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GEOTHERMAL GREENHOUSE DESIGN

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ABSTRACT

The design of a geothermal greenhouse requires a knowledge of different aspects of geothermal utilization. Most important of these are the geothermal field, water transmission, structure design, heating system and disposal of waste water. The transmission-distribution systems from the source to the greenhouse are studied and the geothermal greenhouse layout described. Furthermore, the main parameters which influence the design are mentioned, emphasizing indoor conditions. During the design description the heating installations are analysed more than the other components because the heating system is the most important factor in the geothermal greenhouse layout and constitutes the main difference from greenhouses using conventional fuels or electricity. Methods of waste water disposal are discussed. Design of a geothermal greenhouse in the Alexandroupolis area in North Greece is described, with emphasise on the heating system.

1. INTRODUCTION

A greenhouse's purpose is to provide and maintain an environment which results in optimum crop production. A geothermal greenhouse is a greenhouse which uses geothermal energy for space heating. The design of a geothermal greenhouse is analogous to that of a greenhouse using conventional fuels or electricity for heating energy. The differences include the energy source for space heating, the selection of the site and the cost. A geothermal greenhouse is almost always located close to the geothermal source for economic reasons. The cost is a great advantage of the geothermal greenhouse. The initial construction costs are almost independent of the heating energy but the operating cost is usually incomparably cheaper in geothermal greenhouses. The price of geothermal energy depends on the policy of the country. Sometimes the user has to pay the owner of the source, possibly the government, an individual, a private enterprise, etc. The costs of geothermal energy cover drilling, the pumps, the transmission and the distribution system, expenses which are not present when other forms of energy are used. Thus, the cost is high when the source is used for the first time but the total cost, including operation, is lower in a geothermal greenhouse. In Greece there are plenty of geothermal sources but most of them are not exploited.

2. TRANSMISSION SYSTEM FROM THE SOURCE TO THE GREENHOUSE

2.1 Pumps

The origin of geothermal water can be a natural spring or a well. The well can have an artesian flow or a non-artesian flow. In the case where there is no artesian flow or the flow rate of the geothermal water is very low, the installation of a pump is necessary to supply enough flow rate. The most ordinary pumps are downhole pumps. There are two types of downhole pumps, lineshaft pumps and submersible pumps. If a lineshaft pump is installed, the well must be relatively straight or oversized to accommodate the stiff pump and column. The submersible pump can be initiated in crooked wells. The stage efficiencies for the two types are similar, about 68% to 78% (Gunnarsson, 1996).

2.2 Transmission pipelines

The transmission and distribution systems are divided into two categories. In the first category the systems are divided into open loop and closed loop systems. In an open loop system the return water is discharged to waste or pumped back into the geothermal reservoir. On the other hand, in a close loop system, clean water is circulated within the heating system, taking heat from the geothermal water in a heat exchanger. In the second category there are either single pipe or two pipe systems. A single pipe system consists of one transmission pipeline and the return water is discharged to waste at each user. This kind of system is also classified as an open loop system. The two pipe system consists of one supply pipe and one return pipe for water collection of used water to some central point.

The selection of pipes depends on the geothermal water, the properties of pipeline material and the local, technological and economic conditions. The main types of pipelines are described in Appendix I. All these types are single pipe systems except the steel pipe preinsulated with polyurethane and the steel pipe laid on a concrete conduit, which are met in single and double pipe systems.

The open air installation for geothermal water transmission is the usual system for greenhouses. It is cheaper than underground installation, enables good control of the elements during exploitation and the support construction is simple. On the other hand, it is exposed to damages and the changeable outside climate conditions influence this system. There are cases which do not permit open-air systems of pipeline. When the geothermal water is being simultaneously used for many purposes or when the greenhouses are very near to town concentrations, it is necessary to use underground installation (Popovski, 1993).

The choise of pipeline diameters is based mainly on two factors, the pressure drop in the pipes and the water velocity. First of all, a diameter is suggested and the factors are evaluated. The water velocity is designated as

$$u = \frac{m_V}{A} \tag{1}$$

where

u = Water velocity [m/s];
m_V = Volumetric flow rate [m^3/s];
A = Cross-sectional area of the pipe [m^2].

The pressure drop is calculated as

$$\Delta P = L \frac{f}{D} \rho \frac{u^2}{2} \tag{2}$$

where

ΔP	= Pressure drop [Pa];
L	= Pipeline length [m];
f	= Friction factor;
D	= Pipe diameter [m];
ρ	= Density of water [kg/m^3].

The friction factor for turbulent flow in rough pipes is estimated approximately from the following formula:

$$f = 0.0055 \left[1 + \left(20000 \frac{k}{D} + \frac{10^6}{Re}\right)^{1/3}\right] \tag{3}$$

where

k	= Pipe roughness;
Re	= Reynolds number.

Acceptable values of pressure drop are around 50-100 kPa per km pipeline and 1-1.5 m/s for the water velocity. Sometimes, when the well pressure is high enough, pump installation can be avoided by choosing greater pipe diameters in spite of higher cost.

2.3 Connection of heating system with the source

The connection of the greenhouse heating system with the transmission system can be accomplished directly or indirectly. The chemical composition of the geothermal water is the main factor in connection classification. In direct connection the geothermal fluid is used as heating fluid in the installation. The source is connected directly in most of the Mediterranean greenhouses (Popovski, 1995) because the water permits this connection, also for economical reasons, especially when the greenhouses are used for the early spring crop. When the water has very high temperature and scaling or corrosive components, the connection is indirect and a heat exchanger is inserted. Environmental constraints and water with high mineral content entail more complicated connection systems than direct ones, including deaeration equipment, regulators of CO_2 content and pH, corrosive preventer etc. (Popovski, 1993).

The purpose of the heat exchangers is to transfer the heat from geothermal well to the heating setup, keeping the two phases separated. Generally, the heat exchanger is placed between two circulating loops, the geothermal and the clean loop. The presence of the heat exchanger results in some temperature loss which depends on the type of heat exchanger. For the plate type this is 3-6°C, for the shell and tube heat exchanger 8-11°C, and for homemade configurations the temperature loss is 11-22°C (Rafferty, 1991). Displayed in Figure 1 is the plate heat exchanger, the type most commonly

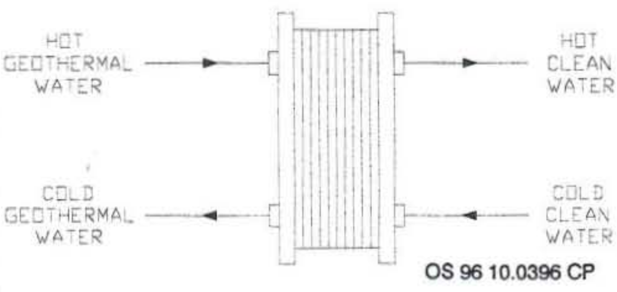

FIGURE 1: Plate heat exchanger

used. It has proven to be the best solution for geothermal water with high salinity. Moreover, their large heat exchanging surfaces are contained within a small space and the cross fluid flows provide high heat transfer coefficients. The important advantage of this type is that the plates can be assembled and dismantled resulting in easy cleaning (Popovski, 1995).

3. MAIN DESIGN PARAMETERS

3.1 Climate or outdoor conditions

The climate of an area is very significant in the design of a greenhouse. The main climate parameters are outside temperature, sun, wind and snow. These parameters will determine the layout of the greenhouse, that is the selection of structural material, shape, orientation, heating system and the positions of the windows. The greenhouses are necessary in severe cold climates, but only during the winter in mild climate areas.

The outside temperature is the principal feature which characterizes a climate. The maximum and minimum temperatures and the duration of them are highly significant in the design of the greenhouse. The temperature influences the energy balance of inside conditions with convective heat transfer to (or from) the greenhouse covering. In cold climates the demands in heat supply are augmented. The heating requirements are also increased when minimum temperatures have long duration. The opposite happens with the maximum limits. Accordingly, temperature is a parameter which will principally influence the selection of the heating system and the material of the greenhouse.

The sun influences the greenhouse climate via radiation. Sun light is a vital determinant for plant life and development. It is found that only the part of the total solar spectrum between 400 and 700 nm significantly influences plant life (Popovski, 1993). It is known that the duration of light over the course of a year is not the same in all countries. The duration of light is very important for the layout of the greenhouse. It can influence the cover material, the existence and the position of artificial light and the location of the heating system. In areas with darkness during the growing season, the covering material must allow light transmission so it has to be thin, light and single. The existence of artificial light is sometimes indispensable and the location of the heating system must not shade the vegetation. Sometimes, however, shade curtains are needed to protect the plants from sunlight. The shade system is applied during the summer when the sun is strong enough to harm cultivation.

The periodicity, the velocity and the direction of the wind are the most notable wind characteristics. Mainly velocity and its direction will influence the material, the orientation of the greenhouse, the selection of heating system and the position of windows. The wind speed strongly influences the heat transfer coefficient, taking part in the transmission heat losses. Consequently, it affects the heating requirements and the selection of the heating system.

Snow can influence the selection of greenhouse material (wall, roof and frames) and the heating system. The covering material must be resistant and also the frames have to be strong enough to support the load of the snow. If it is heavy, the heating system must be selected carefully to facilitate snow melt. Moreover, it will influence the temperature and the convective heat transfer and thus, the selection of the heating system.

3.2 Indoor conditions

The essential task of greenhouse construction is to enable the creation and maintenance of optimal conditions for protected plant cultivation controlled according to outside conditions. The indoor conditions are characterized by physical factors and parameters relating to the nature of the requirements of growing plants inside. The foremost involved phenomena are plant photosynthesis and respiration. Photosynthesis is an active process, characterized by the formation of carbon dioxide using solar radiation. Respiration is the opposing process to photosynthesis. The "greenhouse climate" parameters are interdependent and changeable depending on the external climate changes, the stage of plant development and other influencing factors. Therefore, cultivation will determine the optimum greenhouse climate according to plant requirements. Important indoor factors are lighting, air temperature, soil temperature, CO_2 concentration and humidity.

3.2.1 Light

The light in a greenhouse can be solar, artificial, or a combination of the two. The influence of the sunlight has been mentioned previously. The use of artificial light is most common in recent years as lamp design and lighting methods have been improved. It is used for ornamental cultivation and also for vegetables, especially in places and time periods where sunlight is limited. Figure 2 shows the influence of the light on air temperature for different cultivations (Popovski, 1993). The parameters which will influence artificial light applications are plant response to light, light influence on other parameters, plant requirements in light, initial cost and operating cost. It can be applied in many ways. Supplementing daylight in order to increase the irradiance level for photosynthesis and also increase the effective daylength (photoperiodism) is one application. Artificial light is also used as a substitute for daylight in growing rooms where plants are grown for commercial purposes under tightly controlled environmental conditions. Colour discrimination for crop sorting is another use of artificial lighting (Philips Company, 1995).

