recent years. As a result, different technologies to take profit of this resource have become technologically and economically feasible being the PV and the thermal collectors the most implemented. China is leading in terms of PV installed capacity since 2015. Germany is the European country with the higher installed capacity. The best solar resource in Europe is found in the south, in the Mediterranean region. In that context, Spanish PV sector lead the market until 2008 when a change in the regulation change this trend. Due to the regulation change and the strong promotion of this sector in other countries, Spain is nowadays the eighth country in terms of PV capacity installed behind countries like UK and Germany. Solar resource is commonly used for heating and cooling application, in this sector, despite the high resource found in Spain, the country is the thirteenth in terms of capacity installed. Notwithstanding, Spain leads the market in the third largely
implemented solar technology, the CSP, with 2.3GW installed, [3].

2.1. Origin of the project

In 2007 started a project that involves the Universitat Politècnica de Catalunya (UPC), the Royal Melbourne Institute of Technology (RMIT) and Solvay Company. The main aim of the project was to investigate the underdeveloped technology of solar ponds and its potential application.

After a theoretical study of the system, reported in [4], the team decided to build up a pilot plant facility in Solvay facilities in Martorell. Different studies were carried out in this small installation and published in [5], [6] to test the feasibility of the technology.

As good results were obtained an important investment take place to construct the first industrial solar pond in Europe. Although different industrial solar ponds were constructed in the world, scare information about them was reported in literature. In that context, the industrial facility started its operation with a certain uncertainty in different aspects, such as efficiency, operation and maintenance patterns, …

Although the pilot plant facility successfully operated during some years and had a good response to the different experiments carried out, some problems were detected in the industrials facility. In that context, this project goes depth in analyzing the system from different points of view.

2.2. Motivation

The main motivation of this project is working on an innovative renewable technology. The solar pond may be a good solution for specific applications. However, few documents are reported about this technology in literature.

This project gives me the opportunity to go depth on energy and exergy topic enlarging my knowledge in both aspects. Additionally, the complex analysis contained in this work and the few information found represent an important challenge.

Finally, this project means an important opportunity to deeply know a new renewable technology, its maturity, reliability and feasibility. Moreover, the main advantages and disadvantages of this technology and its specific applications are also commented.
3. State of the art

In this project an innovative technology to take profit on the high solar resource found in Spain is deeply investigated. A solar pond is a water pond capable to store part of the received solar radiation for a long period of time. Hence, the system may provide heat for different applications. Compared with other solar technologies, a solar pond is the only one that can store energy for a long period of time. PV system need batteries to store the electricity produced which are expensive and the storage capacity is limited. CSP may include different system to store the heat produced such as molten salts, [7]. In Spain, the largest storage system installed in CSP plants, Termosol 1 and Termosol 2 as published by Protermosolar in [8], allows the operation of 9 hours, at nominal power, without solar radiation. The thermal collectors are notably smaller systems, which also include accumulators of several hours, around 10.

Different researchers developed pilot plans to investigate the technology. In Bhavnagar, India, the largest solar pond for research purposes was constructed in 1980 with a total surface of 1600m². For industrial purposes 17 solar ponds have been identified in the world. Two of these industrial solar ponds are much larger than the others with a total area of 25,000m², located in Eliat (Israel) and Italy. The first one was constructed to produce electricity, the second one to desalinate water. Table 1 collects all solar ponds constructed in the world.

Table 1. Solar pond systems constructed and operated in the world.

<table>
<thead>
<tr>
<th>Country</th>
<th>Region</th>
<th>Name/Site</th>
<th>Cons. year</th>
<th>Area (m²)</th>
<th>Application/s</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Israel</td>
<td>Eilat</td>
<td>Ein Boqek solar pond</td>
<td>1977</td>
<td>6250</td>
<td>Electrical production</td>
<td>[9]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beith Ha’rava solar pond</td>
<td>1982</td>
<td>25000</td>
<td>Electrical production</td>
<td>[10]</td>
</tr>
<tr>
<td>USA</td>
<td>Ohio</td>
<td>Ohio State University</td>
<td>200</td>
<td></td>
<td>Pilot Plant (research)</td>
<td>[11]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ohio State University</td>
<td>400</td>
<td></td>
<td>Pilot Plant (research)</td>
<td>[12]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ohio Agricultural Research and Development Centre</td>
<td>1977</td>
<td>156</td>
<td>Heating building (Greenhouse)</td>
<td>[13]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Development Centre Miamisburg</td>
<td>1978</td>
<td>2020</td>
<td>Heating building (Swimming pool and recreational building)</td>
<td>[14], [15]</td>
</tr>
<tr>
<td>New Mexico</td>
<td>University of New Mexico (Albuquerque)</td>
<td>1975</td>
<td>175</td>
<td></td>
<td>Heating building (House)</td>
<td>[16], [17]</td>
</tr>
<tr>
<td>Texas</td>
<td></td>
<td>University of Texas (El Paso)</td>
<td>1983</td>
<td>3355</td>
<td>Industrial process heat (food canning factory); Desalination, electrical power production</td>
<td>[18]–[22]</td>
</tr>
<tr>
<td>Illinois</td>
<td>University of Illinois</td>
<td>1987</td>
<td>2000</td>
<td></td>
<td>Heating building (swine research facility)</td>
<td>[22]</td>
</tr>
</tbody>
</table>
The first solar pond was constructed in 1964 in Aspendale, Australia, as shown in Table 1. Although since the first solar pond several research and industrial projects have been constructed, the technology is still under development in several aspects.

In Spain, the technology arrived in 2009 when Solvay decided to construct the first pilot plant in Martorell. The good results obtained in terms of efficiency and performance, [6], lead to the

<table>
<thead>
<tr>
<th>Country</th>
<th>Region</th>
<th>Organization/Location</th>
<th>Year(s)</th>
<th>Capacity (KW)</th>
<th>Project details</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>Bhavnagar</td>
<td>Central Salt and Marine Chemicals Research Inst.</td>
<td>1970</td>
<td>1200</td>
<td>Pilot Plant (research) [23]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Institute’s experimental salt farm</td>
<td>1980</td>
<td>1600</td>
<td>Pilot Plant (research) [24]</td>
</tr>
<tr>
<td>Bangalore</td>
<td>Institute of science in Bangalore (Pondicherry)</td>
<td>100</td>
<td>Pilot Plant (research) [25]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karnataka</td>
<td>Indian Institute of Science</td>
<td>1984</td>
<td>240</td>
<td>Pilot Plant (research) [26],[27]</td>
<td></td>
</tr>
<tr>
<td>Karnataka</td>
<td>Masur</td>
<td>400</td>
<td>Heating building (Rural community) [23]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hubli</td>
<td>300</td>
<td>Heating building (To supply hot water for college) [23]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gujerat</td>
<td>Khuj Dairy (Bhuj)</td>
<td>1987-1991</td>
<td>6000</td>
<td>Industrial process heat (Milk processing dairy plant) [28]</td>
<td></td>
</tr>
<tr>
<td>Asutralia</td>
<td>Aspendale (Victoria)</td>
<td>Commonwealth Scientific and Industrial Res. Org.</td>
<td>1964</td>
<td>44</td>
<td>Pilot Plant (research) [29]</td>
</tr>
<tr>
<td>Laverton (Victoria)</td>
<td>Cheetham Salt Works</td>
<td>1981</td>
<td>900</td>
<td>Pilot Plant (research) [30]</td>
<td></td>
</tr>
<tr>
<td>Alice Spring</td>
<td>Northern Territory</td>
<td>1980</td>
<td>2000</td>
<td>Electrical power production [31]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1984</td>
<td>1600</td>
<td>Electrical power production [32]</td>
<td></td>
</tr>
<tr>
<td>Pyramid Hill (Victoria)</td>
<td>Pyramid Salt Ltd facility/RMIT University</td>
<td>2000</td>
<td>3000</td>
<td>Industrial process heat [33]</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>Martorell</td>
<td>Solvay Martorell</td>
<td>2009</td>
<td>50</td>
<td>Pilot Plant (research) [4]–[6]</td>
</tr>
<tr>
<td>Granada</td>
<td>Solvay Granada</td>
<td>2014</td>
<td>500</td>
<td>Industrial process heat [34]</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Argentina</td>
<td>Puna</td>
<td>1981</td>
<td>400</td>
<td>Chemical production [35],[36]</td>
</tr>
<tr>
<td></td>
<td>Margherita Di Savoia</td>
<td>25000</td>
<td>Desalination [37]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>Zabuya Lake (Qinghai Tibet Plateau)</td>
<td>2500</td>
<td>Chemical production [38]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
construction of larger solar pond in its facilities in Granada. While the first solar pond installed in Martorell had 50m$^2$, the one constructed in Granada have a surface of 500m$^2$, 10 times larger. In Granada, Solvay carries out a mining activity, which requires water at 60ºC. Previously to solar pond construction the heat was produced using a fuel oil boiler. In that context, the company decided to construct the solar pond to obtain the heat in a more sustainable way.

Once constructed, the Granada solar pond was monitored. In this work, all data obtained from the installation is used to deeply analyze the system.

In a first stage, the efficiency of the system is investigated. Several authors, [33], [34], [39]–[43], studied the efficiency of this systems. However, most of them are only considering the energy efficiency. Some authors, [40], [44]–[46], include in their studies an exergy analysis. However, all of them are theoretical models or investigated in pilot plants. In this work, the first energy and exergy analysis of an industrials solar pond is carried out.

The solar pond, constructed in 2015, has been operating successfully along 2 operation periods. Along the first operation period, from July 2014 to June 2015, all variables were successfully recorded. The second operation period started in September 2015 and until summer 2016 no problems were detected in the system. However, the environmental data was only successfully measured until April 2016. Thus, this work includes both periods in the analysis. However, the first one provides more reliable information due to is based in a longer period.

The energy and exergy analysis are a useful tool to understand the feasibility of the technology. However, the economic feasibility of the system is equally important to conclude how mature is the technology. In that context, a thermoeconomic analysis is carried out.

The successful operation in Granada solar pond is based on a salinity gradient, as described in Section 4. The maintenance of this gradient along time is necessary to guarantee the good performance of the system. In Martorell, no problems with the gradient were recorded along the several operation years. In Granada, due to the larger dimensions of the system, some problems to keep the Gradient were detected. After one-year operation the salinity gradient was damaged. In that context, the system was replenished.

A second stage of this project investigates the stability of the solar pond along the first operation year to understand which factor may cause the salinity gradient destruction and when this phenomenon started to occur. In literature, not a single problem with salinity gradient is reported for any solar pond. Additionally, only the solar pond of El Paso in Texas (USA) reports a stability analysis, [47].

As said, the stability of a solar pond is crucial to ensure the proper operation. Despite that,
experimental studies in industrial or pilot plants solar pond are difficult to be found, only in the solar pond of el Paso, Texas, a kind of stability analysis is reported. Different theoretical models are identified in literature.

Stability concept is generally related with stratification. Stratification in water is produced when masses of water at different properties, such as salinity, density or temperature, form different layers without mixing.

A solar pond is a system composed by three main parts: the UCZ, the NCZ and the LCZ. The upper and lower parts of the system are characterized to transfer heat by convection. Convective heat transfer implies water movements; as a consequence, stratification is not possible. On the other hand, the NCZ is the only part of the system where no convective movements are found. When the solar pond is filled, the NCZ is created overlapping layers with different salt concentrations. As a result, the NCZ of a solar pond should be initially stratified, a stability analysis in this region provides information about the initial stability and the evolution of the different layers, put differently, the stability evolution.

The solar pond of El Paso, Texas, has become a reference facility in the world. Constructed in 1985 started its operation in 1985. Different articles and documents have been published reporting different data of the installation. In [33], [47] a kind of stability analysis is reported. The study is based in the NCZ and the boundary regions, NCZ-UCZ and NCZ-LCZ. The internal stability is quantified through the Stability Margin Number (SMN), which may be defined as the ratio of the measured stability coefficient to the calculated stability coefficient required to satisfy the dynamic stability criterion. The solar pond of El Paso was the first system that included the stability analysis of the NCZ as a part of its operation. The difficulty to find in literature some reliable models resulted in the development of a specific methodology for this system, [48].

In Ibrahim Alenezi thesis, [49], the theoretical model to analyze the stability of a solar pond is described in detail. The work is based on the idea that the minimum requirement to keep the stability in the solar pond is that the density in the gradient zone should increase downward to prevent the different layers of the NCZ from mixing and consequently to prevent the salinity gradient to be degraded.

The author insists on the importance of the filling process. As described in Section 4 of this project, during the filling process the salinity gradient is created. If during this process the salinity gradient is not perfectly implemented, the stability of the NCZ will be rapidly affected and consequently there is highly probable to identify gradient degradation after a short operation period.
Two different stabilities are described by I. Alenezi in [49]: static and dynamic stability. Basically, static stability only considers the internals situation of the system. With this parameter the vertical convection movements may be identified. Notwithstanding a solar pond can be also affected by external perturbations, especially by environmental factors such as rain or wind. This may result in an oscillatory movement of the surface of the system, if these waves arrived to the NCZ, the different layers would be mixed. Dynamic stability provides information about all these effects.

Focusing the explanation on the static stability, Alenezi points out that the salt concentration should increase downward. Thus, the lower layers should have a higher salt concentration than the upper ones. This situation is called as positive gradient. The opposite situation, salt concentration decreasing downward, would be called negative gradient. If a negative gradient dominates the system, the salinity gradient will be destroyed or at least the operation of the solar pond affected, resulting in an important efficiency reduction.

