Chapter 12
Heating

If growers want to produce a healthy crop, with good quality and high yield, they have to provide appropriate climatic conditions for crop production inside the greenhouse. Night temperatures and even day temperatures can sink below the biological optimum in a subtropical climate during winter. That means that greenhouses have to be heated for appropriate quality.

The advantage of heating is rapid growing and earliness, but heating is an economic problem because of high energy prices. Bailey (2006) reported: all types of heating systems must increase productivity and earliness sufficiently to justify the investment and running costs.

But heating has some more advantages that are often underestimated. The inside humidity and therefore the danger of disease infestation can be controlled much better by heating systems. The use of chemicals will be reduced, with positive consequences on the environment and health (Baille 2001).

The area of heated to unheated greenhouses can be a characteristic for the standard of greenhouse management in areas where the temperature can sink below the biological optimum for crop growth (Montero et al. 2009).

The choice of heating system has a significant influence on heat energy requirement (Tantau 1983; von Zabeltitz 1986a)

The greenhouses themselves have to be constructed according to the rules for energy conservation.

Heating systems have to be controlled very well. The whole crop can be destroyed if they break down in nights with frost, Fig. 12.1.

The following questions have to be answered for the design of appropriate heating systems for greenhouses:

1. Is heating necessary, based on crop requirement and climatic conditions?
2. How much heating energy is required for maintaining a design temperature on cold nights (heat requirement). How much heat energy or fuel will be required in the different months of the growing season (heat or fuel consumption)?
3. Which kind of energy sources are available?
4. What is the temperature level of the heating energy?

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Fig. 12.1 Crop totally destroyed by breakdown of the heating system for one night

5. Which kind of heating system is appropriate for the available energy?
6. What is the expected expenditure for the use of energy?
7. What are the consequences for the greenhouse structure, grower, and crop cultivation?

To answer the first question, one has to compare the climatic conditions of a region with the requirements for crop growth (see Chaps. 2 and 3).

12.1 Heat Requirement

The heat requirement of a greenhouse can be calculated by the equation

$$q = \mathrm{u} \times (A_\mathrm{c}/A_\mathrm{g}) \times (t_\mathrm{id} - t_\mathrm{od})\ (\mathrm{W/m^2}) \qquad (12.1)$$

$$u = u_\mathrm{t} - u_\mathrm{a}$$

A_c (m^2) = surface of greenhouse cover.
A_g (m^2) = greenhouse floor area.
t_id (°C) = design inside temperature depending on crop requirement.
t_od (°C) = design outside temperature.

The overall heat consumption coefficient u depends on the cladding material, the sealing of the greenhouse structure, the heating system, the irrigation system, the wind speed, the cloudiness and the rainfall. The u-value consists of two parts; the heat transfer coefficient for heat loss by heat transmission through the cladding material $u_{t,}$ and the heat transfer coefficient for heat loss by air exchange through leakage u_a. The value u_a is about 10–30 % of the *u*-value. The tightness of the greenhouse has a significant influence on the heat loss.

The main influencing factors on the overall heat transfer coefficient *u* are the heating system and the cladding material of the greenhouse, including thermal screens for energy-saving.

Table 12.1 shows the *u*-values depending on the cladding material, and Table 12.2 depending on the heating system. The choice of the heating system has an influence on the possible energy saving.

The *design outside temperature* t_{od} can be taken as the mean minimum temperature of the coldest month (Müller 1996). This is for

- Almeria (Spain) 8°C
- Antalya (Turkey) 6.1°C
- Catania (Sicily) 7.7°C
- Gafsa (Tunisia) 4°C

The value of A_c/A_g depends on the greenhouse structure and becomes:

Tunnel greenhouse, 8 m width, 3.5 m height	$A_c/A_g = 1.5$
Multi-span greenhouse, 8 m width, 4 m ridge height, 2.5 m gutter height	$A_c/A_g = 1.33$

Table 12.1 Overall heat transfer coefficient *u* (W/m^2 K) for different cladding materials. Mean values of various measurements and calculations (mean wind speed 4 m/s and mixed heating system) (von Zabeltitz 1982, 1986; Tantau 1983; ANSI/ ASAE standard 2003; Meyer 1981, 1982)

Material	*u* (W/m^2 K)
Single glass	6.0–8.8
Double glass	4.2–5.2
Double acryl sheet (16 mm)	4.2–5.0
Single PE film	6.0–8.0
Double PE film	4.0–6.0
Thermal screen below single glass or film	3.2–4.8

Table 12.2 Overall heat transfer coefficient *u* (W/m^2 K) for different heating systems and single-layer greenhouse cladding (Tantau 1983, 1998)

Heating system	*u* (W/m^2K)	Relative value (%)
Tube heating at eaves height	8.2	100
Tube heating below table	7.4	90
Tube heating at side wall	8.1	99
Tube heating on soil, bench heating	6.7	82
Free discharge air heater, low fan speed	9.9	121
Free discharge air heater, middle fan speed	7.1	87
Free discharge air heater, high speed	8.0	97
Air heater with perforated plastic tube	7.0	85
Convector heating	7.8	95

The *heat requirement* for assumed design inside temperatures of 12°and 16°C in a multi-span greenhouse for Almeria, covered by single PE film ($u = 7$ W/m^{2}K) is

$$q_{(12)} = 7 \times 1.33 \times (12 - 8) = 37.2\mathrm{W/m^2}$$

$$q_{(16)} = 75\ \mathrm{W/m^2}$$

The corresponding heat requirements for Antalya, Catania, and Gafsa are:

Antalya:	$q_{(12)} = 55$	$q_{(16)} = 72$	W/m^2
Catania	$q_{(12)} = 4$	$q_{(16)} = 77$	W/m^2
Gafsa	$q_{(12)} = 75$	$q_{(16)} = 111$	W/m^2

A greenhouse span of 8 m width and 60 m length requires a heater with the following heat capacities for the design temperatures:

	Gafsa	Almeria	Antalya	Catania
12°C	36 kW	18 kW	26 kW	19 kW
16°C	53 kW	36 kW	35 kW	37 kW

12.2 Fuel Consumption

The yearly fuel consumption should be roughly calculated to get an impression about the economic situation if greenhouses are heated.

Normally, the calculation of heat consumption is based on hourly temperatures of all days when heating is necessary. Those data very often are not known.

The mean maximum t_{mmax} and mean minimum t_{mmin} temperatures can be obtained from different stations (Müller 1996). Hallaire (1950) developed a method for calculating the hourly temperatures and the mean day and mean night temperatures from the daily mean maximum and minimum temperatures (Hallaire 1950).

The mean hourly temperature of the day is

$$t_{\mathrm{h}} = t_{\mathrm{mind}} + f_{\mathrm{d}} \times A \tag{12.2}$$

The mean night temperature is

$$t_{\mathrm{mn}} = t_{\mathrm{mind}} + A \frac{\Sigma f_n}{24 - d_{\mathrm{l}}} \tag{12.3}$$

The mean day temperature is

$$tm_{\mathrm{d}} = t_{\mathrm{mind}} + A \frac{\Sigma f_{\mathrm{d}}}{d_{\mathrm{l}}} \tag{12.4}$$

Table 12.3 Coefficients for (12.2)–(12.4) (Hallaire 1950)

d_l	Σf_n	$\Sigma f_n/(24\text{-}d_l)$	Σf_d	$\Sigma f_d/d_l$
7	8.21	0.48	4.25	0.61
9	6.0	0.4	5.67	0.63
11	4.5	0.375	6.99	0.635
13	3.45	0.31	8.10	0.623
15	2.51	0.28	9.29	0.62
17	1.58	0.23	10.96	0.644

t_h = hourly temperature

$A = t_{maxd}–t_{mind}$ = difference of mean minimum and mean maximum day temperature

f_d and f_n = coefficients depending on day length d_l (Table 12.3).