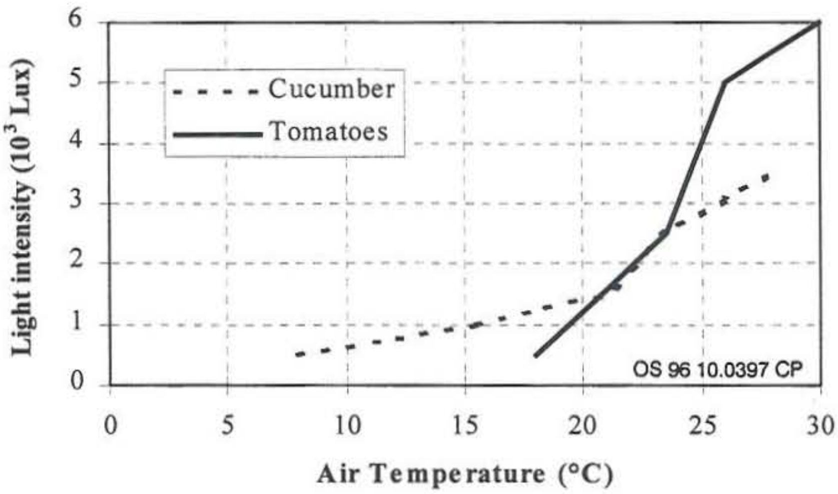

FIGURE 2: Influence of light on optimal air temperature for different cultivations (Popovski, 1993)

3.2.2 Relative humidity (RH)

Normal plant growth generally occurs at relative humidity (RH) between 25-80%. It affects the transpiration and the response of pathogenic organisms. For example, numerous pathogenic spores cannot germinate at RH < 90-95%. In order to reduce heat losses from a greenhouse, the air exchange is reduced, resulting in higher relative humidity. Thermal blankets or double glazing layers can also increase the RH. The simplest method for relative humidity control in cool or cold weather is to bring in outside air, heat it and allow it to absorb moisture, before exhausting it to the outside. Accordingly, the position of the windows and especially the control system should meet the best ventilation in order to decrease the pathogenic problems (Aldrich and Bartok, 1994).

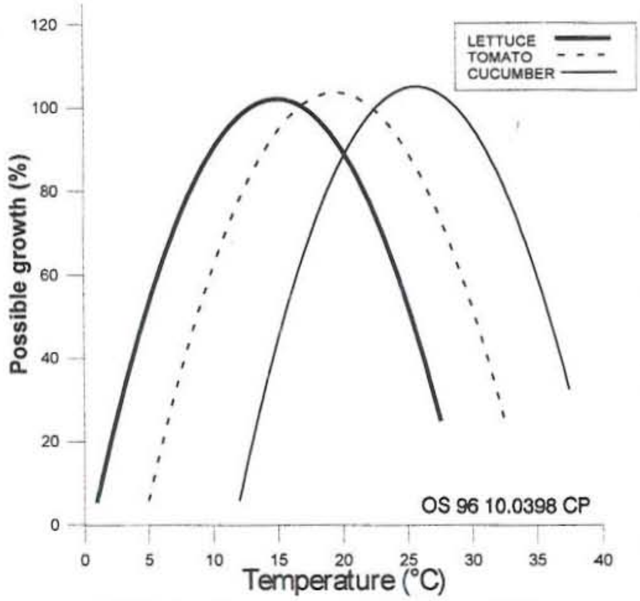

FIGURE 3: Stage growth for three different cultivations versus temperature (Lund, 1996)

3.2.3 Temperature

The demands in temperature are disparate for dissimilar cultivations and for different plant growth stage as is shown in Figure 3 (Lund, 1996). The soil temperature is also a meaningful parameter and depends on the kind and stage of development of the cultivation and on the light intensity at disposal. The soil temperature influences the value of the optimal air temperature. Hence, the heating system should be able to provide the optimum temperatures in the greenhouse.

3.2.4 Carbon dioxide (CO_2)

This is the raw material which, along with water, is required for photosynthesis. It is usually the limiting parameter in a greenhouse environment. In tight greenhouses, CO_2 concentration may be 400 ppm before daylight and drop to 150 ppm shortly after light is available. Figure 4 shows the CO_2 optimal concentration as a function of light intensity (Popovski, 1993). The outside air CO_2 concentration is 300 ppm. The rate of absorption during the photosynthesis depends on several factors including concentration, stage of growth, temperature and light intensity. The combination of high carbon dioxide concentration (1500 ppm), elevated day temperatures and optimum light levels can reduce the time between germination and harvest by 50% for some crops. Increases in CO_2 levels result in improved plant quality, yield and development. The optimum combination of CO_2, temperature and visible light energy has been determined for very few cultivations. The supply of CO_2 in greenhouses is carried out mainly to keep its concentration at a similar level with outside air concentration. Supply of CO_2 to give higher concentrations than 300-400 ppm is not common as it is not economically profitable (Aldrich and Bartok, 1994).

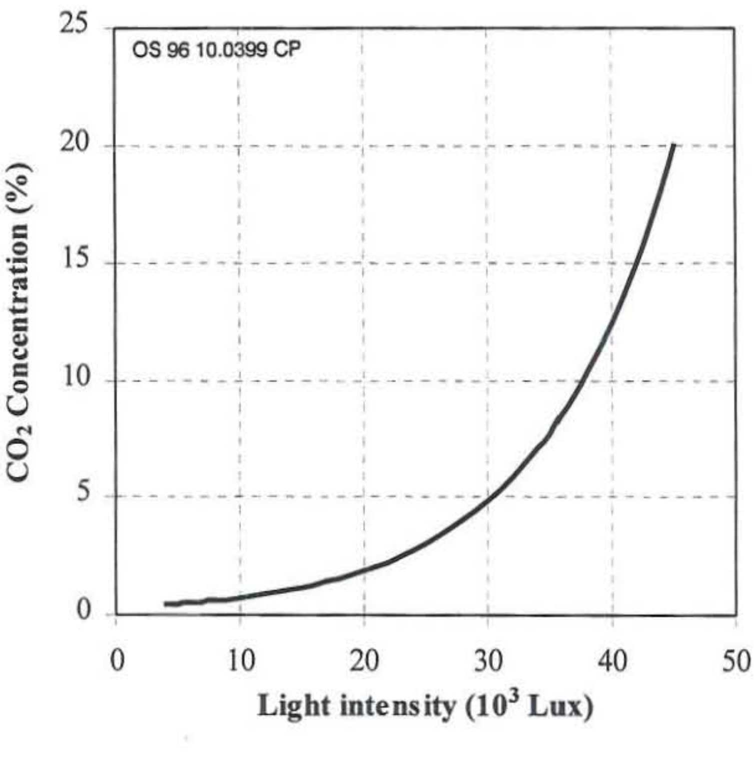

FIGURE 4: Optimal CO_2 concentration in a closed room greenhouse as a function of light intensity (Popovski, 1993)

3.3 Geothermal water

3.3.1 Chemical composition

The chemical composition of the geothermal water influences the design of a geothermal greenhouse in the selection of pipe and heat exchangers. Scaling and corrosion create problems and many treatments are frequently applied in order to avoid them. The dissolved solids tend to precipitate and form scaling. Scaling can reduce the efficiency of the heat exchangers and increase the pressure drop in pipelines. Well-known scales are silica, the most common, calcite, sulfides, magnesium silicates, iron oxides and silicates. The components which provoke corrosion are dissolved oxygen, hydrogen ion, chloride ion, hydrogen sulfide species, carbon dioxide species, ammonia, ammonium anion and sulfate ion (Ármannsson, 1996). In addition, low pH-value increases corrosion formation. Types of corrosion are uniform, pitting, crevice, stress cracking, erosion, intergranular and galvanic.

Carbon steel is exposed to corrosion from the outside of the pipe or heat exchanger, especially when they are buried in moist soil. Ductile iron is also exposed to corrosion. Copper materials are subject to crevice and uniform corrosion and aluminium to pitting corrosion. In stainless steel, the kind of corrosion depends on the chromium and molybdenum content and the thermal water temperature. Titanium has extremely good corrosion resistance and PB, PVC and CPVC are not sensitive to corrosion. Asbestos-cement consists of calcium resulting in corrosive danger.

3.3.2 Physical properties

The meaningful physical properties are the water temperature, pressure and flow rate. The temperature of the geothermal water is measured in the preliminary investigation and monitored during the utilization of the well. The temperature partly indicates the extent of the exploitation. Formerly, a common temperature for greenhouse heating was 80°C or higher. The applications of heat pumps now enable the utilization of low temperature sources. The pressure depends on the existence of pumps and the elevation of the greenhouse. If the greenhouse level is lower than the source, suitable pressure in some cases can be provided without pumping but in other cases pumping is necessary. The flow rate should be low providing durability of the source.

3.4 Cost

The investment cost of a geothermal greenhouse can be divided between the cost of the greenhouse building, the heating system, control of indoor conditions and cost related to preparation of the site, parking area, etc. The investment cost depends strongly on the type of house and equipment chosen and varies also from one country to another. Total cost includes not only initial costs but also interest, tax rates and maintenance costs. The costs of the site preparation before greenhouse installation is shown in Table 1 according to Aldrich and Bartok (1994).

TABLE 1: Greenhouse pre-building costs in USA

	Cost (US $/m²)
Site preparation	8-11
Drive way and the parking area	4-11
Concrete floor 3''	11-13

Building costs vary considerably and cost comparison should not be made unless detailed knowledge of services and materials provided is available. For example, a glasshouse cannot be compared with a PE film house if all the specifications for each greenhouse are not compared and related to the intended use of the greenhouse. Construction costs vary also from country to country and between companies. Actual prices in the Netherlands are relatively low (Glass Trading Europe Company, 1996), for example, material costs of a glasshouse with aluminium frames range from 30 to 37 US$/m^2. Construction cost in Germany is similar to the Netherlands. Total costs in Iceland range from 100 to 145 US$/m^2, and in Greece the costs are similar or even higher than in Iceland. These prices include material and labour cost. In Table 2, construction cost in the USA is given with 1994 prices (Aldrich and Bartok, 1994).

TABLE 2: Greenhouse building cost in USA

Types	Material costs (US$/m^2)	Erection labour costs (US$/m^2)	Total cost (US$/m^2)
Conventional glass greenhouse Concrete foundation - galvanized frame - truss roof	75-97	32-43	107-140
Ridge and furrow greenhouse Concrete piers - galvanized steel frame - double poly covering	27-48	16-22	43-70
Steel pipe arch greenhouse Pipe foundation - galvanized pipe - polycarbonate structured sheet glazing	48-70	8-10	56-80
Steel pipe arch greenhouse Poly cover - pipe foundation - galvanized pipe	16-27	5-8	21-35
Rigid frame wood greenhouse poly cover - wood post foundation - clear span	11-16	5-8	16-24

The prices for two heating systems, unit heaters and fan coils, are given in Figure 5 according to their capacity (Rafferty, 1991). The cost of the pipes depends on the diameter, length and material.