In [50], [51] the methodology described in [49] is used to numerically simulate a trapezoidal solar pond of pilot plant dimensions (2.4m x 2.4m an surface and 1m x 1m at the bottom) and to model a SFSP in the south of Tunisia, respectively.

Finally, due to the few articles found analyzing the stability of a solar pond, references based on seawater are also considered. In [52] the static stability is defined as a formal measure of the tendency of water column to overturn. The authors relate the static stability with the stratification, the higher is the stratification the higher the stability. A layer of water is stable if a parcel of water that is moved adiabatically is capable to return to its original position. This capacity depends on the density difference between the layer and the immediately above and below layers. Except the solar pond of El Paso, which developed a specific methodology to study the stability of the system, the other publications only suggest theoretical models, some of them proved with simulation tools but none of them tested in an operative solar pond. In that context, all methodologies previously reported are considered and adapted for the study of Granada solar pond.

All variables were measured every 5 and 10 minutes. Most of the variables are aggregated in 1-hour average variable. Notwithstanding, it represent that a large amount of data need to be treated. In that context, MATLAB codes are necessary to optimize the time and the computational capacity needed for all the studies suggested in this work.
3.1. Scope of the project

The scope of this project is the solar pond constructed in Solvay facilities, Granada. In this work, the system is analyzed in order to have a deep vision of the system.

Previously to any technological and economic analysis, the system needs to be understood. Thus, several sections are dedicated to understand the technology describing the different construction stages. One of the most critical tasks before starting the operation of a solar pond is the filling process. In this way, the different stages of the filling process, the time required to carry out them and the methodology used are also deeply described. During the filling process both temperature and density gradients were tracked, this control process is also included in this work. Although, temperature and density are good parameters to analyze the gradient formation, this section must include information about the salinity gradient. Salinity gradient could not be directly measured during the filling process. However, considering the literature, the salinity gradient may be calculated.

After this description of the system, the maturity of the technology is analyzed through an energy and exergy analysis. In this section, a mathematical model is defined, considering the different literature published, to analyze, specifically, the solar pond installed in Granada. As said in previous section, the system generated an important amount of data. Thus, the mathematical model developed is implemented in MATLAB to provide results with enough accuracy.

The results obtained from technological analysis need to be complemented with the economic perspective. Thus, thermoeconomic methodology is used. As a result, a mathematical model to analyze the Granada solar pond is also developed.

Finally, as previously introduced, the stability of the system is a significant parameter to guarantee the successful operation. In that context, considering all available literature, a mathematical model to analyze the stability and its evolution along operation periods is developed. Once again, due to the large amount of data recorded by the sensors installed in the system, a MATLAB code is necessary to manage the mathematical model.

After the methodology description a long section is dedicated to analyze all the results obtained and to draw the most important conclusions. The results section contains the energy, exergy, thermoeconomic and stability analysis.

With all this analysis the most relevant aspects of the Granada solar pond are analyzed. At the
end, conclusions about the technology reliability, maturity and feasibility, both technical and economic are drawn.
4. Methodology

In this section, the solar pond as a general technology is deeply described as well as the specific characteristics of the Granada solar pond. Additionally, the mathematical models created to analyze the Granada solar pond are also described and justified in this section.

4.1. Operation principles

Solar pond is a technology capable to store part of the solar radiation received in form of heat. The heat may be extracted from the system using heat exchangers. Thus, the heat extracted from the system at one period may have been stored some months before.

The most common solar pond system is composed by water and salt, known as salinity gradient solar pond. The main characteristic of this system is that the water salinity changes along height, from a concentrated solution near the bottom to a diluted solution at the top. Thus, a solar pond is composed by three main zones: The Upper Convective Zone (UCZ), the Non Convective Zone (NCZ) and the Low Convective Zones (LCZ), each zone have a complete different function and, consequently, different physical characteristics.

The UCZ is the highest part of the system, in contact with the environment. The water salinity is constant along this part and, as a result, the density too. This part absorbs and transmits the solar radiation to the zones below. Usually, the UCZ is the thinness part of a solar pond. Additionally, the UCZ protects the NCZ of environmental disturbances, such as wind conditions or water evaporation. The water evaporation is compensated in this zone adding water with low salinity. Immediately below the UCZ, the NCZ is found. Typically, the NCZ is the most width region of a solar pond. In the NCZ, a salinity gradient is necessary; as a result, different layers may be identified in this region with different density and temperature characteristics. Consequently, a density and temperature gradient exist in the NCZ. The NCZ have two main aims, on one hand, transmits the solar radiation to the zone immediately below, the LCZ, on the other, isolates the LCZ and prevents heat stored in this region from escaping. In the lowest layers of the NCZ the temperature is significantly high due to the important isolation provided by the layers of the same zone located immediately above. Finally, the LCZ is the part of the system is charge of storing the solar radiation in form of heat. The salinity of water is constant along this zone and, as a result, the density and temperature are almost constant too.

A solar pond constructed as previously defined is only a storage system. However, the potential of solar pond technology may be enlarged combining this system with other
technologies. In literature, different solar pond defined have been constructed only for investigation. In real applications a solar pond need to have a heat exchanger installed to extract the heat stored. The most common way to extract heat from a solar pond is using a heat exchanger located in the bottom due to is the part with the highest temperature. However, the high temperatures also detected in the lowest layers of the NCZ leave open the possibility of installing a heat exchanger in the solar pond walls, occupying the walls of the UCZ and the lowest part of the NCZ. [6], [33], [43], [53] proves that heat extraction from both LCZ and NCZ may increase solar pond overall efficiency.

As the capacity to store heat in a solar pond is proved in literature. Some researchers, such as [54], studied the possibility to combine a solar pond with solar collectors. The hot water produced in the solar collectors is conducted to the heat exchangers installed in the solar pond to provide heat to the system. The problem of this systems combination is that if only one heat exchanger is installed, heat extraction and heat supply cannot be carried out at the same time. This shortcoming may be overcome installing two heat exchangers in the system, one in the bottom and one in the walls of the LCZ and of the lowest layers of the NCZ. However, this solution notably increases the cost of the system.

4.2. Environmental benefits and sustainability

A solar pond, as renewable energy technology, has different environmental benefits. The large capacity of these systems to store solar radiation makes them attractive for those applications where the heat is not instantaneously consumed. A system composed by several solar collectors may produce the same amount of heat than a solar pond. However, storing large amounts of heat is a difficult task for a solar collectors system, which also have an important cost.

Additionally, most of the solar technologies use an important amount of minerals being silicon the most relevant. The mining associated to these minerals has an important environmental cost. Additionally, these minerals need to be processed, transported and once used disposed off. All this process may cause significant environmental damages.

On the other hand, a solar pond is a system directly constructed in the operation place. Although the materials used in the construction process have an environmental cost, none of them need an intensive mining activity.

The fact of construction the system in the place where is used have several advantages. First, although the materials need to be transported, the final system is installed directly in place where is used. Second, a local activity is created along the solar pond, which may have a positive impact on job creation. Apart from constructing the system, people are needed to carry
out the maintenance tasks along the whole lifetime.

Thus, a solar pond as a renewable system is capable to provide energy without environmental impact. Considering the whole life cycle, not only the operation, a solar pond causes less environmental damages than other renewable technologies. From social point of view a solar pond may have a positive impact on the construction region.

4.3. System description

The Granada solar pond has a clear aim, providing water at least at 60°C to the mineral flotation unit. The flotation unit is not constantly operated. Hence, in some periods the system should be capable to provide more heat than in others. Before the installation of the solar pond all hot water was obtained by using fuel oil combustion. Thus, the solar pond is installed to reduce the amount of fuel oil used and the cost associated while the sustainability of the process increases.

4.3.1. Solar pond general specifications and site characteristics

Table 2 summarizes the main environmental characteristics recorded by the meteorological station installed in the solar pond facilities along the first year of successful operation.

Table 2. Environmental characteristics recorded by the meteorological station along period July 14 - June 15.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Solar Radiation (MJ/m² day)</td>
<td>681</td>
<td>755</td>
<td>496</td>
<td>426</td>
<td>250</td>
<td>266</td>
<td>281</td>
<td>290</td>
<td>511</td>
<td>591</td>
<td>711</td>
<td>766</td>
</tr>
<tr>
<td>Minimum Solar Radiation (MJ/m² day)</td>
<td>25.0</td>
<td>24.3</td>
<td>20.1</td>
<td>17.7</td>
<td>11.0</td>
<td>6.5</td>
<td>6.6</td>
<td>4.6</td>
<td>10.7</td>
<td>13.8</td>
<td>19.4</td>
<td>21.4</td>
</tr>
<tr>
<td>Maximum Daily avg. Temperature (°C)</td>
<td>2.88</td>
<td>2.70</td>
<td>2.72</td>
<td>2.69</td>
<td>3.62</td>
<td>1.91</td>
<td>2.37</td>
<td>3.05</td>
<td>2.78</td>
<td>2.93</td>
<td>3.09</td>
<td>3.82</td>
</tr>
</tbody>
</table>
The total area of the solar pond is 500m\(^2\), the SP is a rectangle of 20m per 25m and have a depth of 2.2m. The total depth is divided by the three regions, from 0 to 0.65m the LCZ, from 0.65 to 2m the NCZ and from 2 to 2.2m the UCZ.

### 4.3.2. Materials

Once the terrain was prepared for the solar pond construction a first layer of insulation material was installed, ChowAFOAM 300-M50 with the characteristics shown in Table 3.

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0.034 W/mK</td>
</tr>
<tr>
<td>Thickness</td>
<td>50mm</td>
</tr>
<tr>
<td>Maximum pressure</td>
<td>300 kPa</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>65°C</td>
</tr>
</tbody>
</table>

Then, a layer of clay pellet (Arlita) was installed on the bottom of the solar pond with a total height of 50mm. The aim of this layer is to protect the insulation from the higher temperatures expected in the LCZ. The insulation of the walls is protected with a geotextile (non-woven polyester GTXnw PS NTL, Atarfil, Spain) of 1mm. Finally, a secondary (PE) liner was installed to prevent leakages in the solar pond, the thickness of this layer 2mm.

---

**Figure 1. Photos of the different materials used in the Solar Pond construction.**

**4.3.3. Measurements and control of solar pond**

The successful operation of a solar pond is based on the salinity gradient. For that reason, different sensors were installed in the system to monitor internal parameters in order to plan...
the optimal maintenance operation tasks. The internal sensors also provide information about
the amount of energy stored and extracted at each period of time.

The stability is related with the density profile along the depth. The operators of the solar pond
manually measured the density, pH and turbidity. The density was measured by a DMA 35
portable densimeter (Anton Par; accuracy of ±0.001 g/cm3), the pH by portable pH meter
(Crison pH25, accuracy of ±0.01 pH) and the turbidity by a portable turbidity meter (Hanna
HI93703C, accuracy of ±0.5 NTU). All this samples were taken every 10cm from the bottom
area.

The temperature inside the solar pond provides information about the current state of the
system and about the capability of the system to provide heat at some period. For that reason,
42 sensors are permanently installed in the solar pond, (thermo-resistances, PT100 type,
Abco, Spain), and uniformly distributed at intervals of 5cm.

Temperature samples are takes every 2 seconds. However, only the 10min average values
are recorded. Hourly, daily and monthly average values are thereafter determined considering
the data exported directly from the system.

The weather parameters are also important to explain the data measured inside the solar pond.
In that context, a meteorological station is also installed in the system. The sensors to measure
each variable and its accuracy are summarized in Table 4.

Table 4. Sensors of the meteorological station in Granada solar pond.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>52202/52203, 2% up to 25 mm/h</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>CS300, ±5% for daily total radiation</td>
</tr>
<tr>
<td>Wind speed</td>
<td>03002, ±0.5 m/s</td>
</tr>
<tr>
<td>Relatively humidity</td>
<td>CS215, ±2%, 10 to 90% RH</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>CS106, ±0.6 mb, 0° to 40 °C</td>
</tr>
<tr>
<td>Air temperature</td>
<td>CS215, ±0.4 °C, over +5 to +40 °C</td>
</tr>
</tbody>
</table>

All previous parameters are measured every 10seconds.

Finally, to control the heat extraction process, the inlet and outlet temperatures of the heat
exchanger installed in the solar pond are measured with thermal sensors (PT100) and the total
inlet flow rated is controlled by a flow meter (SMC).
4.3.4. **Heat extraction system.**

In Granada solar pond only one heat exchanger is used to extract heat from the system, located in the bottom.

The heat exchanger was built using a PE pipe with 28mm of internal diameters and 32mm of external. The thermal conductivity is approximately 0.33 W/mK. As for the length, the heat exchanger is divided in six independent spirals of 200m, consequently, the total length of the heat exchanger is 1200m.

The heat stored in the solar pond is extracted using the previously described heat exchanger. The main aim of this heat extraction is preheating the water needed in the flotation unit.

Figure 2 shows a scheme of the integration of the solar pond with the flotation unit and how heat is extracted from the system. The system has two systems to hot the water needed by the flotation unit: the solar pond and a fuel oil boiler, both systems can be combined.

![Scheme of solar pond integration on Solvay facilities in Granada.](image)

In the simplest operation mode, the fresh water is directly directed to the fuel oil boiler where is heat up to 60ºC. This operation mode was used before construction the solar pond. However, this mode has a high operation cost associated due to the cost of the fuel oil.

To reduce the operation cost and to increase the sustainability of the system the solar pond was constructed next to the facilities. The introduction of the solar pond changed the operation pattern. In this case, the fresh water is firstly directed to the solar pond heat exchanger where the water is heated up. This water flux is directed to a second heat exchanger where transmits
the heat to the flotation unit water circuit. After this second heat exchanger, the water in the flotation unit circuit almost never achieve the 60ºC. In this case, the fuel oil boiler is used to complement the solar pond and to increase the water temperature up to 60ºC.