Assuming that heating in mild subtropical and arid climates is necessary mainly during night hours, the mean fuel consumption for the winter months and summarised for the year can be estimated by the following equation, using the Hallaire method to calculate the mean night hours.

$$Q_{(\text{month})} = u \times (A_c/A_g) \times (t_{id} - t_{st} - t_{mn}) \times n_n \times n_d (\text{Wh/m}^2\text{month}) \qquad (12.5)$$

u (W/m^2 K) = overall heat consumption coefficient (Table12.1)

A_c/A_g = surface of greenhouse cover/greenhouse floor area

t_{id} (°C) = design inside temperature

t_{mn} (°C) = mean night temperature (12.3)

t_{st} (°C) = mean temperature increase at night by heat storage in the soil from daytime

n_n (–) = number of night hours

n_d = number of days per heated month.

The temperature increase by heat storage from day to night t_{st} can be assumed to be 1–2°C.

It can be shown that the calculation of mean fuel consumption with mean night temperature gives nearly the same value as the calculation just with night hours, which is more complicated.

To calculate the fuel consumption (l oil equivalent), the figures of (12.5) have to be divided by the heat capacity of the oil (about 10 kWh/l oil) and by the efficiency of the heater system (assumed to be 80%).

Examples.

Single film cover with $u = 7$ W/(m^2 K), $A_c/A_g = 1.33$; $t_{id} = 16$°C; $t_{st} = 2$°C.

The details for the calculation are shown in Annex 2.

The estimation of heat consumption by (12.5) gives the following results, which are roughly calculated values, because the heat consumption depends on various influencing factors as climate conditions inside and outside as well as greenhouse structure, surface, heating system, and soil storage capacity.

The yearly heat consumption Q_{year} as sum of Q_{month} of heated months for some Mediterranean locations results in

Almeria, Spain (36°50′N)	$Q_y = 35.6$ (kWh/m^2 year)
Antalya, Turkey (36°53′N)	$Q_y = 56.1$ (kWh/m^2 year)
Catania, Sicily, (37°30′N)	$Q_y = 46.4$ (kWh/m^2 year)

The fuel consumption (l oil equivalent/m^2 year) becomes $Q_{\text{oil}} = \text{Q}_{\text{year}}/10 \times 0.8)$

Almeria	$Q_{\text{oil}} = 4.4$ (l/m^2 year)
Antalya	$Q_{\text{oil}} = 7$ (l/m^2 year)
Catania	$Q_{\text{oil}} = 5.8$ (l/m^2 year)

Although all locations are on nearly the same latitude, the fuel consumption is very different.

The calculated values correspond very well with those calculated by a simulation program, HORTEX, developed by Rath (1992).

12.3 Heating Systems

One has to distinguish between the generation of the heat energy and the distribution of heat energy inside the greenhouse.

The following energy sources for generation of heat energy can be applied in horticulture:

- Combustion of fossil fuels, oil, gas, coal
- Combustion of biomass, wood, straw
- Combustion of biomass from waste of fruits such as stones and husks
- Geothermal energy
- Waste heat from industry
- Solar energy

Heat generation by combustion can be done in a:

- central warm water boiler
- decentralised warm water boiler
- directly fired air heater

The combustion of fuels or biomass results in high temperature energy for the heating systems. The geothermal energy, waste heat and solar energy are normally low-temperature energies below 60°C with special demands to the heating system.

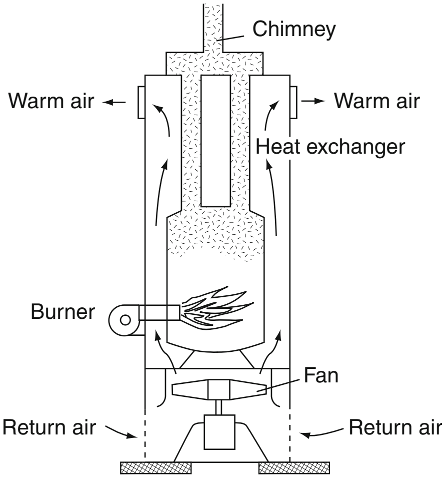
There are still very simple, self-made heaters used in some areas (Fig. 12.2). They may keep the greenhouse frost-free, but they are not sufficient to produce a healthy crop and good quality.

Fig. 12.2 Simple but not sufficient heating systems. These heating systems are still used in several countries

Figure 12.3 shows the cross-section of a directly fired air heater. The combustion gas flows through a heat exchanger and leaves the heater through the chimney. The greenhouse air is blown through the heat exchanger by a fan, where it is warmed up.

Coming out of the heater, the warm air is distributed through perforated plastic film tubes, which lie between the rows of the crop.

