THE IMPROVEMENT OF MICROCLIMATE IN AGRICULTURAL GREENHOUSES USING DIVERSE SOLAR HEATING SYSTEMS

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ACKNOWLEDGMENTS

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ABSTRACT

Greenhouses are used regardless of the climate condition to assure a favorable environment for the crops’ growth including a temperature scale adequate for the crop species, protection from the wind and other weather issues. The thermal aspect of a greenhouse differ from one crop to another, there exist hot season crops and cold season crops that both require different conditions for growing. In order to maintain a favorable temperature inside the greenhouse, almost all farmers use combustion 4000 MAD/ha/year for heating issues. As a result of the increasing of fossil fuels used for heating the greenhouses and also the need of having hot season crops grow in all seasons including the winter, there is a need of opting an alternative source for heating the greenhouse using non-conventional energy sources.

The objective of this capstone project is to help in the improvement of the microclimate of the greenhouse by designing a heating system based on solar thermal energy in order to keep the productivity of a certain crop remain constant throughout the year. The design of the greenhouse itself will be modeled in the graphical editor of Simulink Matlab that is a block diagram designated for multi-domain simulation and model based designs. Simulink does have a special tool which is Simscape that involves a library that will further help us design physical systems for instance the thermal model one.

Keywords: Greenhouse, Solar heating system, Thermal energy storage, climate, heat transfer, Simulink, Simscape, crops, tomatoes, Gembloux Greenhouse Dynamic Model.
1. INTRODUCTION

1.1 Capstone Project Overview

Solar heat technologies do vary and have big impacts on the productivity of agriculture if they were well implemented into greenhouses. There are various types of thermal heat storages technologies: sensible heat storage, latent heat storage, and thermo-chemical heat storage. Each type does have its own benefits and in parallel some constraints to be taken into consideration before selecting the adequate technology.

The Mediterranean region is well known by various types of agricultural cultivations and uses a lot of greenhouses but the majority of them are either old based greenhouses that use thermal plastic covers to maintain a certain scale of temperature or they are based on fuels which are conventional energy sources and harm the sustainability of our environment.

The Morocco Green Plan concerns the improvement of the agricultural sector in Morocco since it is contributing into the gross national product by 19 %, with 15% from agriculture and 4% from agro-industry. The sector of agriculture plays a major role in the development of Morocco and especially in improving the societal since 80% of rural inhabitants depend on agriculture to generate their daily revenues [1].

The green strategy consists of building blocks:

1. Make agriculture the pillar of growth of Morocco in the next decade.
2. Adopt aggregation as an organizing model for agriculture.
3. Improve all types of agriculture’ sectors including the modern and traditional agricultures.
4. Improve the private sector (private investments).
5. Engagement of all sectors into the development of agriculture.
6. Focus on a sustainable agriculture.

In order to improve the sustainability of agricultural sector nationally and contribute into the feasibility and success of the Moroccan Green Strategy, we need to think about the amelioration of microclimate of greenhouses. To do this, we will be designing three different models of heating systems but to do this, we need to simulate the actual microclimate of the greenhouse in climate conditions of the site using Simulink Matlab in order to select the adequate solar system that can further be used in greenhouses not only in the Moroccan frame but in further similar places that exhibit the same climate conditions.

1.2 Steeple Analysis

The steeple analysis is an approach that is applied to analyze the external marketing environmental factors that have an impact on the process of the work in an organization. The steeple analysis include 6 factors that help in monitoring the impact of each of them can have on a business which are: social, technological, ethical, economic, political, legal, and environmental.

As for the social aspect of a project, all the cultural and demographic factors need to be
considered for instance population growth rate. Technologically, some of the factors that we need to deal with are research and development activities. When it comes to the economic factor, it includes everything that might have an impact on the firm’s capital cost and not only that, but also involves the customer’s purchasing power. Environmentally talking, the steeple analysis targets all the factors that a business can have on the environment and especially the agricultural field. Moreover, the political aspect of a business deals with all the governmental regulations a business must not violate while processing a certain work. Last but not least, when it comes to the ethics, the company needs to pay attention to the social values influencing their business [2].

The steeple analysis is then conducted to identify the weaknesses and strengths of a certain project or what is known by SWOT analysis.

For my capstone project, it will surely be implemented in Morocco and it will leave positive impacts on the population since it will improve the productivity of the crops and this means an increase in food production and fulfilling the needs of everybody: High demand vs higher supply.

Technologically speaking, the models will be designed using MATLAB Simulink and the simulations will be conducted using the same software. Simulink MATLAB is widely used in academic researches and in industry.

As for the economic aspect of this project, it is clear that opting for a solar heating system for the greenhouse to increase the productivity of the crops will be much more beneficial for the country as it the export rate will increase due to the excess of the production of certain species. Moreover, agriculture is contributing into the gross national product by 19 %, with 15% from basic agriculture and 4% from agro-industry [1].

Environmentally, since solar energy is a form of renewables, the heating using some
types of fuels will be abandoned and thus the system as a whole will be environmentally friendly. Not only this, but this project will help in the development of the country and reinforce its environmental positions as it is moving towards the adoption of renewable energies.

Politically speaking, as it was discussed before, Morocco is currently setting up a strategy for a green Morocco. One of the main objectives and blocks of the strategy is to maintain a sustainable agriculture. Therefore, the government is now aiming to support and handle grants for whoever is orientating towards improving the agricultural sector by integrating renewables in the field.

As for the legal aspect of this project, Morocco is setting up some laws that concern the production and preservation of biodiversity. One of the main laws found in the first rubric is to contribute into the sustainability of the agriculture by protecting the environment and the crops production [3].

Last but not least, ethically speaking, it is compulsory to raise the awareness of people and especially farmers about the importance of integrating renewables in the agricultural field and especially for the heating system by opting for the solar energy solution and to avoid using fuels for heating the greenhouse.

1.3 Literature Review

Conventional energy technologies nowadays do receive heavy burden because of the fast growth of the world population, and contribute into the heavy emissions of CO₂ and thus to the global warming. It is today the time to make a huge change and go for the most efficient, affordable and green technologies. Solar energy has previously received extensive research and especially the solar thermal energy storage which can be challenging to balance between the input and output solar thermal energy.

The thermal energy storage has first been mentioned in 1970s to answer to the shortage
of solar energy. If the storage needed for the solar heating is well implemented, it would not only meet the demands of space heating and domestic water supply, but also offer a high efficiency all over the year regardless the season or time constraints, reduce the emissions of CO2, and lower the need for costly peak power and heat production capacity. According to [4], thermal energy storage is a technology that has as goal stocking thermal energy by either heating or cooling so that the stored thermal energy can be used later for adequate purposes.

