Evaluation of a soil heat exchanger-storage system for a greenhouse. Part II: Energy saving aspects

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Bernier, H., Raghavan, G.S.V. and Paris, J. 1991. **Evaluation of a soil heat exchanger-storage system for a greenhouse. Part II: Energy saving aspects.** Can. Agric. Eng. **33**:099-105. A soil heat exchanger-storage system consisting of 26 non-perforated, corrugated plastic drainage pipes, 102 mm in diameter, was installed in a commercial-type greenhouse. Two rows of 13 pipes, 12 m long, were buried at 450 mm and 750 mm depths, respectively. The pipes run parallel to the horizontal axis of the greenhouse, and are spaced 450 mm apart. Ambient air from the greenhouse is circulated through the pipes at a flowrate of 0.91 m^3/s.The system performance is more influenced by greenhouse air temperature than by incident solar radiation. Results indicate that solar energy contributed to 58 % of the heating requirements from February to June and from September to December 1986. This contribution represents approximately a 33 % energy saving. The payback period for the system is from one to five years, depending on costs and crop productivity improvements.

Un système combiné d'échange et de stockage de chaleur constitué de 26 tuyaux de plastique ondulé on perforé, de 102 mm de diamètre, a été installé dans une serre de type commercial. Deux rangées de 13 tuyaux de 12 m de long ont été enfouies à des profondeurs de 450 mm et 750 mm, respectivement. Les tuyaux sont installés suivant l'axe longitudinal de la serre et sont espacés de 450 mm. L'air recueilli au faîte de la serre est poussé dans les tuyaux par un ventilateur centrifuge ayant un débit de 0.91 m^3/s. La performance du système semble plus influencée par la température ambiante de l'air dans la serre que par le rayonnement solaire. Les résultats montrent que la contribution de l'énergie solaire au chauffage de la serre a été de 58% pour la période couvrant de février à juin et de septembre à décembre 1986. Cette contribution représente une économie d'énergie d'environ 33%. La période de retour sur l'investissement associée au système est de un à cinq ans, suivant le scénario économique considéré.

INTRODUCTION

Typical commercial greenhouses have a low thermal mass and therefore cannot store the available excess heat captured by a greenhouse during the day. Heat storage can be achieved by increasing the thermal mass. Soil beneath a greenhouse could be used effectively for increasing the greenhouse thermal mass. By improving heat transfer to the greenhouse soil, excess heat can be stored and utilized when required. The performance of a wet soil heat exchanger-storage system for a commercial type greenhouse located in a cold climatic region, has been evaluated in a study (Bernier 1987). The results of the study are covered in two parts. Part I (Bernier et al. 1991) describes the performance of a soil heat exchanger-storage system and this part (Part II) describes the energy saving aspect for a commercial type greenhouse.

OBJECTIVES

The objectives of the study were:

1) To establish the contribution of solar energy to the total heat requirement of a greenhouse equipped with a wet soil heat exchanger-storage system.

2) To estimate the system payback period for different scenarios.

THEORETICAL CONSIDERATIONS

The evaluation of the impact of the heat exchanger-storage system on the greenhouse thermal energy consumption, was based on energy balance and standard heat transfer equations. From an energy balance point of view, the contribution of solar energy to the heat requirements of a greenhouse, can be calculated by subtracting the amount of heat from auxiliary sources from the overall greenhouse heat requirements; therefore, a solar energy contribution ratio can be defined as:

$$SF = (Q_{THL} - Q_{AUX}) / Q_{THL} \tag{1}$$

where:

SF = solar energy contribution to the greenhouse heat requirement,
Q_{THL} = greenhouse total heat loss (kJ), and
Q_{AUX} = auxiliary heat use by the greenhouse (kJ).

The total heat loss of the greenhouse, Q_{THL}, should include losses from the structure, soil perimeter, and ventilation system, as indicated by:

$$Q_{THL} = Q_{GHL} + Q_{SHL} + Q_{VHL} \tag{2}$$

where:

Q_{GHL} = greenhouse structure loss (kJ),
Q_{SHL} = greenhouse soil perimeter heat loss (kJ), and
Q_{VHL} = sensible heat loss by ventilation (kJ).

To compensate for the heat losses, heat (kJ) is supplied by one or more of the following sources:

i) solar energy, Q_S,
ii) heating system, Q_F,
iii) irrigation water, Q_{IR}, and
iv) artificial lights, Q_{LU}.

Therefore, the term Q_{AUX} in Eq. 1 can be expressed as :

$$Q_{AUX} = Q_F + Q_{IR} + Q_{LU} \tag{3}$$

Among these heat sources, the heat provided by the irrigation water is much smaller than the heat provided by the heating (Portugais and Paris 1983) and artificial lighting systems, and therefore can be neglected. Thus

$$Q_{AUX} = Q_F + Q_{LU} \tag{4}$$

Similarly, the heater contribution, FF, can be defined by:

$$FF = Q_F / Q_{THL} \tag{5}$$

The thermal energy output of a heater can be expressed in terms of its power, therefore:

$$Q_F = P_F \bullet t_F \tag{6}$$

where:

P_F = heater power averaged on an hourly basis (kW), and
t_F = heater operating time (s).