4.4. Filling process

The successful operation of a solar pond is based on the salinity gradient established in the NCZ. Thus, the establishment of this gradient zone is a critical task when the system is filled. Different authors have studied different techniques to create this salinity gradient, being the water injection the most common and efficient one, [5], [20], [55], [56]. This method is valid to establish both the salinity and thermal gradient of the solar pond.

In this section the filling process used to fill the Granada solar pond is described step by step.

First, the pond was filled up to 1.32m, \((h \text{LCZ} + \frac{1}{2} h \text{NCZ})\), with saturated brine. This height corresponds to 662.5 m³, thus, a significant amount of brine is needed, which was transported by trucks to the facility simultaneously with the filling process.

Second, the salinity gradient was created injecting low-salinity water with a specifically designed and constructed diffuser (Figure 3). The overall diameter of the diffuser was 500mm, the thickness 27mmm and the gap vertical dimensions 3mm.

![Diffuser especially constructed to fill Granada Solar Pond.](image)

The injection started with the diffuser at 0.65m from the bottom, as said, this height corresponds to the LCZ-NCZ boundary. The water was injected with a velocity of 250L/min. According to literature, the Froude number \((Fr)\) is a critical parameter to guarantee the successful establishment of the salinity gradient. Froude number is a parameter that related the kinetic energy to the gravitation potential energy of the injection fluid. \(Fr\) may be determined using the following equation described in literature by [56]:
Different authors, [5], [33], reported from experimental experiences that a Froude number of 18 or below is necessary to establish the salinity gradient. In Granada, a Froude number of almost 16 was used near the top of the pond and a value of 4 near the LCZ. To ensure the establishment of the salinity gradient, the total height was divided in different layers of 50mm. Considering the mass flow rate, the system needed 1.7h to fill a layer. Then, the injection system stopped 30 minutes to reach the equilibrium. During the filling, a sampling process is carried out to verify the correct establishment of the salinity gradient, which take to the operators 30 minutes more. Hence, the establishment of a layer needed almost 3 hours. This second stage was repeated until the NCZ-UCZ boundary was reached. 13 injections steps during 5 days were necessary.

Finally, the UCZ was filled injecting fresh water at 25L/min mass flowrate on the surface through a flotation system to avoid mixing.

Figure 4 shows the density results obtained from the sampling process. Clearly, the density gradient was established while the solar pond was filled. During the same period, although when the solar pond was not completely filled, a temperature gradient was detected to the solar pond, Figure 5.

![Figure 4. Density gradient formation during the filling process.](image-url)
4.5. Operation and maintenance

The surface of the solar pond is the part most affected part by the environmental impacts. Windy, rainy, snowy… conditions may produce important turbulences and affect the salinity gradient. The previous environmental impacts are not constant, hence, the affectation caused by these events need to be corrected once they happened. The necessary solar radiation required to successfully operate a solar pond causes an important impact on solar pond surface, water evaporation. The water evaporated need to be supplied in order to keep the UCZ depth as constant as possible. Hence, fresh water is frequently added to the surface using a pipe of 0.15m in diameter. The mass flow rates depend on the season of the year and the intensity of solar radiation and ambient temperature but always between 1 and 3L/min. The average consumption of low-salinity water was 680 ± 20 m3/year with higher consumption (> 100 m3/month on average) during the summer season (May to September) and lower consumption during the winter season (December to February) with values below 5 m3/month on average.

All environmental impacts and the changes in temperature found inside the solar pond causes salt loses by diffusion. In this case, salt added to the system in order to keep enough salt to maintain the level of saturation at LCZ To compensate this loses two salt chargers are employed to add salt to the bottom. The chargers are PVC cylinders of 1.2m diameter. The salt flowing from the chargers produce a semi-con around the cylinder.

Figure 5. Temperature gradient formation during the filling process.
The average consumption of salt during the first operation period was 800 kg/month during the winter season and 1500 kg/month during spring. When the salinity gradient was established, a large consumption of salt was necessary because the storage area was not at the saturation concentration. The frequency of the salt supply varied depending on the season. Therefore, the salt chargers were filled three times a month during the cold months and four or five times per month during the warm months.

The operation of the solar pond is based on the penetration of solar radiation. Hence, the clarity of the system should be guaranteed. For that reason, an acidification system was installed to regulate the pH and to prevent the growth of algae. The system is composed by ten PVC pipes of different lengths to distribute the acid in the different layers of the pond, from LCZ-NCZ interface to the top. The acid added to the system is hydrochloric acid at 35% w/w and is added at low velocity by a peristaltic pump.

Figure 6. Operation and maintenance systems: a) overflow system, b) salt charger and c) acidification system.
4.6. Evolution of the salinity gradient

As have been said in the introduction of this project, some problems appeared in the solar pond of Granada after few operation months. In this section, the evolution of density and temperature gradients is investigated.

In a correct operation, the temperature gradient should change depending on the season, thus, in summer higher temperatures would be measured than in winter. The impact of the season on density gradient should be much lower. As the salinity gradient located in the NCZ is the most critical parameter to ensure the successful operation temperature and density were constantly measured and analyzed to control the evolution of the salinity gradient.

The solar pond in Granada started its operation in July 2014 with the salinity gradient described in Section 4.4 (Figure 7a). In the LCZ, the density was kept almost constant for 10 months with an average value of 1203 kg/m³ and the temperature evolved according to the weather conditions. The initial temperature in the LCZ recorded in the solar pond once the salinity gradient was established was 42.7 °C. Thanks to the high solar radiation during the first month, the temperature in the LCZ increased by 1.5 °C per day on average, reaching a maximum temperature of 89 °C at the end of August 2014 as can be seen in Figure 8. As a result, 63010 MJ was stored in the LCZ alone during the first months of operation.

As for the UCZ, the density was more variable due to two main aspects: the variations in the ambient air temperature on one hand and the diffusion of the salt from the lower area to the surface on the other. During the operation period, this problem was managed adding fresh water on the surface at a low flow rate, as described in Section 4.5. As a result, a maximum surface concentration of 4% was ensured. The degradation of the salinity gradient was detected by the density profile monitoring as the height to the UCZ increases from 0.3 m in July 2014 to 0.8 m in April 2014 (Figure 7a). Although the same trend was observed in the evolution of the temperature profile (Figure 7b) the average monthly temperature of the LCZ not decreased below 40 °C, Figure 8. In April 2015, the salinity gradient was considered to be technically destroyed. Notwithstanding, the system was able to provide the expected heat flow to the flotation unit for two more months, after which the solar pond stopped its operation. During the non-operation period, the system was evaluated based on the recorded data in order to identify the causes of the deterioration of the salinity gradient. As a result, it was concluded that the weather conditions, especially the influence of winds on surface waves, were the main mechanism affecting the stability of the salinity gradient. Additionally, some operation and maintenance patterns would have contributed to the deterioration of the gradient. However, to provide a deeper analysis of the degradation of the salinity gradient a
stability analysis would be also carried out in this project.

In September 2015, the solar pond was refilled using the water injection method as described in Section 4.4 started. Figure 7a shows the density gradient once the solar pond was refilled and how it evolved during this second operation period. Degradation of the gradient was not observed during the second operation period. As for the temperature evolution, the system was able to keep the LCZ monthly average temperature within a reasonable range even though the system started working during a clearly less favorable season (autumn), Figure 8.

Figure 7. a) Evolution of the density gradient and b) evolution of the temperature gradient during operation in 2014 and 2015.
4.7. Salinity of the solar pond

The gradient of the solar pond is controlled along the process measuring the density and temperature due to water salinity cannot be directly measured with the different sensors installed or available in the system. Both temperature and density gradients provide information of the depth of each layer and tracking both gradients the degradation of the salinity gradient, if produced, can be identified.

Notwithstanding, the water salinity is influenced both by temperature and density of water. Although salinity is not essential during solar operation to control the system, this parameter is necessary to perform a deep study in terms of energy, exergy and solar pond stability.

In that context, in this section how the salinity may be determined considering the recorded data in the system is detailed.

Different authors reported tables containing the water salinity at certain temperature and density. In this work the table reported in [57] and shown in Figure 9 is used to determine a function for water salinity from temperature and density.
Figure 9. Density as function of temperature and salinity concentration.

From this table, Figure 10 is created. The figure contains the equation necessary to determine the salinity concentration from density at a certain and known temperature.

Figure 10. Salinity as function of density at certain temperature.

From previous equations, it is concluded that water salinity depends almost linearly on density. Thus, the salinity equation may be described as:

\[ S = a \cdot \rho + b \]  \hspace{1cm} (2)

Where \( a \) and \( b \) coefficients depend on temperature. Hence, the different values of \( a \) and \( b \)
obtained (Figure 10) are independently analyzed to find a function, based only in temperature, to determine them. Table 5 summarizes the different results of these coefficients obtained under different temperatures.

Table 5. Coefficients a and b at given temperatures.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>283</td>
<td>0.1283</td>
<td>-128.03</td>
</tr>
<tr>
<td>298</td>
<td>0.1317</td>
<td>-131.03</td>
</tr>
<tr>
<td>313</td>
<td>0.134</td>
<td>-132.63</td>
</tr>
<tr>
<td>333</td>
<td>0.1357</td>
<td>-133.08</td>
</tr>
<tr>
<td>353</td>
<td>0.1362</td>
<td>-132.04</td>
</tr>
</tbody>
</table>

In Figure 11a and 11b the different values of a and b are represented, respectively. As in previous case, the most appropriate trend line is used to find the equation that relates each parameter with water temperature. In this case, a cubic equation is necessary to describe the tendency of the parameters.

\[
y = 8.8481 \times 10^{-9}x^3 - 1.0328 \times 10^{-5}x^2 + 3.9865 \times 10^{-3}x - 3.7325 \times 10^{-1}
\]

\[R^2 = 1.0000 \times 10^0\]
Thus, the equation to determine the water salinity, based on information reported in Table 5 and its analysis, is defined as follows:

\[
S = (8.8481 \cdot 10^{-9} \cdot T^3 - 1.0328 \cdot 10^{-5} \cdot T^2 + 3.9865 \cdot 10^{-3} \cdot T - 3.7325 \\
\cdot 10^{-1}) \cdot \rho + (-1.150 \cdot 10^{-5} \cdot T^3 + 1.333 \cdot 10^{-2} \cdot T^2 - 5.029 \cdot T \\
+ 4.885 \cdot 10^2) \tag{3}
\]

With previous equation the evolution of the salinity along the different operation period is determined. The sensors installed in the system measure the internal temperature every 10 minutes. However, the density needs to be measure manually. Hence, only 3 or 4 density measures per months were carried out. Figure 12a and 12b shows the salinity gradient evolution along the first and the second operation periods. The days shown in the figure coincide with the density-measured day. As knowing the exact hour of density measurement, it was assumed that all of them were recorded at 12:00h. Thus, the temperature considered is the recorded at 12h of the analyzed day.
Figure 12. a) Evolution of the salinity gradient the first operation period. b) Evolution of the salinity gradient the second period of operation.
As in temperature and density gradients reported in previous sections, in the salinity gradient the three main zones of the solar pond are perfectly identified. In the LCZ, high and constant values of salinity concentration are identified, between 30 and 33%. The NCZ is the most critical part due to the presence of the salinity gradient. The salinity concentration varies from almost 33% in the deepest layers of the zone the 3-4% in the most superficial ones. In the UCZ, as in LCZ, the salinity concentration is almost instant, in this case, with values around 3%.

It is worth to mention that degradation was identified in the gradient of the solar pond. Along each operation period the NCZ tend to decrease its height while the LCZ and UCZ increase. The NCZ is an essential part of the system to ensure heat transmission to the LCZ and its isolation. The degradation of the salinity gradient and the reduction of the NCZ may lead to a reduction in system efficiency.

A long section of this project is dedicated to study the stability of the system to understand when and where the gradient started to degrade. This information may be useful to prevent future salinity gradient degradations.

4.8. Economic parameters of the system

In this section the CAPEX and OEPEX cost associated to the system are detailed. The economic evaluation is essential in a work that wants to analyze the feasibility and maturity of this technology.

4.8.1. CAPEX

The CAPEX cost is referred to the investment cost. The total CAPEX may be divided in seven different chapters associated to the different construction stages:

1. Land movements
2. Coating
3. Pipes installation
4. Civil work
5. Salinity gradient formation
6. Instrumentation
7. Others

In Table 6 the different costs found in each chapter are reported as well as the total cost of the chapter and the total investment cost of the Granada solar pond.
Table 6. CAPEX of Granada solar pond divided in different sections considering the different constructions stages.