This type of technology is typically used in domestic and industrial processes. There are two types of thermal energy storage technologies: seasonal thermal energy storage and diurnal one. The only difference between the two is duration, the seasonal one satisfy 50-70% of annual heat demand and can be called a long term thermal technologies. The diurnal thermal energy storage is a short term one and satisfy only 10-20% of annual heat demand.

The seasonal storage is the most used one but is more technologically challenging. There are three mechanisms under the seasonal energy storage:

- Sensible heat storage
- Latent heat storage
- Chemical/Thermo-chemical heat storage [5].

![Figure 1 Classification of different thermal storage methods [5].](image-url)
1.3.1 Sensible Heat Storage

Thermal energy storage technologies based on sensible heat storage are the most commercially available until now and they are based on converting solar energy into a sensible heat in selected materials and retrieves it when heat is needed. They are considered to be simple, low–cost and adequate for large-scale systems comparing to other types of thermal energy storage.

Compared with other thermal energy storage technologies, the sensible heat storage is considered to be the cheapest and the most mature technique for heating and it was first implemented in Switzerland around the 1980s and has been popularized since then [5].

Studies have found that there are some materials with high temperature range that can be implemented in the sensible heat storage as water and rock-sort materials mostly using gravel, but the most used one is water. Before looking at the most adequate material for sensible heating storage, we should look at the local geological conditions first, the available site size, and finally the investment cost.

Hot water storages classified to either water tank and aquifer are usually used as buffer storage for domestic hot water and have some good output and thus make them a good candidate for thermal energy storage. In addition to that, water has a high specific heat compared to other candidates and high capacity rate while being discharge and charged [6].

Water tank systems using a thick insulation might be placed underground or what is called water pits, or either on the roof of the heated place. In order to maintain a stable thermal stratification in the water inside the tank, a horizontally partitioned water tank might be an efficient solution for that [6].
To maintain a stable thermal stratification in the water too, materials used in insulation must be well chosen, for instance, glass wool and polyurethane are perfect for a better insulation.

This system was first used around the 1976s and it is based on using two thermal wells that are drilled one hot well and the other is cold. This technology is a seasonal one and it is a geothermal energy based one. The aquifer thermal energy storage or ATES requires a suitable aquifer and at least two thermal wells, other than that, the ATES requires heat exchangers, conveyance piping, heating, and ventilating and air conditioning systems [6].

Figure 3 Acquifer thermal energy storage for cooling and heating [7].
Rock bed can be used too as thermal energy storage and they are particular because they save much higher heat than the other technologies. The Rock beds are usually composed of the rock which can be gravel, pebble, or bricks and a heat transfer fluid usually water that was gained in summer and released in winter. Comparing to water based thermal energy storage, the rock beds require larger volumes to achieve the same amount of heat as in water thermal energy storage.

Ground storage is another technology used to store heat and it is based on a drilled soil and implementation of tubes that serve as heat exchangers and water as its transfer fluid. There are some specific materials used for the ground storage as water saturated clay and clay stones that prevent the flow of water into the ground and they have high heat capacities. Similar to the rock beds storage, they require much volume to carry the same amount of heat as in the hot water tanks due to its lower energy density. This type of thermal energy has a lot of disadvantages as it is costly, very complex system since it requires some specific conditions related to the transfer fluid and vapor movement, and also it requires a lot of time to reach a high result [6].

In general, the sensible heat storages do require a lot of conditions that may vary from geological constrains to architectural ones and thus the cost of the investment has to increase. Usually, the cheapest technologies are the ground storage and the aquifer thermal energy storage but requires some strict geological conditions for implementation. Other than that, the water tanks are expensive because the construction requires large volumes.

1.3.2 Latent Heat Storage

The latent heat storage system use the energy absorbed or released by the phase change materials in the form of latent heat of fusion without the change of the periodic temperature. To choose the adequate materials for this type of storage, the selection is based on the melting
temperature of the phase change materials and their temperature should be range between 230°C and 330°C and the operated pressure to be ranged from 30 and 100 bar.

Comparing to other thermal energy storage technologies, the latent heat storage offer high energy densities and are more efficient. The phase change materials candidates for this system are CaCl₂.6H₂O, paraffin, MgCl₂.6H₂O, Na₂SO₄.10H₂O, Na₂S₂O₃.5H₂O, PEG [6]. After some deep research on the characteristics and behaviors of the phase change materials, it is proven that CaCl₂.6H₂O is the best material for storage. To make the system more efficient, these specific materials are mixed with some specific construction materials such as concrete to build the suitable walls, ceilings and floors. This can reach an efficiency of up to 40 % but low solar fraction. To reach a 100% solar fraction for the PCM system, it is now improved using sub cooled liquid PCM for long term storage but it might be complicated to realize [6].

1.3.3 Chemical Storage

Chemical storage is considered to be an efficient technology for thermal energy storage. It is actually able to conserve energy at ambient temperature as long as desired without heat losses. This process can be separated into two main systems: chemical reaction and thermochemical sorption storage. The sorption storage is mainly made of two main processes; the absorption and adsorption which is basically the fact that gases go up to the surface of a solid without creating any new material. Based on some specific criterion related to energy storage density, reactor temperature for storage process, corrosiveness, scientists were able to select some adequate materials that could be good candidates for chemical storage: MgSO₄.7H₂O, SiO₂, FeCO₃, Fe (OH)₂ and CaSO₄.2H₂O [6].
According to [8], the chemical reaction heat storage consists of a dual reaction either absorption or desorption of a sorbent; this process might be either exothermic or endothermic in other words. To store thermal energy, chemical heat storage system uses some specific chemical substances that undergo reversible reactions for example the $\text{SO}_3/\text{O}_2/\text{SO}_2$ chemical reaction heat storage system.

![Figure 4 Schematic diagram of chemical reaction heat storage system [8].](image)

Referring to [9] the absorption process consists of two containers linked together and a working fluid which can be called the absorbent and this process is already implemented in all refrigerators. The storage capacity in fact increases the temperature of evaporation and thus it is necessary to focus on the materials used for those two linked containers. Crystals inside the tanks do contribute into the performance of the storage but have some complex storing specifications.

When it comes to adsorption, the needed specifications that affect the efficiency of this type of thermal energy storage is the pore structure of the materials used as well as the pore architecture of the materials. The most used material for adsorption is MgSO$_4$.7H$_2$O which energy density is very high and has been used in many projects [10].