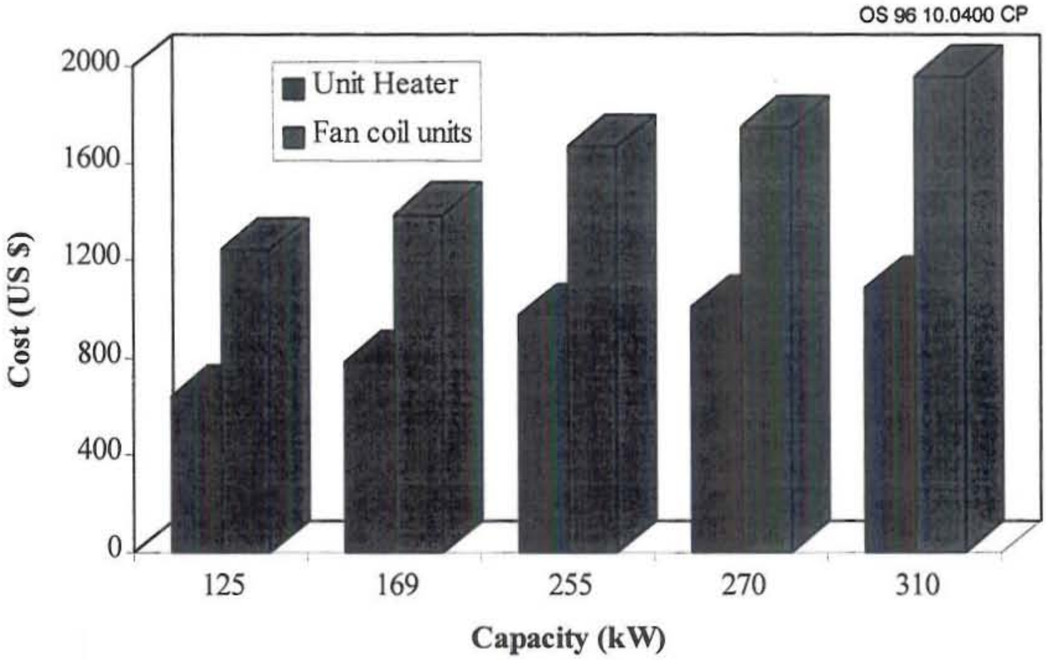

FIGURE 5: Cost of fan coils and unit heaters as a function of capacity

TABLE 3: Cost of indoor conditions control

Systems for control of indoor conditions	Cost of greenhouse floor area incl. labour (US$/m^2)
Ventilation	10-15
Fans with shutter, thermostat and housing	
Electricity	11-16
Supply, material and labour	
Water	8-13
Material and labour	
Heat retention system	
Manual	5-11
Motorized	13-32
Cooling system	5-11
Environment control computer	8-13

The cost of systems for indoor conditions control depends on the applied technology. Some prices are given in Table 3 in US$ (Aldrich and Bartok, 1994)

4. GREENHOUSE DESIGN METHODS

4.1 Structural design - orientation

The structural material of a greenhouse must provide protection from wind, snow or crop load and permit maximum light transmission. This means that the frames should be of minimum size and provide resistance to expected loads. The design loads include the dead load, the live one and loads from snow and wind. Dead load is the weight of the structure and depends on the framing, glazing system and the amount of permanent installations carried by the frame. The permanent installations are the heating and ventilation system, the water lines, etc. The live loads may be hanging plants or other items carried by the frames for short periods and people working on the roof. According to the National Greenhouse Manufactures Association in USA (NGMA), the maximum live load is 3 kg/m^2 of ground area covered, the design wind load is 35 m/s and the minimum value of the snow load is 3 kg/m^2 of ground area covered (Aldrich and Bartok, 1994).

The actual wind load depends on wind angle, greenhouse shape and size and the presence or not of openings and wind breaks. The snow load can be greater than 3 kg/m^2 but because of the heating of greenhouses, the snow melts. Furthermore the snow load depends on the roof slope, the shape of the greenhouse, if it is individual or gutter-connected and the heating system.

The greenhouse orientation is decided mainly on the basis of wind speed and direction, trying to avoid possible damages to the greenhouse in windy weather. Glass and fibreglass are more resistant than poly to the above loads. The simple plastic cover material which is used in cheap constructions is more sensitive to wind damages and orientation is more important in this case.

4.2 Material

4.2.1 Cover material

Formerly greenhouses were almost exclusively made of cypress wood frames and single glass panels. In recent years substantial changes have been carried out in construction techniques and materials. In general, construction materials fall into one of the following four categories: glass, plastic film, fibreglass or similar rigid plastics and combinations of the above (Rafferty, 1991).

Glass as a cover material for greenhouses offers superior light transmission and is preferred for plants which need high light intensity. It is also the most expensive material. The high cost is due to the glass price but also to the frame material which must be strong enough to support the glass. The poor insulating quality of the single glazing and the high infiltration through the many cracks in the construction result in high heating cost. The solution of this problem is the introduction of double glazing panels. However, because of the expense of these panels and their effect upon the light, most glass greenhouses remain single layer. Glass is perhaps the most widely used material because the heat requirements can be met inexpensively while simultaneously offering high light intensity.

Plastic film greenhouses are the newest variation in greenhouse construction techniques. The most common type is the structure with arched roof or "Quonset hut" design. The roof can come all the way down to the ground or can be fitted with side walls. Maintenance requirements for the plastic film are high and the film usually needs to be replaced at 3-year intervals or less, depending on the material quality. Heat loss is higher than for glass but it is seldom used as a single layer. Most plastic film houses have a double layer of film separated by air space. The air space is maintained by a small blower that pressurizes the volume between the layers. This double poly does not only reduce transmission losses by 30% to 40%, but also substantially reduces infiltration. Thus, the double poly reduces the heating requirements and is superior to glass. However, the superior energy efficiency of the film construction is obtained at the expense of reduced light transmission. As a result, highly light sensitive crops cannot be grown in the double poly greenhouse as successfully as in other constructions.

Fibreglass greenhouses are similar in construction to the glass houses described above. This type of structure is almost always of peaked roof design. It is cheaper than the glass because it has lower weight and it does not need a stronger framework. The light intensity is also lower than in glasshouses but the heat losses are similar. Although the fibreglass material has lower heat conductivity than glass, this has little effect.

The most common combination is fibreglass and plastic film greenhouses. The side walls and the end walls are generally from fibreglass construction and double poly is employed for the roof. Another combination is with glass and fibreglass, similar to the above one, where glass is used for the roof construction, but this combination is seldom used.

4.2.2 Frame material

Wood, steel, aluminium and reinforced concrete have been used for building frames for greenhouses. Sometimes combinations of them have been used. Wood must be painted to protect against decay and to improve light conditions. Preservatives should be used to protect any wood in contact with the soil from decay as it must be free of chemicals which are toxic to plants or humans. Wood frames include post, beams and rafter systems, post and trusses, glued laminated arches and rigid frames. Steel and aluminium are used for posts, beams, purlins, trusses and arches. White paint on either material improves the light conditions in the greenhouse. Both materials must be protected from direct contact with the ground to prevent corrosion. The use of reinforced concrete is limited to foundations and low walls because of the large size of available concrete frames.

Aluminium, as a frame material, is relatively light in weight and at the same time very strong. It is malleable, adaptable, waterproof and nonpoisonous. It does not rust or erode and conducts heat and electricity. An additional feature of aluminium is that it retains all of these characteristics even when reused. It loses none of its advantages when it is smelted resulting in energy saving. It is consequently recyclable; aluminium greenhouses that really need to be renewed can be reused almost in their entirety in producing new greenhouses (Alcoa Aluminium company, 1996).

4.3 Size

The size of a new greenhouse is chosen on the basis of several parameters such as kind of cultivation, building cost, farmer preferences, etc. If vegetables like tomatoes, peppers and cucumbers are cultivated, the greenhouse is high; if the vegetables are carrots or cabbage, the house can be very low, and in case of flowers or pot plants on benches, the structure should have an average size. In addition, the way of cultivation influences the size. If climbing plants are going to be hung, the greenhouse should be high.

The most common size for glasshouses is 11 or 13 m wide and the length increases in 6 m modules (Lund, 1996). The same size is used when the material is fibreglass. Plastic greenhouses usually have the width 9 m and length 30 m or 46 m. According to Inveka-Bosch company (1995), which builds greenhouses, the standard widths are 8.0 and 12.8 m, but different sizes from 6.4 up to 20 m are also possible. The roof size in inverted V-glasshouses is usually 3.2 or 4 m for self supporting roof constructions (Alcoa Agro company). Larger spans for more free working space are possible by placing more span-roofs, thus increasing the side roof; spans can vary from 6.4 to 16 m.

4.4 Shape

The most common shapes of greenhouses are shown in Figure 6. These are:

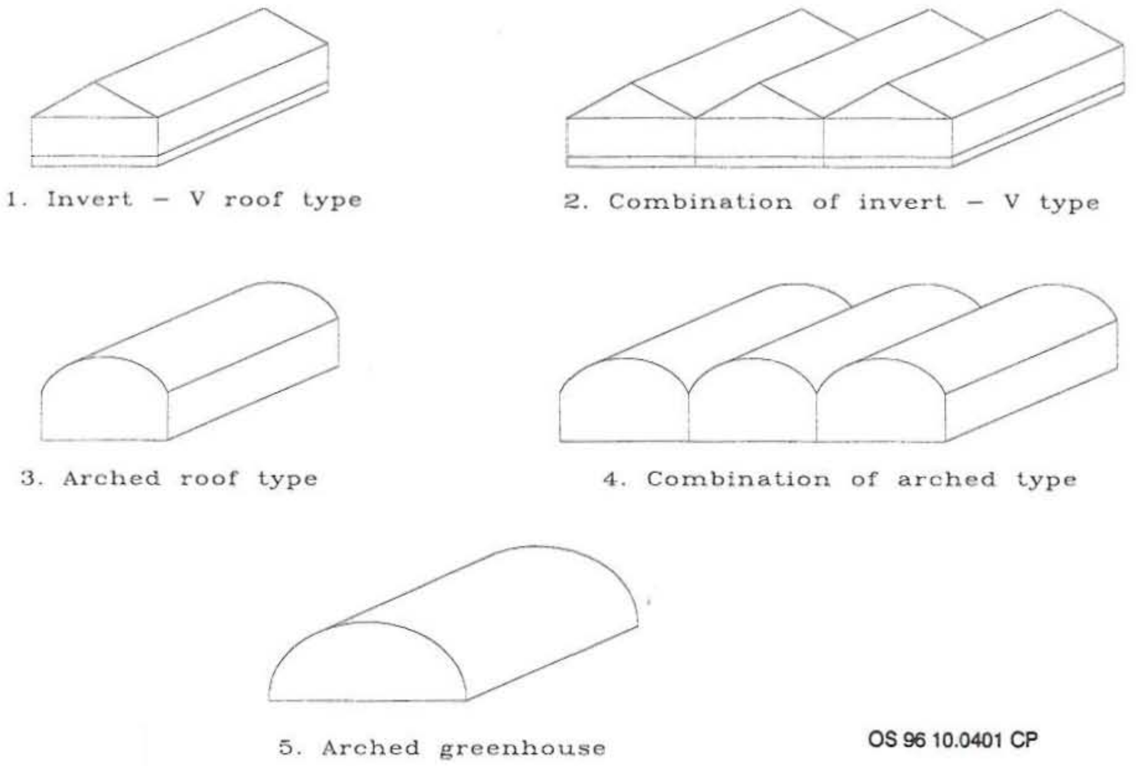

FIGURE 6: Types of greenhouses

1. Inverted V-roof type;
2. Combination of inverted V-roof type;
3. Arched roof type;
4. Combination of arched roof type;
5. Arched greenhouse.

Glasshouses are almost always inverted V-roof or combination of inverted V-roof types. If a combination of fibreglass and plastic film material is used, the greenhouse is usually of arched roof type and the roof is constructed with double poly and the walls with fibreglass.

4.5 Greenhouse heating

4.5.1 Heating requirements

Before a heating system for a greenhouse is selected, the peak heating requirements have to be calculated. The heating system must be designed to provide cultivation with the optimum temperature during plant life, and also when the outside climate temperature is very low. It is important to choose a covering material which affords this quality. The heating system selection may be the most significant for good quality and yield of cultivation.

Heat losses (in W) from a greenhouse are composed of two components

$$Q = Q_T + Q_I \tag{4}$$

where

Q_T = Transmission losses through the roof and the walls [W];
Q_I = Infiltration and ventilation losses due to the heating of cold outside air[W].

To evaluate transmission losses, the first step is to calculate the surface area of the structure. This surface area is probably subdivided into various materials used, i.e. m^2 of double plastic, glass, fibreglass, etc. After determining the total area of the various construction materials, this value is then combined with the design temperature difference and a heat loss factor for each, which is the reverse of the overall thermal resistance as follows:

$$Q_T = Q_{Tcover} + Q_{Trest} \tag{5}$$

Q_{Tcover} = Transmission heat losses through the glazing-covering material [W];
Q_{Trest} = Transmission heat losses through the unglazed area (e.g. gutter, frame, masonry) [W];

and

$$Q_{Tcover} = \frac{A_{cover}}{R_{kcover}} (T_i - T_o) \tag{6}$$

where

A_{cover} = Glazing area including frames [m^2];
T_i = Indoor temperature [°C];

T_o = Design outside temperature [°C];
R_{kcover} = Overall thermal resistance [m² °C/W].