<table>
<thead>
<tr>
<th>CAPEX</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 1: Earthwork</td>
<td>10,066.8 €</td>
</tr>
<tr>
<td>Land movement</td>
<td>6,461.8 €</td>
</tr>
<tr>
<td>Hours of crane</td>
<td>240.0 €</td>
</tr>
<tr>
<td>Hours of earthwork machines</td>
<td>1,797.5 €</td>
</tr>
<tr>
<td>Excavation hours</td>
<td>1,567.5 €</td>
</tr>
<tr>
<td>Chapter 2: Liner</td>
<td>4,153.3 €</td>
</tr>
<tr>
<td>Liner installation</td>
<td>4,153.3 €</td>
</tr>
<tr>
<td>Chapter 3: Pipes</td>
<td>5,394.8 €</td>
</tr>
<tr>
<td>Pipes installations</td>
<td>2,750.0 €</td>
</tr>
<tr>
<td>Hydraulic Pump</td>
<td>106.6 €</td>
</tr>
<tr>
<td>Plumbing</td>
<td>2,538.2 €</td>
</tr>
<tr>
<td>Chapter 4: Civil work</td>
<td>28,984.6 €</td>
</tr>
<tr>
<td>Construction</td>
<td>28,672.6 €</td>
</tr>
<tr>
<td>Iron mesh</td>
<td>312.0 €</td>
</tr>
<tr>
<td>Chapter 5: Salinity gradient formation</td>
<td>11,678.5 €</td>
</tr>
<tr>
<td>Salt consumption</td>
<td>11,678.5 €</td>
</tr>
<tr>
<td>Chapter 6: Monitoring</td>
<td>22,013.6 €</td>
</tr>
<tr>
<td>Solar pond instrumentation</td>
<td>18,817.5 €</td>
</tr>
<tr>
<td>Lab instrumentation</td>
<td>3,196.1 €</td>
</tr>
</tbody>
</table>
The total investment cost of construction and starting the operation of Granada solar pond ascend to \(91,083.7\)€. The investment cost per unit surface corresponds to approximately \(190\$/m^2\) as published in [58].

### 4.8.2. OPEX

The OPEX cost is referred to the operation and maintenance costs. The most important operation and maintenance costs in a solar pond are the substances that should be added in the system to keep the salinity gradient and to ensure the proper operation of the system.

In Table 7, OPEX associated to Granada solar pond are summarized.

**Table 7. OPEX of Granada solar pond.**

<table>
<thead>
<tr>
<th>OPEX</th>
<th>Amount (annual)</th>
<th>Unit cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>540 m(^3)/year</td>
<td>0.25 €/m(^3)</td>
<td>135.0 €/year</td>
</tr>
<tr>
<td>Salt (NaCl)</td>
<td>10000 Kg/year</td>
<td>0.1 €/kg</td>
<td>1,000.0 €/year</td>
</tr>
<tr>
<td>Reactants</td>
<td>1320 l/year</td>
<td>0.25 €/l</td>
<td>330.0 €/year</td>
</tr>
<tr>
<td>Communications</td>
<td></td>
<td></td>
<td>144.0 €/year</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td>1,000.0 €/year</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>2,609.0 €/year</strong></td>
</tr>
</tbody>
</table>

The total operation and maintenance cost associated to Granada solar pond ascend to **2,609.0€/year**. As reported in [58], the operation and maintenance cost ascend to 3% of the investment costs.

### 4.9. Energy and exergy analysis

A solar pond is a system capable to store part of the received solar radiation for a long period of time and provide heat to an external application. Thus, the heat extracted one day from the solar pond may have been stored some months before. In that context, this work suggests a cumulative study to analyze the performance of the system, i.e. all variables are considered since the beginning of the operation period.
As previously described, each zone of the system has a different purpose in the solar pond. Thus, the energy and exergy performance of each zone, independently analyzed, have a special interest. However, a global vision of the system in terms of energy and exergy is also necessary to understand the maturity, reliability and technological feasibility of the technology. In Figure 13 the heat fluxes in each layer of the system are represented, each flux has associated an energy and exergy value.

Figure 13. Schematic heat fluxes in the solar pond.

Different authors, such as H.O. Njoku et al. in [46], suggested theoretical models to study both the energy and exergy performance, other authors, [40], [41], [44], [45], developed and implemented the energy and exergy models in small solar ponds. In this work, the mathematical models reported in literature are considered and adapted in order to evaluate the energy and exergy performance of an industrial solar pond.
4.9.1. Energy

4.9.1.1. Energy flows

In this section, all energy fluxes found in the system are detailed. As said, a solar pond is a system created to store heat, which is provided to an external application some time later. Hence, the amount of energy stored can be determined as the difference between all input and output energy fluxes.

\[
Q_{\text{stored layer}_i} = \sum_{t=0}^{t} Q_{\text{in layer}_i,t} - \sum_{t=0}^{t} Q_{\text{out layer}_i,t}
\]  

\(Q_{\text{in layer}_i,t}\) is composed by the solar radiation absorbed by the layer \((Q_{abs layer_i,t})\) and by the heat transferred from lower or/and upper layers \((Q_{int layer_i,t-layer_{i+1},t})\). \(Q_{out layer_i,t}\) is composed by the heat transferred to lower and/or upper layers \((Q_{int layer_{i+1},t-layer_i,t})\), by the heat extracted from the system \((Q_{ext,t})\) and by the heat lost \((Q_{loss layer_i,t})\).

The heat stored in each zone along a certain period may be obtained comparing the temperature at the beginning of the period with the temperature at the end.

\[
Q_{\text{stored layer}_i,t} = \text{mass}_{layer_i} \cdot C_{layer_i} \cdot (T_{layer_i,t} - T_{layer_i,t-1})
\]

Where \(T_{layer_i,t}\) is the temperature of the layer at the end of the period, \(T_{layer_i,t-1}\) is the temperature of the layer at the beginning, \(C_{layer_i}\) is the water heat capacity and \(\text{mass}_{layer_i}\) is the total mass of the zone.

The \(Q_{\text{stored layer}_i,t}\) in the LCZ and UCZ may be determined using the average temperature of the zones because of there is small temperature variations. However, in the NCZ the presence of the temperature gradient results in significant variation in temperature values from one sensor to another. Hence, the NCZ should be divided in different sub-layers and the energy stored in each sub-layer independently determined. At the end, the energy stored in the NCZ is the sum of energy stored in all layers.
The input energy to each layer coming from solar radiation is the result of multiplying the net solar radiation at depth of the layer \(I_{xt}\) by the area of the layer \(A\).

\[
Q_{\text{sin}_{lt}} = I_{xt} \cdot A_i
\]  

(6)

The net solar radiation \(I_{xt}\) may be obtained through the methodology described in ANNEX Section 1.

Solar radiation is represented in Figure 13 as an input. However, \(Q_{\text{sin}}\) represents the amount of energy that arrives to each layer. Part of this energy is transmitted to the layer immediately below. Hence, there is a solar radiation input and output flux. In this way, to consider solar radiation only as input flux the concept of absorbed energy is suggested which balances the input and output fluxes of solar radiation in each layer.

\[
Q_{\text{abs}_{layer_{lt}}} = Q_{\text{sin}_{layer_{lt}}} - Q_{\text{in}_{layer_{i+1,t}}}
\]  

(7)

The different zones of the system in contact between them have different temperature characteristics. As a result, part of the heat is transmitted from the layer at higher temperature to the one at lower one. Typically, the heat is transferred from LCZ to NCZ and from NCZ to UCZ. However, in some periods these heat fluxes may be reversed.

These internal heat fluxes are mostly transmitted by conduction and may be determined through the general equation described in [57]:

\[
Q_{\text{int}_{layer_{lt} \rightarrow layer_{i+1,t}}} = \frac{T_{lt} - T_{i+1,t}}{R_{\text{cond}_{i \rightarrow i+1,t}}}
\]  

(8)

The previous equation assumes that the heat fluxes are transferred from layer \((i)\) to layer \((i + 1)\). A negative result would indicate the opposite heat transfer. \(T_{i}\) is the temperature measured by the sensor of the heat emitter zone closest to the close heat receiver one, \(T_{i+1}\) is the temperature measured by the sensor of the heat receiver zone closest to the heat emitter one and \(R_{\text{cond}_{i \rightarrow i+1}}\) is the conductive resistance, which can be determined as follows:

\[
R_{\text{cond}_{lt}} = \frac{\Delta z}{A_i \cdot k_{lt}}
\]  

(9)

Where \(\Delta z\) is the thickness of the contact zone, i.e. the height difference of the sensors used in
temperatures measurements, \( A \) is the area of the contact zone and \( k \) is the thermal conductivity, Eq. 22. Thermal conductivity is defined in [62] relating the temperature in the contact zone \( (T) \), the composition of the water \( (m) \), Eq. 23, and an optimal coefficients \( (a) \).

\[
\kappa_{i,t} = \sum_{l=0}^{2} \left( \sum_{j=0}^{2} a_{ij} T_{i,t}^j \right) m^l
\]

(10)

Thus, the water composition is proportional to the salinity \( S_{i,t} \) of the solar pond.

\[
m_{i,t} = \frac{S_{i,t} \cdot 1000}{54.44 (1 - S_{i,t})}
\]

(11)

The heat extracted from the solar pond is an output energy flux only found in the LCZ. The amount of heat extracted may be determined through the following equation:

\[
Q_{\text{ext}} = \dot{m}_{\text{ext}} \cdot C_p \cdot (T_{\text{ext}} - T_{\text{in}}) \cdot \text{Time}
\]

(12)

Where \( \dot{m}_{\text{ext}} \) is the mass flow rate of the extractions directly measured, \( C_p \) is the water heat capacity, \( T_{\text{ext}} \) the water temperature after solar pond heat exchanger, \( T_{\text{in}} \) the water temperature before heat exchanger and \( \text{Time} \) the period in seconds while heat is extracted from the system.

Finally, part of the energy that arrives in the system is lost in different ways. Energy losses are found in the bottom, walls, surface... due to the difficulty to determine each type of losses, all of them are considered in a single variable determined as the difference between all energy input fluxes to the zone and all energy output fluxes from the zone and the energy stored in the zone.

\[
Q_{\text{loss}_{\text{layer}_i}} = \sum_{0}^{t} \left[ Q_{\text{abs}_{\text{layer}_i,t}} + Q_{\text{int}_{\text{layer}_{i+1,t} \rightarrow \text{layer}_i,t}} + Q_{\text{int}_{\text{layer}_{i-1,t} \rightarrow \text{layer}_i,t}} \right] - \sum_{0}^{t} \left[ Q_{\text{int}_{\text{layer}_i,t} \rightarrow \text{layer}_{i+1,t}} + Q_{\text{int}_{\text{layer}_i,t} \rightarrow \text{layer}_{i+1,t}} \right] + Q_{\text{stored}_{\text{layer}_i,t}} (Q_{\text{ext}_t})
\]

(13)
4.9.1.2. Energy efficiency

Different models to determine the efficiency of solar ponds are defined in literature, [33], [39]–[43]. Both energy and exergy efficiencies are defined as the ratio between the useful energy/exergy and the total input energy/exergy to the system. In a solar pond system useful energy and exergy correspond to the stored and the extracted fluxes, the input energy and exergy are the associated to the solar radiation. Notwithstanding, the efficiency of each zone independently has an important interest to understand the function of each layer and how it works. In this case, the input energy/exergy also contains the internal gains.

An instantaneous efficiency analysis suggested by [63] have important shortcomings. First, the instantaneous efficiency in periods while the solar pond is storing energy is not representative of the global efficiency of the system. Second, the heat extracted at some period is not a result of the instantaneous solar radiation is the result of the previously stored solar radiation. Third, in periods while the solar pond is not storing energy and no heat extractions take place an efficiency of 0% would be obtained which is neither representative.

This shortcoming may be overcame considering longer periods, in [34] a monthly efficiency is suggested and the overall efficiency of the system is determined as the average of all monthly efficiencies.

As previously said, the heat stored at some period of time may be used some months later. For that reason, a cumulative model is suggested in this work. Hence, the energy efficiency at the end of a period considers all events occurred since the beginning of the operation period.

Thus, energy efficiency of each layer and the overall energy efficiency are determined through Eq. 35 and Eq. 36, respectively.

\[
\eta = \frac{\sum Q_{\text{stored layer } i, t} + Q_{\text{ext } t}}{\sum Q_{\text{abs layer } i, t} + Q_{\text{int layer } i+1, t \rightarrow \text{layer } i, t} + Q_{\text{int layer } i-1, t \rightarrow \text{layer } i, t}}
\] (14)

The overall efficiency of a solar pond is determined considered all layers of the system. Additionally, when the whole system is analyzed the internal heat transfers are compensated. The following equation is used to determine the overall energy and exergy efficiency.
\[
\eta = \frac{\sum_{i=L}^{0} \sum_{t} \left[ Q_{\text{stored layer },lt} + Q_{\text{ext },t} \right]}{\sum_{i=L}^{0} \sum_{t} \left[ Q_{\text{abs layer },i,t} \right]} \quad (15)
\]

In previous equation the, the time and depth variables are eliminated in order to have a global vision of the system after a long operation period. Thus, the result obtained is the overall energy efficiency of the solar pond at the end of the operation period.

### 4.9.2. Exergy

#### 4.9.2.1. Exergy flows

Energy does not provide information about the quality of the energy form. The exergy analysis may overcome these shortcomings. The exergy considers the useful part of the energy flux in a given environment with a given parameters.

As in energy analysis, the exergy stored at the end of one period is the difference between all exergy input and output fluxes.

\[
E_{\text{stored layer },i} = \sum_{0}^{t} E_{\text{in layer },i,t} - \sum_{0}^{t} E_{\text{out layer },i,t} \quad (16)
\]

\(E_{\text{in layer },i}\) is composed by the exergy of the solar radiation absorbed by the layer (\(E_{\text{abs layer },i}\)) and by the exergy transferred from lower or/and upper layers (\(E_{\text{int layer },i-1}^{\text{layer },i+1}\)). \(E_{\text{out layer },i}\) is composed by the exergy transferred to lower and/or upper layers (\(E_{\text{int layer },i+1}^{\text{layer },i}\)), by the exergy extracted from the system (\(E_{\text{ext }}\)), by the exergy losses (\(E_{\text{loss layer },i}\)) and by the exergy destroyed (\(E_{\text{destroyed layer },i}\)).

