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GEOTHERMAL UTILIZATION FOR HEATING, IRRIGATION AND SOIL DISINFECTION IN GREENHOUSES IN TUNISIA

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ABSTRACT

There has been a rapid development of greenhouses heated by geothermal water in the southern part of Tunisia. This evolution has placed the country third throughout the world with 80 ha after only 11 years of development. The government emphasizes the importance of this agricultural activity which gives the opportunity to produce and export to Europe during the cold period. Greenhouses which use geothermal water both as a source of heat and irrigation are considered among the most complicated systems in agriculture. Planning is needed before creating a geothermal greenhouse project. Several parameters should be taken into consideration in order to avoid high risk and failure of the project. Different important aspects will be discussed in detail such as site choice and organization of the greenhouse project, as well as temperature and flow regulations. Water equilibrium between heating and irrigation in oases and greenhouses will be presented in order to avoid loss of geothermal resources, very important in this arid zone. The technical use of geothermal water in irrigation and fertilisation for vegetables grown in greenhouses will be presented. A new method, developed in Tunisia, using geothermal water for soil disinfection against nematodes is presented. Geothermal greenhouses created close to the oasis present numerous advantages to this system.

1. INTRODUCTION

Geothermal energy has been used most extensively over the world in agriculture in greenhouse heating (Popovski, 1993). It is used in about 700 ha of greenhouses in 23 countries in Europe and other parts of the world for producing commercial out-of-season vegetables, flowers and fruits. Tunisia, a Mediterranean and North African country, has rapidly developed mainly tomato and melon production in greenhouses heated and irrigated with geothermal water. The development of this sector has been going on under adverse climatic conditions in the southern part of the country in arid and desert regions known for their lack of rain. Deep wells were drilled by the government for irrigation purposes in oases where ventilated cascade towers are used for cooling. Creating geothermally heated greenhouses close to an oasis system is complicated and needs careful planning and studies on many aspects such as the choice of the appropriate site, the organization and arrangement of the greenhouses, temperature regulation in the greenhouses and flow regulation of the geothermal water. Water equilibrium needs to be obtained between heating greenhouses and irrigation purposes in oasis and greenhouses in order to avoid the loss of water resources which are considered non-renewable and very expensive in these regions.

The geothermal water is also used in irrigation for the vegetables grown in the greenhouses. The 80 ha irrigated by this resource may be the largest area in the world. The geothermal water is relatively saline with total dissolved solids 2.2-4 g/l. This salinity has a negative effect on the yield, but the gustative quality is improved. Tomato and melon products exported have a special savour and taste which are in high demand in European markets and get high prices. Some technical methods are used for irrigation and fertilisation to provide the appropriate quantity and quality of geothermal water for crop growth. Geothermal greenhouses in Tunisia can in some cases be infested by nematodes which attack and harm the vegetable roots. This disease can significantly affect the yield of protected cultivation. Several methods are in use over the world to treat against nematodes. One method which was designed in Tunisia after experimental research, uses geothermal water during the summer season in order to control the population of nematodes in the soil and to limit their negative effects on vegetable production in greenhouses.

2. DEVELOPMENT OF GEOTHERMAL GREENHOUSES IN TUNISIA

2.1 Initial development

The development of geothermal greenhouses in the southern part of Tunisia is the result of several historical and technical steps. Late in the seventies and during the eighties, a large amount of low-enthalpy water from artesian geothermal wells was identified. Theses wells were drilled mainly for irrigation purposes by the Ministry of Agriculture. Due to the lack of rain in the southern part of the country, this area is considered an arid zone with a natural water deficiency too low to ensure normal crop development. However, the Ministry of Agriculture drilled many deep wells to exploit these geothermal resources for complementary irrigation in oases where date palm is the most dominant crop. The geothermal water used for irrigation is generally cooled by ventilated atmospheric cooling towers. As a consequence, a large amount of energy is lost and water of high quality is evaporated into the atmosphere. Simultaneously, the salinity of the irrigation water is increased. The loss of water is estimated at 7-10%.

On the other side, the development of unheated greenhouses in Tunisia has been going on since 1975 mainly in the more favourable coastal regions, Monastir, Sousse, Mahdia, Sfax and Nabeul (Mougou et al., 1987). But, as in most Mediterranean countries, obtaining early production and good quality of products needed for export was very difficult without heating, because of too low night temperatures during the winter when the minimum air temperatures were mostly below 7°C and, particularly, lower than 5°C in the desert regions. Therefore, the idea was accepted to use geothermal water in the southern regions (Tozeur, Gabes, Kébili) for heating greenhouses and to raise the air temperature inside greenhouses for about 7-8°C in order to maintain a minimum temperature of 12°C. Several experiments have been carried out since 1983 by the National Agronomic Institute of Tunis. In 1985, the United Nations Development Project was created (UNDP-TUN/85/004) with the object of promoting production in greenhouses for export by using geothermal resources for heating and irrigation. The efforts of the national research were supported by the Ministry of Agriculture. The results of the experiments were very encouraging giving earlier productions, higher yields and better quality compared to unheated greenhouses. Subsequently, many greenhouse projects were installed in different regions. In 1991, the Ministry of Agriculture implemented a second project in cooperation with the Belgium government (AGCD) for technically and economically developing production in greenhouses for export target. In

1993, a national strategy was delineated for this in greenhouses and defining the national perspective of this sector. At present (1997), 80 ha of plastic greenhouses heated by geothermal water are in production. This area places Tunisia third in the world after the United States and Hungary.

2.2 Selected regions for heating greenhouses

In accordance with the National Strategy, eight regions were identified with geothermal resources with potential for greenhouse development as shown in Table 1. Generally in these regions, geothermal water is considered as a nonrenewable resource. Therefore, some severe restrictions have been placed in order to optimize the utilization of these resources both for heating and irrigation. Thus, only three regions were selected and maintained for further development, Kébili, Tozeur and Gabes. The reasoning behind the selection of these 3 regions was based on several agronomical and hydrological factors, such as:

- The total dissolved solids (TDS) of geothermal resources are in the range 2.2-4 g/l and lower than in other regions. This water can be used for irrigation purposes without any high risk to date palm trees, while for vegetables grown in greenhouses, some technical measures need to be taken.
- Taking into account that heated greenhouses require smaller amounts of water for irrigation than the amount needed for heating, the selected regions (Gabes, Kébili, Tozeur) are favourable for development because they have a large area of oases which can use the return water from greenhouses for irrigation purposes.
-The quantity of exploited geothermal water in Gabes, Kébili and Tozeur regions is higher than in the other regions as shown in Table 1. The exploited geothermal resources in these three regions come from two aquifers. The deeper one is named **Continental Intercalaire** and the other one **Complexe Terminal**. These regions include 68% of the total exploitable resources in the country. In addition, the temperatures of the geothermal water are higher than in the other regions. Thus, they represent a higher total enthalpy which allows the construction of approximately 305 ha of greenhouses which is 81% of the total greenhouse potential in the country. The high temperatures in these regions limit the volume of geothermal water needed for heating. As a consequence, the utilisation of these resources will be minimized and the number of loops required to be installed in greenhouses will be limited too.

TABLE 1: Exploited geothermal water resources and greenhouse potential in Tunisia (Ministry of Agriculture in Tunisia, 1993)

Region	**Geothermal temperatures (°C)**	**Exploited geothermal resources**		**Greenhouse potential**	
		(l/s)	**(%)**	**(ha)**	**(%)**
Gabes		1680		100	
Kébili	30-75	960	68	105	81
Tozeur		357		100	
Sidi Bouzid + Gafsa		687		38	
Mahdia	20-42	278	32	22	19
Mednine + Tataouine		278		13	
Total		485		378	

2.3 Greenhouse production system

Greenhouse-oasis relationship: The oasis and greenhouse project should be located close to each other in order to supply most of the return water from greenhouses to oasis for irrigation.

Selected crops for production: The vegetables which can be grown in greenhouses are mainly tomatoes and melons, which can be exported to Europe.

Growing period: Greenhouses can remain in use for nine months from September til May (Figure 1). Greenhouses are free during three months in the summer season due to the excessive high temperatures inside and outside.

Heating period is estimated to be 5 months, from November 15 to April 15 when the minimum air temperatures in the greenhouses drop below 14°C. Generally, during the daylight there is no need for heating. During the night, heating is required and estimated up to 16 hours during the cold period.

The export period: It starts December 15 and continues up to the end of April. Tomatoes and melons are the main products which are exported to the European markets. Tomato products can be exported continuously during the entire period, while melon has two short periods for production and export. The first period is during the winter and the second is during the spring.

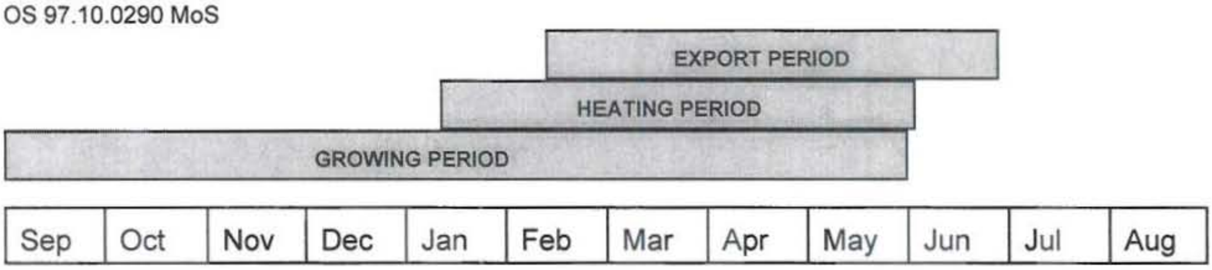

FIGURE 1: Simplified timetable of greenhouse production system in Tunisia

2.4 Area, production and export evolution

After the positive results of the experimental work, the first project with 1 ha was implanted during 1986 in collaboration between the Ministry of Agriculture and the Tunisia Agency of Energy Control. Each grower started with 2 plastic greenhouses, then several projects were created in different regions.