Fig. 12.3 Directly fired air heater



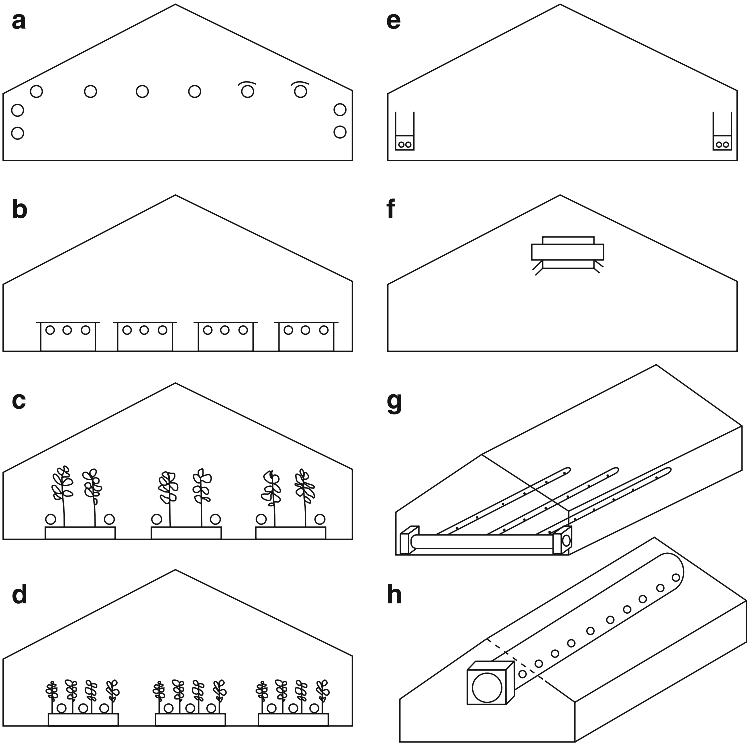


Fig. 12.4 Heating systems for greenhouses

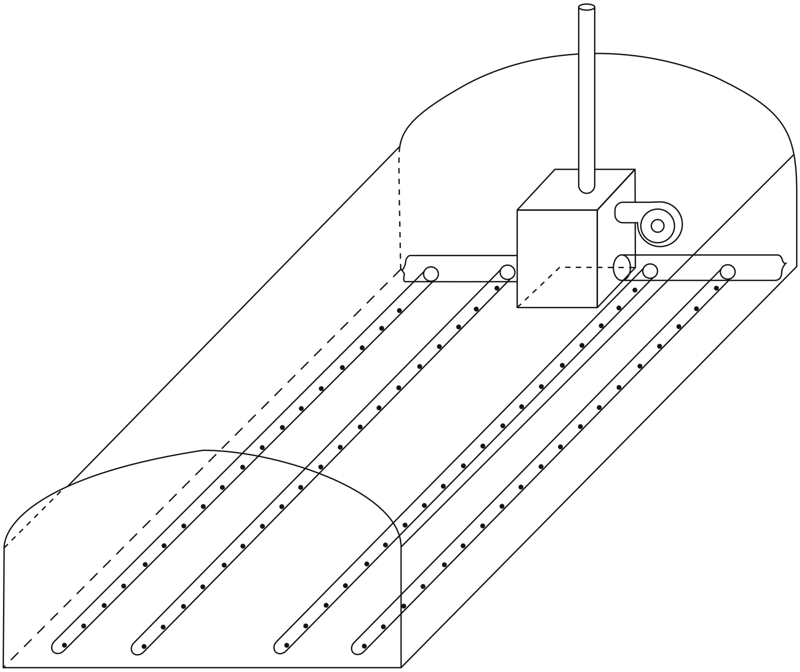


Fig. 12.5 Directly fired air heater and air distribution by perforated plastic tubes

The heat *distribution inside the greenhouse* is either by water- or air-heating systems.

If the heat energy comes from a warm-water boiler or from geothermal sources, it can be distributed inside the greenhouse by air heating systems or by warm-water heating systems.

Figure 12.4 shows various possible heating systems for greenhouses. The overall heat transfer coefficients differ between heating systems (Table 12.2).

Directly fired air heaters with air distribution through perforated plastic tubes are used very often in subtropical climates (Fig. 12.5). The plastic tubes lie between the rows of the crop.

The diameter of the tubes is about 30–60 cm. The discharge holes are located on opposite sites of the tube, about 30–45° above the horizontal if the tubes are positioned on the ground, and about 30–45° below the horizontal if the tube is hanging above the crop. The holes are typically spaced 0.3–1.0 m apart along the axis of the tube, depending on tube diameter and length. The total area of the holes should be in between 1.5 and 2 times the cross-sectional area of the tube.

One tube is generally sufficient for about a 9 m greenhouse width or less. More tubes are necessary for wider greenhouses (ANSI/ASAE Standard 2003).

Fig. 12.6 Well-installed plastic tubes

Fig. 12.7 The plastic tubes are installed too high above ground and plant level

This kind of air-heating system has advantages:

- The air will be distributed evenly across the greenhouse, and the temperature distribution can also be even.
- The air humidity between the plants will be reduced by forced air movement.

The consequence is a reduced disease infestation and necessity of fewer chemicals.

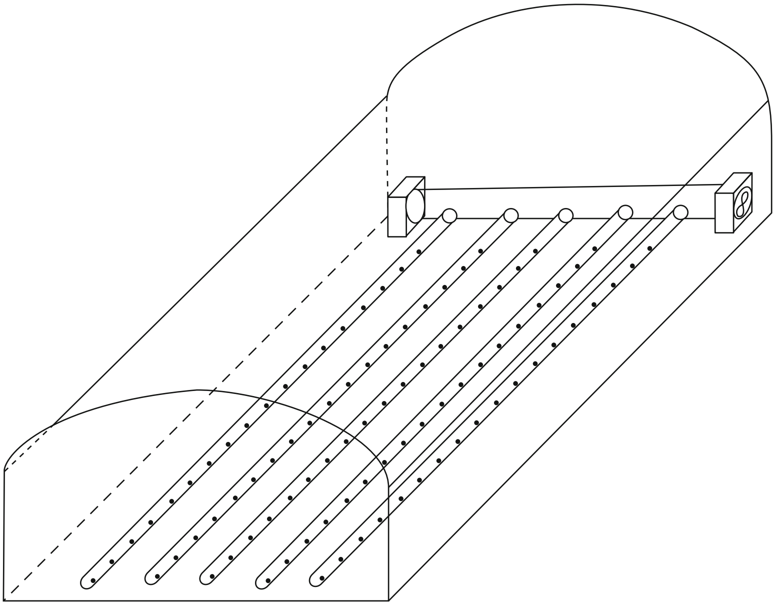


Fig. 12.8 Air heating by warm-water to air heat exchanger

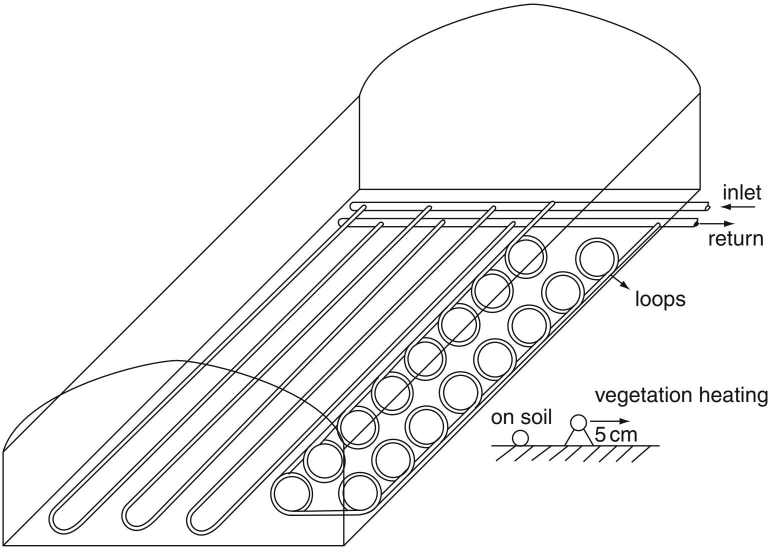


Fig. 12.9 Warm-water heating system by plastic tubes

It is very important that the perforated plastic tubes are installed as low as possible, next to the plant area, and that the tubes lie between the plant rows if possible, even if this is uncomfortable for the workers.

Fig. 12.10 Corrugated plastic tubes for greenhouse heating

If the tubes are installed too high above the plant area, the warm air rises up and does not heat the plant area. This is a waste of heat energy, and infestation by diseases can occur more easily (Figs. 12.6 and 12.7).

Figure 12.8 shows another air heating system. A water-to-air heat exchanger with a fan transfers the heat energy from the heater to the air, which will be distributed by perforated plastic tubes in the greenhouse.

Figures 12.9 and 12.10 shows a warm-water heating system. Flexible corrugated plastic tubes with a diameter of 20–25 mm lie on the ground and distribute the heat energy into the plant area. The plastic tubes are installed longitudinally or in form of loops. The installation and the number of tubes depend on the inlet temperature of the warm water. Tubes manufactured from polypropylene are suitable for temperatures up to 60°C. The tubes should lie directly on the ground if soil and air heating is wanted at the same time. The heat transfer only to air is better if there is a space between tube and soil of about 5 cm.

The heat transfer of tubes that lie on the ground floor is 0.67–1.6 W/(mK) per 1 m length of tube. The heat transfer is a little bit higher if there is free convection around the tube, which means if the whole tube is surrounded by air.