### 1.3.4 Comparison of Available Thermal Energy Technologies

To sum up a little bit what was analyzed, sensible and latent heat storage are direct thermal energy storage whereas the chemical heat storage is not because it is adopting some endothermic and exothermic reactions in order to store the heat.
Each of the technology has its own advantages and its own disadvantages but the most reliable technology to be implemented is the sensible heat storage since it is feasible, doesn’t have any complex structures and do not require expensive materials as in the latent heat storage. In recent years, the underground thermal energy storage is the most implemented because they are cheap in comparison with the other sensible heat alternative which is basically the water tank storage. The only constraints that might be easy to overcome is the geological conditions related to the underground heating technologies.

2. MATERIALS AND METHODS

2.1 Selection of Model Parameters and Heat Exchange Equations

It is well known that the growth of crops inside a greenhouse is a bit sensitive in comparison with the outdoor growing, thus, it is compulsory to pay attention to all the greenhouse parameters that may influence the growth of specific crop. In order to do this, there are plenty of physical models that can be opted to in order to analyze and understand the heating system inside the greenhouse that take into consideration a list of parameters that can classified into two: the outside and the inside parameters.

In the problem of analyzing the greenhouse heating system, we need to consider these two parameter list:

- The situation outside the greenhouse including air temperature, humidity, solar radiation, speed of the wind

- The inside situation including the air temperature, humidity, soil temperature and the heating energy relieved (as for example the solar heating energy integrated) [10].
2.2 The Greenhouse parameters

2.2.1 The Site of the Greenhouse

The greenhouse pilot that will be experienced for heating purposes is located in Agrotech of the region of Souss Massa Draa, situated in the western coastal of Morocco latitude of 30.5 and longitude of -9.5, 271 m above the sea. The site has a warm dry climate with a yearly average temperature of 21.9 °C according to the NASA Surface meteorology and Solar Energy data [16]. In addition, the greenhouse is approximately a 30m*40m area base and a 2.5m height (See Appendix A).

![Figure 5 The Geographic location of the site, its climate zone, elevation, and average temperatures Retrieved from RETScreen.](image)

2.2.2 The Vegetation: Tomatoes Growing and Harvest Information

Because tomatoes do require a long warming growing season, and its roots need consistently warm days and nights and a warmer soil before proceeding the planting day and night, we
decided to select it as vegetation to be planted in our greenhouse. In addition to this, the climate conditions of the site (Agadir) and the soil organic elements are adequate for this type of crop.

### Table 1 Tomatoes Growing and Harvest Information [14]

<table>
<thead>
<tr>
<th>Temperature</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Germination</td>
<td>15°C -29 °C</td>
</tr>
<tr>
<td>For Growth</td>
<td>21 °C -24 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Space between plants in rows</td>
<td>0.11 m</td>
</tr>
<tr>
<td>Root depth</td>
<td>0.20m-1.82m</td>
</tr>
<tr>
<td>Height</td>
<td>0.9m-1.22m</td>
</tr>
</tbody>
</table>

#### 2.2.3 Thermal Parameters

Before digging into the thermal and heat transfer analysis of the parameters of the greenhouses, it is necessary to set up the thermal and radiation parameters for each of the soil, cover, vegetation, and air.

### Table 2 Thermal and Radial Parameters of the Greenhouse different Subsystems.

<table>
<thead>
<tr>
<th>Soil characteristics</th>
<th>First layer</th>
<th>Second layer</th>
<th>Third layer</th>
<th>Fourth layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W m-1 K-1)</td>
<td>0.15</td>
<td>0.76</td>
<td>1.38</td>
<td>2</td>
</tr>
<tr>
<td>Layer thickness (m)</td>
<td>0.05</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Density (kg m-3)</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>Heat capacity of soil (kJ kg-1 K-1)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cover characteristics, 200 µm diffused polyethylene</th>
<th>Thermal conductivity (W m-2 K-1)</th>
<th>4.5</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Vegetation characteristics (tomatoes)</th>
<th>Specific heat capacity of tomatoes (kJ kg-1 K-1)</th>
<th>3.98</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Air characteristics</th>
<th>Humid air density (kg m-3)</th>
<th>0.99</th>
</tr>
</thead>
</table>
2.3 Mathematical Modeling

2.3.1 Gembloux Greenhouse Dynamic Model Equations

As in one of the three solar heating systems we will have to deal with the underground heating, it is compulsory to investigate the underground heating by opting for this model that not only deals with the heating analysis of the soil but 4 layers under soil.

According to [11], the GGDM model or Gembloux Greenhouse Dynamic Model has been used for a large number of experiments and is considered to be a very powerful approach to analyze and understand all the heating exchanges occurring inside the greenhouse. As the GGDM is a bit complex, the system of the GGDM model will be divided into subsystems. In this way, the GGDM consists of subsystems of different equations all based on heat exchanges and mass balances of the layers of the greenhouse.

In order to be able to solve the climate problem inside the greenhouse, it is necessary to take into account various parameters and that will directly influence the crop’s growth. The physical processes involved in describing the microclimate of the greenhouse can be schematized according to the figure below:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric heat capacity of humid air (kJ m(^{-3}) K(^{-1}))</td>
<td>1</td>
</tr>
<tr>
<td>Latent heat of condensation of water (kJ kg(^{-1}))</td>
<td>2442</td>
</tr>
<tr>
<td>Inside air velocity (m s(^{-1}))</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Figure 6 The schematic diagram showing the Gembloux Greenhouse Dynamic Model heat and mass exchanges between different layers of the greenhouse [13].

The greenhouse microclimate as a whole is a distinct from the outdoor climate but dependent on it. Inside the greenhouse, there are diverse parameters that can be manipulated and controlled in order to improve the growth of a certain crop such as tomatoes that do definitely run on warmth by requiring at least 6 hours of sun to bring out their best. Therefore, parameters such as soil’s pH and organic elements, CO₂ concentration, humidity and air temperature are so compulsory to maintain adequate microclimate conditions for the growth of tomatoes.

The relationship among the greenhouse parameters when it comes to heat exchanges is a bit complex due to the changing dynamics depending on the geographical area and depending on time variations. Therefore, a list of assumptions are to be made in order to simplify the heating analysis of the greenhouse:

- Cover: The material used for covering the greenhouse is polyethylene, its thermodynamic properties and material have to be homogeneous.
- Crop: The vegetation used need to have a uniform density and uniform temperature through the system.
- Air: It is considered homogeneous throughout the greenhouse and has a unique heat capacity.
- Soil: The layers of the soil, as we will be referring to three sub-layers need to be homogenous
in term of organic elements in order to assume a uniform heat capacity and temperature through the layer or the subsystem.