The exergy stored in each layer may be also determined as follows:

\[
E_{\text{stored layer },i,t} = e_{\text{ph}} + e_{\text{ch}} \\
= \text{mass}_{\text{layer },i} \cdot C_{p_{\text{layer },i}} \cdot \left( T_{\text{layer },i,t} - T_{\text{layer },i,t-1} \right) \left( T_0 \ln \left( \frac{T_{\text{layer },i,t}}{T_{\text{layer },i,t-1}} \right) \right) + x_i \cdot e^0_{\text{ch}} \cdot x_{\text{ch}} \\
+ R \cdot T_0 \cdot x_i \ln (x_i) \quad (17)
\]
The exergy stored is composed by the physical exergy \( e_{ph} \) and the chemical exergy \( e_{ch} \). According to L. Fitzsimons et. al., [64], the chemical exergy has much less influence than the physical one because there are no chemical reactions and the chemical changes are relatively small. For that reason, this term is omitted in all solar ponds studies from an exergy point of view. This work, in order to provide a more accurate analysis also includes this term which is based on the study of L. Fitzsimons et al., [64].

In Eq. 38, some terms are included for the first time in the analysis. Thus, \( x_i \) is the molar fraction of the solute (NaCl), \( e_{x, ch}^0 \) is the standard molar chemical exergy of the NaCl, obtained from [65], and \( R \) is the universal gas constant. As in energy analysis, while the \( E_{stored_{layer_1}} \) in the LCZ and UCZ may be determined using average values, the NCZ should be divided in different sub-layers due to the temperature gradient.

The solar radiation energy flux is a radiative energy; the exergy associated to radiative heat fluxes may be defined as follows:

\[
E_{abs_{layer_1,t}} = Q_{abs_{layer_1,t}} \left( 1 - \frac{4}{3} \left( \frac{T_0}{T_s} \right)^2 + \frac{1}{3} \left( \frac{T_0}{T_s} \right)^4 \right)
\] (18)

The exergy is transferred from an emitter source (the sun) at a given temperature, \( T_s \) (\( \approx 6000 K \)), to the solar pond through a medium at ambient temperature.

This work analysis each zone of the solar pond independently, the heat transferred between the different layers is mainly done by conduction. Conductive, convective and evaporative exergy may be determined using the following equation:

\[
E_{int_{layer_{i,t} \rightarrow layer_{i+1,t}}} = Q_{int_{layer_{i,t} \rightarrow layer_{i+1,t}}} \left( 1 - \frac{T_0}{T_{i,t} - T_{i+1,t}} \right)
\] (19)

The exergy of the extracted energy may be determined using the same exergy equation than in exergy stored. However, in this case and as in energy analysis, instead of using the mass, the mass flow rate and the extractions time are used.

\[
E_{ext_t} = \dot{m}_{ext_t} \cdot C_p \cdot \left( T_{ext_t} - T_{int_t} \right) - \left( T_0 \ln \left( \frac{T_{ext_t}}{T_{int_t}} \right) \right) \cdot Time
\] (20)

Part of the exergy of the system is lost to the environment and part of the exergy is destroyed.
due to irreversibility. In energy analysis, the variable $Q_{\text{loss}_{layer_t}}$ contains different types of energy losses; consequently, determining the associated exergy to this parameter is not possible. The exergy associated to energy losses cannot be independently determined with the available data measured by the sensors. Thus, this work aggregates the exergy losses and the exergy destroyed due to irreversibility in the same parameter. This variable contains all useless exergy of the system.

\[
E_{\text{useless}_t} = \sum_{0}^{t} \left[ E_{\text{stored}_{layer_{lt}}} + E_{\text{int}_{layer_{t+1}\rightarrow layer_{lt}}} + E_{\text{int}_{layer_{t-1}\rightarrow layer_{lt}}} \right] \\
- \sum_{0}^{t} \left[ E_{\text{int}_{layer_{lt}\rightarrow layer_{t+1}}} + E_{\text{int}_{layer_{t}\rightarrow layer_{t-1}}} \right] \\
+ E_{\text{stored}_{layer_{lt}}} \left( +E_{\text{ext}_{t}} \right) \tag{21}
\]

### 4.9.2.2. Exergy efficiency

Solar pods from exergy point of view are not as deeply studied as from energy perspective. However, some authors report studies regarding the exergy efficiency of this system. M. Khalilian in [45] determined the exergy efficiency of a pilot plant solar pond as the ratio between the exergy stored by the system and the solar exergy received by the system. However, heat extractions were considered because were no carried out in this small system. H.O. Njoku et al., [46] suggested that the exergy efficiency of an industrial solar pond should consider heat extractions. Thus, the exergy efficiency is represented as the ratio between the exergy stored plus the exergy extracted from the system and the solar exergy received. This model is only mathematically defined and experimental results were not reported.

Additionally, a solar pond is a system based on mid-term operation due to its capacity to store exergy several months. Hence, the cumulative exergy should be determined. The overall exergy efficiency of the system is the one obtained after one-year of successful operation.

Thus, the exergy efficiency of each layer can be calculated through the following equation:

\[
\psi = \frac{\sum_{0}^{t} \left[ E_{\text{stored}_{layer_{lt}}} + E_{\text{ext}_{t}} \right]}{\sum_{0}^{t} \left[ E_{\text{stored}_{layer_{lt}}} + E_{\text{int}_{layer_{t+1}\rightarrow layer_{lt}}} + E_{\text{int}_{layer_{t-1}\rightarrow layer_{lt}}} \right]} \tag{22}
\]

The overall exergy efficiency of the system after one-year period operation may be determined
considered all layers of the system.

\[
\psi = \frac{\sum_{i=0}^{i_{TOT}} \sum_{t} \left[ E_{\text{storedlayer}_k} + E_{\text{ext}_k} \right]}{\sum_{i=0}^{i_{TOT}} \sum_{t} E_{\text{abslayer}_k}}
\]

(23)

As in energy analysis, the overall exergy efficiency eliminates the time and depths variables. Thus, a global vision of the system at the end of an operation period may be obtained.

### 4.9.3. Thermoeconomic analysis

As described by E. Querol et al., [66], thermoeconomics is an important branch of engineering that combines theories and methodologies of thermodynamics and economics. The main difference between thermoeconomics and thermodynamics is the variable considered. While energy is considered in thermodynamic analysis, exergy is considered in thermoeconomics. As previously introduced, exergy accounts only the fraction of energy that may be useful in a certain environment. Hence, in thermoeconomic not only the system or the technology is considered, thermoeconomic considers the feasibility, technical and economic, of a certain system in a certain environment.

The exergy of associated to the different variables involved in the system are taken as basis for the economic cost allocation between the different fluxes, inlet and outlet.

The authors also identify different purposes of a thermoeconomic analysis:

1. Calculate the cost of all fluxes of the system analyzed.
2. Analyze the cost formation process and flow inside industrial processes.
3. Evaluate the cost of the exergy destroyed.
4. Give information to optimize the performance of the system and of each component in the system independently.
5. Give information to optimize the products production.

In [67] thermoeconomic analysis are pointed out as a useful tool to obtain information not available in conventional energy and economic evaluations. The methodology is interesting not only in the design stage but only to find the optimal operation point.

In [67], G. Tsatsaronis et al. identify 4 main aims of a thermoeconomic analysis.

1. Calculate the cost of each product, independently, generated by a system.
2. Understand the cost formation process and the flow of costs in the system.
3. Optimize specific variables of a component or of the whole system.
4. Optimize the overall costs in the system.

Most of the examples found in literature of thermoeconomic analysis are based on energy conversion systems, such as [67]–[69], using Rankine or Bryton cycles. In these analyses the authors optimize each element of the systems. As a result, the whole system is optimized by the optimization of each element.

Mathematically, a thermoeconomic analysis may be described by the equation reported by S. de Oliviera, [70].

$$\sum_{k} \dot{\eta}_{ik} + \dot{Z} = \sum_{l} \dot{\eta}_{ol}$$

(24)

Where, $\dot{\eta}_{ik}$ is the economic value of the input exergy fluxes to the system, $\dot{Z}$ is the total capital costs, which include the investment and the operation and maintenance costs and $\dot{\eta}_{ol}$ is the economic value of the output exergy fluxes from the system.

In turn, $\dot{\eta}$ may be calculated through the following equation:

$$\dot{\eta} = c \cdot \dot{E}$$

(25)

Where $c$ is the price associated to the exergy flux and $\dot{E}$ is the corresponding exergy flux.

The solar pond is a complex system because part of the input flux is stored in the system for a long period of time. Hence, there is no balance between the input and output fluxes. In literature, none of the existing solar ponds, industrial or pilot plants, have been analyzed from thermoeconomic point of view. This study is the first thermoeconomic analysis in the field of solar ponds.

In that context an exhaustive literature review was carried out to identify some thermoeconomic analysis, applied in different technologies that may be useful to develop a methodology to analyze a solar pond technology. The methodology developed and used by A Kazimm, [71] to thermoeconomically analyze a fuel cell may have certain parallelism with the solar pond.

Frist, the fuel cell was analyzed in that work as a black box that means, that the system is studied as a whole and the different elements are not independently analyzed. The solar pond analysis considers the same principle and it is only analyzed as a whole system. However, the fuel cell charge-discharge cycles are relatively short. Hence, the authors consider as inputs the hydrogen and the air and as outputs the water, the air and the electricity. The analysis omits the time variable, put differently, omits the period of time, that may be short or long, the energy is stored in the fuel cell. Hence, a balance between the amount of reactants and products is found.
At this point, the solar pond system differs from the fuel cell. In a solar pond part of the heat stored in the system would be never extracted. Once the system starts its operation, the temperature inside the LCZ never again arrives to the initial value. Despite part of the heat stored is never used, this heat also has an economic value for the owners of the facility because is an important reserve that may be used in case of necessity.

In that context, the model suggested to analyze a solar pond from thermoeconomic point of view might be determined using the following equation:

\[ c_{\text{solar}} \dot{E}_s + \dot{Z}_{\text{SP}} = c_{\text{ext}} \dot{E}_{\text{ext}} + c_{\text{stored}} \dot{E}_{\text{stored}} \]  

(26)

Where \( c_{\text{solar}} \) is the exergy cost of the solar exergy (\( \dot{E}_s \)), \( c_{\text{ext}} \) is the exergy cost of the extracted exergy from the system (\( \dot{E}_{\text{ext}} \)), \( c_{\text{stored}} \) is the exergy cost of the stored exergy in the system (\( \dot{E}_{\text{stored}} \)) and \( \dot{Z}_{\text{SP}} \) is the annual cost of the system, which include the proportional part of the investment cost and the operation and maintenance costs.

\[ \dot{Z}_{\text{SP}} = \dot{Z}_{\text{CI}} + \dot{Z}_{\text{OM}} \]  

(27)

Where \( \dot{Z}_{\text{CI}} \) is the annual investment cost and \( \dot{Z}_{\text{OM}} \) the annual operation and maintenance cost.

Although the investment cost is paid during the construction of the solar pond. The annual capital cost is considered. The annual capital cost considers both the investment cost and the economy inflation. Thus, the annual capital cost may be determined through the following equation:

\[ Z_{\text{CI}} = \text{Inv. Cost} \cdot \frac{i_r (1 + i_r)^{n_y}}{1 + i_r^{n_y} - 1} \]  

(28)

Where \( \text{Inv. Cost} \) is the investment cost, \( i_r \) is the inflation rate and \( n_y \) the lifetime of the system. The annual operation and maintenance cost, \( \dot{Z}_{\text{OM}} \), are determined as a percentage of the investment cost.

4.10. Stability

As previously introduced, stability is a key parameter to ensure the proper operation of a solar
pond. In that context, an important and detailed section of this work is dedicated to this topic. In this section the literature related with solar pond stability is reviewed. Then, a mathematical model is defined to study the Granada solar pond stability. At the end, the results obtained from the mathematical model are ported and analyzed to draw some conclusions.

As described in the state of the art, few authors have studied the stability of this kind of systems. The solar pond of El Paso, Texas, is the only industrial solar pond that has reported a stability analysis, which, as previously introduced is based on the Stability Margin Number (SMN), which is its own methodology. The SMN may be defined as:

\[
SMN = \frac{\alpha S_a / \partial z}{\alpha S_j / \partial z}
\]  

(29)

Where \( \alpha S_a / \partial z \) is the actual salinity gradient, in percentage, and \( \alpha S_j / \partial z \) is the theoretical salinity gradient, also in percentage, necessary to satisfy the stability criterion for the temperature profile of the solar pond at height \( z \) within the NCZ. In principle, the SMN should be higher than 1 to ensure the stability of the system. However, it is also reported that when the SMN is lower than 1.6 the gradient may be degraded.

The main problem with the model suggested in El Paso solar pond is that the methodology to determine \( \alpha S_j / \partial z \) is not specified.

The static stability described by H. Xu et al. in [48] is defined as:

\[
\alpha \frac{\partial T}{\partial x} \leq \beta \frac{\partial S}{\partial x}
\]  

(30)

Where \( \partial T / \partial x \) is the temperature gradient with depth, \( \partial S / \partial x \) is the salinity gradient with depth, \( \alpha \) is the thermal expansion coefficient and \( \beta \) is the salinity expansion coefficient.