The overall thermal resistance is defined as

$$R_{kcover} = R_{icover} + R_{\lambda cover} + R_{ocover} \tag{7}$$

where
R_{icover} = Inside convection resistance [m² °C/W];
$R_{\lambda cover}$ = Thermal conductivity resistance [m² °C/W];
R_{ocover} = Outside convection resistance [m² °C/W].

The transmission heat losses through the unglazed area Q_{Trest} is negligible so it is assumed that

$$Q_T \approx Q_{Tcover} \tag{8}$$

For greenhouse design, infiltration is generally analysed via the air change method. This method is based upon the number of times per hour that the air in the greenhouse is replaced by cold air leaking in from outside. The number of air changes which occur is a function of wind speed, greenhouse construction and inside and outside temperatures. It is assumed that the infiltration will meet winter ventilation requirements. If artificial ventilation is required in excess of infiltration, this should be added to the peak load. In order to calculate the infiltration losses Q_I, the value of the determined surface area is combined with the design temperature difference and the thermal resistance for infiltration caused by leaky joints, as follows:

$$Q_I = \frac{A_{cover}}{R_{vcover}}(T_i - T_o) \tag{9}$$

where
R_{vcover} = Thermal resistance for infiltration caused by leaky joints [m² °C/W].

In conclusion, this is the peak or design heating load for the greenhouse. The heating requirement selected for the structure should be capable of meeting these requirements. Tables 4-7 show the values of the resistances, R_{vcover}., R_{ocover}, $R_{\lambda cover}$ and R_{icover} .

TABLE 4: Greenhouse thermal resistance caused by air infiltration R_{Vcover} (DIN 4701)

Cover material	R_{vcover} **[m²°C/W]**
Glass in putty	1.0
Plastic film greenhouse	2.0
Plastic tent (tunnel)	2.0
Puttyless glazing in metal, frame with rubber gaskets	1.0

TABLE 5: Greenhouse thermal resistance by outside convection, R_{ocover}, as a function of windspeed (DIN 4701)

Windspeed [m/s]	R_{ocover} [m² °C/W]
1	0.102
2	0.0725
3	0.0562
4	0.0459
5	0.0388
6	0.0307
7	0.0346
8	0.0277
9	0.0252
10	0.0232

TABLE 6: Greenhouse thermal resistance by glass conduction, $R_{\lambda cover}$ (DIN 4701)

Cover material	$R_{\lambda cover}$ [m²°C/W]
Single glass	0.01
Plastic panel corrugated GFK 1 mm	0.01
Double glass in steel frame	
space 15 mm	0.14
space 12 mm	0.11
space 6 mm	0.09
Double poly frameless	
space 12 mm	0.15
space 5 mm	0.08
Double plastic film, space 10 mm	0.10
Single plastic film (PVC, PE) thickness of 0.2 mm	0.01

TABLE 7: Greenhouse thermal resistance by inside convection, R_{icover} (DIN 4701)

Heating System	R_{icover} [m²°C/W]
Pipes suspended from the ceiling	0.09
Pipes on the walls	0.09
Pipes under the raised tables	0.01
Pipes on the floor between the plots	0.12
Fan coil units	0.09
Unit heaters	0.01
Finned pipes	0.09
Combination of the above	0.1

4.5.2 Heating systems

The heating systems can be classified according to the position of the heating installation. The categories are the following:

1. Heating systems in the soil;
2. Heating systems laid on the soil surface or on the benches;
3. Aerial heating systems;
4. Cascading;
5. Combinations of the above.

Soil heating
In this system the soil is used as a large radiator. An example is demonstrated in Figure 7. The tubes are buried in the soil and the determination of their size and spacing is a function of heat output required, mean-water temperature, soil conductivity and burial depth. The warm water is circulated through the tubes and the produced heat is transferred to the soil and eventually to the air of the greenhouse. In recent years, material used for pipes is polypropylene, polyethylene or polybutylene because of the corrosion and expansion problems of steel. The polybutylene is the most resistant of these in the high temperature range and the most expensive.

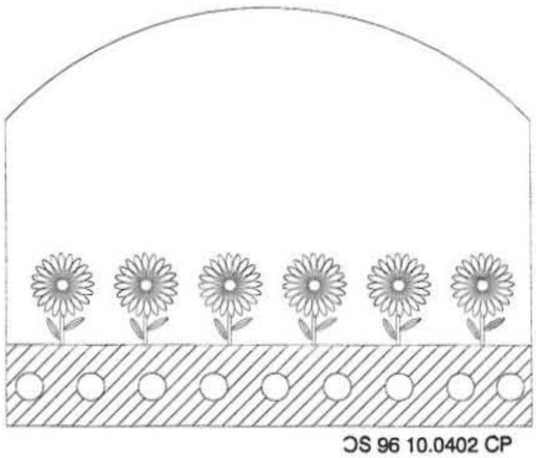

FIGURE 7: Soil heating

This system results in an even air temperature distribution from the floor to the ceiling, it does not obstruct floor space and does not cause shadows. Furthermore it is proven that the use of soil heating is very positive for a list of vegetables and bulbous flower cultivations providing earlier harvesting, improved yield and quality of products. Also, it is convenient for root temperature control and for covering minimal heat requirements. Consequently, if it will be used as the only heating system, it should be applied in mild climate areas and low inside design temperature. This is caused by the nature of heat transfer in the system. When the heating requirements increase, the floor temperature must be increased to meet these requirements. As a result, such a hot and radiant floor cannot be used for extended periods because excessive heat transfer to the plants is created. The solution is the combination of this system with other types of heating installations as, for example, unit heaters.

Heating systems laid on soil surface or on the benches
This category includes thin pipes, polyethylene sleeves or plastic pipes located on the ground as is shown in Figure 8. The thin pipe system is widely used and the others are installed only in small, or inexpensive small greenhouses. The pipes are made of steel or poly material. The location of the pipes can be between the plant rows or directly in the plant rows. The system can be arranged in unit loops or in a loop with a parallel system of two or three pipes.

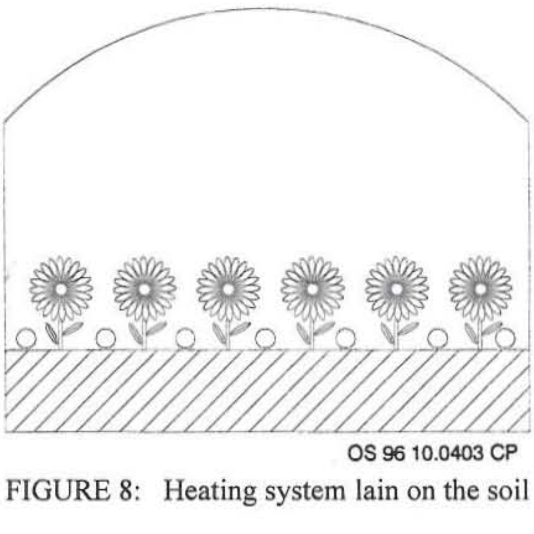

FIGURE 8: Heating system lain on the soil

A disadvantage of this system is that after the end of the production season the plastic pipes must be collected and the steel ones lifted for soil cultivation. Moreover, when the pipes are made by polyethylene they periodically need rearrangement because of the uncontrolled temperature dilations and they do not allow temperatures above 60°C. When the temperature is below 60°C, the heating system will consist of a great number of pipelines. Such a system might not be feasible because of high investment cost and the shading of the pipelines. Another disadvantage is the unprotected top leaves of the plants against the cold sky radiation and condition. For this reason in cold climates it is used in combination with another heating system. This system has a small but significant influence on the soil temperature and as in the soil heating system, provides earlier harvesting, improved yield and good quality of the products in most of the known cultivations.

Aerial heating systems

The dominant aerial systems are pipe heater units and fan coil units. The pipes can be smooth or finned steel pipes or smooth plastic pipes which are placed along the length of plant rows, along the side walls, under the roof or below the cultivation benches. In Figure 9 the pipes are placed along the walls and hung from the roof. The position of the system depends on the cultivation, the plant requirements, the greenhouse construction, farmer preference, the climate and the cultivation technology. This heating system is the oldest known system. It is convenient in any climate and usable in big greenhouses. It is not economically feasible in small and inexpensive greenhouses. The system is also convenient for combination with other heating systems. The aerial pipes benefit several cultivations but there are differences in the yield and quality of the products depending on the location of the pipes. The temperature of the geothermal water should be above 60°C for the same reason as the above systems.

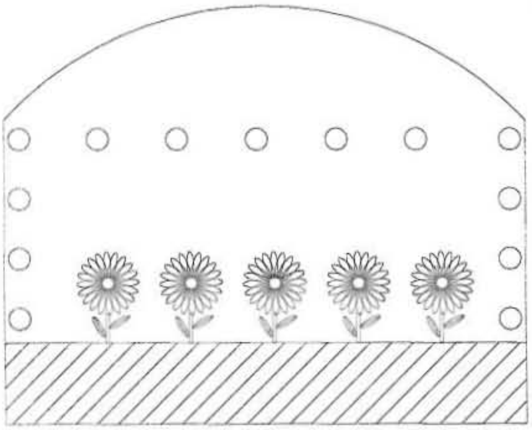

FIGURE 9: Aerial pipe heating system

The limitation of the water temperature can be solved with the spaghetti aerial heating system. It consists of plastic pipes with very small diameters, placed below the heated benches and results in even temperature distribution in the greenhouse. The temperature of the geothermal water should be low and the quality of the water very high because of the small diameter. This system is costly and is used only for pot plants and similar extravagant cultivations.

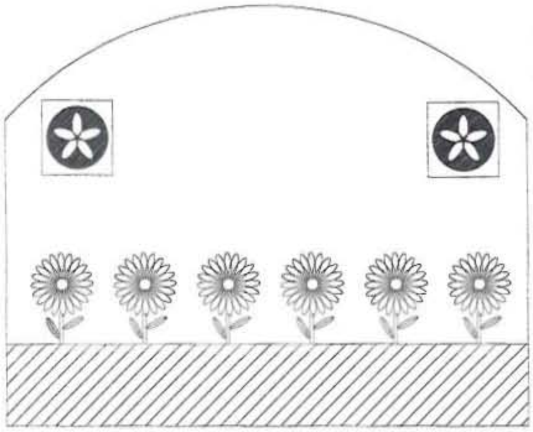

FIGURE 10: Forced air heated units

The forced air heated units are usually aerial systems, placed along the greenhouse side walls, between the plant rows or hung from the roof (Figure 10). The two main categories are the unit heaters and the fan coil units. The difference is primarily in the coil itself. The unit heaters usually have one or two row coils. The coil in the fan systems is much thicker and has closer fin spacing than in unit heaters. It has six or eight rows creating more surface area. The additional area gives more effective heat transfer, resulting in the ability to extract more heat from the water. The fan and the units systems usually need high geothermal fluid temperature because with low temperatures the efficiency of the system is lower and some adjustment of unit capacity is necessary. The geothermal fluid must be clean enough because the most common construction material of the units is copper and it is very sensitive to corrosion. In addition, the long path through which the water flows can result in scaling, thus making a heat exchanger necessary.

Cascading

This heating system is applied only in double layered constructions and is common in cheap plastic greenhouses. A water pipeline is installed into the space between the two layers and warm water is sprayed in this space. As a heating method, it is effective but it has a lot of disadvantages and is not widely applicable. The water must be extremely clean and without inclination of deposition. The problems of the depositions are not resolved, though many trials with chemical additives have been performed. After some months of exploitation, the plastic permits less light quantities. Also, the installation of roof windows is not possible. Additionally, the down positioned layer must be absolutely tight because infiltration of geothermal water can harm the plants.