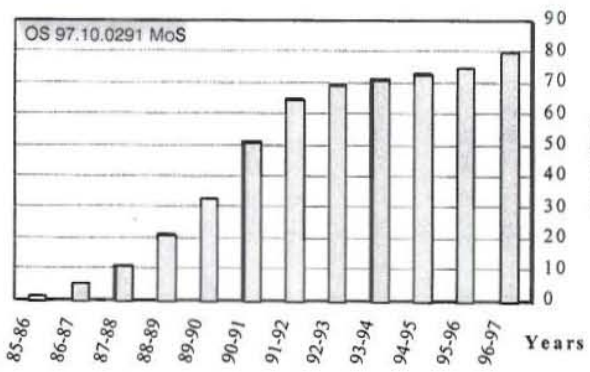

FIGURE 2: Area evolution of geothermal greenhouses in Tunisia (Saïd, 1997)

The area evolution of geothermal greenhouses can be divided into 3 different stages as shown in Figure 2. The first stage was characterised by a rapid increase of the area, reaching 70 ha after seven years of development (1986-92). The second stage (1992-96) was characterized by a relatively slow increase of the area due to time needed for strategy preparation, feasibility and profitability studies for each project, financing and fitting up the basic substructure of the project. The third stage, from 1996 and for the future, will be characterized by a fast increase as 15 ha will be installed next year. At present, 80 ha are installed in 4 regions (Gabes, Kébili, Tozeur, Nabeul) as shown in Figure 3. In Nabeul region, one project with 3 ha utilises geothermal water for heating, but not for irrigation due to the high salinity of the water (19.3 mg/l).

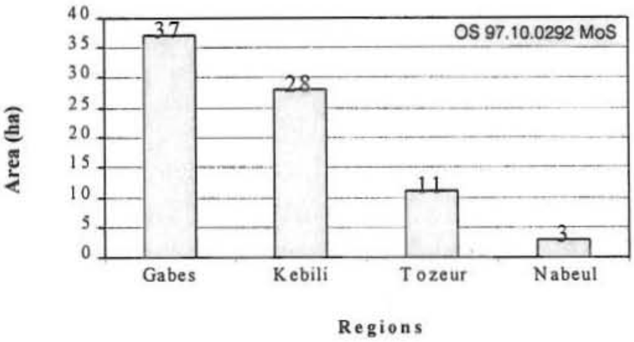

FIGURE 3: Regional area distribution of geothermal greenhouses in Tunisia

The main products are tomato, melon and cucumber. The total production has always been increasing by the time, while the export has been fluctuating as shown in Figure 4. Melon and tomato are the main products which are exported to Europe and in some cases to Canada. The export is restricted to the big farmers who have a large area of greenhouses, while the small growers have not the capacity to export.

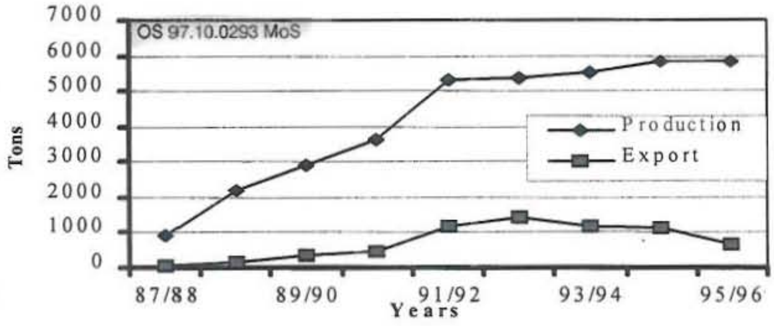

FIGURE 4: Production and export evolution from geothermal greenhouses in Tunisia

2.5 National strategy

The national strategy for developing production in greenhouses which use geothermal water for heating and irrigation was conceived in 1993. The objective is the proper use of the geothermal resources and the avoidance of waste of return water from greenhouses by using it for irrigation in oases. The government's role has been to make technical and economical studies for the entire project and to finance the basic substructures required outside the project. Private investment is supported and encouraged by the government. This encouragement varies with the size and category of the greenhouse project for production as shown in Table 2.

TABLE 2: The finance scheme of private investment in geothermal greenhouses

Finance sources	New promoter (engineers) (%)	Normal promoter (%)	Big firm (%)
Self finance	16.6	22	26.3
Subsidy	6.4	6.4	7.1
Endowment	14.3	9	-
Loans	62.7	62.6	66.6

The targets of the strategy are as follows:

- To create 305 ha of greenhouses in Tozeur, Kébili and Gabes regions. As a first step, 100 ha should be installed with 30 ha in Gabes area, 40 ha in Kébili area and 30 ha in Tozeur area.

- To produce products of good quality which can be exported during the appropriate time without high competition in the international markets.
- To organize the export circuit by creating a national structure to ensure this operation.
- To reach 48,000 tonnes of production in which 60% should be exported with a flash back of return currency $US 21,000.
- To create about 2,100 permanent jobs and 270,000 occasional workdays per season.

3. GREENHOUSE HEATING

Greenhouses that use geothermal water, both for heating and irrigation, are considered to be very complicated systems. For a new project, careful planning and technical aspects are required in order to guarantee efficiency without a high risk of mistakes and failures. The government and the private sector are both involved in the capital investment of the project. Each one has a role and responsibility to ensure sufficient and better use of geothermal resources in the country. However, accurate analysis and technical parameters should be taken into consideration when creating a geothermal greenhouse project. These parameters can be classified into four aspects as follows: The site choice of the greenhouses; the organization and arrangement of the greenhouses; the temperature regulation inside the greenhouses; and the flow regulation of geothermal water.

3.1 Site choice for a greenhouse

It is obvious that the choice of an appropriate site for a geothermal greenhouse is very important (Figure 5). The first step is to make a series of field observations in which several criteria should be taken into considerations, such as: Emplacement of the project, topography, sensibility of water blocking, soil quality and land ability.

A greenhouse should be placed close to the geothermal well and to the ventilated cascade cooling tower. It must be located close to the pipelines connecting the well and the cooling tower. This location is justified for two reasons. The transportation of geothermal water for a long distance needs high capital investment. Thus, instead of installing about 5-6 km geothermal pipeline, drilling of a new well would be more advantageous. In addition, the long distance increases significantly pressure loss in the pipeline.

The topography of the site is an important parameter in which the level and the slope should be taken into consideration. The greenhouses should be located at a higher level than the oasis or other utilisers. This position has several advantages, such as:

- The circulation of return water from the greenhouse is facilitated to the oasis by gravity without any requirements for pump installations.
- The evacuation of the drainage water from the greenhouses is facilitated by gravity.
- The drainage water from the oasis cannot reach and invade the greenhouses.
- The recuperation of drainage from greenhouses is possible. It can be used as a fertilized water for field irrigation for crops which can tolerate the high salinity. The quality of the water should be improved by adjusting the pH value and the electrical conductivity of the nutritive solution.

In addition, the installation of greenhouses in proper slope is important. Indeed, the width of the greenhouse should follow the direction of the higher slope and the length the direction of the lower slope. This orientation presents two advantages:

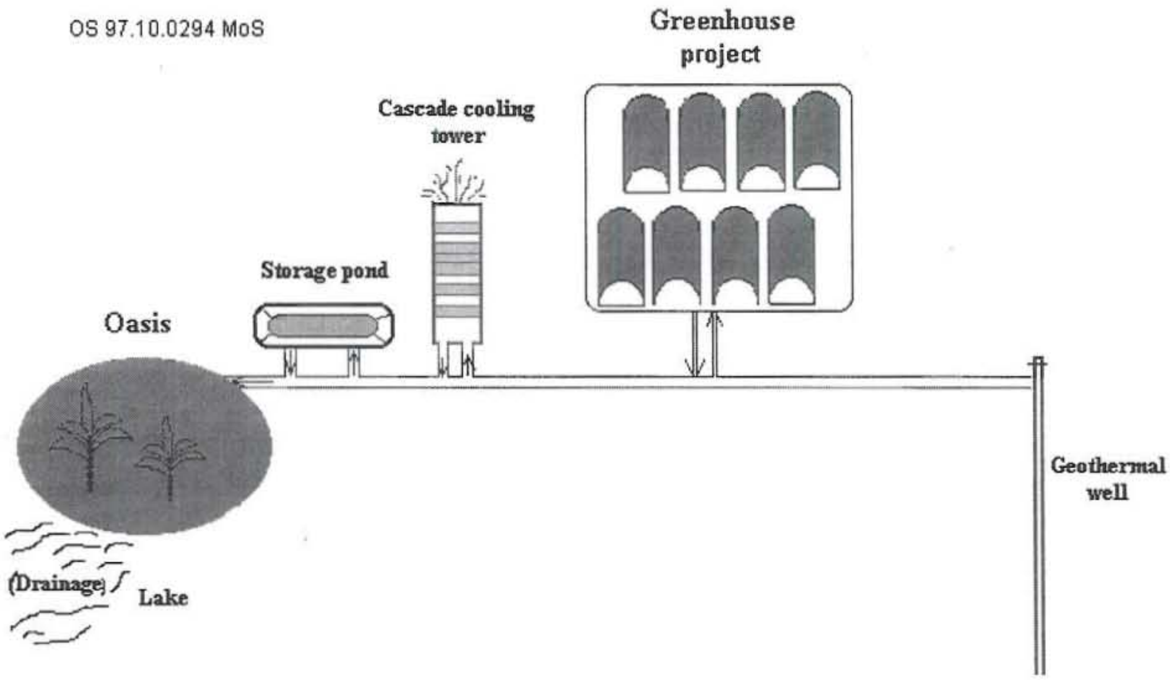

FIGURE 5: Simplified arrangement of a geothermal greenhouse project in relation with oasis in Tunisia

- The levelling work of the soil is much easier and therefore the costs of this operation limited.
- There is not high risk for decreasing the soil quality in the top level which is considered agronomically as the most suitable layer for growing vegetables.