The thermal global energy balance of the greenhouse can be described by only one equations:

\[ Q_{in} - Q_{out} = \text{Instantaneous variation of the greenhouse generated energy} \quad (1) \]

Referring to [18], the thermal equations that describe the heat energy exchanges occurring inside in the greenhouse are as follow:

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>inside air</td>
</tr>
<tr>
<td>e</td>
<td>external air</td>
</tr>
<tr>
<td>c</td>
<td>cover</td>
</tr>
<tr>
<td>w</td>
<td>inside air mass vapor</td>
</tr>
<tr>
<td>v</td>
<td>vegetation</td>
</tr>
<tr>
<td>s</td>
<td>soil surface</td>
</tr>
<tr>
<td>s0,s1,s2,s3</td>
<td>layers of soil</td>
</tr>
<tr>
<td>M</td>
<td>density</td>
</tr>
</tbody>
</table>

For radiative, convective, conductive equations, refer to appendix B for heat transfer equations.

The initial conditions:
\[ T_c = T_i = T_v = T_e = 0 \]

Energy equilibrium for the cover:

\[ C_c \frac{dT_c}{dt} = (Q_{Rvc} + Q_{Rsc}) \frac{As}{Ac} + Q_{Vci} + Q_{Lci} - Q_{Vce} - Q_{Lce} + Q_{Sc} \quad (2) \]

Energy equilibrium for the interior air:

\[ C_a \frac{Vol}{As} \frac{dT_i}{dt} = Q_{Vsi} + Q_{Vvt} - \frac{Ac}{As} Q_{Vci} - Q_{dryair} + Q_{heating sys} \quad (3) \]

- \( Q_{dryair} \): Thermic flux of dry air
- \( Q_{heating sys} \): The heat flux due to the heating system (to be added when the solar system is added to the greenhouse)
Mass equilibrium equation for the water in the inside air:

\[ C_{Lat} \frac{\text{Vol}}{A_s} \frac{dW_i}{dt} = Q_{lsi} + Q_{lvi} - \frac{A_c}{A_s} Q_{lci} - Q_{watervapour} \]  \hspace{1cm} (4)

- \( Q_{watervapour} \): Thermic flux of water vapour

Energy equilibrium for the vegetation:

\[ C_v M_v \frac{dT_v}{dt} = Q_{RSV} - Q_{RVC} - Q_{Lvi} + Q_{SV} \]  \hspace{1cm} (5)

Energy equilibrium for the soil surface:

\[ Q_{SS} - (1 - P_v) Q_{RSc} - P_v Q_{RSv} + Q_{VSi} + Q_{LSi} - Q_{DS1} = 0 \]  \hspace{1cm} (6)

Energy equilibrium for the soil’ layers:

First soil layer:

\[ \frac{dT_{s1}}{dt} = \frac{Q_{Ds1}}{\rho_{s1} C_{s1} l_1} - \frac{Q_{Ds2}}{\rho_{s2} C_{s2} l_2} \]  \hspace{1cm} (7)

Second soil layer:

\[ \frac{dT_{s2}}{dt} = \frac{Q_{Ds2}}{\rho_{s2} C_{s2} l_2} - \frac{Q_{Ds3}}{\rho_{s3} C_{s3} l_3} \]  \hspace{1cm} (8)

Third soil layer:

\[ \frac{dT_{s3}}{dt} = \frac{Q_{Ds3} - Q_{Dunderground}}{\rho_{s3} C_{s3} l_3} \]  \hspace{1cm} (9)

As stated before, in equation (1), the thermal global balance can be described by only one equation which means the supplies mince the losses will be equal to the instantaneous internal energy.

Energy supplies will then concern the solar one: \( Q_{Sc} + Q_{SV} + Q_{SS} \) positive during the day and null during the night, then the \( Q_{heating\_sys} \) as stated in (3) can be added to the \( \sum \)Supplies. The losses are stated in the Fig. 6.
Figure 7 Overview of the heat exchange flux inside the greenhouse: the supplies and losses [18].

As the energy equilibrium equation of the inside air is the one that consists of the heat energy needed to heat the greenhouse, we will mainly focus on it in order to calculate the energy needed for heating the greenhouse to reach the microclimate conditions needed for the harvest and growth of tomatoes in the area concerned. In the energy balance of inside air (3), only the convective heat transfer is not negligible, it is assumed that the solar radiation entering the greenhouse is almost zero in order to simplify the solution of the heat transfer equations.

For the temperature of soil layer 1, we need to set up an initial value for the temperature of underground layers for soil and this is going to be assumed to be 13°C for the winter season (December) referring to [19].
The equation (7), (8), (9) are first order differential equations solved using analytical methods. For the temperature inside air of the greenhouse is solved using Euler Method assuming $T_c = T_i = T_v = T_e = 0$.

The temperature variation for soil 1 with time is then:

$$T_{s1}(t) = 13°C + e^{-\frac{h}{\rho c_p L}t}$$  \hspace{1cm} (10)

The temperature variation for soil 2 with time is then:

$$T_{s2}(t) = 11°C + e^{-\frac{h}{\rho c_p L}t}$$  \hspace{1cm} (11)

The temperature variation for soil 3 with time is then:

$$T_{s3}(t) = 9°C + e^{-\frac{h}{\rho c_p L}t}$$  \hspace{1cm} (12)

Same thing will be done for $T$ inside air. For Toutside air, referring to [16], we may use the sine function to model the daily temperature variation by setting some parameters. The equation that model this is as follow:
\[ y = A \sin \left( B(x - C) \right) + D \]  
\[ A = \frac{(T_{\text{max}} - T_{\text{min}})}{2}, \quad B = \frac{2\pi}{12}, \quad C\text{(phase)} = 0, \quad D = T_{\text{min}} + A \]  

By setting the parameters to the adequate values by referring to [17] for NASA meteorological data for the site that is used for experiment at 26m elevation from the sea, the function becomes:

By setting the parameters to the adequate values by referring to [17] for NASA meteorological data for the site that is used for experiment at 26m elevation from the sea, the function becomes:

\begin{center}
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\hline
Maximum & 16.8 & 18.7 & 21.0 & 22.2 & 24.4 & 27.6 & 31.6 & 31.4 & 28.5 & 24.6 & 20.7 & 17.8 & 23.8 \\
\hline
Minimum & 9.82 & 11.1 & 12.8 & 13.9 & 15.8 & 18.9 & 22.1 & 22.3 & 20.4 & 17.6 & 14.3 & 11.5 & 15.9 \\
\hline
\end{tabular}
\end{center}

Figure 9 Monthly Averaged Air Temperature at 10m above the Surface of the Earth (°C) [17].

\[ T_e = 3.15 \sin \left( \frac{2\pi t}{24} \right) + 14.65 \]  

For December, the occurring lowest temperature at night is 11.5 °C and the highest one is 17.8°C, for this, the equation that model temperature in December for the site targeted is:

2.3.2 Gembloux Greenhouse Dynamic Model Results

Using Matlab, I was able to solve plot the Temperature variations for the subsystems: soil layers at different depths (0.2 m, 0.15 m, 0.10 m), inside air, and outside air in order to identify the gaps occurring between each subsystems and not only that, be able to identify the subsystems that essentially needs a heating system in order to improve the overall climate of the greenhouse. The figure below sums up the plots, there is a label describing what subsystem the plot refers to:
Figure 10 The average temperature gap between $T_e$ and $T_i$.