H. Xu et al. also say that the density change with depth needs to satisfy the following equation if the system is stable:

\[
\frac{\partial \rho}{\partial x} = \alpha \frac{\partial T}{\partial x} + \beta \frac{\partial S}{\partial x} > 0
\]  

(31)

H. Xu et al. establish also a relation between the saline, \( R_s \), and thermal, \( R_T \), Rayleigh numbers, thermal, \( \Delta T \), and saline, \( \Delta S \), gradients and thermal, \( \alpha \), and saline, \( \beta \), coefficients. According to the author the following equation provide information of the stability behavior.
Finally, as introduced in the state of the art, the methodology used to analyze the static stability of the seawater is also considered in this work due to the similarities between a SPSG and the seawater. Thus, the static stability, \( E \), of a layer is defined through the following equation:

\[
E = -\left(\frac{1}{\rho}\right) \frac{\partial \rho}{\partial z}
\]  

(33)

Where \( \rho \) is in situ density, \( \partial \rho \) the density variation with depth \( \partial z \). If \( E \) is positive, the system would be stable, if 0, the system would be neutral and if negative, the system would be unstable.

As in energy and exergy analysis, the analysis is based on a significant amount of data. Thus, the mathematical model is implemented in MATLAB due to its large computational capacity.

4.10.1. Thermal and expansion coefficients

In most of the previously reported stability analysis appear two coefficients are used: the thermal, \( \alpha \), and salinity, \( \beta \), expansion coefficients. However, in none of the reported methodologies describe how these parameters may be calculated. In that context the methodology suggested by J.L. Lillibridge et al., [72] based on the 1980 Equation of State is used to determine this parameters. A subsection is fully dedicated to these parameters due to the large number of equations required.

The model is based on the polynomial structure of the 1980 Equation Of State (EOS) to determine the expansion coefficients. The model studied the differential equations reported in 1980 EOS and develops a model based on proved coefficients that notably simplifies the calculation process.

Both thermal and salinity gradients depend on density, pressure and temperature or salinity, respectively. Hence, these parameters are not constant neither along the system nor along the time, put differently, each point of the system in each time have a different value of these coefficients.
Thus, the thermal, ($\alpha$), and salinity, ($\beta$), expansion coefficients are determined through the following equations:

$$\alpha = -\left(\frac{1}{\rho}\right) \frac{\partial \rho}{\partial T} = -\left(\frac{1}{\rho}\right) \left( \frac{\partial \rho_o}{\partial T} - \rho_o P \frac{\partial K}{\partial T} \left(\frac{1}{K} - \frac{P}{(K - P)^2}\right) \right)$$  \hspace{1cm} (34)

$$\beta = -\left(\frac{1}{\rho}\right) \frac{\partial \rho}{\partial S} = -\left(\frac{1}{\rho}\right) \left( \frac{\partial \rho_o}{\partial S} - \rho_o P \frac{\partial K}{\partial S} \left(\frac{1}{K} - \frac{P}{(K - P)^2}\right) \right)$$  \hspace{1cm} (35)

Thus, seven different terms needed to be calculated: $\rho$, $\rho_o$, $K$, $\frac{\partial \rho_o}{\partial T}$, $\frac{\partial \rho_o}{\partial S}$, $\frac{\partial K}{\partial T}$ and $\frac{\partial K}{\partial S}$. The pressure, $\frac{\partial K}{\partial S}$, of each layer is considered an input parameter. The pressure on solar pond surface can be assumed equal to atmospheric pressure and the pressure in each layer is the sum of the atmospheric pressure and the pressure caused by the above layers.

In the following lines, the equations needed to calculate the previous derivations and parameters are reported. In the equations will appear some coefficients, marked in red, all of them will be tabulated at the end of this section. Apart from the coefficients, temperature, $T$, and salinity, $S$ are both used.

To determine the density, first, the surface density ($\rho_o$) needs to be determined:

$$\rho_o(T, S) = \rho_w(T) + \Delta \rho(T, S)$$  \hspace{1cm} (36)

These terms may be obtained using the following polynomial expressions:

$$\rho_w(T) = \sum_{i=0}^{5} a(i) T^i$$  \hspace{1cm} (37)

$$\Delta \rho(T, S) = \sum_{j=2}^{4} \sum_{i=0}^{n(j)} b(i, j) T^i$$  \hspace{1cm} (38)

Thus, the surface density may be expressed in only one equation as follows:

$$\rho_o(T, S) = \sum_{i=0}^{5} a(i) T^i + \sum_{j=2}^{4} \sum_{i=0}^{n(j)} b(i, j) T^i$$  \hspace{1cm} (39)

The subsurface densities are calculated from surface densities, $\rho_o$, the pressure of the layer
of water, $P$, and the compressibility, $K$.

$$\rho(T,S) = \frac{\rho_0(T,S) + 1000 \frac{P}{K}}{1 - \frac{P}{K}}$$  \hfill (40)$$

The bulk modulus of compressibility, $K$, depends on $P$, $T$, and $S$. Its dependence on $P$ is reported in the following equation:

$$K(P,T,S) = K_0(T,S) + PA(T,S) + P^2B(T,S)$$  \hfill (41)$$

The terms that multiplies the pressure, $K_o$, $A$ and $B$, may be expressed in polynomial equations as $\rho_o$.

$$K_0(T,S) = \sum_{i=0}^{4} e(i)T^i + \sum_{j=2}^{3} \sum_{i=0}^{j} f(i,j)T^i$$  \hfill (42)$$

$$A(T,S) = \sum_{i=0}^{3} h(i)T^i + \sum_{j=2}^{3} \sum_{i=0}^{j} i(i,j)T^i$$  \hfill (43)$$

$$B(T,S) = \sum_{i=0}^{2} k(i)T^i + \sum_{j=2}^{3} \sum_{i=0}^{j} m(i,j)T^i$$  \hfill (44)$$

The general equations of $\alpha$ and $\beta$ include some derivatives, $\frac{\partial \rho_0}{\partial T}$, $\frac{\partial \rho_0}{\partial S}$, $\frac{\partial K}{\partial T}$ and $\frac{\partial K}{\partial S}$, the main advantage of this method is that previous equations can be relatively easily derived.

Thus, utilizing the notation $a'(i) = ia(i)$, the following set of equations contains derivatives of the previous parameters depending on temperature.

$$\frac{\partial \rho_0}{\partial T} = \sum_{i=0}^{5} a'(i)T^{i-1} + \sum_{j=2}^{4} \sum_{i=0}^{j} b'(i,j)T^{i-1}$$  \hfill (45)$$

$$\frac{\partial K}{\partial T} = \frac{\partial K_0}{\partial T} + P \frac{\partial A}{\partial T} + P^2 \frac{\partial B}{\partial T}$$  \hfill (46)$$

Where,
\[
\frac{\partial K_0}{\partial T} = \sum_{i=0}^{4} e'(i) T^{i-1} + \sum_{j=2}^{3} \sum_{i=0}^{n(j)} f'(i,j) T^{i-1} \]

(47)

\[
\frac{\partial A}{\partial T} = \sum_{i=0}^{3} h'(i) T^{i-1} + \sum_{j=2}^{3} \sum_{i=0}^{n(j)} l'(i,j) T^{i-1} \]

(48)

\[
\frac{\partial B}{\partial T} = \sum_{i=0}^{2} k'(i) T^{i-1} + \sum_{j=2}^{2} \sum_{i=0}^{n(j)} m'(i,j) T^{i-1} \]

(50)

Finally, the same parameters need to be derivated depending on salinity, \(\frac{\partial \rho_0}{\partial S}\) and \(\frac{\partial K}{\partial S}\). These parameters may be determined using the following equations:

\[
\frac{\partial \rho_0}{\partial S} = \sum_{j=2}^{4} S_{j-1}^{i} \sum_{i=0}^{n(j)} b(i,j) T^{i} \]

(51)

\[
\frac{\partial K}{\partial T} = \frac{\partial (\Delta K)}{\partial T} + P \frac{\partial (\Delta A)}{\partial T} + P^{2} \frac{\partial (\Delta B)}{\partial T} \]

(52)

The parameters required to determine \(\frac{\partial K}{\partial T}\) can be obtained using the following equations, which are the derivatives of the initial ones but, in this case, depending on salinity.

\[
\frac{\partial (\Delta K)}{\partial T} = \sum_{j=2}^{3} \sum_{i=0}^{n(j)} f(i,j) T^{i} \]

(53)

\[
\frac{\partial (\Delta A)}{\partial T} = \sum_{j=2}^{3} \sum_{i=0}^{n(j)} i(i,j) T^{i} \]

(54)

\[
\frac{\partial (\Delta B)}{\partial T} = \sum_{j=2}^{2} \sum_{i=0}^{n(j)} m(i,j) T^{i} \]

(55)

All coefficients included in previous equations, and marked in red color, are reported in Table 8:

**Table 8. Coefficients to determined thermal and saline expansion coefficients, \(\alpha\) and \(\beta\).**

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>(T^0)</th>
<th>(T^1)</th>
<th>(T^2)</th>
<th>(T^3)</th>
<th>(T^4)</th>
<th>(T^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(S^0)</td>
<td>(-0.156406)</td>
<td>(6.703952e^{-2})</td>
<td>(-9.095290e^{-3})</td>
<td>(1.001685e^{-4})</td>
<td>(1.120083e^{-6})</td>
</tr>
</tbody>
</table>
4.10.2. Stability analysis methodology

In the state of the art included at the beginning of this project, different methodologies to control the stability of a solar pond are reviewed. The methodology developed to control the stability of El Paso solar pond is not completely reported and how the theoretical salinity gradient needs to be calculated is unclear. Additionally, the other methodologies have not been tested in a solar polar pond in operation; only simulations are included in some cases. In that context, this work combines some of previously defined methods to generate as much results as possible and to draw accurate conclusions.

On one hand, the first part of the methodology suggested by I. Alenezi et al., [49] is considered. The author expresses the stability condition through the following equation:

\[
\alpha \frac{\partial T}{\partial x} \leq \beta \frac{\partial S}{\partial x}
\]

(56)
Which can be also expressed as:
\[
\alpha \frac{\Delta T}{\Delta x} \leq \beta \frac{\Delta S}{\Delta x}
\] (57)

In this part of the analysis, the previous equation is plotted for each depth along time to appreciate the evolution of each parameter and to identify where and when instabilities are produced.

Complementary, the methodology described by L. D. Talley et al., [52], which analysis how stratified is a mass of water, is also included to found common points and divergences with the results obtained from previous analysis. This methodology is based on the following equation:
\[
E = - \left( \frac{1}{\rho} \right) \frac{\Delta \rho}{\Delta z}
\] (58)

If the parameter was positive, the system would be stable, if zero, neutral and if negative, unstable.

Both methodologies are based on the same principle; stratification as synonym of stability: However, the use of different methods provides a wider picture of the system stability and helps to understand where and when gradient started to degrade.
5. Results

5.1. Energy and exergy analysis

Although Granada solar pond operates since July 2014, different problems with the salinity gradient required a stop during summer 2015. After the shutdown the solar pond was refilled again with the same process as in first operation period. The operation restarted in September 2015 and no problems were detected until April 2015, when the salinity gradient started to deteriorate again. In this section, the results of the energy an exergy analysis are detailed for the two operation periods.

First, the system is viewed from energy point of view. In figures 14a, 14b and 14c the energy analysis of each zone of the system is represented.

Figure 14 shows that the UCZ is not capable to store energy; almost all solar radiation absorbed by this zone is lost through the surface, evaporative and convective losses, and the walls. Considering these results, the efficiency of this region independently is not analyzed because there is no storage and no heat extraction.

![Figure 14. Energy fluxes of the UCZ](image)

As Figure 15 shows, the NCZ have a small capacity to store part of the solar radiation,
especially in the initial months. The main aim of the NCZ is preventing heat stored in LCZ from escaping, i.e. works as isolator. Thus, the important isolation that the lowest layers of the NCZ have above them result in a notable capacity to store heat. The low temperature of the water when the system was filled and the high ambient temperature and solar radiation given in summer resulted in an increase of the energy stored in the NCZ. However, under winter conditions the system was not capable to keep the heat stored in this region, which decreased to 0MJ stored in the NCZ. The system started to store again part of the solar radiation in the NCZ when the environmental conditions were notably better. The energy stored in the zone has a direct impact on the energetic efficiency. The NCZ had an efficiency of almost 60% in the first operation month that decreased to 0% in the winter months as a consequence of the important heat losses recorded in the region. As this work considered a cumulative analysis of the system, the efficiency obtained at the end of the operation period is the overall efficiency of the zone. This efficiency considers all environmental events occurred since the operation started. Thus, the NCZ has and overall efficiency of 3.4% and 5.9% the first and second operation periods, respectively.

![Energy fluxes and efficiency of NCZ](image)

**Figure 15. Energy fluxes and efficiency of NCZ**

The large capacity and potential of the system is clearly represented in Figure 16, which contains the analysis of the LCZ. The LCZ is the part of the SP in charge of storing heat to be provided to an external application some time later. In this zone the system has a larger capacity to store heat than any other region. Once this region is filled the temperature started to increase and never achieved the original state again.

In the first operation period, the fraction of energy stored increased abruptly in first operation months due to the good environmental conditions and due to the large capacity of the system.
to increase the temperature. In September, the system started to loss part of the energy stored. However, the LCZ always kept a significant amount of heat stored, also under adverse environmental conditions. In March 2014, due to the improvement in environmental conditions the LCZ started to increase the energy stored increasing its temperature. Along all the year, also in winter months, an important amount of energy was extracted from the system. As a result, the LCZ independently analyzed shows a high efficiency. The large capacity of the system to store energy at the beginning of the operation period resulted in efficiencies of 57.8% and 46.6% after one and two months of operation, respectively. The lowest energy efficiency registered in the LCZ was 19.6%, when the first six months of operation were considered. After one-year operation, the overall efficiency of this region was 23.1%.