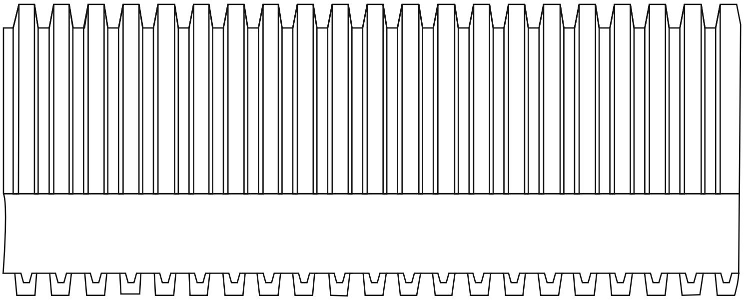


Fig. 12.11 Corrugated plastic tube for warm-water heating

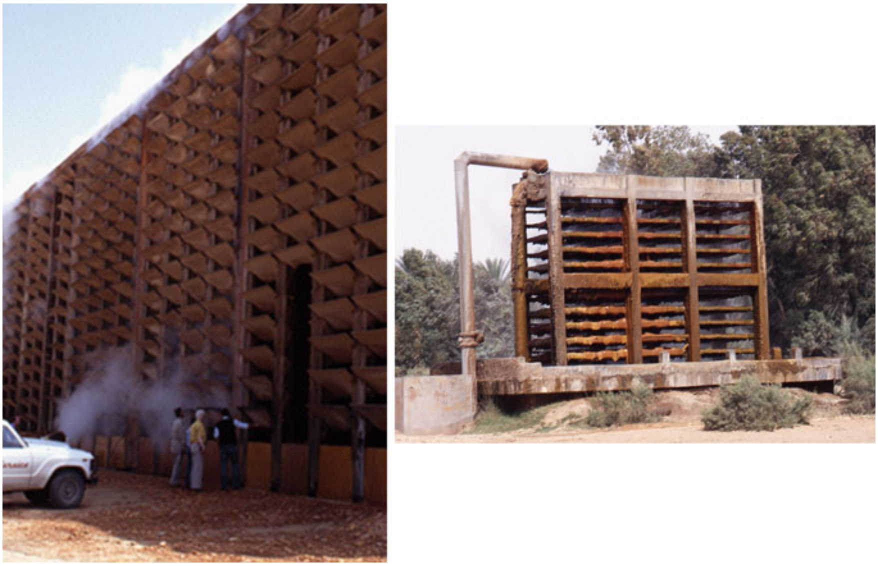


Fig. 12.12 Cooling towers to cool geothermal water for irrigation in Tunisia

Figure 12.11 shows the cross-section of a corrugated PP tube that has an increased surface for better heat transfer and is very flexible.

12.4 Geothermal Energy for Greenhouse Heating

The use of geothermal energy for greenhouse heating is a very good solution, if the geothermal water is available not too deep in the subsoil, if the water temperature is suitable, and if the water is not too corrosive. This is the case for example in Tunisia and in Turkey.

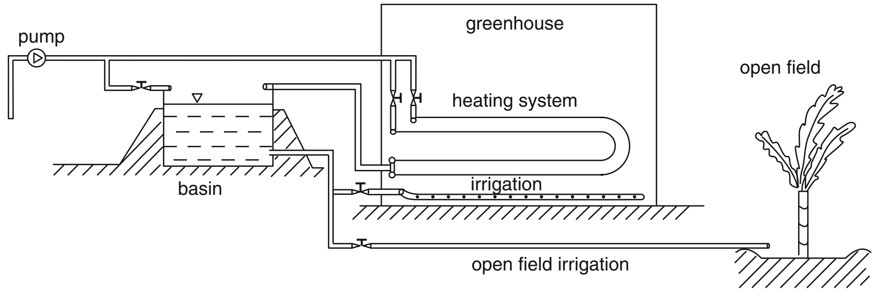


Fig. 12.13 Heating and irrigation with geothermal water in Tunisia

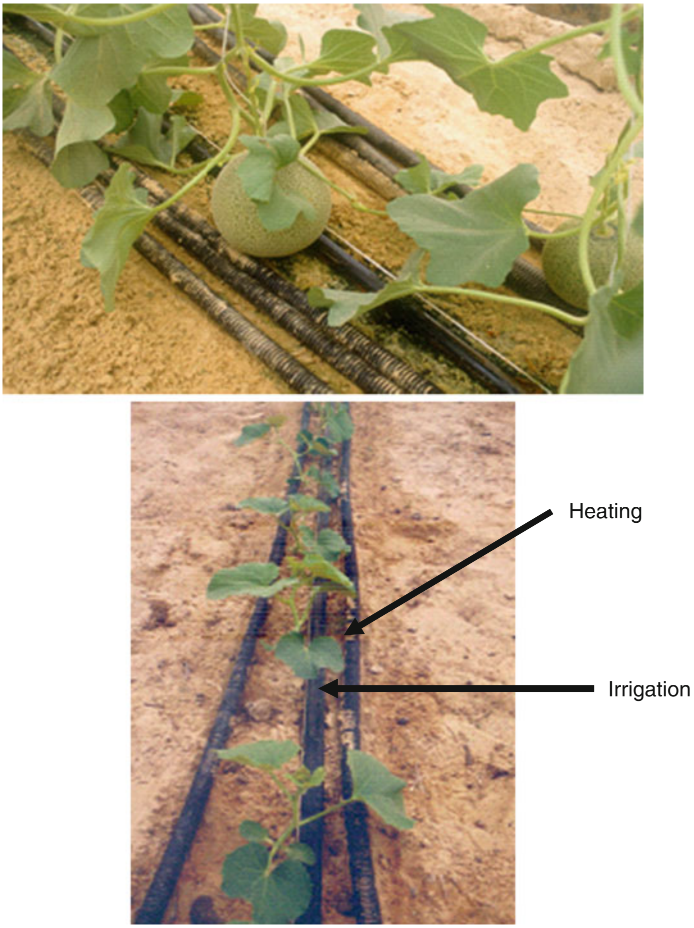


Fig. 12.14 Corrugated PP tubes for heating the greenhouse by geothermal water in Tunisia

Fig. 12.15 Corrugated PP tubes outside the greenhouse for cooling the geothermal water, when no heating is necessary, Tunisia

Geothermal water is used for irrigation in Tunisia, and has therefore to be cooled down. For this reason, huge cooling towers have been built for cooling the irrigation water at the start (Fig. 12.12).

Then growers started to use the geothermal water for irrigation and heating at the same time. Figure 12.13 shows a principle of such a system (von Elsner 1990). The geothermal water comes from the well and flows either into a basin which acts as a cooling pond, or through a heating system, if heating is necessary. After it has been cooled down to about 20°C, it will be used for irrigation in the greenhouse or open field. The salt content is 2–3 g/l. Corrugated PP tubes, 25 mm diameter, are used for heating, because the water is corrosive (Fig. 12.14). Cooling tubes outside the greenhouse are an alternative for cooling the irrigation water when no heating is necessary (Fig. 12.15).

The precondition for the irrigation system is a low outlet temperature of the water. This causes problems of temperature distribution in the greenhouse, if the inlet temperature is for example 60°C and the outlet has to be 20°C. The flow rate has to be very low, and the heat output of the tubes is very different. One possibility for minimising the problem is the installation of different numbers of tubes in the forward and return flow, for example ten forward and 14 return.