Upon installation of greenhouses one should ensure that they will not be invaded and damaged by rain which is not frequent in these regions but does happen. However, the installation of a drainage system is required. If the drainage is an open system, it will be covered rapidly by sand blown by the wind. It would be preferable to replace it with an underground drainage system.

To select an appropriate soil for vegetables grown in greenhouses, sandy and deep soils are preferred. This soil has the advantage of better root aeration, efficient leaching and water drainage without any high risk of salt accumulation in the soil. But, nowadays, the soil quality is not considered a limiting factor for modern greenhouse projects. Soilless culture, which uses for instance substrates as a growing media, is a good tool for obtaining higher yield and better quality of products. On the other hand, it requires high technical knowledge from the growers.

There are three categories of land propriety in Tunisia; private, collective and governmental. After selecting the site for the future project, one specialized organisation in the country has the role to negotiate and regulate legally the situation of land available for agricultural activities.

3.2 Organization and arrangement of a geothermal greenhouse

3.2.1 Exploitation and operation of geothermal wells

It is very important to determine the flowrate needed for irrigation in an oasis during the heating period in order to calculate the appropriate area of the greenhouse project and to avoid water disequilibrium between heating and irrigation purposes. Theoretically, the greenhouses can exploit the maximum flow rate from the well, but for better use and optimization of geothermal resources without any losses of water, it is preferable to understand very well the existing system and to identify the different utilisers of the geothermal well and their needs of water over time, such as

- Water needed for heating greenhouses.
- Geothermal water needed for greenhouse irrigation.
- Geothermal water needed for oasis or other users.
- The possibility of water intensification in the future for open field irrigation.

According to Tunisian experience in this field, the flowrate needed for heating greenhouses is on average 6 l/s per ha during the coldest period, while that needed for irrigation in greenhouses is on average 0.6 l/s per ha during the growing period. Similarly, the total volume of water needed per season for heating is approximately 60,500 m^3/ha, while for irrigation in greenhouses the need is estimated at 6,500 m^3/ha. Thus, the total volume of water needed for greenhouse irrigation is only about 10-11% of the total volume needed for heating. As a consequence, for installing a greenhouse project the exploited flowrate from the well is related directly to the possibilities of using the return water for irrigation. However, the water equilibrium between heating and irrigation should be maintained. It means that the amount of return water from the greenhouses must be used totally for irrigation purposes during the heating period.

In addition, competition between greenhouses and oasis should be avoided. Water supply to the greenhouses must be stopped during the summer season, because of the high water demand of the oases. The total water demand of the oasis is estimated to average 25,000 m^3/ha per year with a mean flowrate of 0.8 l/s. During the summer period the oasis needs a high flowrate from the well, while during cold periods the flowrate is at a minimum. Thus, this minimum flowrate should be taken normally as a flowrate for the future greenhouse project to be created. However, two important rules should be kept in mind all the time when creating a new geothermal greenhouse project:

- The oasis should be created before the greenhouse project.
- The proper flowrate needed for heating greenhouses should be related to the water demand of the oasis during the heating period in the winter season.

If future water intensification for open field irrigation, like oasis extension is envisioned, it should be possible to increase the flowrate from the geothermal well during the cold period and then increase the area of the greenhouse project. If for any reason, the volume of geothermal water cooled by greenhouses exceeds the demand of the traditional utilisers, it is preferable to plan an open field extension for irrigation purposes only for winter production such as winter vegetables (potato, carrot), forage cultures and barley, but not plantation of trees, thus increasing the national production of vegetables and meat.

There are two variants of arrangement and organization of a greenhouse project related to the number of existing wells. The project can be connected either directly to one well or to a group of wells. Individual well operation is more advantageous than a group of wells for two reasons. First of all the choice of a favourable greenhouse project is much easier with one well. Secondly, individual well control generally means a shorter distance between the project and the well or the storage pond. This reduces the investment costs of pipelines. On the other hand operating different wells for heating greenhouses enables continuous supply of hot water even if one well is damaged. Also, the unit costs of the big pond decreases due to its higher water storage capacity.

3.2.2 Storage of return water

Heating greenhouses is needed during the night, while irrigation in oasis and greenhouses is operated during the day. Therefore, it is necessary to store the return water from greenhouses in ponds during the night and use it later for irrigation purposes. Two types of ponds should be installed. The first one is for the oasis and the second one for the greenhouses.

The first pond is a big one used for irrigating the oasis. The return water from the greenhouses is stored during the night. The storage capacity should be at least equal to the total volume of return water for 2 or 3 nights. The maximum time needed for heating greenhouses is 16 hours during the critical cold period. The government's role is to install this type of pond.

The second pond is smaller than the first one. It is used for irrigation of vegetables grown in the greenhouses. Each grower builds his own pond and takes a part of the return water during the night. The storage capacity depends on the area of cultivation grown in the greenhouses, and the highest water demand of the crops. A provision of water supply for 2 or 3 days for the greenhouses should be ensured.

In order to facilitate water supply to the oasis or greenhouses, the ponds should be placed at elevated levels, if not, pumps should be installed.

3.2.3 Form of the greenhouse complex

Greenhouse complexes with square forms as shown in Figure 6 are more advantageous than those with long forms, because the total length of pipelines needed for the supply and the return water is lower than in the complexes with long forms. Also, the diameter of the pipelines and the price of the accessories are lower. For example, if we wish to install 96 round-arched greenhouses of 500 m^2 ground area, there are many possibilities for designing the form of the complex. The lengths of PEHD ϕ 50 pipelines and the number of accessories needed vary with the form of the complex as presented in Table 3. It is clear that the square form, 2, is more advantageous than the other forms.

The orientation is a very important factor especially for long greenhouses with a small width. The recommended greenhouse orientation for Mediterranean countries is N-S. This orientation has the advantages that the light distribution inside the greenhouse is more homogeneous with better photosynthesis activity. The E-W orientation results in heat excess in the south side of the greenhouse.

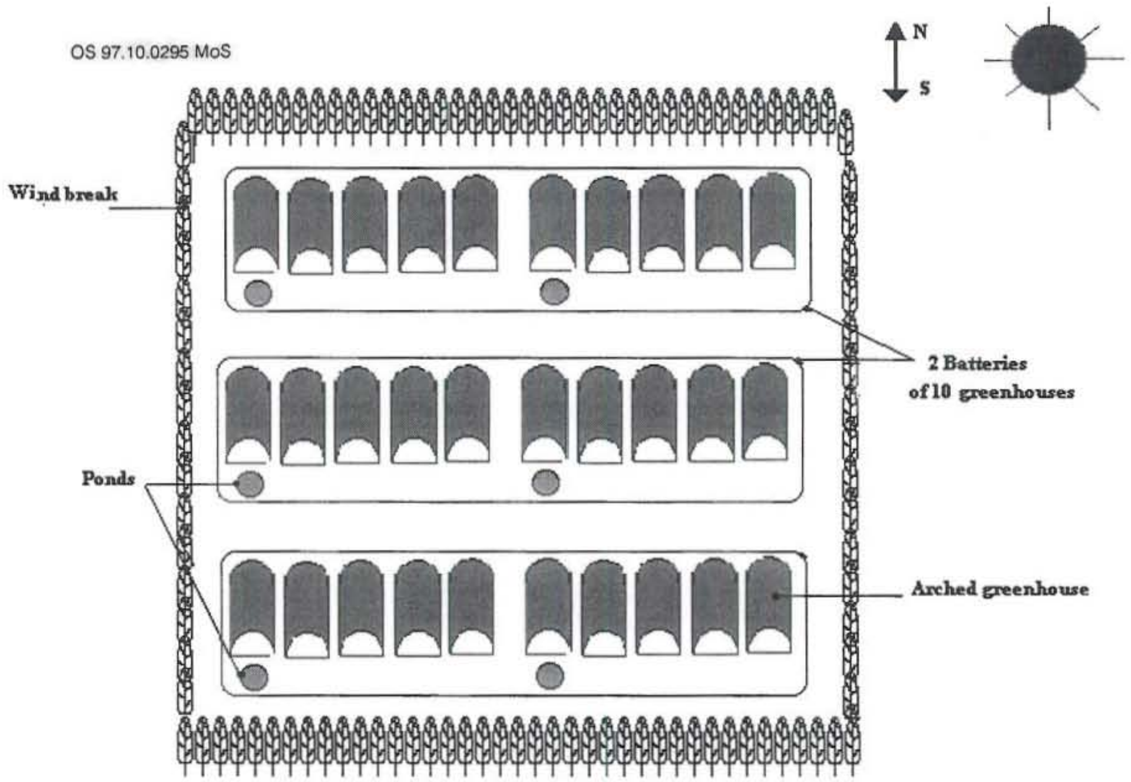

FIGURE 6: Organization of a geothermal greenhouse project

TABLE 3: Influence of the greenhouse form on the total pipeline length (Verlodt, 1991)

	Type of greenhouse complex	Form (m x m)	Pipeline length (m)	Number of accessories
1	2 batteries of 48 greenhouses	700 x 150	2100	200
2	4 batteries of 24 greenhouses	350 x 300	1825	350
3	6 batteries of 16 greenhouses	240 x 450	2190	350

3.2.4 Protection against the wind

Sites known for strong, frequent and sandy wind should be totally avoided when considering a new greenhouse area. Normally, modern plastic houses in theses regions must be designed to withstand three different loadings, due to wind, culture and the frame.