In the second operation period, despite starting the operation on September 2015, the system was able to increase the energy stored and to provide heat to the flotation unit. In this second operation period, the amount of heat stored in the pond started to decrease in November 2015. Even so, the LCZ never achieved the initial temperature during winter months. On March 2015 the system started to increase the amount of heat stored. In the second operation period, a larger amount of heat was extracted from the system, considering that the second operation period was shorted. Heat extraction have a positive impact on the system because increase the capacity of the solar pond to store energy. As a result, higher efficiencies were achieved in the second operation period. The efficiency after one and two months of operation was 66.03% and 52.7%, respectively. The lowest efficiency of this operation period was 36.4% registered on January 2016. The overall efficiency at the end of the second operation period was 39.6%. It is worth to mention, that the overall efficiency of the second operation period was based on an eight months analysis while the overall efficiency obtained in the first operation period was based on a year analysis.
Figure 16. Energy fluxes and efficiency of the LCZ.

The exergy quantifies the quality of the energy fluxes in a given environment. Considering the results previously reported, the UCZ and the NCZ are essential in the system to ensure the proper operation of the LCZ. However, the LCZ is the part of the system that produced an energetic value due to its capacity to store and provide heat. Thus, the exergy analysis is focused on the LCZ and is compared with the energy analysis.

Figure 17 shows all energy and exergy fluxes of the LCZ. Clearly, the exergy analysis is less favorable than the energy one because part of the energy is always useless. As higher is the difference between the temperature of the energy flux and the ambient temperature, higher is the exergy, i.e. more useful is the energy flux. The solar radiation is the variable with the smallest variation due to the large temperature difference between the source, the sun, and the ambient temperature. The internal heat transfers and the heat stored decreased notably due to the small difference between the LCZ temperature and the ambient temperature, the maximum and minimum monthly average differences were 55.5ºC on August 2014 and 29.8ºC on January 2015, respectively, during the first operation period and 55.9ºC on April 2016 and 33.0ºC on September 2015, respectively, in the second operation period. Clearly, the smallest difference between the ambient temperature and the LCZ average temperature was recorded in the first operation month because it takes time to increase the LCZ temperature.

The efficiency of the heat exchanger installed at the bottom of the pond resulted in a lower temperature of the water after heat exchanger than the LCZ temperature. As a consequence, the heat extraction is the variable with the smallest difference between its temperature range and the ambient temperature. Hence, the exergy of the heat extracted is much lower than the energy of this heat flux.
Heat stored and heat extracted were much lower in percentage than the solar radiation in exergy analysis. As a consequence, the values obtained in exergy efficiency are clearly much lower. The overall exergy efficiency of the LCZ after the first and second operation periods was 1.6% and 2.3%, respectively.

As in energy analysis the fact of increasing the amount of heat extracted from the system enhance also the exergy efficiency. As a result, the exergy efficiency was significantly higher in the second operation period.

![Energy and exergy fluxes and efficiencies of the LCZ.](image)

**Figure 17. Energy and exergy fluxes and efficiencies of the LCZ.**

Finally, the energy and exergy performance of the global system is compared in Figure 16.

As for the energy analysis, the energy efficiency is clearly less favorable when the whole system is considered than when the LCZ is independently analyzed as a consequence of being the whole system influenced by the low efficiencies of the NCZ and UCZ. As have been said, the NCZ and the UCZ have low efficiencies because of these regions have a low capacity to store heat and no heat extractions are carried out. However, its presence in the system is crucial to ensure the proper operation, thanks to the UCZ and the NCZ, the LCZ have a large capacity to store heat and consequently a large efficiency.

Figure 18, shows that at the end of the first operation period the overall efficiency of the system is 5.3% and 9.0% at the end of the second operation period. Once again, the larger amount of
heat extracted from the system is reflected in a higher overall efficiency of the system.

The results of the exergy follow the same trend, the exergy efficiency of the whole system is clearly lower than the exergy efficiency of the LCZ because of, the influence on the NCZ and UCZ. Additionally, the exergy efficiency is always lower than energy efficiency; the exergy considers the fractions of energy that may be useful. This fraction is higher as bigger is the difference between the temperature of the energy flux and the ambient temperature. The Granada solar pond registered a maximum temperature in the LCZ of almost 92ºC during the operation period 2014-2015, [34]. Hence, this system was working at temperatures close to the ambient temperature. As a consequence, the efficiency decreases significantly when this is based on exergy.

The overall exergy efficiency at the end of the first and second operation periods was 0.34% and 0.43%, respectively.

![Figure 18. Energy and exergy fluxes and efficiencies of complete system.](image)

### 5.1.1. Thermoeconomic analysis

In this section, the results of the thermoeconomic analysis are reported. Frist, the assumptions and input data are described and then, the results are detailed.

As defined in section 5.1.3 Thermoeconomic analysis, apart from the exergy, the costs associated to each exergy flux are necessary to analyze a solar pond from thermoeconomic point of view.

The cost associated to the input exergy, the solar exergy, \((c_{solar})\) can be assumed in 0€/MJ.
The sun is always available and is completely free for the owners of the facility. As previously said, the main aim of the solar pond constructed in Granada is to reduce the amount of fuel oil used to heat the water necessary in the flotation unit. The fuel oil, a part of being really pollutant, is also expensive. Consequently, being the input exergy of the solar pond completely free is an important advantage for the technology.

The cost associated to the extracted exergy ($c_{ext}$) is more difficult to be quantified. As the extracted exergy directly means a reduction in the fuel oil consumed, the value attributed to the extracted exergy flux is the fuel oil cost. Nowadays, different scenarios are found in literature, published by different national and international organizations, regarding the evolution of fuel oil prices. In this work, the approximation reported by EIA (Energy International Agency), [73] is considered. In this scenario, the fuel oil prices will increase by 2050 as can be seen in Figure 19.

![Figure 19. Fuel oil prices evolution according to [73].](image)

To determine the annual capital cost ($\dot{Z}_{SP}$), which is composed by the investment and operation and maintenance costs, the values reported in [58] are considered. The investment cost of Granada solar pond was approximated in 190$/m^2$. 67$ were fixed and independent of the surface of the installation and 123$/m^2$ were variable and depended on the surface of the solar pond. The annual investment cost depends on the economy inflation rate and the lifetime of the facility. The economy inflation is initially assumed as 3% and the lifetime of the facility, considering is approximated in 30 years [58]. As for the annual operation and maintenance
cost, also reported in [58], a 3% of the total investment cost is considered.

As previously introduced, the exergy stored in the system may have an important value because is an important reserve that may be used in case of necessity. This cost \( c_{\text{stored}} \) is completely uncertain because no references are found in literature. In that context, this variable is deeply studied in this work. In that context, two different thermoeconomic analyses are suggested in this work.

In a first analysis, the \( c_{\text{stored}} \) is considered as the unknown variable. Hence, considering 3% inflation and the actual dimension of the solar pond, the minimum cost associated to the exergy stored that ensures the thermoeconomic feasibility of the solar pond is determined.

In a second analysis, the exergy stored is considered as a fuel oil reserve. Hence, the price of fuel oil is attribute to this exergy flux. In this second study, the minimum surface that ensures the thermoeconomic feasibility of the solar pond under different scenarios of inflation and investment cost reduction are determined.

Apart from the cost, the exergy fluxes need to be also considered in this analysis. The exergy results have been reported in section 5.2.1. In Figure 20a and 20b the exergy stored in the system and the exergy extracted from it along the first and second operation periods are independently plotted. As shown, similar values are obtained in both operation periods. Regarding the exergy stored, the fact of being the operation period shorted and starting the operation of the first and second periods in different months may lead to these small differences. As for the exergy extracted from the system, this variable is more difficult to be predicted due to heat is extracted according to the energy demand at the flotation unit.
Figure 20. a) Exergy stored in the solar pond in the first and second operation period. 
b) Exergy extracted from the system in the first and second operation period.

In that context, and as approximation, the average values of both exergy stored and extracted are considered in this analysis. Additionally, both variables are considered constant along time, put differently, the same values of exergy stored and extracted are considered in each year. Although this is not completely true, a better approximation of exergy stored and extracted is not possible. First, because the solar radiation tends to be constant along time and second, the exergy extracted cannot be predicted because the extractions depend on an irregular external demand that cannot be predicted.

5.1.1. Minimum price for the exergy stored

In this section, the actual dimensions of the solar pond are considered to determine the minimum cost associated to the exergy stored that ensures the thermoeconomic feasibility of the system.

As previously introduced, the annual exergy extracted from the system and the annual exergy stored in the system are considered constant along the lifetime, every year the same amount of exergy is extracted from the system and stored on it.

Regarding the annual capital cost, considering a 3% economy inflation and 30 years lifetime, the annual capital cost ascends to 7696.8$/yr, 4846.8$/yr are referred to the annual investment cost and 2850$/yr to the operation and maintenance cost. The annual capital costs are constant along the lifetime.

Additionally, as 0$/MJ are assumed for solar exergy, this parameter can be neglected in the
analysis.

Thus, all variables considered in the analysis are constant along the lifetime of the solar pond except the fuel oil cost, which tend to increase with time. The increase in fuel oil prices is an important advantage in the solar pond feasibility due to the higher is the fuel oil price the higher are the savings of using the heat stored in the solar pond instead of burning fuel oil.

Eq. 41, described in section 5.1.3, is used to determine the price evolution of heat stored in the pond that makes the facility feasible from thermoeconomic point of view. Figure 21 shows the necessary evolution in exergy-stored price. As expected, the cost tends to the decrease oppositely to the fuel oil price. The increase in fuel oil prices improve the thermoeconomic feasibility of the facility and thus, the cost of exergy stored may decrease.

Figure 21. Minimum annual cost of exergy stored in the solar pond to ensure the thermoeconomic feasibility.

Comparing the minimum annual cost necessary in the exergy stored in the system (Figure 21) with the fuel oil prices evolution (Figure 19), the cost of the exergy stored need to be between 4 and 5 time higher than the fuel oil price. Although the exergy stored in the system have a monetary profit, with difficulty, this price will be higher than the fuel oil price. Thus, as a conclusion, the current facility cannot be considered feasible from thermoeconomic point of view. At the current level of development, the technology would only be feasible if perceives some economic incentives, taxes avoidance or other economic advantages.
5.1.2. Minimum surface to ensure the thermoeconomic feasibility under different scenarios.

C. Valderrama et. al [58] the authors point out that a technology as a solar pond takes advantage of the economy of scale and higher surfaces make have better thermoeconomic results. Moreover, form the study reported in the previous section, the technology cannot be considered feasible at the current state of development.

In this study, as previously described, the exergy stored in the solar pond is assumed as a fuel oil reservoir and consequently, the fuel oil prices are associated to it. The difficulty of this section is quantifying how much energy would be stored and extracted in/from the system. First, because in literature there is no references about the evolution of exergy stored when the system is enlarged. Second, because the exergy extracted from the system depend on external necessities and almost never is constant. In that context, and as approximation, the exergy stored and extracted under different surfaces are calculated proportionally to the exergy stored and extracted under the current system (500m²). The results and conclusions from this section need to be carefully managed because, in reality, the systems are less ideal. However, this section is considered useful to understand the impact of surface on thermoeconomic feasibility.

The minimum surface necessary to make the technology feasible under different scenarios of cost reduction and economy inflation is determined. In that context, the minimum surface is studied under 5 different inflation rates (1%, 2%, 3%, 4% and 5%) and under a cost reduction between 51 and 80%. A minimum cost reduction of 51% is considered because below this percentage the technology is not feasible under any inflation rate.

Figure 22 shows the minimum surface necessary to make a solar pond feasible considering a thermoeconomic study.
Figure 22. Minimum surface to ensure the thermoeconomic feasibility of the solar pond under different inflation and cost reduction rates.

As shown, under the same inflation rate, the surface can be lower as higher is the cost reduction. Under the same cost reduction, as lower is the inflation rate smaller can be the solar pond to be feasible. Additionally, at higher inflation rates, higher cost reduction rates are necessary to be feasibly, i.e. under 2% inflation a minimum cost reduction of 55% is necessary.

This work also confirms the conclusion reported by C. Valderrama et al., [58] that economy of scale is an advantage for this technology. As larger is the solar pond, higher inflation and lower cost reduction rates are allowed.

5.2. Stability

In this section the initial stability of the solar pond at the beginning of each operation period and its evolution along each period. As stability analysis of large solar ponds are not found in literature, the stability analysis of Martorell pilot plant is reported in the Annex section. Although the solar pond installed in Martorell was a pilot plant, the salinity gradient never degraded and was a good example of successful operation.
5.2.1. **First operation period**

In this subsection the stability of the first operation period is deeply analyzed. Figure 23 and 22 shown the analysis of stability suggested in [52]. In Figure 23 the different depth of the NCZ are represented in x-axis, the different lines contained in the graph represent the stability profile in each depth.

**Figure 23. Stability profile along first operation period using the methodology described in [52].**

From Figure 23, important instabilities cannot be identified. However, there are some points that have a trend to be neutral, $E = 0$, specially, from 1.3 meters from the bottom. At some measured points, 0.7, 1.3, 1.6, 1.7 and 1.9 meters from the bottom small unstable periods were identified. Along these periods the $E$ parameter become negative. However, in this figure is not possible to identify when these instabilities were produced and if the system was capable to recover the stability in the next measure or not.

In that context, Figure 24 represents the evolution of stability, $E$, in each depth can be easily

![Density variation: Dates](image-url)
identified. This figure is useful to understand when the previously mentioned points started to be unstable. Each line of the figure represents the evolution of the layer stability along the operation period.