Another problem is the control of the heating system. In many cases, no electricity is available, and automatic control systems are too expensive. To adapt the heating system to outside and inside temperature, the heating system can be divided into two independent circles of 1/3 and 2/3 of the heat capacity. The adaptation can be made by switching the valves according to the heat capacity required.

To improve the control, simple thermostat valves with temperature sensors are used, when no electricity is available (Fig 12.16). These thermostat valves have to

Fig. 12.16 Simple control system by thermostat

Fig. 12.17 Heat exchanger for geothermal water in Turkey

be installed at the end of the return flow to avoid emptying of the heating system at times of standstill. This is a good, cheap and simple solution.

If the geothermal water is very corrosive as in Turkey, heat exchangers have to be installed, Fig. 12.17.

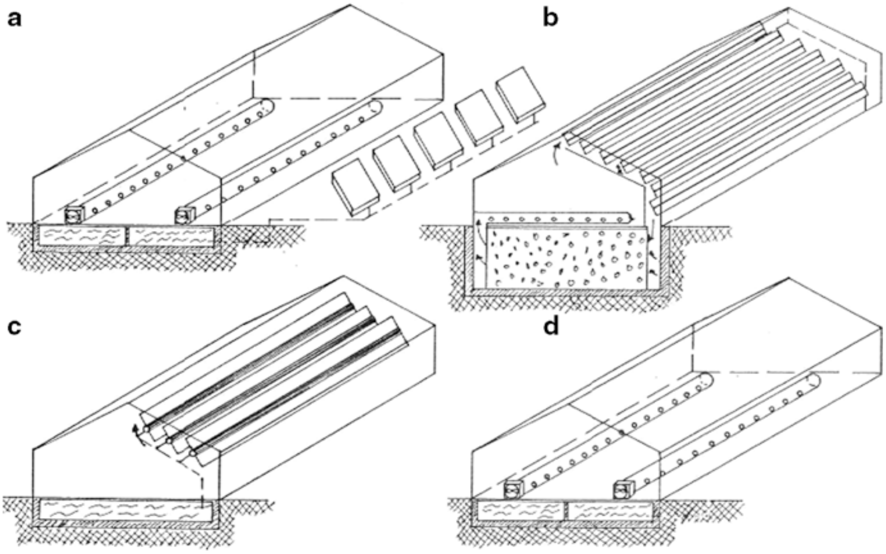


Fig. 12.18 Principles of solar heating systems for greenhouses. **a** Separate collectors near the greenhouse; water storage and heat distribution by water-to-air heat exchanger and perforated plastic tubes. **b** Solar air collector integrated into greenhouse structure; rock bed storage and warm air distribution by perforated plastic tubes. **c** Water collector integrated into the greenhouse structure. **d** Greenhouse as collector. Heat exchanger for energy collection and distribution

12.5 Solar Heating

Solar energy covers a part of the heating energy that is needed during the daytime. To use solar energy for heating during the night, two problems have to be solved (von Zabeltitz 1987, 1988a):

- The conversion of global radiation into thermal energy,
- The storage of the thermal energy for heating purposes during night time.

The *conversion of global energy* into thermal energy is based on the following principles (Fig 12.18):

1. Separate solar collectors (air or water collectors are placed outside the greenhouse and serve to heat the thermal storage.
2. Solar collectors are an integral part of the greenhouse, loading fluid or solid/air storages.
3. The greenhouse itself is a collector; a part of the global radiation that penetrates the greenhouse is being converted into thermal energy.

Normally short-term storage from day to night is used for the *storage of heat energy*. Long-term storage from summer to winter needs huge storage volumes. Storage materials are gravel, water solar ponds, soil and phase change material.

Gravel or rock storages act as store and heat exchanger simultaneously. With other storage materials, one needs extra heat exchangers.

With regard to heat storage, the following technical details have to be determined:

- The storage medium.
- The storage capacity. The maximum of storable energy in kWh/m^3 or kWh/kg.
- The loading and unloading energy per time unit.
- The efficiency. The relationship between useable energy out of the storage and the sum of input energy, including the energy that is necessary for loading and unloading (electricity).
- The storage position, i.e., where the storage is located.
- The storage configuration.

In order to design a solar heating system, the following questions must be answered:

1. What kind of solar system should be applied?
2. What is the amount of energy that will be converted from solar energy into thermal energy?
3. How much solar energy is available each day during the heating season, including hourly distribution?
4. How much energy is required to heat the greenhouse?
5. How much of the heat energy consumption can be covered by the thermal energy produced from solar energy?
6. What difference in temperature between inside and outside can be achieved by solar heating?
7. Is solar heating economically feasible?

The actual outside temperature as well as the global radiation have to be considered for the calculation of heat consumption. The effective hourly heat consumption q_{h} can be estimated by the following equation (Damrath 1982, 1983; von Zabeltitz 1988a).

$$q_{\mathrm{h}} = (A_{\mathrm{c}}/A_{\mathrm{g}}) \times u \times (t_{\mathrm{i}} - t_{\mathrm{oeff}}) - q_{\mathrm{o}} \times \tau \times \eta\, \mathrm{W/m_2}$$

In this equation:

$A_{\mathrm{c}}/A_{\mathrm{g}}$ (–) = relationship of greenhouse cover to floor area.

t_{oeff} (°C) = actual outside temperature.

t_{i} (°C) = inside temperature.

τ (–) = transmittance of greenhouse. $\tau = 0.6$–0.7 for single plastic film cover.

η (–) = conversion factor of global radiation energy to thermal energy inside the greenhouse. $\eta = 0.5$–0.7.

q_{o} (W/m^2) = outside global radiation.

u (W/m^2 K) = overall heat transfer coefficient.

The heat requirement has to be calculated for every hour of the day with corresponding values of temperature and global radiation. The daily sum of the hourly values results in the daily heat requirement. If the hourly value of q_{h} becomes

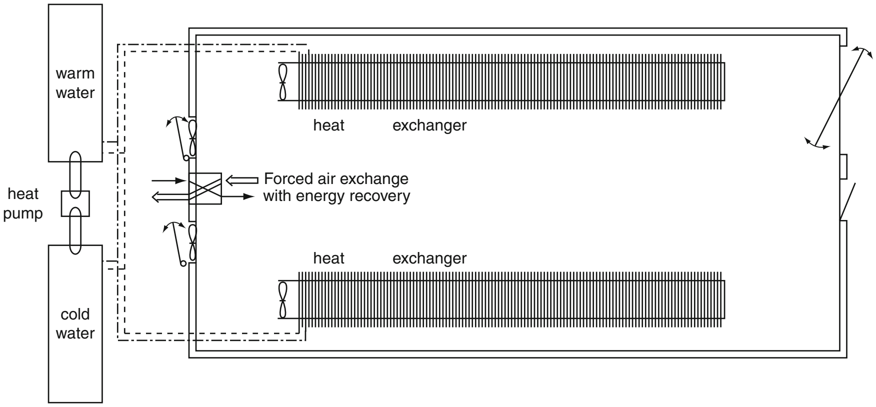


Fig. 12.19 Principle of solar greenhouse, Hannover, Germany

negative at daytime, the sum of these values results in the excess heat energy that can be theoretically stored out of the greenhouse for heating at night (Fig. 12.20).

Many systems using solar energy for greenhouse heating have been developed, both highly sophisticated and very simple ones (von Zabeltitz 1984, 1985, 1987, 1989). Some examples will be demonstrated, although some of them were not successful in practice. Maybe some new ideas can be created from this research and development.