Combination

A combination of different heating systems is necessary in cold climates. The forced aerial systems are usually applied together with soil heating systems (in or on the soil) providing even temperature distribution in the greenhouse. Common combinations of aerial heating systems are for example systems with pipes placed along the walls and under the roof (Figure 9), or hung from the roof and beside the plants, or on the roof, on the wall and beside the plants (Figure 11). When the pipes are placed only on the roof and the walls, the plants have pathogenic problems (fungus). This happens because the moisture remains on the plant leaf surface but when the thermal pipes are placed beside the rows of cultivation, a significant amount of moisture disappears.

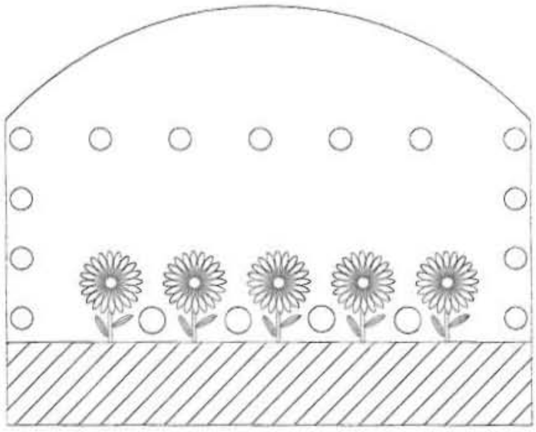

FIGURE 11: Combination of pipe heating systems

4.6 Cooling systems

4.6.1 Ventilation system - position of the windows

Greenhouses need to be ventilated to remove excess heat, humidity and any undesirable gases. The ventilation system supplies the necessary cooling all year round in cold severe climates and during the winter in all climates. In mild climates, there are usually summer cooling systems in addition to the windows. The direction of the windows can allow less heat losses and provide suitable ventilation. Glasshouses use upwards opening ventilator windows along the roof close to the ridge. The ventilation is partly caused by wind blowing and partly by "stack effect" of warm air rising through the upper parts of the windows and being replaced with cooler air entering through the openings. Most of the poly-plastic structures are ventilated through open ends or an opening strip along the base of each wall. The system usually has automatic control and the windows are placed on both sides. Accordingly, when the wind is blowing from one direction, the windows open from the other. In recent years forced ventilation has been used and is in some areas necessary equipment. It consists of fans which produce a horizontal current of air flowing either from end to end in small greenhouses or crosswise in larger ones.

4.6.2 Summer cooling system

The summer cooling system is employed in warm areas. The temperature inside the greenhouses is frequently 11°C higher than the outside one, in spite of the open ventilators. The high temperatures can have a detrimentally effect on the plants by losses of stem strength, reduction of flower size, delay of flowering and even bud abortion. The fan and pad evaporating summer cooling system is a frequent and old system. The pad is usually placed vertically, along one wall and the water is passed through this pad. Exhaust fans are placed on the opposite wall. Warm outside air is entranced in through the pad. The water in it, through evaporation, absorbs heat from the surrounding pad and frame as well as from the air passing through the pad. Both of the above systems can reduce the air temperature in the greenhouse below the outside temperature by 14°C or more (Balls, 1986).

5. DISPOSAL OF GEOTHERMAL WATER

After use in the greenhouse the geothermal water can be used again for another or the same purpose, can be reinjected or be thrown in a river or lake. The outlet geothermal water can be used in many ways depending on its temperature which is usually in the range 30-65°C, although higher and lower temperatures have been noticed. The uses can follow the Lindal diagram in Figure 12.

80°C -	Space heating (buildings and greenhouses)
70°C -	Refrigeration (lower temperature limit)
60°C -	Animal husbandry Greenhouse with combined space and hotbed heating
50°C -	Mushroom growing Balneology
40°C -	Soil warming
30°C -	Swimming pools, biodegradation, fermentation Warm water for year-round mining in cold climates De-icing
20°C -	Fish hatcheries, fish farming

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FIGURE 12: Lindal diagram

Another possibility is the cascading system. The outlet geothermal water is used many times e.g., when after greenhouse heating the outlet thermal fluid warms a swimming pool, and is then used for fish farming. Such a system results in water and energy savings.

The re-injection of the used water is a different kind of energy saving. After heating of the greenhouse, the water is injected again into the reservoir influencing the reservoir management. This increases the life of the reservoir, keeps the pressure almost stable, improves the energy extraction of the rock and is friendly to the environment. The high capital investment costs and exploitation cost are the main re-injection disadvantages. It is used more in the high-enthalpy fields and its limitations are more in the low-enthalpy fields. For example, where low-temperature water is utilised from sedimentary rocks, reinjection has succeeded only in France in a fractured limestone. In spite of the obstacles, reinjection is now widely practised all over the world (Gunnarsson, 1996).

After use, the geothermal water can be thrown in a river, lake or the sea. Almost always this action has a lot of negative effects on the environment. The geothermal water often contains heavy minerals and the temperature is above 20°C. The hot water in a cold river can harm the organisms living there. This disposal of the geothermal water is used in few countries and under environmental regulations. It is not recommended without prior investigations.

6. GEOTHERMAL GREENHOUSE DESIGN FOR GREECE

6.1 General

Geothermal research started in Greece in 1970. Over the last six years, exploration activities have focused on the low enthalpy fields, especially in Thrace and Macedonia and secondarily in Central Greece. Geothermal activity of the country includes geothermal greenhouses with a floor area of approximately 160 acres. The greenhouses are municipal and private and the main cultivation is vegetables as shown in Appendix 2. Thrace has revealed geothermal potentials but sources are unutilized yet. The most notable geothermal areas are one field in Evros near by Alexandroupolis (Loutros-Aristino), and two fields in Xanthi (Magana and N. Kessani). In Table 8 a few characteristics of these fields are presented.

TABLE 8: Fields of interest in Thrace in North Greece (Fytikas et al., 1995)

Region	Area (km^2)	Aquifer depth (m)	Proven flow rate (m^3/min)	Temperature of aquifer (°C)	Type of water	Expl. wells	Prod. wells
Loutros-Aristino (Alex/polis)	50+	50-150 110-200	100 100	38-50 79+	Na-Cl-Ca-K	6	0
N. Kessani (Xanthi)	15	100-400	250-350	45-80	Na-Cl-HCO_3	29	5
Magana (Xanthi)	15	200-400	400	55-65 40-50	Na-HCO_3-Cl	11 10	3 0

Project site

A design of greenhouses in the field of Loutros-Aristino close to Alexandroupolis will be described. This area is located at the western margins of a huge sedimentary basin. Two main fault systems trending NNW-SSE and NNE-SSW controlled the spatial evolution of sedimentation and volcanism which started in the middle of Eocene. Six boreholes 110-210 m deep were drilled in 1994. Until now surface and subsurface investigations have covered only a very limited part of the area of geothermal interest which may be over 50 km^2. The aquifers are located in altered volcanic formations of secondary permeability. A first upper aquifer zone from 40 to 150 m with the temperature range 40-55°C and salinity up to 5 g/l, and a lower one from 110 to 250 m with temperature higher than 79°C and salinity exceeding 10 g/l have been identified. Two wells with a temperature of 54.6°C and a third one of 92.8°C can be utilised. The design of the geothermal greenhouses is incorporated with these wells (Fytikas et al., 1995).

Location

The Loutros-Aristino geothermal field, in which the greenhouses are going to be located, is near the town Alexandroupolis and 5 km from the airport. The location is a very meaningful advantage because it provides market for the out-of-season products of the greenhouses. The existence of the airport is a kind of guaranteed market, even if it is used for domestic traffic only. The field is also near the villages and electricity and water supply can easily be applied. The location between two villages and one town with a population of about 70,000 inhabitants can provide a number of suppliers for general construction, mechanical and electrical work, but the greenhouse itself will be constructed in another area in Greece or imported.

Transmission system from the source to the wells

The heating requirements of the greenhouse have not yet been calculated, thus, the actual geothermal water requirements are unknown. It is assumed that the maximum flow rate will be m_1 = 10 kg/s and this amount of water will be used to heat as big a greenhouse area as possible. Further, it is assumed that the distance between the greenhouse and the source is 500 m and that the pipes are new and made of steel.

The density, ρ, and the kinematic viscosity of water, ν, are functions of temperature and according to thermophysical properties reported by Wong (1977) for 92.8°C, $\rho_1 = 969.238$ kg/m^3 and $\nu_1 = 3.388\times10^{-7}$ m^2/s, and for 54.6°C, $\rho_2 = 992.1249$ kg/m^3 and $\nu_2 = 6.094\times10^{-7}$ m^2/s. The pipe roughness for new steel pipes is around 0.05 mm. By using Equation 1 for the 92.8°C warm well and choosing pipe diameter 100 mm, which gives admissible results, the water velocity u_1 is:

$$u_1 = m_{V1}/A_1 = (m_1/\rho_1) / \pi(D/2)^2 = 1.3 \text{ m/s}$$

The friction factor, f, and the pressure drop, ΔP_1 are, according to Equations 2 and 3

$$f = 0.18 \text{ and } \Delta P_1 = 0.76 \text{ bars.}$$

For the 54.6°C warm geothermal water and a pipeline size of is 100 mm, $u_2 = 1.283$ m/s and $\Delta P_2 = 0.775$ bars. Thus, the diameter is the same in both cases. The pipes should be buried steel pipe preinsulated with polyurethane foam with a polyethylene cover. The system should be a double pipes system, one supply pipe and one return pipe.

Climate - design loads

The area around Alexandroupolis is very windy. Usually the winds are not strong but they are very frequent. During the winter it snows but the snow is not enough to destroy construction and usually the day after snowfall, it has disappeared. The wind and snow loads follow the standard from National Greenhouse Manufactures Association (NGMA) which are described in Chapter 4.1. In this area the temperature drops below 0°C but the design outside temperature is taken as 0°C. The temperature during the summer is rather high, maybe above 35°C.

Structure design

The geothermal greenhouse is demonstrated in Figure 13. It should be constructed of one layer glass with the frames of aluminium. These materials are chosen in spite of high cost because they provide stability to the structure and superior light transmission in the greenhouse. The cultivation will be cut roses and the products are going to be sold to the nearby town but can also easily be transferred to the capital of the country. The length L of the greenhouse is 50 m, the width W 16 m, the width of every roof w is the usual width 3.2 m, the total height H is 3.5 m. The angle is about 25°, the roof height h_2 is 0.75 m and as a result the side roof s_{roof} is 1.767 m. The construction dimensions of the greenhouse permit changes to the crop and the way of cultivation.