![Figure 24](image.png)

**Figure 24.** Stability evolution in each depth along first operation period using the methodology described in [52].

In Figure 24, although contains the same information of previous figure, the information is much clearer. Initially, the system was clearly stable. However, at 2m from the bottom $E$ rapidly, only 5 days after the operation starting, decreases to 0, neutral situation. This situation is transmitted to the lower layers of the NCZ. At 1.9 meters from the bottom a slightly unstable situation is detected on 21st July 2014. However, the system was stable again on 26th July. The next measures at this point resulted in a stable situation. The system was not able to recover again the stability. One month later, on 20th August 2014, the neutral situation was also detected at 1.8 m from the bottom; once stable situation was achieved the system never was stable again.

The stable situation was slowly transmitted to the layers immediately below. On 20th September 2014, this pattern was detected at 1.7 meters from the bottom, on 8th October 2014, at 1.6 m from the bottom, on 30th November 2014 at 1.5 m from the bottom and finally, on 12th April 2015, at 1.4m.
A neutral situation is not desired due to it is difficult to completely avoid convective movements under this scenario. The neutral tendency started at the beginning of the first operation period at 2 meters from the bottom. On average, the stable situation need around one month to be detected in the immediately above layer. However, once the layer located at 1.5 meters from the bottom become stable, the layer located at 1.4 meters was not affected for a long time, almost five months were necessary to detect a stable situation at this depth.

On the other hand, the layer located at 0.7 from the bottom, which is the one in contact with the LCZ, started to be unstable on 6th April 2015. At this point the gradient was considered severely damaged.

The degradation in the highest layers of the NCZ may be consequence of the environmental conditions that affect the UCZ and inevitable were transmitted to the lower layers. However, the reason because the gradient started to degrade from the bottom is more complex. This degradation may be consequence of the heat extractions or a secondary consequence of the upper degradation of the gradient.

The system is also analyzed using the methodology described by I. Alenezi et al., [49], according to this methodology $\beta \frac{\partial s}{\partial x}$ should be always higher than $\alpha \frac{\partial T}{\partial x}$. Figure 25-38 analyses what happens in each recorded depth.
<table>
<thead>
<tr>
<th>Figure 25. Stability analysis using the methodology described in [49] at 0.7m</th>
<th>Figure 26. Stability analysis using the methodology described in [49] at 0.8m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 27. Stability analysis using the methodology described in [49] at 0.9m</td>
<td>Figure 28. Stability analysis using the methodology described in [49] at 1m</td>
</tr>
<tr>
<td>Figure 29. Stability analysis using the methodology described in [49] at 1.1m</td>
<td>Figure 30. Stability analysis using the methodology described in [49] at 1.2m</td>
</tr>
</tbody>
</table>
Figure 31. Stability analysis using the methodology described in [49] at 1.3m

Figure 32. Stability analysis using the methodology described in [49] at 1.4m

Figure 33. Stability analysis using the methodology described in [49] at 1.5m

Figure 34. Stability analysis using the methodology described in [49] at 1.6m

Figure 35. Stability analysis using the methodology described in [49] at 1.7m

Figure 36. Stability analysis using the methodology described in [49] at 1.8m
Despite being a completely different methodology, the results reflect the same tendency than the obtained using the methodology proposed by L. D. Talley et al., [52]. This study gives more accuracy and depth in the results.

Clearly, the main problem of the system started in the layer located at 2 meters from the bottom, where the temperature gradient was sometimes higher than the salinity one, hence, the stability condition is not satisfied. This irregular profile may be caused by the environmental conditions that affect the UCZ and are inevitably transmitted to the NCZ.

This irregular profile detected in the highest part of the NCZ is slowly transmitted through the NCZ until the layer located at 1.4 meters from the bottom. Additionally, this study also confirms a gradient degradation from the lowest part of the NCZ, detected at the end of the operation period at 0.7 meters from the bottom.

### 5.2.2. Second operation period

In this subsection the second operation period is analyzed. As in previous case, two different methodologies are used to have a deep view of the second operation period stability evolution. The second operation period is shorter than a year. Although the system was operated for a longer period, some problems in the gradient were detected in the NCZ in April 2016 and some variables, such as density, were not recorded afterwards.

Figure 39 shows the stability profile evolution along the second operation period obtained using [52].
Figure 39. Stability profile along second operation period using the methodology described in [52].

In this case, stability problems are identified from 1.6 m to 2 m from the bottom. The lowest layers of the NCZ are not degraded in this case. Figure 40 plots the same information than figure 39, but in this case the evolution of the stability of each layer along the operation period is identified.
Along the second operation period, a similar pattern than in the first is identified. The layer located at 2 m from the bottom is clearly unstable since the beginning of the operation period. This instability is transmitted to the lower layers along the operation period. On 10th October 2015 the layer located at 1.9 m from the bottom become neutral. Three months later, on 30th January 2016, the neutral situation was reached at 1.8 m from the bottom. Few days later, on 14th February 2016, the same situation is identified in the layer located at 1.7 m from the bottom. At the end of February also the layers located at 1.6 m from the bottom become neutral, however, this layer was capable to recover from the neutral situation.

To complement this information, the stability condition described in [49] is plotted, in Figure 41-54. According to this methodology $\beta \frac{dS}{dx}$ should be always higher than $\alpha \frac{dT}{dx}$. 

**Figure 40. Stability evolution in each depth along second operation period using the methodology described in [52].**
Figure 41. Stability analysis using the methodology described in [49] at 0.7m
Figure 42. Stability analysis using the methodology described in [49] at 0.8m
Figure 43. Stability analysis using the methodology described in [49] at 0.9m
Figure 44. Stability analysis using the methodology described in [49] at 1m
Figure 45. Stability analysis using the methodology described in [49] at 1.1m
Figure 46. Stability analysis using the methodology described in [49] at 1.2m
Figure 47. Stability analysis using the methodology described in [49] at 1.3m

Figure 48. Stability analysis using the methodology described in [49] at 1.4m

Figure 49. Stability analysis using the methodology described in [49] at 1.5m

Figure 50. Stability analysis using the methodology described in [49] at 1.6m

Figure 51. Stability analysis using the methodology described in [49] at 1.7m

Figure 52. Stability analysis using the methodology described in [49] at 1.8m
As in first operation period, the second methodology confirms the results obtained with the previous one. In this case, the problem, again, started at 2 meters from the bottom. This layer is clearly unstable since the beginning of the operation period. This instability may be consequence of the different environmental conditions that affect the UCZ and are, inevitably, transmitted to the NCZ. Once a layer becomes unstable, soon or latter, this instability is transmitted to the lower layers. In this case the instability condition was transmitted until 1.6 meters from the bottom. Unexpectedly, the layer located at 1.6 meters form the bottom was capable to recover the stability condition.

In the second operation period, although a larger amount of heat was extracted from the system, the NCZ was not degraded from the bottom.
6. Maturity of the technology

Clearly, the efficiencies reported in section 5.1. Results may seem relatively low. However, these efficiencies need to be contextualized to understand the maturity of the system.

In this section, the overall efficiencies previously obtained are compared with the efficiencies reported in literature for other renewable technologies, specifically, with solar technologies.

[74] reports an energy and exergy analysis of a photovoltaic system to produce electricity and the combination of a photovoltaic and thermal collector to produce both electricity and heat. The authors used both the exergy and exergy methodology to determine the efficiencies of the systems.

At the end, when a photovoltaic system is independently used to produce electricity and energy efficiency between 9 and 12%, depending on ambient temperature, is obtained. When the PV system is integrated with solar collectors the electrical efficiency is again around 9-12%, however, the thermal efficiency may vary from 7 to almost 45% depending on the ambient temperature. As a result, the overall energy efficiency is much higher when the PV includes a thermal collectors system.

As for the exergy efficiencies, when the PV system is used only to produce electricity the exergy efficiency is very close to the energy efficiency. However, when solar thermal collectors are integrated to the system the overall exergy efficiency notably decreases compared with the energy efficiency. While the exergy efficiency of the electricity fraction is, again, close to the values obtained for energy efficiency, the exergy efficiency of the thermal flux is much lower, around 0 and 2%. The water in solar thermal collectors may increase around 20ºC between the inlet and the outlet, as a consequence, the temperature range of the water in this system is close to the ambient temperature resulting in a low exergy.

[75] reports an energy and exergy analysis for the different components of a solar thermal power plant based on parabolic trough collectors and Rankine heat engine. The study is based on different real CSP plants located in India and suggests different alternatives to increase both efficiencies. The maximum energy efficiency obtained in a CSP plant in India is around 23.66%, in Delhi. As in previous works, the values of exergy efficiency reported in thermal applications is much lower than energy efficiency, in this case, an exergy performance of 1.49% is reported.

[76] also reported in an energy and exergy analysis of a CSP plat but in this case based on central tower. Central tower is the technology used in CSP plants that allows the highest operation temperature range. As a consequence, both the energy and specially the exergy are much higher compared with previous described technologies. At the end, the authors report
an overall exergy efficiency of 24.5% and include some suggestion that in case of being implemented in the system may increase the exergy efficiency up to 25.6% or to 27.4%.

Hence, different values of energy and exergy efficiencies are found in solar technologies. The difference in energy efficiency are relatively small. The energy efficiency in renewable technologies, especially in solar and wind based renewable technologies, is much less important than in traditional technologies based on fossil fuels for several reasons. First, because the primary energy in solar based renewable technologies have no cost for the owner of the facility. Hence, if the economic feasibility of the technology is proved, not using part of the available resource is less important. Second, because the primary energy has almost non-environmental impact. Thus, environmental taxes do not affect these technologies. Notwithstanding, the exergy analysis is a good tool to understand the maturity of each technology due to provide information about the capability of the system to make useful the available energy.

The exergy efficiency of a solar pond is significantly small and similar to the solar thermal collector. These systems work at temperatures close to the ambient one which reduces the capacity to take profit of all available energy. In a tower based CSP plant the exergy efficiency is much higher than in other solar technologies due to the high operation temperatures.
7. Conclusions

The main aim of this project was to deeply analyze the solar pond technology considering the first industrial facility constructed in Europe.

The system started its operation on July 2014 and since then the different sensors installed in the system measured and reported different variables. At the beginning of this study an important amount of data was available.

In the first section of this project, the technology and the main problems associated to it have been described. The construction process as well as the filling methodology used are described in this first section. At this part, how the system operates and the importance of the salinity gradient is pointed out. Additionally, the data collected from the sensors was used to plot the evolution of the main variables of the system, i.e. temperature, density and salinity. At this point, the main problem associated to the technology is clearly identified, the deterioration of the salinity gradient. The deterioration of the salinity gradient was a severe problem after one year of successful operation because the system stopped its operation and was replenished, as a result an important amount of time and money was lost. Although after two months of operation and maintenance tasks, the system was capable to restart a successful operation period. Notwithstanding, the deterioration of the salinity gradient was also identified in this second operation period. In that context, the necessity of a deeper study was identified.

After this first theoretical part, two important studies were considered. First, to determine the development, maturity and reliability of the technology, an energy and exergy studies were carried out. Additionally, a thermoeconomic analysis is also included. Second, to understand where and when the salinity gradient deterioration problems started a stability analysis was suggest.

Although in literature different industrial solar ponds were analyzed through an energy analysis, none of them was analyzed using an exergy analysis. In literature, some authors suggest exergy analysis to analyze solar ponds but all of them are based on theoretical models or pilot plants. In the same time, few information was found regarding the stability analysis of the solar pond. In that context, some references based on sea water are necessarily used.

The energy and exergy analysis are useful to understand the maturity of the technology. While under energy analysis overall efficiencies are 5.79% and 8.98% after the first and second operation period, respectively, under an exergy analysis the overall efficiencies are 0.34% and 0.43%. This important divergence between the energy and exergy analysis is obtained because the exergy considers the useful part of the exergy flux. A solar pond is a low temperature system, the maximum temperature achieved in the LCZ was below 95%. Hence, the temperatures of the system are near the ambient temperature and, consequently, a low
fraction of the energy flux is useful. Oppositely, the solar radiation is emitted from an element at much higher temperature than the ambient temperature so a larger part of solar energy is useful. As a result, lower efficiencies are obtained under an exergy analysis.

As for the thermoeconomic analysis, which is based on exergy fluxes of the system and its costs, the current facility cannot be considered feasible from thermoeconomic point of view. To be feasible, the price of the exergy stored in the system should be between 4 and 5 times higher than fuel oils costs, which is impossible. The current system would need economic incentives or taxes reduction to be feasible. In a second stage of this part of the project, the minimum surface that makes the system feasible under different scenarios is calculates. From this part, the influence of the positive effect that economy of scale has on the technology profitability is pointed out.

As said, a stability analysis is also included in this project. The idea of analyzing the stability inside the solar pond and its evolution along each operation period arise from the salinity gradient deterioration. The stability analysis has had a large difficulty due to the inexistence of literature about it. In that context, two different methodologies were used to verify the results. Considering the results of this study, the initial stability problems started in the boundary between the UCZ and NCZ. The UCZ is the most affected part by the different environmental impacts, such are wind, rain or snow. In Granada this instability is slowly transmitter to the NCZ. Although the Granada system was based on Martorell system, while in Martorell the UCZ measured almost 80cm, in Granada this width was reduced to 20cm. This reduction may be the cause of the instabilities transmission from the UCZ to the NCZ.

At the end of this work, the solar pond system can be considered a mature from technological point of view. However, the price of the technology need to be significantly reduced to increase this kind of systems. A solar pond is a valid technology for specific applications. The applications susceptible to have a solar pond should have a low temperature heat demand, a large surface available and high solar radiation.
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9. Bibliography