Even in a well designed and built greenhouse, damage can occur when a plastic sheet has a tear or the greenhouse is not well closed. However, it is possible to reduce the risk of project failure especially in a windy climate like in regions which are frequently exposed to sandy wind during the spring season. The installation of an effective windbreak is recommended for both heated and unheated greenhouses. The wind break has several considerable advantages such as:

- It reduces the convective heat losses from the greenhouse, particularly at night during the cold period. It results in a direct benefit by reducing the heat supply and limiting the use of geothermal water for heating greenhouses.
- It protects the greenhouse project against invasion of sand.
- It promises considerable savings in construction and longer life of the greenhouse.
- It permits better work conditions.

Two categories of windbreaks are used for protection. The first one is the inert or dry windbreak taken from the leaves of date palm trees. The second one is the vegetative windbreak shown in Figure 6. Irrigation and fertilization are recommended to ensure rapid growth of trees.

3.2.5 Drainage system

Vegetables grown under greenhouses are sensitive to salinity. Since greenhouses are irrigated and fertilized intensively, the risk of soil salinisation is high. In addition, the salinity of the geothermal water is relatively high. Therefore, the installation of a drainage system is necessary in greenhouse projects. The role of the drainage system is to drain the excess water, especially during leaching of the soil, and to avoid the high accumulation of salts in the soil. Thus, the design of the drainage network depends on many parameters such as soil permeability, electrical conductivity of the nutritive solution and the accepted limit of soil salinity for the crop.

3.3 Temperature regulation

Greenhouses are used because they provide a favourable climatic environment for plant growth. Controlling temperatures, however, is important for the economic production of protected cultivation. There is no existence of a universal calculation model and there is no final solution to the problem. The energy balance of the greenhouse depends on the type and quality of the greenhouse construction, its location, its species and cultivar inside, and irrigation technology. The approach adopted in Tunisia is using a model for calculation of peak loading. Several different models are in use over the world and their level of precision depends on the accepted boundary conditions and incorporated simplification. Simplification of the heat losses is reached by introducing two main heat flows, by transmission (conduction-convection) through the transparent cover of the greenhouse and by air infiltration in the greenhouse. Also, heat gain from solar radiation is incorporated if one is calculating heat losses during the day. Usually the heat losses to and from the soil, latent heat transfer of the plant canopy and heat transfer of condensation are neglected in a fully cropped house. This method can result in significant mistakes during the daylight conditions of exploitation. The calculation presented below for greenhouses in the south of Tunisia is done for night conditions only.

3.3.1 Heat requirement

It is necessary to calculate the total heat loss from the greenhouse in order to determine its heat demand from the geothermal water. The general equation used to determine the heat loss q (W/m^2) from the greenhouse can be expressed per unit of covered soil as (Popovski, 1993)

$$q = q_c + q_i + q_l \tag{1}$$

and the total heat loss Q (W) as

$$Q = A_g q \tag{2}$$

where
- A_g = Ground area of the greenhouse [m^2];
- q_c = Transmission (conduction-convection) heat loss of the greenhouse [W/m^2];
- q_i = Heat loss by air infiltration [W/m^2];
- q_l = Specific heat gain from solar radiation [W/m^2].

Since the heat supply is only active during the night, there is no heat gain by solar radiation. Also, there is no heat loss by air infiltration since the plastic greenhouse will be airtight. The above equations can therefore be simplified as follows:

$$q = q_c$$

$$Q = A_g\, q_c$$

The total transmission heat loss which is the conductive-convective heat loss from the greenhouse can be determined by use of the following equations:

$$q_c = K(A_c/A_g)\ (T_i - T_o) \tag{3}$$

$$Q = KA_c(T_i - T_o) \tag{4}$$

where
- K = Total heat transfer coefficient through the greenhouse cover [W/m^2 °C];
- A_c = Area of the greenhouse cover [m^2];
- T_i = Air temperature inside the greenhouse [°C];
- T_o = Outside air temperature [°C].

The heat required from the geothermal water for maintaining the desired temperature inside the greenhouse is equal to the heat loss, Q, already described. The heat requirement can also be related to the ground area by defining a new heat transfer coefficient k',and the equation will be as follows:

$$Q = k' A_g(T_i - T_o) \tag{5}$$

k' values of the heat loss coefficients are based on experimental work (Verlodt, 1991). It can be expressed as the heat loss per unit (m^2) of the floor surface in greenhouse construction. In Tunisia, the most popular materials used for covering greenhouses are plastic films with different heat loss coefficients as shown in Table 4. These coefficients have a security margin of 15-20% compared with real measured values.

TABLE 4: Heat loss coefficients of plastic films used for covering greenhouses in Tunisia (Verlodt, 1991)

Cover material	**Heat loss coefficient, k′ (kcal/h m² °C)**	
	Airtight greenhouse	**Not airtight greenhouse**
Polyethylene (PE)	10.5	13
PE Infra-red	9.5	11
EVA	8.5	10
Tri-layer (tricouche)	7.5	9

The inside air temperature T_i is the internal temperature of the greenhouse. It can be called the reference temperature that is required by the crop during the night to ensure favourable conditions for its growth. The optimum responses of vegetables to temperatures vary between species, stage of crop growth and between night and day, as shown in Table 5. The temperature values presented in Table 5 can be slightly different for some varieties within the same species.

TABLE 5: Optimum temperatures for some vegetables grown under greenhouses (Popovski, 1993)

Crop	**Development /night**	**Development /day**	**Germination**	**Flowering**
Tomato	13-16	26-28	20-30	11-12
Melon	18-20	25-28	25-30	-
Cucumber	18-20	24-26	25-30	-
Pepper	16-18	22-26	25-30	18

The T_i value used in this approach is 14°C. It is the minimum temperature desired to be maintained inside greenhouses during the heating period. This value (14°C) is chosen as the most favourable temperature for a tomato crop during the night. The reason for that is the large area of tomato production which is used for export. For melon and some tomato hybrids which require higher night temperatures, it is recommended to raise the reference temperature (T_i) about 2-3°C.

The outdoor design temperature of the greenhouse, T_o , should be determined by the nearest local meteorological station in the region. It is defined as the average of the daily minimum temperatures recorded during the coldest month of the year which in Tunisia is normally January. The absolute minimum temperature should not be used, because it only occurs for a short period and the plants will survive such a cold spell. Thus, the use of the absolute minimum temperature will result in uneconomical design.

If the location of the geothermal greenhouse project is a relatively warm or cold place compared to the meteorological station, the temperature value T_o should be corrected. Table 6 shows the outdoor design temperatures in some southern regions of Tunisia.

TABLE 6: The design value of outdoor temperature in the southern regions of Tunisia

Region	Average daily minimum temperature (°C)
Gabes	6.5
El Hamma of Gabes	6
Kébili	4.5
Douz	4
Tozeur	5.5

From the above data and equation, the calculation of energy needed for greenhouse heating is possible.

Example:
If we heat one airtight greenhouse located in the Kébili region of 544 m^2 covered by PE infra-red, the total heat requirement is

$$Q = k' A_g (T_i - T_o) = 9.5 \times 544 \times (14 - 4.5) = 49{,}096 \text{ kcal/h or } 57{,}100 \text{ W}$$

3.3.2 Geothermal water requirements

The determination of the geothermal water flowrate needed to supply heat for the greenhouse can be expressed as (Wong, 1977):

$$Q = m c_p (T_{in} - T_{out}) \tag{6}$$

where

$$m = v \rho \tag{7}$$

and

v	= Flowrate of geothermal water for heating the greenhouse [m^3/s];
ρ	= Density of the geothermal water [kg/m^3];
c_p	= Specific heat capacity of water at constant pressure [J/kg °C];
T_{in}	= Inlet temperature of the geothermal water [°C];
T_{out}	= Outlet temperature of the geothermal water [°C];
m	= Mass flowrate of geothermal water in the pipe [kg/s].

The temperature of the geothermal water in Tunisia is relatively low and is on average 60°C. Based on this, the specific heat capacity, c_p, can be taken as 4.184 kJ/kg°C. The total dissolved solids in the geothermal water is very low (2-3 g/l). So, the density of the water is approximately 1000 kg/m^3.

It is important to keep in mind that the outlet temperature of the geothermal water should be as low as possible. Generally, the design value of outlet temperature is 25°C. The low outlet temperatures present simultaneously two considerable advantages:

- Extracting the maximum energy from the geothermal water.
- Minimising the use of geothermal resources for heating greenhouses.