Windows are placed on both of the roof sides and they open and close automatically. The water and fertilizer supply are also automatic and they are placed outside the production area. Generally the environment control is computerized and the control room placed in a protected building beside the greenhouse structure. The carbon dioxide supply is realised only for the maintenance of carbon dioxide

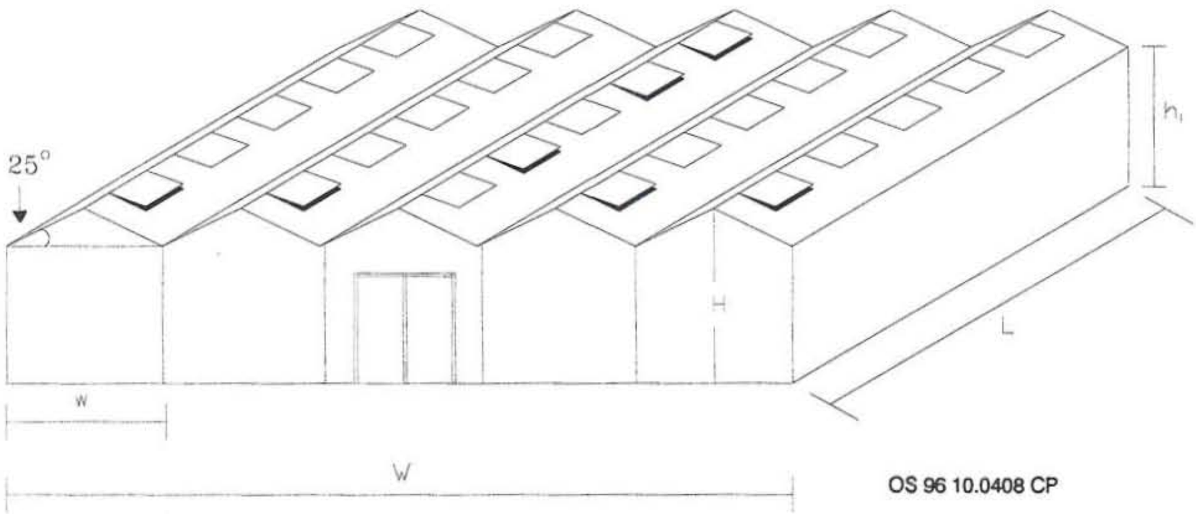

FIGURE 13: Greenhouse civil construction

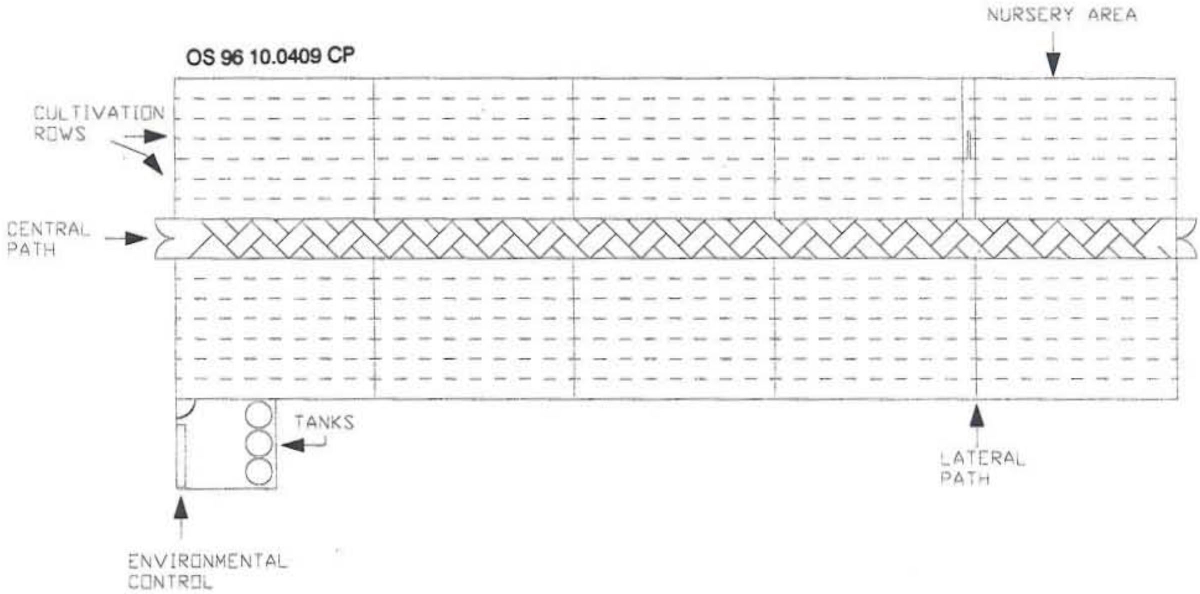

FIGURE 14: Top view of the greenhouse internal distribution

concentration at the atmospheric air level. This is because of the CO_2 cost. Part of the greenhouse can be used for a nursery area for seedlings, especially when the cultivation is vegetables. The internal parts of the greenhouse are demonstrated in Figure 14.

Cost

The cost of the greenhouse can be estimated using Tables 1, 2 and 3 excluding the heating system cost. The site of the greenhouse occupies totally 1,000 m^2. The greenhouse construction occupies 800 m^2, the parking area 100 m^2 and the control room 20 m^2. Site preparation for 1,000 m^2 costs 8,000 US$, the area of parking 500 US$, the concrete floor of the paths and the control room 1,375 US$ and the construction cost are estimated to be 116,000 US$. The aggregate prices of equipment which control the indoor conditions are 64,000 US$. Consequently, the total cost without the heating system is 182,675 US$, including labour.

Heating requirements

Before making heating system selection, heating requirements have to be calculated. The first step is to evaluate the total glass area:

The walls area is $2 \times [L \times (H-h_2)] + 2 \times [W \times (H-h_2)] = (2x50x2.75) + (2x16x2.75) = 363m^2$

The roof area is $10 \times 0.5 \times (w \times h_2) + 10 \times (L \times s_{roof}) = (5x3.2x0.75) + (10x50x1.76706) = 895.5\ m^2$

Hence the total glass area A is: $363 + 895.5 = 1258.5\ m^2$

The next step is to calculate the overall thermal resistance R_{kcover} for the evaluation of transmission losses. From Tables 5, 6 and 7, the inside convection resistance $R_{icover} = 0.1$, the thermal conductivity resistance $R_{\lambda cover} = 0.01$ and the outside convection resistance $R_{ocover} = 0.0307$ (it is assumed that the air speed is approximately 6 m/h).

$$R_{kcover} = R_{icover} + R_{\lambda cover} + R_{ocover} = 0.1 + 0.01 + 0.0307 = 0.1407$$

The temperatures are

T_i = Inside temperature for the roses, about 18°C;
T_o = Outdoor design temperature, assumed to be 0°C;
ΔT = Temperature difference, 18°C.

Thus, the transmission losses through the roof and the walls according to Equation 6 are

$$Q_T = A_{cover} \times \Delta T / R_{kcover} = 1258.53 \times 18 / 1.1407 = 161.0 \text{ kW}$$

The transmission heat losses from the unglazed area are negligible resulting in the total transmission losses being equal to the transmission losses through the glazing cover area.

The infiltration losses can be evaluated from Equation 9. The thermal conductivity resistance by infiltration, R_{vcover} is 1.0 according to Table 4 and the area and ΔT are the same as before

$$Q_I = A_{cover} \times \Delta T / \text{R}_{cover} = 1258.53 \times 18 / 1 = 22.7 \text{ kW}$$

The total heat losses according to Equation 4 are

$$Q_T + Q_I = 161 + 22.7 = 183.7 \text{ kW}$$

These are the heating requirements and the heating system has to be able to meet them. In the following chapter, calculations based on the utilisation of geothermal water at 92.8°C are described. Thereafter, similar calculations are shown for a geothermal water temperature of 54.6°C.

6.2 Well with 92.8°C water

This well is located between the villages Loutros and Aristino and the maximum flow rate is 100 m^3/h or 27.8 l/s. A heat exchanger for transferring heat from the geothermal water to the closed loop heating system in the greenhouse is chosen by means of a computer program, CAS-200, provided by the company Alfa Laval Thermal AB (1996). The program interface is shown in Figure 15. The heat exchanger chosen by the program is type CB76 1.00, plate configuration with 107 plates. In the greenhouse the water temperature drops from 90°C to 70°C and then is circulated again. A tank is interposed in the system and it contributes to the water expansion.

The heating system should meet the heating demands, be as cheap as possible and must not cause damages to the plants (e.g. provoke shadow, let moisture on the leaves, be very far or very close to the plants). The heating system chosen is a pipe system on the walls, under the roof and beside the plant rows. Two fans with low capacity are installed at the two opposite ends of the house, placed in parallel, contributing to even temperatures. These fans may be used with the installation of a pad for the cooling system during the summer. The cooling system has to be installed because temperatures in July and August are very high.

The pipes will be made of steel and have a diameter of 38 mm. The total length of the pipes is related to the total heat requirements and the heat which the steel pipes can release to the air. The equation is

$$L_{pipe} = \frac{Q}{q_{pipe}} \tag{10}$$

where

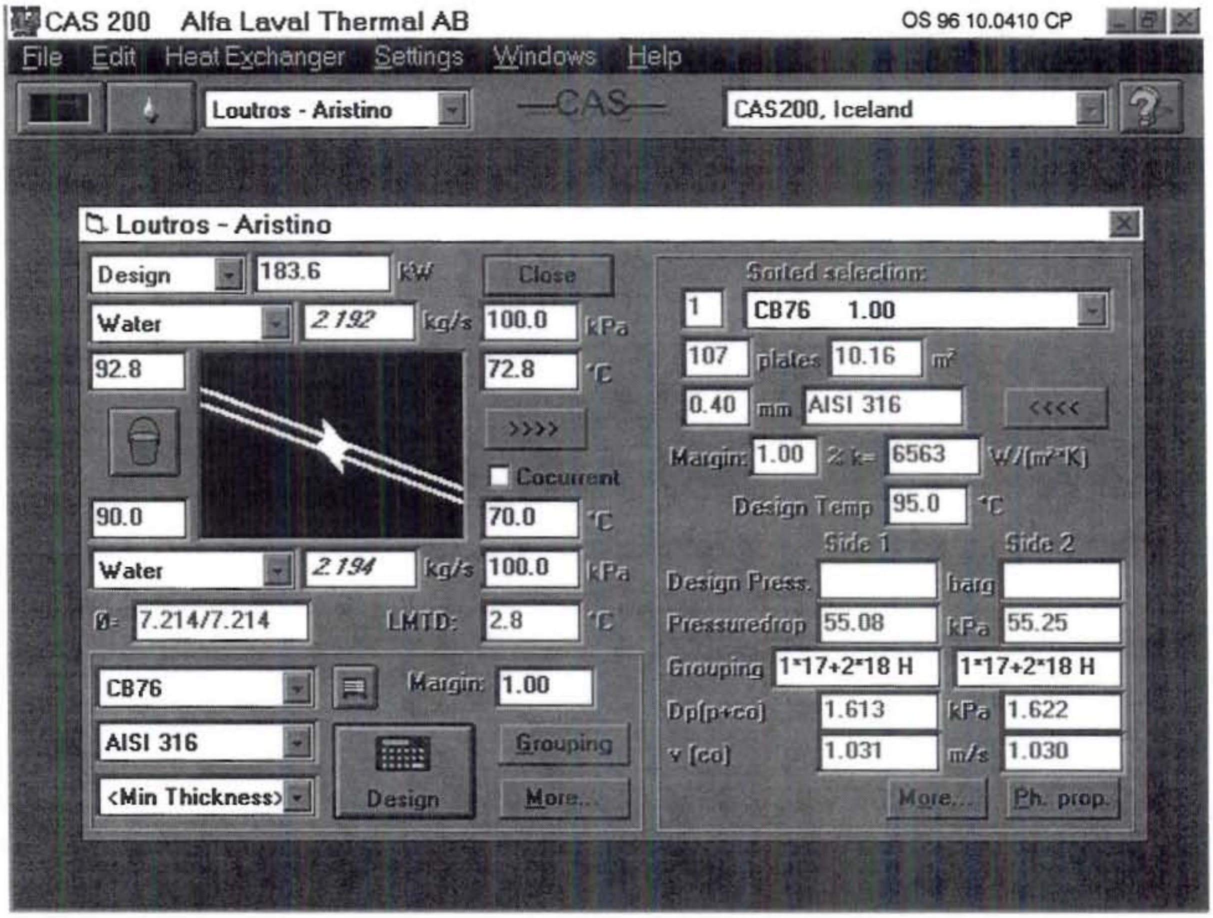

FIGURE 15: Interface for the CAS-200 computer program for calculation of plate heat exchangers showing values for the well with 92.8°C warm water

L_{pipe} = Total length of the pipe [m];
Q = Total heating demands in the greenhouse [W];
q_{pipe} = Heat output per metre of pipe [W/m].

The heat output q_{pipe}, is a function of the mean temperature of the water inside the pipe and the air temperature in the greenhouse as shown in Figure 16 (Tantau, 1982).