Detailed experiments and calculations were carried out with the system "greenhouse as collector" in the Institute for Horticultural Engineering Hannover (Damrath 1982, 1983; von Zabeltitz 1984, 1986).

Figure 12.19 shows the principle of the solar greenhouse. Cold water of 2–6°C is pumped from cold water storage through an air–water heat exchanger in the greenhouse during the daytime. The greenhouse air that is warmed up by solar energy is thus cooled down, and energy is transferred to the water in the heat exchanger. The cold water storage will be heated up to 18–24°C in the daytime. A heat pump is installed between cold- and warm-water storage that increases the water temperature in the warm-water storage to a level suitable for heating at night. The greenhouse will be heated at night by the same heat exchanger. The heat pump can operate for 24 h independently from the climate control for heating and cooling, and therefore has relatively low power. The greenhouse itself remains closed, but has forced ventilation for excessively warm days, and an additional heat exchanger for fresh air exchange with heat recovery (Rüther 1989).

A theoretical simulation model has been developed with the results of experimental data for the design of solar systems (Damrath 1982).

The heat exchanger in the greenhouse is a water–air exchanger with connected perforated plastic film tubes for air distribution.

Figure 12.20 shows the calculated mean daily heat requirement and the energy that can be stored in the daytime depending on the season in Germany, Cyprus, and

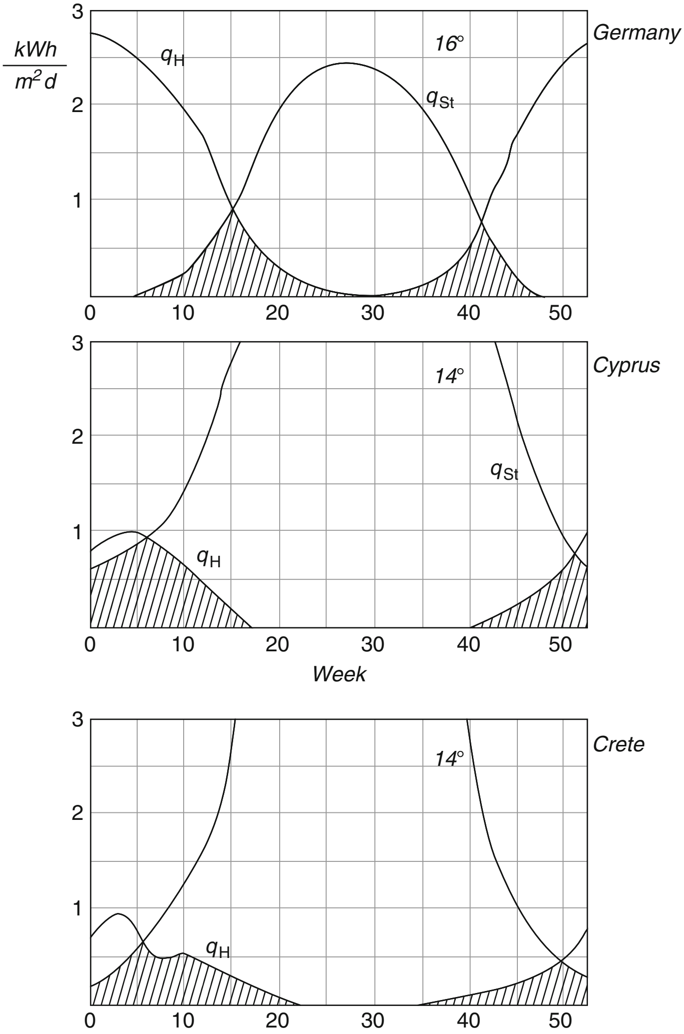


Fig. 12.20 Mean daily heat requirement q_H and storable energy q_{St} from the solar greenhouse

Crete. The dashed fields below the curves q_H and q_{St} show the amount of solar energy that can be used for heating with day-to-night storage. The contribution of solar energy amounts to 15–25% of the necessary heat energy in Germany, if the greenhouse is heated throughout the year to 16°C. Nearly 100% can be substituted in Mediterranean areas with 14°C inside temperature. The amounts in Fig. 12.20 are the maximum possible values with unlimited storage capacity. The design and layout of the heat exchanger, storage and heat pump have considerable influence on the gain of energy, and the components of the solar system influence each other. For short-term storage from day to night, a storage volume of 0.2 m^3/m^2 greenhouse

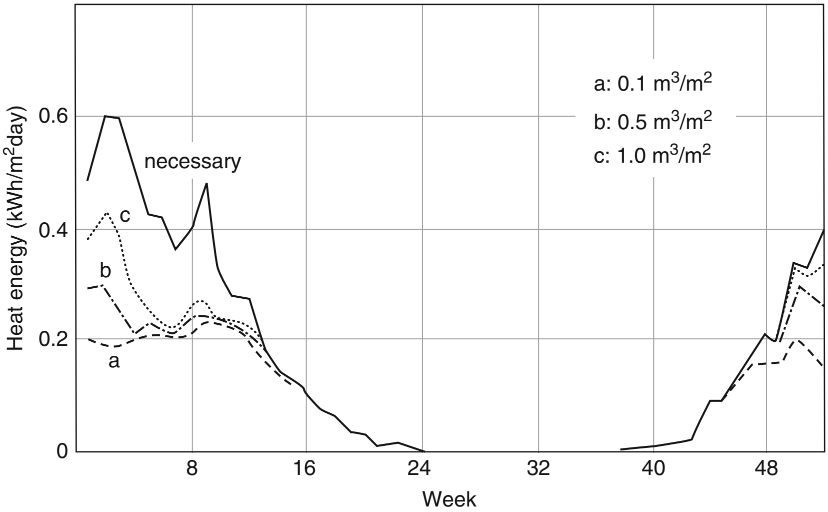


Fig. 12.21 Calculated heat energy and storable energy with different storage volumes for climate of Crete

floor area is a reasonable value. For long-term storage from summer to winter, 12–18 m^3/m^2 would be necessary. An energy balance has shown that significant amounts of electric energy are required for the heat pump and fans. Thus, the use of such a system may be questionable for temperate climates. The conditions can be better in subtropical climates.

Figure 12.21 shows a calculation for a greenhouse on the Island of Crete with the model of Damrath (1982) for an inside temperature of 12°C but without the use of a heat pump (Bredenbeck 1982). Heating at night took place with water temperatures that could be stored in the daytime. The curves a, b, c demonstrate the storable solar heat energy that could be stored out of the greenhouse with different storage volumes in comparison to the necessary heat energy for 12°C inside temperature. With 0.5 m^3/m^2 storage volume, 67% of the yearly heat energy can be covered (von Zabeltitz 1986).

A simplified "greenhouse as collector" system was installed in a commercial greenhouse under German climate conditions (Bredenbeck 1986, 1992). It was a rock bed storage below the greenhouse, Fig 12.22. During the daytime, the hot air was collected above a shading system and thermal screen, and at night was delivered below the thermal screen.

The calculated percentages of heat energy gained by solar energy and stored in the rock bed storage are given in Table 12.4 for climate conditions in Hannover and Munich, Germany (Bredenbeck 1992).

More solar heating systems, developed in several countries, are described by von Zabeltitz (1987), but only a few of them came into practical use by growers because of economic problems.