Figure 11 The average temperatures gap for the soil layers 3/2, 2/1, 1.
The average temperatures gap for the soil' layers 3/2, 2/2, 1 are respectively: 9°C, 11°C, and 13°C.

The average temperature for the external air is: 14.4 °C.

The average gap temperature between internal air and external air is: 10.719 °C.

In order to heat up the inside air to a temperature of 18 °C, mathematical analysis results show that an energy of 90 Wh/m² is needed to reach that goal, which means a total energy of $Q_h=108000$ Wh is required.

### 2.4 Simulink Matlab

According to [15], Simulink is a block diagram environment integrated with MATLAB that provides its user with multidomain simulation and Model based design. Simulink provides a graphical editor that you can use to build in the model you want by taking out the features
from the customizable block library, and then proceed to the modeling solvers and simulation dynamic systems.

In addition, there is an important feature called “Simscape” that enables the user to build in physical models in Simulink graphical editor. Simscape in opposite of Simulink contains additional constructs to specific physical modeling, for instance:

- Mechanical building blocks
- Electrical building blocks
- Magnetic building blocks
- Hydraulic building blocks
- Thermal building blocks

![Greenhouse Heating System](image)

**Figure 13 Overview of the Greenhouse Thermal Model as it was Built on Simulink Matlab.**

Reading the details on Simulink limitation, we found out that Simulink physical block cannot handle complex models as it is the case for the greenhouse (many layers, diverse temperatures all over the greenhouse), this means Simulink can only handle lumped parameters model by assuming constant temperature across the building. This is problematic as it didn’t allow us to have clear and logical simulations.
In Addition to this issue, the Matlab Simulink doesn’t allow to configure the area of the building or the greenhouse, it only considers the whole block as a rectangle, it doesn’t allow also to set up the distances between each layers (soil layers, vegetation, inside air, cover). The model of the greenhouse as it was built on Simulink block diagram is shown in the figure below:

Figure 14 Overview of the Greenhouse Thermal Model as it was Built on Simulink Matlab.
3. HEATING SOLUTIONS

Greenhouses’ system normally should provide a controlled environment for crops growth, with letting the needed sunlight radiations go through the cover, an adequate temperature, and humidity; therefore greenhouses need a full exposure to sunlight throughout the year. In winter seasons, the temperatures of the site that is located in the latitude 30.4/longitude -9.5 drop to approximately 9.82 °C in January and 11.1 °C in February. As stated before in Table 1, the needed temperatures inside the greenhouse to maintain the appropriate microclimate conditions are between 15°C and 29°C for germination and between 21°C and 24°C for growth.

In order to heat up the inside air to a temperature of 18 °C, mathematical analysis results show that a total energy of $Q_h=832.25 \text{ kWh}$ is required.

In our capstone project, we will mainly use solar energy as main source for heating up the greenhouse, for that, it is compulsory to specify some important solar data and parameters such as the average diffuse radiation incident for the site concerned, the optimum tilt of solar panels. According to [17], the monthly averaged diffuse radiation incident on a horizontal surface in the site with latitude 30.4, longitude -9.4 for December is 5.30 kWh/m²/day.

Rather than this, it is important to know the solar angle or optimum tilt of the solar thermal panels that are going to be used. To reach a high efficiency and to be able to increase the energy output of solar collectors, it is preferable to have a tracking. This device change the orientation or inclination angle of the panels throughout the day to maximize the energy capture using the sensors and mechanical linear actuators in the system. Unfortunately, the tracking system are a bit expensive for farmers in Morocco.

To help the farmers, researches have been done to find the optimum tilt angle of collectors by means of mathematical analysis. Using the solar angle calculated as provided by
The optimum angle that can be taken into consideration while placing the solar collectors on the site concerned is 36° during winter time:

Figure 14 Solar angle calculations for the region of Agadir [20].

| Tableau 1 Solar Potential of the Site (Irradiation for optimum tilt of 36°) |

The surface area that we will need of solar thermal collectors assuming the efficiency of the type of panel used is going to be calculated using the formula that will be further used in the upcoming subsections:

$$A = \frac{Q_{heating}}{\eta \times \text{Average diffuse irradiation}} = \frac{832.25 \text{ kWh}}{\eta \times 5.30 \text{ kWh/m}^2/\text{day}}$$

There are four main categories of solar water heaters or collectors:

- Low Temperature Unglazed Collectors
- Concentrating Collectors
- Flat Plate Collectors
- Evacuated Tube Collectors
- Selective Absorbers
3.1 Sensible Heating System Using Flat Collectors

3.1.1 Overview on Flat Collectors

Thermal energy storage technologies based on sensible heat storage are the most commercially available because they are considered to be simple and low cost systems. To maintain a good climate for the greenhouse experienced, water is going to be chose as the most adequate material for sensible heating storage. Water has indeed a high specific heat compared to other candidates such as blue methylene and high capacity rate while being charged and discharged from the tank to the pipes.

A typical flat plate collector is used for residential buildings when the heating of water is having a great negative impact on the energy bills. This collector is a metal box with a glass cover and black absorber on the top that is used further for attracting the solar radiations. It is selected among all of the collectors discussed before as it absorbs irradiation from all directions which means a tracking system is not highly required thus less expenses. Flat collectors are preferably used over evacuated tubes as they overheat easily when installed flat not on the roof of the greenhouse, more maintenance cost comparing to flat collectors.

Figure 15 Flat Plate Collectors Main Components [23]
3.1.2 System Design

The heating system of the greenhouse will consist of subsystems connected to each other through polybutylene pipes as it is designed using eDraw in the figure below:

![Diagram of the Greenhouse Heating System]

Figure 16 Design of the Greenhouse Heating System Using eDraw (For both Flat Plate and Evacuated Tube Collectors).

1- Cold water tank of 1m³

2- Flat solar collectors inclined by an angle of 36 degrees.

3- Hot water tank of 1m³

4- Polybutylene tubes+ valves+ fans+ one water pump

During the day, the valves for cold water as it is shown in the figure are open and the valves for night are closed, letting the flow of cold water coming from the blue tank to the solar collectors ensured by the pump, the hot water tank stores then the hot water that is saved for night heating. The circulation of water is closed, which means that the cold water
tank are used for both recuperation and supply during the day.