Example:
The same greenhouse as treated in the previous example is heated with geothermal water with 70°C inlet temperature and 25°C outlet temperature. The flowrate needed for heating one greenhouse of 544 m^2 is:

$$v = 1092.7 \text{ l/h, or } 0.303 \text{ l/s, or } 5.6 \text{ l/s ha.}$$

3.3.3 Determination of greenhouse area

The maximum growing area of a new geothermal greenhouse complex depends on the maximum flow rate from the geothermal well and can be calculated from the following equation:

$$S_{max} = v_{max} / v \tag{8}$$

where

S_{max} = Maximum growing area in the greenhouse complex [m^2];
v_{max} = Flowrate from the geothermal well [l/s];
v = Water flowrate needed for heating a greenhouse complex [l/s m^2].

The maximum number of greenhouses which can be built is

$$N_{max} = S_{max}/S_g \tag{9}$$

where

S_g = Ground area of one greenhouse [m^2].

In practice, some consideration is needed and the flowrate exploited from the well should be corrected in order to have a daily water equilibrium between the volume of water needed for heating the greenhouses and the volume needed for irrigation in the oasis and the greenhouses. However, the volume of water needed for irrigation in an oasis should be known to be able to calculate the real flowrate required by the greenhouse complex. To determine this flowrate, we have to take into consideration the total time needed for heating during the coldest period for the entire night which is 16 hours. The equation used to calculate the real flowrate is simple:

$$v_r = V/t \tag{10}$$

where

v_r = Real flowrate needed for heating greenhouses [l/s];
V = Total volume needed for oasis and greenhouse irrigation [l];
t = Maximum time for heating the greenhouses in one night during the coldest period [s].

As a consequence, the theoretical greenhouse area S_{max} can be corrected with the actual daily water demand of the oasis. The real area S_r of the greenhouse complex which should be created is

$$S_r = v_r/v \tag{11}$$

The number of greenhouses in the complex is:

$$N_r = S_r/S_g \tag{12}$$

where S_r = Real total area of greenhouses;
N_r = Real total number of greenhouses.

Example:
If the flowrate of the geothermal well is 100 l/s and the daily water demand of the oasis is 1650 m^3, then

S_{max} = 100/5.57 = 18 ha
N_{max} = 18 x 10^4/ 544 = 330 greenhouses
v_r = (1650 x 10^3)/(16 x 3600) = 28.6 l/s
S_r = 28.6 /5.57 = 5.1 ha
N_r =(5.1 x $10^{4)}$/544 = 94 greenhouses.

3.3.4 Heating system

Characteristics and selection of the heating system for greenhouses
Different heating systems are used for greenhouses (Popovski, 1993). They can be classified according to their heat transfer to the environment, material of the heat exchangers or allocation of the heat exchangers. The most used and known classification is the following:

- Heating systems with pipes (heat exchangers) in the soil.
- Heating systems with pipes on the soil or on the benches.
- Aerial heating systems.
- Fan-assisted convectors (forced air heating units).
- Different combined heating systems.
- Non-standard heating systems.

According to experimental work carried out in the south of Tunisia and taking into account the horticultural aspects and others parameters, the most appropriate and advantageous heating system adapted is the air-soil heating system with heat pipes placed on the soil. The pipes used are corrugated polypropylene (PP) ϕ 25 mm and in rare cases evenyl acetate (EVA) sleeves. The loops of PP are placed on the soil between the plant rows or directly in the plant rows. The number of loops depends on the geothermal temperature and the outdoor temperature. Generally, the PP pipes do not allow a temperature above 75°C, but with Tunisian conditions, it gives good results. It has the advantage of a fast response on the short lasting changes of temperature. Both manual and automatic regulation can be used, but the last one is recommended. The pipes should be clean. EVA sleeves should be used for water temperatures below 50°C. From the point of view of heat transfer, these heating systems are considered as conductive, convective and radiative, because the heat is transferred by conduction to the soil, by natural convection to the air and by radiation/convection to the plant. The heat transfer from the pipe to the surrounding air and soil varies between the surface and environment as shown in Table 7.

Surface area of the pipes

The total surface area of the pipes in the greenhouse can be calculated from (Wong, 1977)

$$Q = U \times S \times LMTD \tag{13}$$

where *LMTD* is the logarithmic mean temperature difference calculated as

$$LMTD = (T_{in} - T_{out}) / \ln[(T_{in} - T_i)/(T_{out} - T_i)] \tag{14}$$

where U = Total heat transfer coefficient for the heat exchanger pipes (loops) [kcal/h m² °C];
S = Total surface area of the heat exchanger pipes [m²];
T_{in} = Geothermal water inlet temperature [°C];
T_{out} = Geothermal water outlet temperature [°C];
T_i = Air temperature inside the greenhouse [°C].

To simplify practical calculations, results with reasonable accuracy can be obtained by using, instead of *LMTD*, a mean temperature difference $\Delta T = T_w - T_i$ calculated as:

$$\Delta T = T_w - T_i = (T_{in} + T_{out})/2 - T_i \tag{15}$$

The heat transfer coefficient U varies with the type of installed heat exchanger pipes and the water temperature inside them as shown in Table 7.

TABLE 7 : Heat transfer coefficients U of the corrugated PP ϕ 25 pipe and EVA ϕ 55 sleeves used for heating greenhouses (Verlodt, 1991)

Water temperature (°C)	Heat transfer coefficient U (kcal/h m²)	
	Corrugated PP ϕ 25	EVA sleeves ϕ 55
+70	14	-
67.5-70	13.75	-
65-67.5	13.5	-
62.5-65	13.25	-
60-62.5	13	-
57.5-60	12.75	-
55-57.5	12.5	-
52.5-55	12.25	-
50-52.5	12	-
47.5-50	11.75	7.75
45-47.5	11.5	7.5
42.5-45	11.25	7.25
40-42.5	11	7
37.5-40	10.75	6.75
35-36	10.5	6.5
33-34	10.25	6.4
31-32	10	6.3
29-30	9.75	6.2
27-28	9.5	6.1
25-26	9.25	6

Length and number of loops

The total length of PP ϕ 25 pipes and EVA sleeves needed for heating greenhouses is determined through the surface area of the pipes, *S*. PP pipe of 1 m length has 0.0785 m^2 and 1 m length of EVA sleeves has 0.18 m^2 of surface. Thus,

for PP ϕ 25 pipes: $L = S / 0.0785$; and for EVA sleeves ϕ 55: $L = S / 0.18$.

The number of loops needed for one greenhouse is related to the length of the greenhouse and the arrangement in the greenhouse, as

$$N = L/l \tag{16}$$

where

- L = Total length of heat exchanger [m];
- l = Length of one loop in the greenhouse [m];
- N = Number of loops.

3.3.5 Heat supply control

The temperature inside greenhouses is regulated automatically by thermostatic valves. Normally for modern glasshouses proportional valves with three ways are utilised, but this type of valve is very expensive and needs a source of energy to be operated. For greenhouses in Tunisia, simple thermostatic valves are used with a proportional regulation. This category of valves is normally utilised for temperature control in urban heating.

There are two types of thermostatic valves for regulating temperature. The first type is used to regulate the temperature of the air and the second type is used to regulate the temperature of the water. The first type is utilized in Tunisia for controlling temperatures in greenhouses. It has two different models, one with the sensor incorporated in the valve and the other with the sensor placed horizontally some distance from the valve. The last one is more reliable. Both of them can regulate the air temperature between 6 and 28°C. The second type of valves which regulates the water temperature can adjust the temperature of the return water between 20 and 70°C.

The thermostat can be operated proportionally around the desired temperature in the greenhouse by turning the valve to the right position. However, the thermostatic valves have the ability to automatically regulate the flowrate in relation to the need for geothermal water and the level of the detected temperature inside the greenhouse. The valve cannot change the flowrate for one proportional band of temperatures between 2-3°C. Thus, they cannot accurately control the temperature, but if we use a reference temperature of 15-16°C, the excess of high temperatures inside the greenhouse can be avoided in order to have a normal pollination of flowers.

3.4 Flow regulation

3.4.1 Heating distribution system

The main task of flow regulation is to avoid disequilibrium of the water supply between the different loops inside the same greenhouse and also between the different greenhouses in the same project. One greenhouse can be considered as one loop in the greenhouse complex. However the distribution of hot water should be regulated in the greenhouse and between greenhouses in order to obtain equal heat supply for all the different PP loops and greenhouses in the same complex.