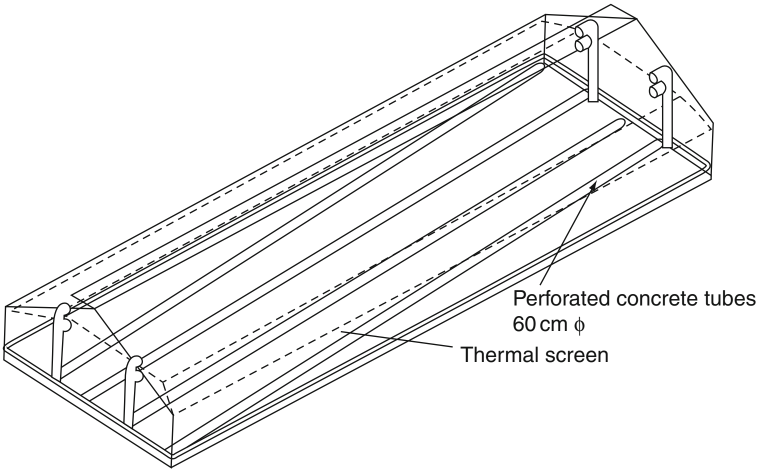


Fig. 12.22 Greenhouse as collector design in a commercial greenhouse

Table 12.4 Percentage of heat energy gained by solar energy in a greenhouse with rock bed storage thickness and air fluxes, inside temperature 18°C (Bredenbeck 1992)

Storage thickness (m)	Air flux (m^3/m^2 h)	Solar heat energy Hannover (%)	Solar heat energy Munich (%)
0.6	13	25	32
0.6	26	28	35
0.6	52	28	37
0.9	13	25	33
0.9	26	30	36
0.9	52	33	37

The *passive system*, using transparent, water-filled PE tubes, was installed by growers in practice. Figure 12.23 shows the principle of the system. Transparent PE plastic-film tubes are laid between the rows and filled with water. The tubes serve as collector, storage and heating system at the same time.

The layout is about 60–100 l water per m^2 floor area. The diameter is 30–35 cm. One can raise the temperature at night by 3–5°with these tubes. This is not really a heating system, but a good measure for improving the conditions in unheated greenhouses and for frost protection. The efficiency of transparent tubes is much better than that of black tubes (Figs. 12.23 and 12.24).

The *passive solar heating system* inside the greenhouse has a positive influence on:

- Air temperature at night
- Maximum air temperature during daytime
- Plant temperature
- Soil temperature

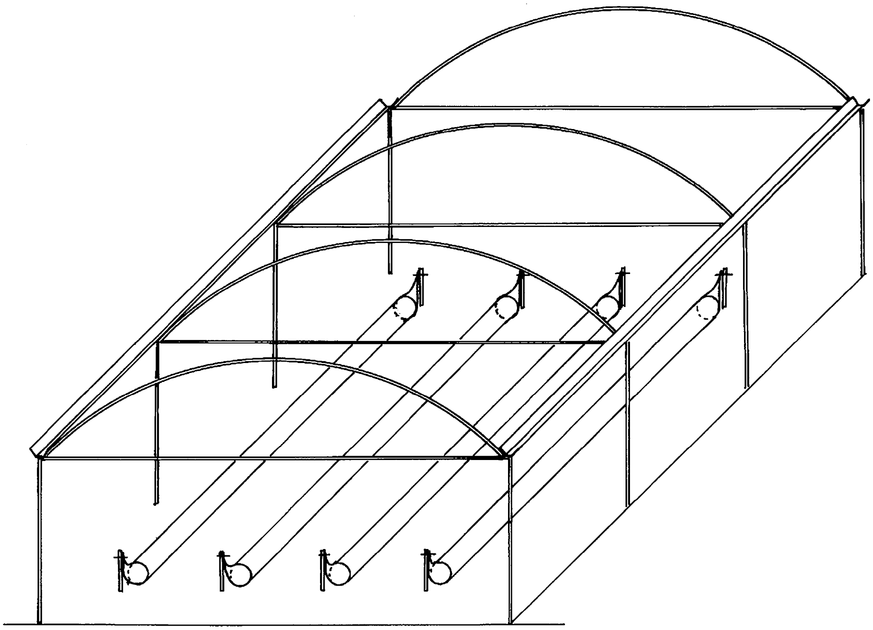


Fig 12.23 Principle of passive solar heating system using water-filled transparent plastic tubes

- Air humidity

The efficiency of the tubes depends on:

- The number of tubes or amount of water
- The tightness of the greenhouse structure
- The cladding material
- The height of the crop
- The outside weather conditions.

The greenhouse should have no leakage, and the cladding material should have high transmission for global radiation and low transmission for long-wave radiation.

Measurements and calculations have been carried out in Germany (Thomas 1994). Figure 12.25 shows the possible temperature difference inside to outside depending on the outside daily global radiation for a plastic-film greenhouse with double-inflated roof. The curves are degressive because of the influence of shading by plants and the ventilation necessary with increasing solar radiation. The inside temperature can be increased 3–4°C by the solar system, and 5°C by the solar system and additional thermal screen. The outside wind speed has a significant influence on the temperature difference.

Fig. 12.24 Some examples of solar sleeves in different greenhouses

Figure 12.26 shows the temperature difference depending on outside global radiation for different covering ratios of the solar system. If the water-filled plastic tubes cover 40% of the greenhouse floor area, the inside temperature can be increased by 4°C above outside temperature with a global radiation of 6 kWh/ m^2 K on the day before and a wind speed of 2.5 m/s (Fig. 12.27).

A joint experiment about the use of water-filled PE tubes was organised for the growing seasons 1986/87 and 1987/88 in 11 countries (von Zabeltitz 1989). Two typical examples may be mentioned from Greece and Tunisia:

Greece (M. Grafiadellis, G. Spanomitsios, K. Mattes).

Water-filled PE tubes, 32 cm diameter, on black PE film.

Minimum temperature increase from 1.6°C in unheated to 4.5°C in heated greenhouse.

Increase of plant temperature by 2–4°C

Reduction of relative humidity by 6–12%.

Main yield of tomato in g/plant in 1987 season:

	Unheated	Heated by water-filled tubes
Early yield	1,292	1,793
Total yield	6,313	7,793

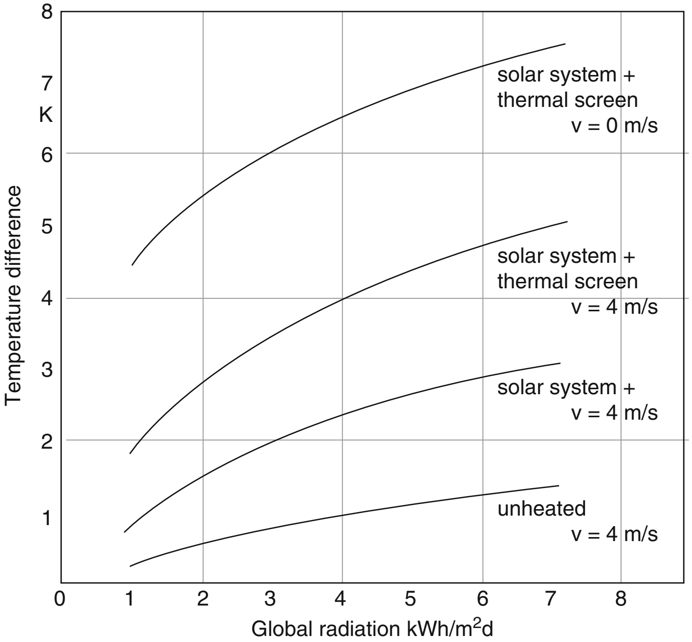


Fig. 12.25 Possible temperature difference with the passive solar heating system (Thomas 1994)