3.2 Sensible Heating System Using Evacuated Tube Collectors

3.2.1 Overview on Evacuated Tube Collectors

According to [23], evacuated tube collectors are composed of four components: evacuated tube (absorbs solar to heat), heat pipe (mainly deals with transferring the heat), manifold (the insulator of the header pipe) and mounting frame. The figure below shows an overview of the evacuated tube collector:

![Evacuated Tube Collectors](image)

Figure 17 Evacuated Tube Collectors Showing its Main Components [23].

3.2.2 System Design

This heating system of the greenhouse will consist of subsystems connected to each other through polybutylene pipes as it was described in the previous section, the only main
difference will be where to place the collectors. As stated before, evacuated tube collectors overheat easily when installed flat not on the roof of the greenhouse, that’s why we will consider placing them at a height of 2m instead of placing them directly on the floor and this by having a support.

3.3 Underground Heating System

The underground heating of the greenhouse involves using the soil or the floor as a large radiator, warm water is circulated through tubes transferring then heat to the soil and eventually to the internal air. Because of expansion and corrosion issues, the material selected for these tubes is not going to be steel or iron as it has always been the case, but rather a nonmetallic materials such as polybutylene [22].

Polybutylene pipes (k=10.17 W/m²K)are going to be opted for in underfloor heating as they ensure long durability prevents the metallic components of the system from corrosion throughout the usage time. To work as oxygen barriers for the system, the pipes should be of type “barrier” pipes as shown below:

![Polybutylene tubes for underfloor heating](image)

**Figure 18 Polybutylene tubes for underfloor heating [22].**

Before moving to the calculation part, and how much area of pipes is needed for the heating system, we need to know by how much the soil heat energy is contributing into the increase of ambient
air’s temperature of the whole system, we refer to equation (3) and also the data generated in Fig. 10:

\[
\begin{array}{|c|c|}
\hline
Q_{\text{soil}} & 3200 \text{ W} \\
Q_i & 7000 \text{ W} \\
\text{Ratio} & 46\% \\
\hline
\end{array}
\]

Figure 19 Different Soil Layers Energy Needed to Heat up The inside Air of the Greenhouse to 24°C.

4. DIVERSE SOLAR HEATING SOLUTIONS

4.1 Underfloor Heating Using Flat Plate Collectors

The heating of the soil layer 3 can cover up to 46% of the heating goals of the ambient air. As stated before, the energy requirement to heat the ambient air to 24 °C during day and night in winter time is: 108000 Wh. Therefore, the needed heat supplied by the soil heating system is: 49680 Wh.

We should place the pipes in layer 3 at a depth of 0.2 m because this will not break up the growth of vegetation and at the same time we will not be considering a very high gap between pipes. For the two other layers, we will mainly consider a higher gap between pipes in order to facilitate the germination and growth of tomatoes’ crops.

The pipe area is given by: \( \pi \times d \times l = 3.14 \times 0.02m \times 50m = 3.14m^2 \)
The number of pipes needed to cover up the heating of 988 m² of soil considering a gap of 20 cm and 46% of inside air is:

- \( n = \frac{A}{2 \times 3.14} = 157 \text{ polybutylene pipes of 50 m} \)

157 pipes are needed to cover the demand of the greenhouse in terms of soil heating.

Now it is necessary to calculate the needed area of solar collectors (either selective or flat solar collectors) required to reach the required Q energy needed to heat the soil and the ambient air.

- \( C_p = 4.19 \text{ kJ/kg.K} \)
- \( \rho = 1000 \text{ kg/m}^3 \)
- \( T_i = 5 \text{ °C} \)
- \( T_f = 30 \text{ °C} \)
- \( Q = 49680 \text{ Wh} \)

Therefore, the volume of tank required is:

- \( Q = C_p \times \rho \times V \times (T_f - T_i) = 4.19 \times 1000 \times (30 - 5) \times V \)
- \( V \approx 1 \text{ m}^3 \)

According to [21], the efficiency of flat plate collectors for a temperature difference of 25°C is approximately 60%, the needed area of solar collectors can be calculated using the formula discussed before:

- \( A = \frac{49.68}{0.6 \times 5.30} \frac{\text{kWh}}{\text{m}^2/\text{day}} = 15.62 \text{ m}^2 \)
- \( \sqrt{15.62} = 4 \text{ m} \)

We need approximately 15.62 m² of flat collectors in order to heat up the soil and 46% of the greenhouse of area 1200 m². According to [23], the aperture area of a flat collector is 2.3 m², this means we need approximately 7 flat plate collectors.
4.2 Underfloor Heating Using Evacuated Tube Collectors

The number of pipes needed to cover up the heating of 988 m² of soil considering a gap of 20 cm and 46% of inside air is:

\[ n = \frac{A}{2 \times 3.14} = 157 \text{ polybutylene pipes of 50 m} \]

157 pipes are needed to cover the demand of the greenhouse in terms of soil heating.

Now it is necessary to calculate the needed area of solar collectors (either selective or flat solar collectors) required to reach the required Q energy needed to heat the soil and the ambient air.

- \( C_p = 4.19 \text{ kJ/kg.K} \)
- \( \rho = 1000 \text{ kg/m}^3 \)
- \( T_i = 5 \text{ °C} \)
- \( T_f = 30 \text{ °C} \)
- \( Q = 49680 \text{ Wh} \)

Therefore, the volume of tank required is:
\[ Q = C_p \rho V (T_f - T_i) = 4.19 \times 1000 \times (30-5)V \]

\[ V \approx 1 m^3 \]

According to [21], the efficiency of evacuated tube collectors for a temperature difference of 25°C is approximately 80%, the needed area of evacuated tube solar collectors can be calculated using the formula discussed before:

\[ A = \frac{49.68 kWh}{0.8 \times 5.30 \frac{kWh}{m^2/day}} = 11.72 m^2 \]

\[ \sqrt{11.72} = 3.42 m \]

We need approximately 11.72 m² of evacuated tube collectors in order to heat up the soil and 46% of the greenhouse of area 1200 m². According to [23], the aperture area of evacuated tube collectors is 2.83 m², this means we need approximately 4 evacuated tube collectors.

![Figure 21 The Needed Components for Underfloor Heating Using Evacuated Tube Collectors.](image)
4.3 On floor Heating Using Flat Plate Collectors

The heating of the soil layer 0 can cover up to 78% of the heating goals of the ambient air. As stated before, the energy requirement to heat the ambient air to 24 °C during day and night in winter time is: 108000 Wh. Therefore, the needed heat supplied by the soil heating system is: 84240 Wh.