In this design the air temperature is 18°C, the inlet temperature is 90°C and the outlet 70°C so the mean water temperature is

T_{wmean} = (90 + 70) /2 = 160 /2= 80°C

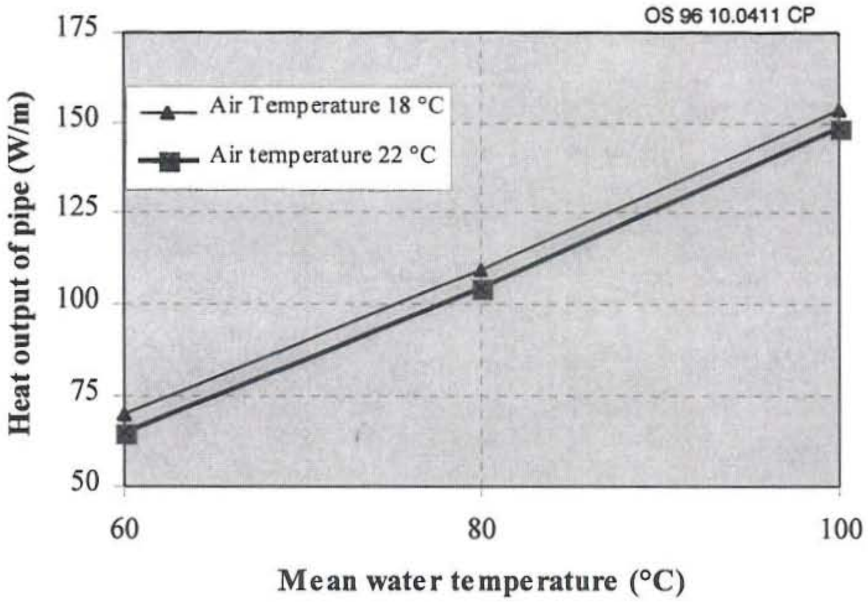

Figure 16: Heat output of a pipe as a function of mean water temperature

For 18°C air and 80°C water, the tube releases 109 W of heat per m of tube. The total heating requirements are 183,659 W. This means that the total length of the pipe needs to be

L_{pipe} = 183659/109 =1685 m.

The length of the greenhouse is 50 m. The arrangement of the tubes is parallel to the length of the greenhouse. The number of pipes n is calculated as

$$n = \frac{L_{pipe}}{L_{house}} \tag{11}$$

where

n = 1685 / 50 =33.7.

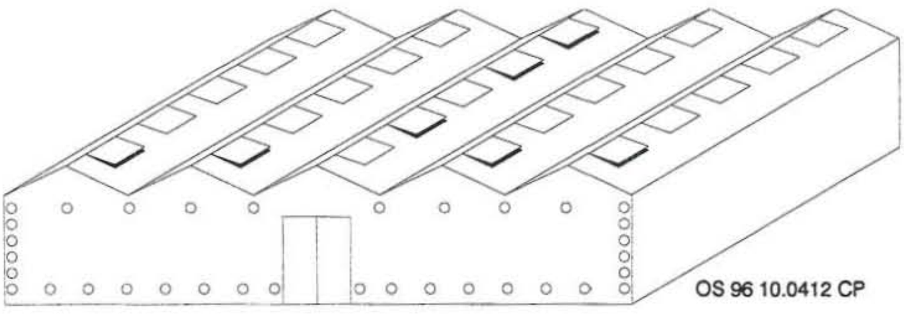

FIGURE 17: Pipe arrangement in the greenhouse

This means that 34 pipes must be placed in the greenhouse, on the walls, the roof and above the floor near to the plant rows. The arrangement is shown in Figure 17. The distance between the pipes on the wall needs to be 0.45 m and the number of pipes on the walls 12 (6 pipes on each wall). The distance in the roof is 1.6 m and the number 10 (two of them are in common with the wall pipes, resulting in 8 pipes). The distance between the rows on the floor is 1 m and the total number of pipes 16 (two of them are in common with the walls). The number of pipes above the floor are less than might be expected because, as mentioned before, in the middle of the house there is a place without plants. This space is reserved for people movement and is about 2 m wide. The pipes are placed 0.3 m above the ground.

Cultivation change

If the greenhouse would be designed for the cultivation of vegetables like tomatoes, cucumber, eggplants or paprika instead of roses, a different size heating system would be needed. In this case, the indoor temperature needs to be 22°C, ΔT is now different and the heating requirements are

$Q_T = A_{glass} \times \Delta T/R_{kglass}$ = 1258.53 x 22 / 0.1407 = 196,785 W;
$Q_l = A_{glass} \times \Delta T/R_{vglass}$ = 1258.53 x 22 / 1 = 27,688 W;
$Q = Q_T + Q_l$ = 196,785 + 27,688 =224,473 W.

The heat output of the pipe according to Figure 16 is 104 W/m of pipe. The total length is then

L_{pipe} = 224473 /104= 2,158 m.

According to Equation 8 the number of the pipes needs to be

n = 2158 / 50 = 43 pipes; or 9 pipes more than when cultivating roses.

Cost

The cost of the heating system depends on the total length and diameter of the steel pipes. For the cultivation of roses the total length was 1685 m and for vegetables it was 2158 m. The total length in each case will be longer because of the pipe joints. In the diagram in Figure 18, prices of the pipes are given approximately. Accordingly, in the first case the cost of heating system is about 5,400 US$ and in the second 6,900 US$.

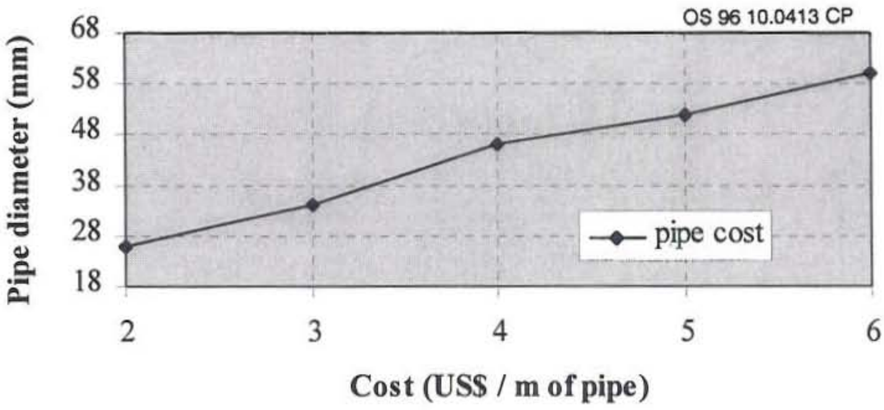

FIGURE 18: Steel pipe cost

Outlet temperature change

The outlet geothermal water temperature is very high, 72.8°C, resulting in a flow rate equal to 2.19 kg/s. The water can be used again for greenhouse heating or in many other ways according to the Lindal Diagram (Chapter 5). If the geothermal water is not used further the outlet design temperature should be reduced. If the outlet temperature for the geothermal water is 45°C, the inlet and outlet temperatures of clean water can fall in one of three representative categories, 1) clean inlet water 80°C - outlet 35°C, 2) 40°C - 30°C, or 3) 65°C - 35°C.

The cultivation is roses so, the heating demands are 183.6 kW. In the first case where the inlet temperature is high, 80°C and the outlet temperature very low, 35°C, according to the CAS-200 Alfa Laval Thermal AB Program, the required heat exchanger is constituted by 58 plates (2.9 m^2) and the flow rate is 0.9 kg/s. The flow rate is very low but the big temperature difference results in uneven air temperature distribution in the greenhouse. In the second case where the inlet temperature is 40°C and the outlet 30°C, the heat exchanger is CB76 1.00 with 58 plates (2.85 m^2) and the flow rate is 4.4 kg/s. The high flow rate results in even air temperature but the pipes have to be very long and of large diameter which is not economical. When the inlet temperature is 65°C and the outlet 35°C, the flow rate is 1.46 kg/s and the required heat exchanger can be CB76 1.00 constituted by 17 plates and occupies 1.7 m^2. The heat exchanger is cheaper in comparison with the others and the temperature is not as stable as in the second case, but the pipes used can be of economical sizes.

6.3 Well with 54.6°C water

It is assumed that the same type of greenhouse is constructed close to the wells with the 54.6°C water. These wells are located near the village Loutros in the area of the ancient town Traianoupolis. The use of a heat exchanger is again necessary. The heat exchanger for these wells according to the same program, CAS-200 Alfa Laval Thermals AB, is CB51 1.00 with 173 plates. The flow rate of the geothermal water is 2.1 l/s and its outlet temperature 32.6°C.

The difference between this greenhouse design and the previous one is the heating system. It will be made of polybutylene plastic pipes with 28 mm diameter. The cultivation is planned to be cut roses and the heating demands are again 183,659 W. The heat output in this case will be calculated in another way according to Lund (1996). The heat output per metre of plastic pipe is given by the following equation:

$$q_{pipe} = \frac{1}{3.2}\ [[4.222 \times (\frac{1}{D})^{0.2} \times (\frac{1}{1.8 \times T_{ave} + 32})^{0.181} \times (\Delta T)^{1.266}]$$
$$+ (15.7 \times 10^{-10})\ [(1.8 \times T_1 + 32)^4 - (1.8 \times T_2 + 32)^4]] \times 11.345 \times A \qquad (12)$$

where

q_{pipe}	= Output heat per metre of pipe [W / m];
D	= Outside diameter of the pipe [mm];
T_{ave}	= 255.6 + $(AWT + T_{air})$ / 2 [°C];
AWT	= T_s-T / 2 [°C];
T_s	= Supply temperature of the water [°C];
T	= AWT-$(T_{air}$ + 3) [°C];
T_{air}	= Inside design temperature [°C]
T_1	= 255.6 + AWT [°C];
T_3	= $(AUST + T_{air})$ /2 [°C];
T_2	= 255.6 + T_3 [°C];
A	= Outside surface area of pipe per unit length [m/m²];
$AUST$	= Average temperature of unheated surfaces (walls, roof) [°C].

The *AUST* is given by the following equation

$$AUST = \frac{(A_1 \times IST_1) + (A_2 \times IST_2)......(A_n \times IST_n)}{A_1 + A_2......A_n} \qquad (13)$$

and, *IST*, the inside surface temperature, is described with the follow equation:

$$IST = T_{air} - (0.091 \times U \times \delta T) \qquad (14)$$

where

U	= Glazing material heat losses factor [kJ/m²hr°C];
T	= Temperature difference between the inside and outside design temperatures [°C].

In this design the covering material is glass everywhere resulting in

$$AUST = IST$$

The U-values depend on wind speed. The wind speed is assumed to be 6 m/s for this area. The U-values for this velocity are shown in Table 9. The water supply temperature is 51°C, the diameter is 28 mm and the U-value is 22.5 kJ/m²hr°C, the inside air temperature is 18°C, consequently, all the parameters can be evaluated. According to Equation 12 the output heat of the plastic pipe is 22.63 W / m of tube. The total heating demands are 183,659 W and the total pipe length according to Equation 10 is:

L_{pipe} = 183659/22.63 = 8115.7 m.

The plastic pipes are longer (total length) than the steel pipes in the previous utilization because the water in the other well was hotter. The length of the plastic pipes results in 162 pipes of 50 m each. The arrangement of this number of pipes is not practical or feasible. If the pipes have larger diameters less

TABLE 9: U-values for 6 m/s wind speed

Material	U-values [kJ/m2 hr°C]
Glass	22.5
Fibreglass	20.4
Single poly	23.5
Double poly	14.3

pipes would be required to heat the greenhouse. For example if the pipe diameter is 42.4 mm then q_{pipe} is 33.23 W/m and the total length 5,525 m. The total length would be much less than 4,000 m if the pipe diameter is 60.3 m. Installation of long pipes or pipes with very large diameters creates shade on the plants and is not recommended as a heating system.