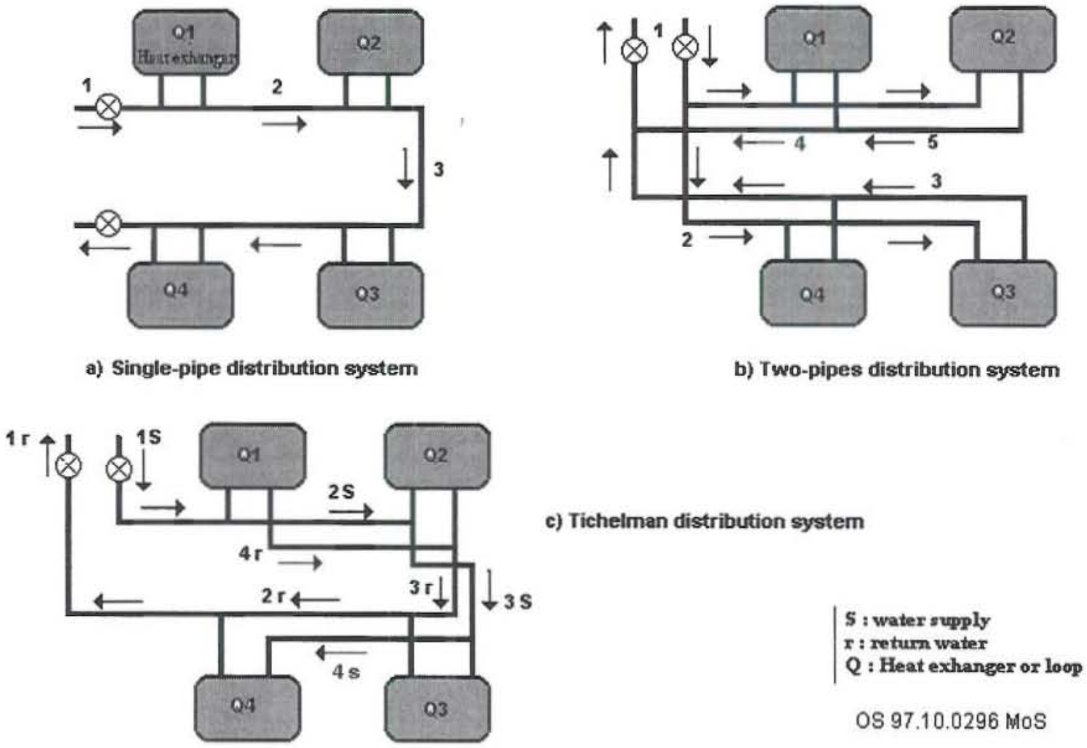

FIGURE 7: Simplified scheme of three different distribution systems for heating greenhouses

The problem is that water flow is associated all the time with significant pressure losses in the heating system inside the greenhouse, while between greenhouses the pressure losses are not important. The aim is to reduce this pressure drop as much as possible in order to avoid the big difference of temperature distribution inside and between greenhouses. Resolving this problem has the considerable advantage of obtaining homogenous distribution of temperatures in greenhouses, better growth and better yields.

There are three main systems of heating water distribution in use for geothermal greenhouses as shown in Figure 7 (Popovski, 1993); a) Single-pipe distribution system, b) Two-pipe distribution system and c) Tichelman distribution system.

3.4.2 Tichelman distribution system

The Tichelman distribution system is recommended because it enables an almost even distribution of water for all the connected loops and greenhouses. This is due to two main reasons. The flow direction of the supply line is the same as that of the return line and the length of the flow path from the central connection point is the same for all the loops and greenhouses. Therefore the pressure drop is almost the same for all the loops and no valves are needed to regulate the flowrate. This is achieved by using the same pipe diameter for both the supply and return pipelines.

The Tichelman distribution is considered an efficient system for relatively small greenhouses, while for bigger and longer greenhouses, above 50-60 m, it is not considered a convenient distribution because of pressure drops which are important because of the length of pipes. However, dividing the greenhouses into many sections is a good solution.

A typical greenhouse layout for corrugated PP ϕ 25 pipes in Tunisia is shown in Figure 8. The supply of hot water and return water for the different loops are arranged with a Tichelman distribution. The Tichelman principle should be applied not only to distribution of the hot water inside the greenhouses,

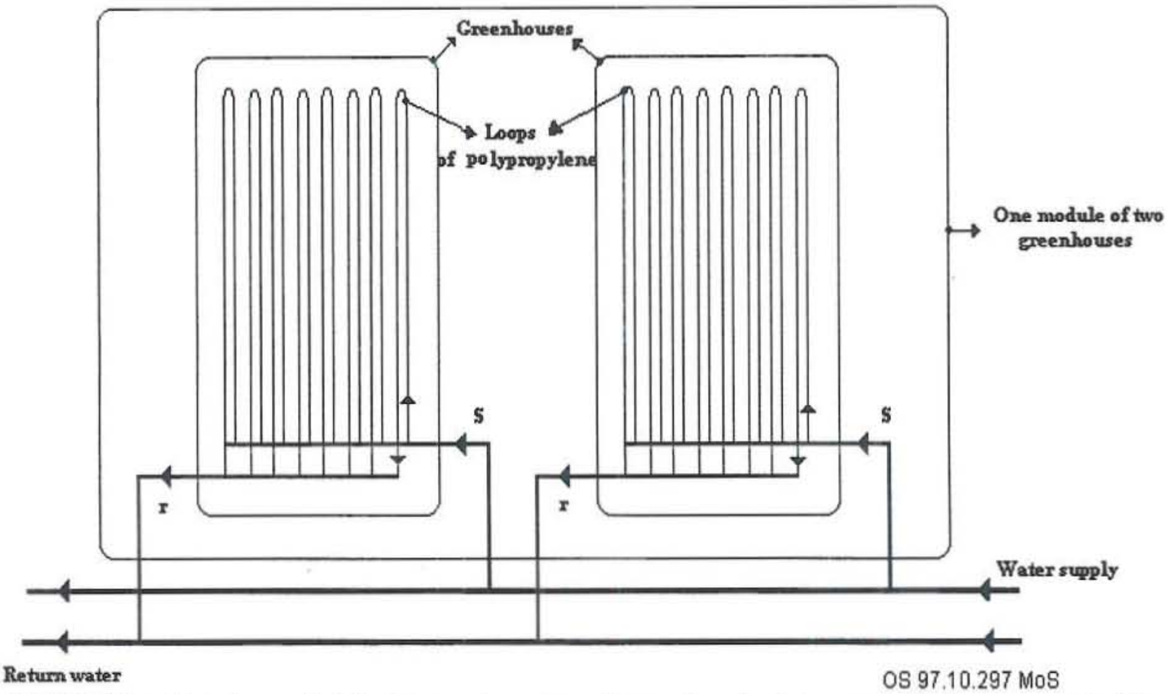

FIGURE 8: Tichelman distribution system of geothermal water between greenhouses and inside greenhouses for polypropylene pipes laid on the soil in Tunisia

but also between greenhouses in the complex as shown in Figure 8.

The advantage of the Tichelman distribution can be clearly explained by the following example. One greenhouse complex has 4 modules of greenhouses and each module contains 3 elements of greenhouses (500 m^2). The main pipeline AC 100 connects the different modules to each other and PEHD ϕ 50 connects the 3 greenhouses. Table 8 clearly demonstrates the advantage of the Tichelman principle and the difference in pressure losses between a Tichelman and a non-Tichelman distribution system.

TABLE 8 : Pressure losses (Pa) in Tichelman and non-Tichelman distribution systems in different networks inside and between greenhouses (Verlodt, 1991).

	Tichelman distribution			Non-Tichelman distribution		
	Supply	**Return**	**Total**	**Supply**	**Return**	**Total**
Main network						
Module 1	553	1030	1583 (2)	553	553	1106 (2)
Module 2	843	983	1826 (1)	843	843	1686
Module 3	983	843	1820	983	983	1966
Module 4	1030	553	1583	1030	1030	2060 (1)
Modular network						
Greenhouse 1	272	419	619 (2)	272	272	544 (2)
Greenhouse 2	379	379	758 (1)	379	379	758
Greenhouse 3	419	272	691	419	419	838 (1)
Total pressure losses in the two extreme cases						
Greenhouse 2 module 2			2584 (1)			
Greenhouse 3 module 4						2898 (1)
Greenhouse 1 module 1			2202 (2)			
Greenhouse 1 module 1						1650 (2)

In the Tichelman distribution system, the pressure losses for the greenhouse with the highest losses (1) are 13.6% higher than for the one with the lowest losses (2). In the non-Tichelman distribution system, the pressure losses for the greenhouse with the highest losses (1) are 75% higher than for the one with the lowest losses (2).

4. GREENHOUSE IRRIGATION

4.1 Chemical composition and characteristics of geothermal water

The Continental Intercalaire and Complexe Terminal are the two main geothermal aquifers which are used for irrigation purposes. The chemical composition and characteristics of these aquifers are presented in Table 9.

TABLE 9: Chemical composition (mg/l) and characteristics of geothermal water used for irrigation in greenhouses in Tunisia

Project well	Ca^{++}	Mg^{++}	Na^{+}	k^{+}	SO_4^{--}	Cl^{-}	HCO_3^{--}	TDS	EC (mS/cm)	SAR
Stiftimi	250	95	312	39	613	674	107	2600	3.1	4.14
Kébili	270	85	345	33	670	650	115	2500		
Fareth	282	108	340	36	725	733	113	2660		
Limagues	276	93	342	36	822	639	120	2370		
Jemna	240	80	517	33	736	887	101	2950		
Douz	280	126	830	32	780	1435	110	4190		
Saidane	400	48	386	27	1128	622	101	2970		
Menchia	250	86	312	37	654	710	87	2440		
Tozeur	400	25	299	48	1355	355	93		3.25	3.91
El Hamma	304	19	588	39	1516	390	114		3.99	8.83
Nefta	425	15	437	60	140	532	144		4	567
Khebeyet	344	125	322	32	1018	604	113		3.1	3.77
Chenchou	330	123	441	37	1168	781	132		4	5.25
Bechima	335	60	497	39	952	671	113		3.2	6.55

TDS : Total dissolved solids EC: Electrical conductivity SAR: Sodium absorption ratio

4.2 Quantitative supply of geothermal water

The water demand of vegetables grown in a greenhouse depends on the solar radiation, the temperature inside the greenhouse, the cultivated crop, the stage of crop development and the rate of drainage for leaching the soil. The potential water demand W_p of fully developed culture is related strongly to the global radiation received by the greenhouse. It can be calculated by the following equation (Verlodt, 1991):

$$W_p = 0.00247 R_g - 0.8 \tag{17}$$

where W_p = Potential water demand [l/m²/day];
R_g = Global radiation [J/cm²/day].