Now that we opted for onfloor heating systems, we need to make sure to higher the gap between pipes to facilitate the growth and germination of the greenhouse. We will consider a gap of 40 cm.

The pipe area is given by: \( \pi \times d \times l = 3.14 \times 0.02m \times 50m = 3.14m^2 \)

The number of pipes needed to cover up the heating of 988 m² of soil considering a gap of 20 cm and 78% of inside air is:

\[ n = \frac{A}{3.14} = 105 \text{ polyethylene pipes of 50 m} \]

105 pipes are needed to cover the demand of the greenhouse in terms of soil heating.

Now it is necessary to calculate the needed area of solar collectors (either selective or flat solar collectors) required to reach the required Q energy needed to heat the soil and the ambient air.

- \( C_p = 4.19 \text{ kJ/kg.K} \)
- \( \rho = 1000 \text{ kg/m}^3 \)
- \( T_i = 5 \text{ °C} \)
- \( T_f = 30 \text{ °C} \)
- \( Q = 84240 \text{ Wh} \)

Therefore, the volume of tank required is:

\[ Q = C_p \times \rho \times V \times (T_f - T_i) = 4.19 \times 1000 \times (30-5) \times V \]

\[ V \approx 1 \text{ m}^3 \]

According to [21], the efficiency of flat plate collectors for a temperature difference of
25°C is approximately 60%, the needed area of solar collectors can be calculated using the formula discussed before:

- \[ A = \frac{84.24 \text{ kWh}}{0.6 \times 5.30 \text{ kWh/m}^2/\text{day}} = 26.5 \text{ m}^2 \]

- \[ \sqrt{26.5} = 5.14 \text{ m} \]

We need approximately 26.5 m² of flat collectors in order to heat up the soil and 78% of the greenhouse of area 1200 m². According to [23], the aperture area of a flat collector is 2.3 m², this means we need approximately 12 flat plate collectors.

![12 flat plate collectors of an aperture area of 2.3 m²](image)

![105 of polybutylene pipes of 50 m and 0.02 m diameter](image)

![pump+2 fans+2 water tanks of 1m³](image)

**Figure 22 The Needed Components for On floor Heating Using Flat Plate Collectors**

### 4.4 On floor Heating Using Evacuated Tube Collectors

The heating of the soil layer 0 can cover up to 78% of the heating goals of the ambient air. As stated before, the energy requirement to heat the ambient air to 24 °C during day and night in winter time is: 108000 Wh. Therefore, the needed heat supplied by the soil heating system is: 84240 Wh.

Now that we opted for on floor heating systems, we need to make sure to higher the gap...
between pipes to facilitate the grow and germination of the greenhouse. We will consider a gap of 40 cm.

The pipe area is given by: \( \pi \cdot d \cdot l = 3.14 \cdot 0.02m \cdot 50m = 3.14m^2 \)

The number of pipes needed to cover up the heating of 988 m² of soil considering a gap of 20 cm and 78% of inside air is:

\[ n = \frac{A}{3 \cdot \pi} = 105 \text{ polybutylene pipes of 50 m} \]

105 pipes are needed to cover the demand of the greenhouse in terms of soil heating.

Now it is necessary to calculate the needed area of solar collectors (either selective or flat solar collectors) required to reach the required Q energy needed to heat the soil and the ambient air.

- \( C_p = 4.19 \text{ kJ/kg.K} \)
- \( \rho = 1000 \text{ kg/m}^3 \)
- \( T_i = 5 \text{ °C} \)
- \( T_f = 30 \text{ °C} \)
- \( Q = 84240 \text{ Wh} \)

Therefore, the volume of tank required is:

\[ Q = C_p \cdot \rho \cdot V \cdot (T_f - T_i) = 4.19 \cdot 1000 \cdot (30-5) \cdot V \]

\[ V \approx 1 \text{ m}^3 \]

According to [21], the efficiency of flat plate collectors for a temperature difference of 25°C is approximately 60%, the needed area of solar collectors can be calculated using the formula discussed before:

- \( A = \frac{84.24 \text{ kWh}}{0.8 \cdot 5.30 \text{ kWh/m}^2/\text{day}} = 19.9 \text{ m}^2 \)

\[ \sqrt{26.5} = 4.46 \text{ m} \]

We need approximately 19.9 m² of evacuated tube collectors in order to heat up the soil
and 78% of the greenhouse of area 1200 m². According to [23], the aperture area of evacuated tube collectors is 2.83 m², this means we need approximately 7 evacuated tube collectors.

![7 evacuated tube collectors of an aperture area of 2.83 m²](image1)

![105 of polybutylene pipes of 50 m and 0.02 m diameter](image2)

![pump+2 fans+2 water tanks of 1m³](image3)

**Figure 23 The Needed Components for On floor Heating Using Evacuated Tube Collectors.**

### 5. ENERGY SAVINGS AND CO₂ EMISSIONS

As it is stated in [18], the investments cost for heating up the greenhouse during cold times in Morocco is approximately 4000 MAD/ha/day which is very high if assuming the daily net incomes for a farmer in the region of Souss Massa Draa is moderate.

According to [25], the mass of CO₂ emitted per liter of diesel is approximately 2.68 kg/l. For heating up an area of 1200 m², we need approximately 56.47 l of diesel per day which results in 151.34 kg of CO₂ emitted per day.

- Mass of CO₂ emitted per liter of diesel per day: 2.86*56.47= 151.34 kg of CO₂ emitted per day.
Heating up a greenhouse is necessarily done for the winter or cold time when the temperatures drop out to 8°C, means during the winter season that is taking place between December and February.

- Heat of combustion for diesel is: 45 MJ/kg
- 1 liter of diesel weighs: 0.850 kg/l
- The energy savings from combustion: \(45 \times 0.850 \times 56.47 \times 30 \times 3 = 194397.9\) MJ/year.
- The cost savings from combustion: \(56.47 \times 30 \times 3 \times 8.5 = 43199.55\) MAD/year.

**Figure 24 Yearly Energy savings from heating the greenhouse using Diesel.**
6. COST ANALYSIS

The tables below describe the cost analysis of the four systems excluding the maintenance cost and installation fees that will be added once the optimum and efficient heating system is selected:

Table 3 Expenses of Underfloor/Flat Plate Collectors Covering up 46% of Inside Air Heating.

<table>
<thead>
<tr>
<th>Underfloor Heating Using Flat Plate Collectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy contribution</td>
</tr>
<tr>
<td>Units</td>
</tr>
<tr>
<td>Flat Plate Collectors</td>
</tr>
<tr>
<td>Pump 1kW</td>
</tr>
<tr>
<td>Polybutylene pipes 50 m 0.02 m diameter</td>
</tr>
<tr>
<td>Water of 1m3</td>
</tr>
<tr>
<td>Fans</td>
</tr>
<tr>
<td>Total Cost</td>
</tr>
</tbody>
</table>

Table 4 Expenses of Underfloor/Evacuated Tube Collectors Covering up 46% of Inside Air Heating.