The solution to the problem is a combination of heating systems. First of all the heating requirements should be divided between two heating systems, the pipes and unit heaters. The total pipe length which can be placed in the greenhouse has to be evaluated. The distance between the pipes on the wall is, as previously, 0.45 m resulting in 12 pipes placed on the walls, 6 on each wall. The distance between the pipes above the ground and beside the rows is 0.8 m, resulting in 20 pipes, two in common with the walls and no pipes in the room control part. The total number is 30 pipes. According to the above equations the total heat can be calculated, i.e.

30 pipes x 50 m = 1500 m.

The q_{pipe} is 22.63 W/pipe m and the total heat output Q_{pipe} is

$$Q_{pipe} = 22.63 \times 1500 = 33{,}945 \text{ W}.$$

Unit heaters should meet the remaining 149,714 W or 538,970 kJ/hr. Common unit heaters are divided into the categories shown in Table 10. The air temperature in Table 11 is 16°C and it is assumed that the same factors apply for 18°C. If the unit heaters are two, one at each end of the greenhouse, their capacity needs to be 269,485 kJ/hr. However, this must be divided by the correction factor in Table 11 which is approximately 0.429, thus, the real capacity of the unit heaters has to be at least 628,171 kJ/hr. Such big units are not available, therefore six unit heaters will be placed in the greenhouse. Each one has a capacity of 210,973 kJ/hr and the models selected are the E-models with capacity of 236,000 kJ/hr (Table 10). If fan coil heaters are used, the number of units can be decreased. As already mentioned, a custom designed fan coil can have

TABLE 10: Capacity unit heater models

Model	Capacity (kJ/hr)
A	95000
B	140000
C	146000
D	209000
E	236000
F	288000

TABLE 11: Unit heater correction factors for 16°C temperature of entering air

Entering water temperature (°C)	Correction factor
27	0.143
38	0.286
49	0.429
60	0.571
71	0.714
82	0.857
93	1

six or eight rows but a unit heater only one or two. The heating requirements which the fan has to meet are 543,044 kJ/hr and using the two fan coils with six coils, each of them should have a capacity of 271,522 kJ/hr or the real capacity

$$271{,}522 / 0.429 = 632{,}918 \text{ kJ/hr}.$$

It is assumed that the unit heaters have two coils and the fan heaters six, resulting in the latter having a three times higher capacity. The real capacity of every fan is 210,973 kJ/hr so two fan coils can be used to heat the greenhouse. If it has eight coils then two fans with the same capacity should be used. The six unit heaters can be replaced by two fans with the same capacity. The other advantage of the fans is that the leaving air temperature is raised in comparison with the unit heaters. However, the benefit of the fan coil is not without cost. The definitive selection factor for the last heating system is the cost. In Tables 12 and 13 some of the prices of two systems are shown (Lund, 1996). The capacities are not the same but for similar capacities the fan coils are approximately double the price compared to the unit heaters. In Figure 19 the arrangement of plastic pipes and unit heaters is demonstrated.

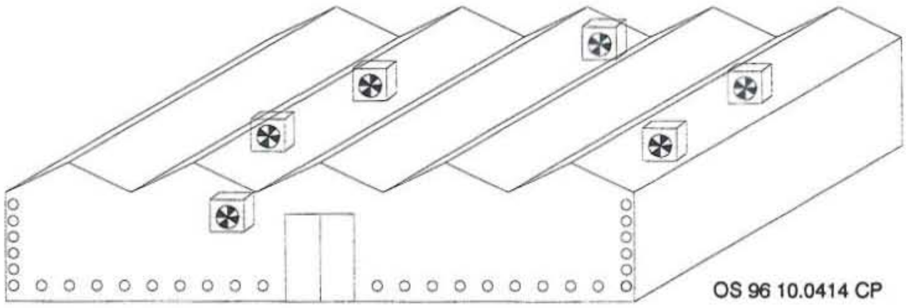

FIGURE 19: Arrangement of plastic pipes and unit heaters in the greenhouse

TABLE 12: Unit heater cost

Capacity (kW)	Cost (US$)
28,500	425
47,500	510
77,000	565
112,000	595
169,000	775
270,000	1005
310,000	1085

TABLE 13: Fan coil units cost

Capacity (kW)	Cost (US$)
125,000	1240
255,000	1670
380,000	2320
505,000	2970

6.4 Disposal of the geothermal water

As mentioned in Chapter 5, waste water after heating the greenhouse can be reinjected, used or be thrown in river or lake. In this area, the geothermal water must be used again. The field is a sedimentary basin and re-injection is difficult to carry out. The discharge of the water in a river is not allowed because the area has rare species of birds and fish and is protected with regulations. According to the Lindal diagram there are several possibilities. The 70°C outlet water can be used in all the ways discussed and maybe again for space heating in the greenhouses. When the water is of a lower temperature, there are not as many possibilities. The best are soil heating for vegetables during the winter, and in fish farming. The winter is windy and cold, consequently the farmers have difficulties in growing vegetables in this season. The rare species of fauna, the short distance from the sea and the already established market, create favourable conditions for fish farming.

7. RESULTS - CONCLUSIONS

- ✔ Cultivation of vegetables, flowers and other crops in greenhouses can easily be performed by utilisation of geothermal water as a heat source. The design of such a greenhouse is similar to others except for the heating system.
- ✔ The geothermal water flow rate needed for a greenhouse of 800 m^2 surface area, is approximately 2 kg/s at the inlet temperature 92.8°C. If the geothermal water from the three wells is utilized completely, then more than 40 geothermal greenhouses can be heated. The water can probably be used in other ways such as heating buildings in the surrounding villages and the outlet water to heat greenhouses.
- ✔ The location of the greenhouses ensures a market for the out-of-season products because of the airport and a number of suppliers for greenhouse construction
- ✔ When utilizing 92.8°C geothermal water the heating system is relatively inexpensive.
- ✔ The crop has to be decided before heating system installation. The crop decides the heating demands and consequently the heating system.
- ✔ The outlet geothermal water should be used in a cascade system. For the disposal of waste water, the investigation of cascade utilization is recommended. The release of the water into the environment is not a viable option because of regulations.

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APPENDIX 1: Types of pipeline (Eliasson et al., 1990)

Pipe description	Application	Advantages	Disadvantages	Cost ratio
Asbestos-cement pipe embedded in soil.	Transmission pipeline. Water transported over long distances. Sufficient hot water available. Low hot water production cost. Sizes 100-500 mm.	Low initial cost	Considerable heat losses. Rather low strength. Vulnerable to corrosion in soft water. Needs careful handling in laying and repairs.	Single pipe 0.3-0.4.
Plastic pipe (polypropylene and polyethylene) laid in ground without thermal insulation.	Transmission pipeline. Low-temperature source (maximum 90°C). Abundance of hot water. Low production cost of hot water. Sizes 20-200 mm.	Low initial cost. Easy pipelaying.	Permits ingress of oxygen by diffusion. High heat losses.	Single pipe 0.3-0.4.
Insulated plastic pipe (polypropylene and polyethylene) with segmented polyurethane insulation.	Transmission pipeline. Low-temperature source (maximum 90°C). Sizes 20-200 mm.	Low initial cost. Easy pipelaying.	Permits ingress of oxygen by diffusion.	Single pipe 0.8.
Steel pipe above ground insulated with mineral wool, a sheet metal protective cover.	Collection and transmission pipelines. Usable where pipelines may be placed above ground. Sizes ≥ 200 mm.	Durability. Low maint. costs. No temperature limits.	High initial cost in sizes under 200 mm compared to buried preinsulated pipes.	Single pipe 1.3-0.8.
Steel pipe above ground insulated with polyurethane, with a spiral wool protective coat.	Collection and transmission pipe-line. Used in unbuilt regions where pipelines may be placed above ground. Sizes ≥200 mm.	Durability. Low maintenance costs.	High initial cost in sizes under 200 mm compared to buried preinsulated pipes. Max. temperature 120°C.	Single pipe 1.3-0.8.
Steel pipe preinsulated with polyurethane foam with a polyethylene cover.	Buried distribution systems. Sizes 20-200 mm, and above ground transmission pipelines up to 900 mm.	Durable. Low maint. costs. Water-tight protective jacket. Easily laid.	High initial cost in sizes >200 mm. Max. water temperature 120°C. Vulnerable to external damage.	Single and double pipe 1.0
Steel pipe laid in a concrete conduit.	Transmission pipelines and distribution network. Short and wide (>200 mm) pipelines which must be laid underground in populated areas. Large consumer market.	Durability. Low maintenance costs. No temperature limits.	High initial cost.	Single pipe 1.2-2.0, double pipe 0.8-1.5.

APPENDIX 2: Geothermal greenhouses in Greece (Fytikas et al., 1995)

Field	Area, (10^3 m^2)	Type	Heating system	Flow rate (m3/h)	T-in (°C)	T-out (°C)	Load factor	Cultivation	Owner-ship
Sidirokastro	6	Glass	Spiral PP-pipes M 28	25	60	45	26%	Roses	Municipal
Sidirokastro	4	Glass	Spiral PP-pipes M 28	50	55	40	26%	Flowers pots	Municipal
Sidirokastro	10	Glass	Spiral PP-pipes M 28, water air- heaters	25 +20	45-38	30	26%	Flowers	Private
Sidirokastro	4	Glass	Spiral PP-pipes M 28, water air- heaters	25	40	30	26%	Roses	Private
Nigrita	9	PE	PE pipes	150	55	30	13%	Vegetables	Private
Nigrita	8	Glass, PE	Finned tubes, transparent large PEpipes	67	41	30	10%	Flowers, vegs	Private
Nigrita	33	Glass	H.E., reinjection	200	60	35	16%	Vegetables	Private
Nigrita	4	Glass	H.E., water air-heaters	50	55	35		Roses	Municipal
N. Apollonia	4.5	PE	PE pipes	45	47	35	16%	Vegetables	Private
N. Apollonia	7		Transparent large PEpipes		42	18	28%	Vegetables	Private
N. Apollonia	4	Glass	Spiral PP-pipes M 28	45	45	30	28%	Flowers pots	Private
N. Apollonia	14	Glass	Spiral PP-pipes M 28	40	48	33	17%	Rose, tomatoes	Private
Langadas	7	Glass, PE	Spiral PP-pipes M 28	40	36	27	28%	Roses	Private
Langadas	2		Transparent large PEpipes		36	27		Vegetables	Private
Langadas	3	.	Not in operation						Municipal
Lisvori, Lesvos isl.	4	Glass	Spiral PP-pipes M 28	25	67	50	22%	Roses	Municipal
Years, Lesvos isl.	4	Double PE	Spiral PP-pipes M 29	30	38	28	17%	Vegetables	Municipal
Polychnitos, Lesvos isl.	9	Pl.gl., PE	Not in operation						Municipal
Polychnitos, Lesvos isl.	3.5	Plastic	Spiral PP-pipes M 28, water air- heaters	7	85	30	20%	Vegetables	Private
Polychnitos, Lesvos isl.	3.5	Plastic	Spiral PP-pipes M 28, water air- heaters	10	85	30	17%	Vegetables	Private
Polychnitos, Lesvos isl.	3	Plastic	Spiral PP-pipes M 28	6	85	30	20%	Vegetables	Private
Polychnitos, Lesvos isl.	6.5	Plastic	Spiral PP-pipes M 28, water air- heaters	25	85	30	15%	Vegetables	Private
Polychnitos, Lesvos isl.	4	Double PE	Spiral PP-pipes M 28, water air- heaters					Vegetables	Private
Milos isl.	7	Glass, PE	PE pipes	6	45	30	65%	Vegetables	Municipal
Milos isl.	5.5	Plastic	PE pipes	15	47	25	27%	Vegetables	Private