From Equation 17, the potential water demand each day of one crop can be calculated if the daily global radiation is known. According to the experimental work carried out in the south of Tunisia, the daily potential of global radiation R_g is determined. The aim is to facilitate a method for growers who cannot measure the daily radiation received. Table 10 shows the daily potential of global radiation in the southern part of Tunisia and the water demand over the year when the cultural coefficient of the cultivated crop is equal to 1.

TABLE 10: Water demand of the crop in relation to potential radiation

Number of week	**Daily potential radiation, R_g (J/cm^2 day)**	**Potential water demand, W_p (l/m^2)**
51/52	900	1.423
1/50	980	1.6206
2/49	1060	1.8182
3/48	1140	2.0158
4/47	1220	2.2134
5/46	1300	2.411
6/45	1380	2.6086
7/44	1460	2.8062
8/43	1540	3.0038
9/42	1620	3.2014
10/41	1700	3.399
11/40	1780	3.5966
12/39	1860	3.7942
13/38	1940	3.9918
14/37	2020	4.1894
15/36	2100	4.387
16/35	2180	4.5846
17/34	2260	4.7822
18/33	2340	4.9798
19/32	2420	5.1774
20/31	2500	5.375
21/30	2580	5.5726
22/29	2660	5.7702
23/28	2740	5.9678
24/27	2820	6.1654
25/26	2900	6.363

A rapid and efficient method was developed in order to calculate the daily water demand for one specific crop grown in a greenhouse. The following equation can be used to determine the real water demand, W_r (Verlodt, 1991):

$$W_r = W_p \times C_c \times C_s \times C_t \times C_{ds} \tag{18}$$

where

C_c = Cultural coefficient of specific crop, ($0.4 < C_c < 1.1$);
C_s = Sky state coefficient, ($0.4 < C_s < 1$);
C_t = Temperature coefficient inside the greenhouse, ($1 < C_t < 1.2$);
C_{ds} = Supplementary drainage coefficient, ($1 < C_{ds} < 1.2$).

4.3 Qualitative supply

4.3.1 Crop requirements

Plants need essential minerals to ensure their normal growth. These minerals are classified into groups; macro-elements (N, P, K, Ca, Mg, S,) and micro-elements (Fe, Mn, Zn, B, Cu, Mo). Macro-elements are more important for plants and Table 11 shows the norms needed for some vegetables grown in greenhouses.

TABLE 11: Minerals required for some vegetables grown in greenhouse in me/l

Crop	N	K^+	Ca^{++}	Mg^{++}	$H_2PO_4^-$	SO_4^{--}	Si
Tomato	15.3	8.8	8.5	4	1.25	7.5	
Melon	14.3	6	8.5	2	1.3	2.5	3
Cucumber	17.3	8	8	2.8	1.3	2.8	3

4.3.2 Fertilization

To calculate the amount of fertilizers which should be diluted in the geothermal water, semi-equilibrate nutritive solutions should be prepared for the macro-elements. The geothermal water cannot be completely equilibrated, since they contain some elements which exceed the need of the crop such as Ca, SO_4 and Mg. K is present in the geothermal water at a low level, while N and P are absent. However, the last three elements (N, P, K) can be equilibrated and the others will be semi-equilibrated. Mg can be equilibrated if it is not sufficiently present in the geothermal water.

The choice and the amount determination of fertilizers that should be diluted in the geothermal water depends on the crop requirement in each element and the chemical composition of the geothermal water. The method used should follow these steps:

- Analyse the chemical composition of the geothermal water in mg/l.
- Transform the concentration of each element into me/l.
- Compare these concentrations with the crop requirements in macro-elements and determine the amount of each element needed if it is not in sufficient concentration in the geothermal water.
- Choose the appropriate fertilizers and start to calculate the needs of phosphoric acid and nitric acid. These two acids have the advantage of supplying phosphorous and nitrate and drop the pH value by neutralizing the HCO_3 which is responsible for the geothermal water alkalinity. Then, if there is not sufficient Mg in the geothermal water, magnesium nitrate should be determined and added. Finally, potassium nitrite and ammonium nitrite determinations are needed.
- Calculate amount of fertilizers which should be diluted in 1 m^3 of geothermal water.

To understand this method better, the example presented in Table 11 for tomatoes is treated for tomato crop irrigated by the geothermal well in Bechima site in the Gabes region, see Table 12.

From Table 12, the nutritive solution for the tomato crop can be calculated and the amount of fertilizers used for preparing the nutritive solution can be determined by using Table 13 which gives the different characteristics of the fertilizers.

TABLE 12: Determination of fertilizers by using geothermal water for tomato crop

Chemical source	Cations					Anions			
	H^+	Ca^{++}	Mg^+	K^+	NH_4^+	$N_{(NO_3^-)}$*	SO_4^{--}	$H_2PO_4^-$	HCO_3^-
Water analysis - mg/l - me/l		 355 16.8	 60 4.8	 39 1			 952 19.8		 113 1.85
Norm		8.5	4	8.8		15.3	7.5	1.25	
Phosphoric acid	1.25							1.25	
Nitric acid	0.6					0.6			
Potassium nitrate				7.8		7.8			
Ammonium nitrate					6.9	6.9			

* All the N fertilizers contain the ammonium form NH_4

TABLE 13: Characteristics of different fertilizers

Fertilizer	Chemical formula	Molar weight	Fertilizer weight of 1 me
Ammonium nitrate	NH_4NO_3	80	NH_4 = 40 NO_3 = 40
Potassium nitrate	KNO_3	101.1	K = 101.1 NO_3 = 101.1
Magnesium nitrate	$Mg(NO_3)_2.6H_2O$	256.3	Mg = 128.15 NO_3 = 128.15
Calcite nitrate	$5Ca(NO3)_2[H_2O]$ NH_4NO_3	1080.5	Ca = 108.05
Phosphoric acid (density 1.65, volume of P_2O_5 50%)	HH_2PO_4	81.2 ml	H^+ = 81.2 ml $H_2PO_4^-$ = 81.2 ml
Nitric acid (density 1.38, volume of HNO_3 50%)	HNO_3^-	91.3 ml	H^+ = 91.3 ml NO_3^- = 91.3 ml

From the above data the amount of each fertilizer needed to be added to one m^3 of geothermal water can be calculated. The results of this example are as follows:

Phosphoric acid:	1.25 x 81.2	= 101.5 ml/m^3
Nitric acid:	0.6 x 91	= 55 ml/ m^3
Potassium nitrate:	7.8 x 101	= 700 g/m^3
Ammonium nitrate:	6.9 x 40	= 276 g/m^3

5. SOIL DISINFECTION

5.1 The problem of nematodes

In intensive cultures and especially in protected cultivation, soil has a high risk of being infested by nematodes. The infestation of nematodes happens when some preventive measures are not taken by the horticulturists. The most common devastating nematode is named Meloidogynes. It can parasite roots of vegetables such as tomato, melon and pepper. Several methods are used to resolve this problem. The methods used to treat against nematodes can be classified as agronomical treatments, chemical treatments, physical treatments and biological treatments. To resolve this problem chemically seems to be difficult and complicated taking into consideration many aspects which include

- The anxious effects of the chemical products (nematicides) which can harm the growers and the environment by destroying the atmospheric ozone layer in some cases.
- The destruction of the soil micro-flora.
- The residues of chemical products which remain in the fruits.
- The complexity of understanding the biology of Meloidogynes and how it can react with the specific nematicide.

In some cases it is possible nowadays to resolve the nematode problem agronomically by using varieties which are resistant against Meloidogynes. Unfortunately, this method has not given good results in the south of Tunisia using tomato hybrids which are considered genetically resistant. The problem is that these hybrids lose their resistance against Meloidogynes due to the existence of special patho-types in the south of Tunisia which are very aggressive to tomato roots. For melon crop, there is no genetic resistance which can be used by seed selectors.

The two most common physical treatments used for soil disinfection are hot steam and solar radiation (solarization). In Tunisia, another method belonging to this group of treatments, was developed by using geothermal water for soil disinfection.

5.2 Soil disinfection

Soil disinfection by geothermal water is combined with solar radiation as shown in Figure 9. The most appropriate time to apply this method is during the summer season because it has the highest solar radiation intensity and then there is no activity in the greenhouses. This method includes three main steps.

1. The soil must be humidified by cooled geothermal water by irrigating the total area of the greenhouse. This operation is very important in order to stimulate the hatching of nematode eggs and to be sure that the nematodes are not in conservative form. Humidifying the soil facilitates the effect of hot geothermal water when nematodes are in active form.