<table>
<thead>
<tr>
<th>Underfloor Heating Using Evacuated Tube Collectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy contribution</td>
</tr>
<tr>
<td>Units</td>
</tr>
<tr>
<td>Evacuated Tube Collectors</td>
</tr>
<tr>
<td>Pump 1kW</td>
</tr>
<tr>
<td>Polybutylene pipes 50 m 0.02 m diameter</td>
</tr>
<tr>
<td>Water of 1m3</td>
</tr>
<tr>
<td>Fans</td>
</tr>
<tr>
<td>Total Cost</td>
</tr>
</tbody>
</table>
### Table 5 Expenses of On floor/Flat Plate Collectors Covering up 78% of Inside Air Heating.

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Price/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate Collectors</td>
<td>12</td>
<td>46244.88</td>
</tr>
<tr>
<td>Pump 1kW</td>
<td>1</td>
<td>3360</td>
</tr>
<tr>
<td>Polybutylene pipes 50 m 0.02 m diameter</td>
<td>105</td>
<td>702.8</td>
</tr>
<tr>
<td>Water of 1m³</td>
<td>2</td>
<td>1199</td>
</tr>
<tr>
<td>Fans</td>
<td>2</td>
<td>1999</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td><strong>638488.56</strong> MAD</td>
</tr>
</tbody>
</table>

### Table 6 Expenses of On floor/Evacuated Tube Collectors Covering up 78% of Inside Air Heating.

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Price/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate Collectors</td>
<td>7</td>
<td>76140.8</td>
</tr>
<tr>
<td>Pump 1kW</td>
<td>1</td>
<td>3360</td>
</tr>
<tr>
<td>Polybutylene pipes 50 m 0.02 m diameter</td>
<td>105</td>
<td>702.8</td>
</tr>
<tr>
<td>Water of 1m³</td>
<td>2</td>
<td>1199</td>
</tr>
<tr>
<td>Fans</td>
<td>2</td>
<td>1999</td>
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<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td><strong>616535.6</strong> MAD</td>
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### Table 7 Expenses of Underfloor/Flat Plate Collectors Covering up 78% of Inside Air Heating.

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
<th>Price/Unit</th>
</tr>
</thead>
<tbody>
<tr>
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<td>46244.88</td>
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<tr>
<td>Pump 1kW</td>
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</tr>
<tr>
<td>Polybutylene pipes 50 m 0.02 m diameter</td>
<td>157</td>
<td>702.8</td>
</tr>
<tr>
<td>Water of 1m³</td>
<td>2</td>
<td>1199</td>
</tr>
<tr>
<td>Fans</td>
<td>2</td>
<td>1999</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td><strong>669002.219</strong> MAD</td>
</tr>
</tbody>
</table>
Table 7 Expenses of Underfloor/Evacuated Tube Collectors Covering up 78% of Inside Air Heating.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Price/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evacuated Tube Collectors</td>
<td>7</td>
<td>76140.8</td>
</tr>
<tr>
<td>Pump 1kW</td>
<td>1</td>
<td>3360</td>
</tr>
<tr>
<td>Polybutylene pipes 50 m 0.02 m diameter</td>
<td>157</td>
<td>702.8</td>
</tr>
<tr>
<td>Water of 1m3</td>
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<td>1199</td>
</tr>
<tr>
<td>Fans</td>
<td>2</td>
<td>1999</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td><strong>636528.852</strong> MAD</td>
</tr>
</tbody>
</table>

Comparison of Different Heating Systems Cost Covering 78% of Inside air energy

Figure 25 Comparison on the Basis of Expenses assuming the same Energy Output.

After setting up the energy output of underfloor heating to 78% of heating the inside air instead of 46% to allow comparison between the different heating scenarios, it is now shown or proven that opting for on-floor heating using evacuated tube collectors and polybutylene pipes might be a good option for farmers in the region of Souss Massa Draa,
excluding the maintenance and installation. The total expenses of the apparatus needed to heat up a 0.12 ha greenhouse is: 616535.6 MAD.

7. CONCLUSION

Generally, heating a traditional greenhouse in Morocco requires the usage of fuel (mainly combustion of diesel) in order to ensure an adequate microclimate for the growth of crops in the winter season. The investment cost for heating up the greenhouse during cold times in Morocco is approximately 4000 MAD/ha/day which is very critical. In order to improve the microclimate of the greenhouse and to contribute into the preservation and sustainability of the system, four heating systems were opted to cover the heating of the ambient air inside the greenhouse up to 78% during winter time. After modeling the greenhouse, and setting up heat exchange equations, we were able to find out the energy requirements to heat up the inside air to an average temperature of 24 °C after solving differential equations. Based on the calculations generated, we were able to select on-floor heating system using polybutylene pipes and evacuated tube collectors as the most efficient and optimum option.
APPENDICES

Appendix A: Drawing of the Actual Greenhouse that will be Heated Using Diverse Heating Systems Created by Ecotaqa Services Company
### Appendix B: Heat Transfer Equations [24]

**Heat Transfer Equations Sheet**

<table>
<thead>
<tr>
<th>Conduction: $q_c = -k \frac{dT}{dx}$</th>
<th>Heat Exchangers: $\Delta T_{in} = \frac{q(T_{in} - T_{ao})}{U(\frac{1}{A} + \frac{1}{A_{in}})}$ Parallel flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convection: $q = hA(T_s - T_o)$</td>
<td>$\Delta T_{in} = \frac{q(T_{in} - T_{ao})}{U(\frac{1}{A} + \frac{1}{A_{in}})}$ Counter flow</td>
</tr>
<tr>
<td>Radiation: $q_r = \varepsilon A T^4$</td>
<td>$NTU = \frac{U A C_{in}}{C_s} \quad C_s = C_{in} C_{out}$ $\varepsilon = \frac{q_{in}}{T_{in}} \quad q_{out} = C_{in}(T_{in} - T_o)$</td>
</tr>
</tbody>
</table>

#### Diffusion equations:

- Uniform properties: $a = \frac{k}{\rho c_p}$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

- Cylindrical coordinates:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( r^2 \frac{\partial T}{\partial \theta} \right) + \frac{\partial^2 T}{\partial z^2} + \frac{1}{\alpha} \frac{\partial T}{\partial t}$$
REFERENCES


http://public.wsu.edu/~sjwang/zhuwang.pdf