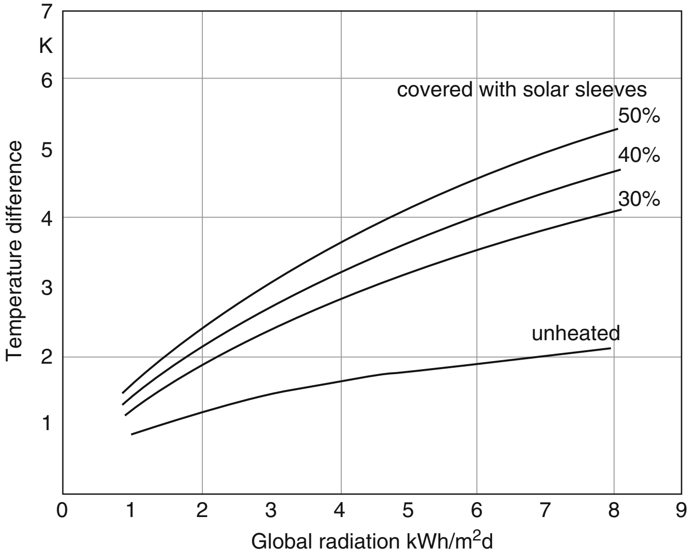


Fig. 12.26 Possible temperature difference for different covering ratios of the solar heating system depending on global radiation. Wind speed 2.5 m/s (Thomas 1994)

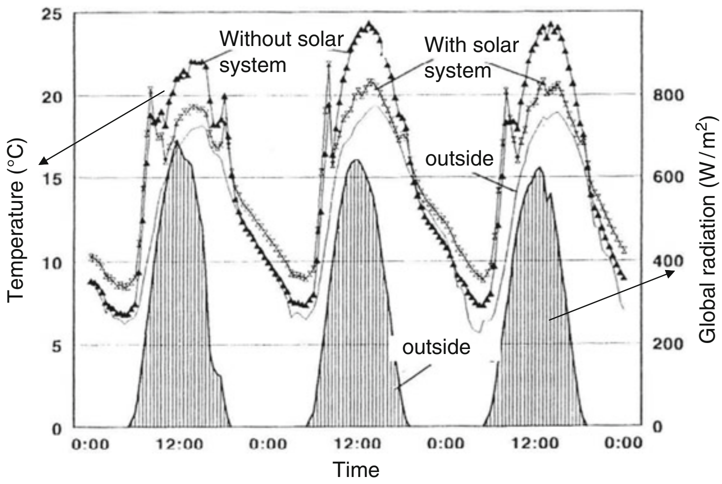


Fig. 12.27 Climate conditions in a greenhouse with a passive solar heating system for 3 days in April 1991. The solar system increases the inside temperature at night and decreases the temperature in the day time (Thomas 1994)

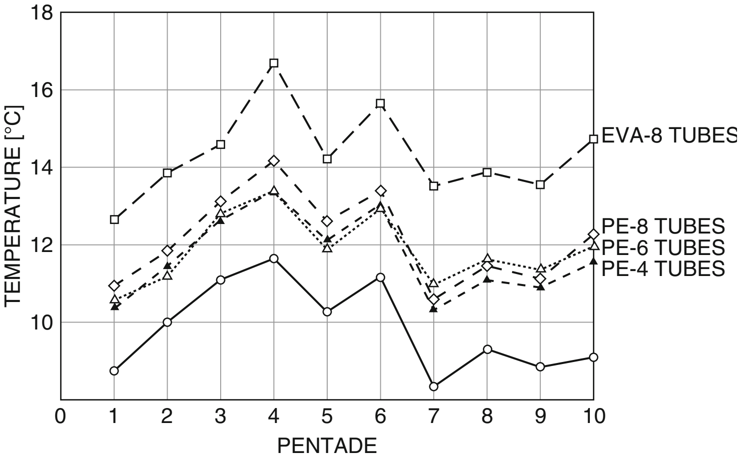


Fig. 12.28 Influence of the number of tubes and cladding material in a 9 m round-arched tunnel-type greenhouse on mean night temperatures in comparison to the unheated control greenhouse (growing season 1987/88). The minimum night temperature with water-filled tubes was about 2°C higher under EVA film than under PE film with eight tubes each. The relative humidity was about 85% under EVA, and thereby about 11–12% lower than under unheated PE film

Tunisia (A. Mougou and H. Verlodt)

One round-arched tunnel-type greenhouse covered by EVA film.

Two round-arched tunnel-type greenhouses covered by PE film.

Water-filled PE tubes, 32 cm diameter (Figs. 12.28–12.29).

Abou-Hadid et al. (1995) compared the effects of a warm-air heater and air distribution through perforated PE tubes with water-filled PE tubes, 40 cm

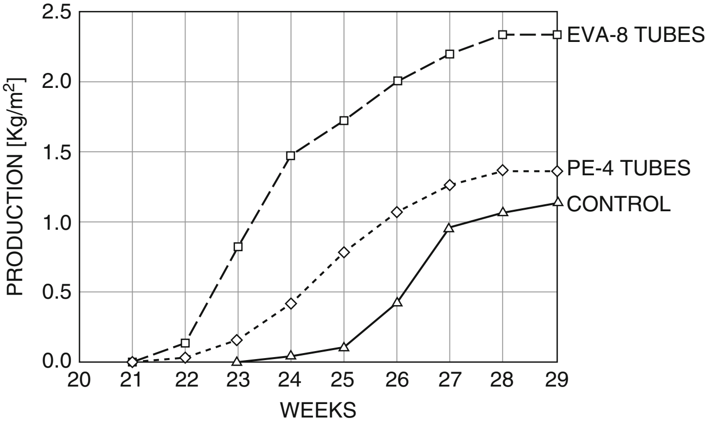


Fig. 12.29 Total yield of Gafsa muskmelons was significantly higher under EVA film than under unheated control

diameter, 80 l/m^2 coverage rate, and an unheated control greenhouse for the vegetable production in Egypt.

Results for Sweet Pepper.

The air heater was able to maintain the 15°C set point temperature, while the water-filled PE tube heating increased the temperature by 2.5–4.4°C above outside temperature. The highest temperature increase could be observed in the early season, when the pepper plants did not shade the tubes and when outside temperature dropped below 4–5°C. The total yield of sweet pepper with the different heating systems from January to May was:

Warm-water heater	10.6–10.94 kg/m^2
Water-filled PE tubes	5.3–6.3 kg/m^2
Unheated control	3.5–4.4 kg/m^2

The total yield with water-filled PE tubes was significantly higher than in the unheated control.

Results with French beans in double-layer plastic-film greenhouses.

The highest total yield and lowest level of malformed fruits could be obtained with warm-air heating, followed by water-filled PE tubes and unheated control.

The water-filled PE tubes can be an inexpensive method for improving the climate conditions during the early few months after planting, when cultivation starts with outside temperature below 5°C.

Cats and birds like the warm-water-filled plastic tubes for resting on. This brings a danger of producing leakage and as a result draining off the water. The danger is reduced when insect screens are installed.