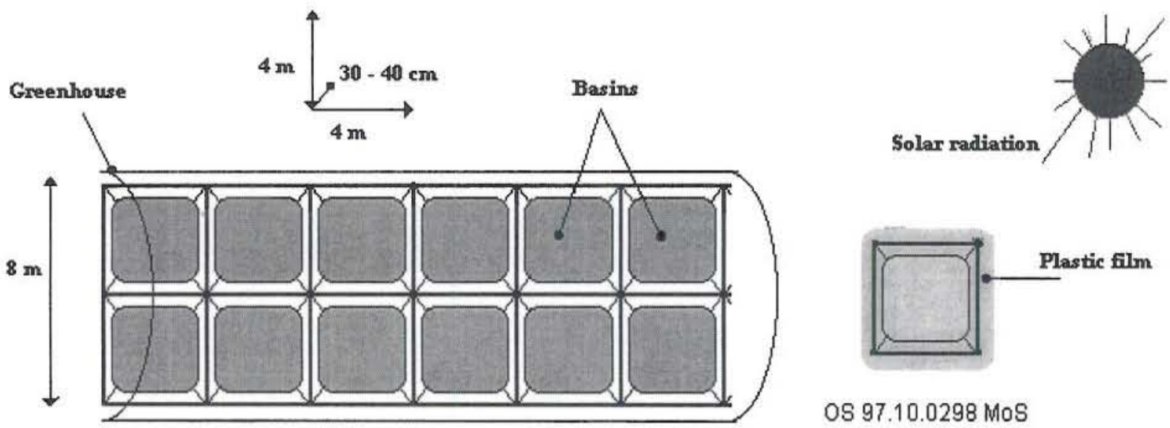

FIGURE 9: Division of greenhouse area into basins for soil disinfection against nematodes in Tunisia by the use of geothermal water and solar radiation

2. The greenhouse should be divided into several small basins which have a square form as shown in Figure 9. The aim of this separation is to provide an equal supply of geothermal water for all the greenhouse area. The basins must be completely submerged by geothermal water.
3. To increase the efficiency of geothermal water on nematodes, all the basins should be covered by plastic films. The plastic keeps the soil temperature as long as possible without any high heat losses and improves the efficiency of solar radiation.
4. The two last operations should be applied twice.

The results depend on many factors, such as the temperature of the geothermal water, the permeability of the soil and the time needed to reach a temperature above 50°C in the soil at 40-60 cm depth.

6. RESULTS AND DISCUSSION

1. Plastic greenhouses heated by geothermal water have developed rapidly in Tunisia during the last 10 years. The total greenhouse area is now 80 hectares and this lets the country take the third position in the world after the United States and Hungary. Tunisia seems to be the first country to exploit geothermal resources in greenhouses for multiple applications including heating, irrigation and soil disinfection.

2. The volume of geothermal water used for heating greenhouses and the extracted energy is relatively low compared to some countries which have long experience in this field. The reason is the relatively short heating period of 5 months during the night with 7-9°C increase inside the greenhouses. Taking into consideration that these resources are used for irrigation purposes mainly in oases, the volume of water utilized for heating greenhouses is very important. If the return water from greenhouses is ensured with the appropriate water equilibrium between heating and irrigation, this will provide a very nice combination to maximize the geothermal water utilization in the south of Tunisia.

3. The corrugated polypropylene pipes laid on the soil for heating greenhouses represent numerous advantages which are related to horticultural, energetic and economical aspects. These advantages can be summarised as follows:
   a. The uniformity of the temperature gradient in greenhouses shows that the ground level heating systems are most effective from an energy conservation point of view.
   b. The temperature distribution inside the greenhouse is very good, both in horizontal and vertical directions and around the plants since the system of pipes is placed on the ground surface, between the plant rows or directly in the plant rows.
   c. The heat transfer to the soil is ensured by conduction in which the shoot/root temperature relationship is an important factor for crop growth.
   d. The installed heating system with 8 to 12 loops of corrugated polypropylene pipes of 25 mm diameter is able to cover the peak of heat requirement with a sufficient heating capacity to maintain the desired temperatures needed for crop growth and development.
   e. Good light conditions are ensured in the greenhouse without disturbing the plant growth and treatment since the crop is above the heating installation.
   f. During soil preparation and plant cultivation, the polypropylene pipes can be lifted up without disturbing these operations.
   g. The labour and the time required for removing and placing the pipes during soil cultivation is rather small.
   h. The polypropylene pipes are made of a soft plastic material. By locating the pipes in the plant rows and not between them, mechanical damages can be minimized and the lifetime of these pipes will be as long as 6 to 8 years.
   i. The cost of the polypropylene pipes is rather low compared to other materials.

4. The creation of a greenhouse sector in this arid zone, which is known for its lack of rain, appeared as a good agricultural activity for economizing and saving geothermal water resources. This is because greenhouses are the most intensive and also the most efficient systems for rationalizing the use of water for obtaining as high a yield as possible. The volume of water needed for irrigation of vegetables grown under greenhouses is approximately 4 times lower than needed for the oasis per hectare and per year.

5. If we compare the evaporative cascade cooling tower used for oasis irrigation with the non-evaporative cooling system used for greenhouse irrigation, the latter system economizes, on average, 7% of the geothermal water. The amount of water saved by this system from 1 ha of heated greenhouses has been estimated to be 4,550 m^3/ha. This quantity can irrigate approximately 0.65 ha of greenhouses, which means that 65% of the of water demand needed for greenhouse irrigation can be ensured indirectly by its own heating system.

6. Heated greenhouses can benefit exporting by producing earlier during the cold period with higher yield and quality. The relative high salinity of geothermal water used for irrigation has a significant negative effect on the yield. On the other hand the gustative quality of Tunisian products is increased and has a special savour and taste due to the sodium and chloride which exist in the geothermal water. This high quality of products contributes to a high demand from consumers, associated with high prices.

7. The sociological effect of the greenhouse activity in these regions is very important because the protected cultivation is known as the most intensive system, requiring a high demand for labour. This sector can create between 7 to 9 permanent jobs per hectare, and this is very important for keeping and maintaining the people in their regions.

8. Greenhouses heated by geothermal water represent several important advantages to oases:
   a. They offer cooled water for irrigation in an oasis during 5 months per year without any need of operating cooling towers which saves electrical costs for ventilation of these.
   b. Cooling geothermal water with a non-evaporative system by corrugated polypropylene pipes used inside a greenhouse avoids the loss of geothermal water in cooling towers by evaporation. The evaporation also increases the salinity of water used for irrigation.
   c. Scaling problems of calcite deposition are not observed in the greenhouse projects since the geothermal water is cooled by the polypropylene pipes under pressure without any contact with the atmosphere. If the geothermal water is cooled by the evaporative method, like the cascade cooling towers used in this area for oasis irrigation, scaling becomes a problem in some geothermal wells due to the CO_2 pressure change. Calcite deposition is observed in cooling towers and cement pipelines connecting the cooling tower to the oasis, but never observed in the greenhouse projects. Thus, heated greenhouses contribute to decreasing the amount of calcite deposition at least during 5 months of heating and to minimizing the costs of maintaining cooling towers and pipes.

9. Normally the big storage pond, which is used to accumulate the return water from the greenhouse project for irrigation in the oasis, should not be considered an investment cost for the greenhouse project only, but also for the oasis since it presents several advantages to the oasis such as:
   a. When the water demand of the oasis is very high during the summer, the pond can be used to satisfy the demand for irrigation when no vegetables grow in the greenhouses.
   b. The pond can help the cascade cooling tower to increase its efficiency of cooling water, mainly during the hot period in the summer season when the air temperature is very high and the water temperature is still above 30°C.
   c. The pond is an important parameter for economizing the water. It can ensure a flexibility of the water supply when there is a high water demand from the oasis.

7. CONCLUSIONS AND RECOMMENDATIONS

1. Vegetables grown in greenhouses and heated by geothermal water during the cold period represent numerous advantages related to oasis systems and to the export opportunity to the country, without any high concurrence in the international market. To reach this target, high quality of products is required and several technical and marketing disciplines should be applied. It is very important to note that Tunisia has realized many successful results in this field, but many measures should be taken to develop better the use of geothermal water for this.

2. To establish a new geothermal greenhouse project in the future without any mistakes and failures, water equilibrium between heating and irrigation should at all times be ensured by using all the return water from greenhouses for irrigation purposes. Also, selection of the appropriate site, organisation and arrangement of the project, temperature regulation in greenhouses and flow regulation of geothermal water for heating must be well studied and executed.

3. To export from the geothermal greenhouse projects, high quality of the products is required. Heating greenhouses by geothermal water is an important factor for obtaining better quality of vegetable products; irrigation and fertilisation (ferti-irrigation) by the use of geothermal water is an important parameter which should be controlled to obtain better quality. The chemical composition of these geothermal resources is known with their changes over time. It is necessary to continue to analyse theses resources at least once a year, in order to realize better programmes for irrigation and fertilisation. The continuous analysis of the geothermal water has a big advantage in controlling better the salinity and reducing as much as possible the negative effect of the geothermal water salinity on the soil and yields.

4. The installation of a drainage system is necessary in the project for a better control of the salinity by leaching the soil. Also, geothermal water mixed with rainwater and collected from the plastic cover of the greenhouses could be a good solution in the future to decrease the effect of high salinity. Soilless culture is also a good tool to control salinity, irrigation and fertilisation.

5. Producing distilled water from geothermal water is under research in Tunisia and more investigation is needed to obtain practical results to reduce the salinity problem.

6. Space cooling can be accomplished from geothermal energy through the lithium-bromide and ammonia absorption refrigeration system. Greenhouses placed in desert regions in the south of Tunisia need some cooling especially during early autumn in the nursery and in late spring. This aspect needs to be adapted better to the special characteristics of geothermal water in the regions.

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