The effective power of the heater can be estimated by:

$$P_F = D_{AF} \bullet V_{AH} \bullet A_I \bullet C_{AF} \bullet (T_{OH} - T_{IH}) \tag{7}$$

where:

D_{AF} = density of humid air in heater (kg/m^3),
V_{AH} = air velocity of heater inlet (m/s),
A_I = heater air inlet cross sectional area (m^2),
C_{AF} = specific heat of air in heater (kJ•kg^{-1}•K^{-1}),
T_{OH} = average air temperature at heater outlet (^{o}C), and
T_{IH} = average air temperature at heater inlet (^{o}C).

Combining Eqs. 6 and 7 gives :

$$Q_F = D_{AF} \bullet V_{AH} \bullet A_I \bullet C_{AF} \bullet (T_{OH} - T_{IH}) \bullet t_F \tag{8}$$

The contribution of artificial lighting to the heat load, LF, is defined by:

$$LF = Q_{LU} / Q_{THL} \tag{9}$$

The heat released by the lamps can be evaluated by:

$$Q_L = P_L \bullet t_L \tag{10}$$

where:

Q_L = heat produced by high pressure sodium (HPS) lamps (kJ),
P_L = power of HPS lamps (kW), and
t_L = HPS lamps operating time (s).

However, when the ventilation system is in operation, it is assumed that the thermal energy released by the lamps is lost by ventilation, since the minimum cooling power of the ventilation system is at least four times the heating power of the artificial lighting system. This rejected heat can be estimated by:

$$Q_{LE} = P_L \bullet t_V \tag{11}$$

where:

Q_{LE} = excess heat produced by the HPS lamps (kJ), and
t_V = ventilation system operating time (s).

This is provided that both the lamps and ventilation are operating simultaneously during the monitoring period. Therefore, the useful energy provided by the lamps is:

$$Q_{LU} = Q_L - Q_{LE} \tag{12}$$

At night, when the ventilation and artificial lighting systems are not operating, the heat losses of the greenhouse will be equal to the heat provided by the heating system under steady state conditions, provided that the average top soil temperature is equal to the air temperature inside the greenhouse, in order to minimize the convective and radiant heat transfer between the soil and the air. The greenhouse structure heat loss is :

$$Q_{GHL} = UG \bullet A_G \bullet (T_{IG} - T_{OG}) \bullet t = P_F \bullet t_F \tag{13}$$

where:

UG = overall heat loss coefficient (kW•m^{-2}•K^{-1}),
A_G = greenhouse walls and roof surface area (m^2),
T_{IG} = inside air temperature (^{o}C),
T_{OG} = outside air temperature (^{o}C), and
t = time interval between data points (s).

Rearranging the terms and substituting Eq. 7 for P_F, the greenhouse overall heat loss coefficient for the above-ground section is :

$$UG = \frac{D_{AF} \bullet V_{AH} \bullet A_I \bullet C_{AF} \bullet (T_{OH} - T_{IH}) \bullet t_F}{A_G \bullet (T_{IG} - T_{OG}) \bullet t} \tag{14}$$

If $t_F = t$, then:

$$UG = \frac{D_{AF} \bullet V_{AH} \bullet A_I \bullet C_{AF} \bullet (T_{OH} - T_{IH})}{A_G \bullet (T_{IG} - T_{OG})} \tag{15}$$

It has been shown that the heat loss coefficient, UG, is directly proportional to the wind velocity (Sheard 1978); therefore, the following empirical relationship can be used to evaluate the average overall heat loss coefficient for different wind velocities:

$$UG = UG_O + c \bullet V \tag{16}$$

where:

UG_O = overall heat loss coefficient with wind ($kW \bullet m^{-2} \bullet K^{-1}$),
c = regression coefficient ($Wh \bullet m^{-3} \bullet K^{-1}$), and
V = wind velocity (km/h).

The perimeter heat losses through the soil can be evaluated using a relationship proposed by ASHRAE (1968):

$$Q_{SHL} = U_{SM} \bullet PE \bullet (T_{SG} - T_{OG}) \bullet t \quad (17)$$

where:

U_{SM} = greenhouse perimeter heat loss coefficient ($kW \bullet m^{-1} \bullet {}^{o}C^{-1}$)
PE = greenhouse perimeter (m), and
T_{FG} = average soil temperature inside greenhouse (°C).

The soil below the heat storage is considered as an infinite heat sink for the storage mode and an infinite heat source for the recovery mode.

The sensible heat loss through ventilation can be evaluated by :

$$Q_{VHL} = D_{air} \bullet C_{air} \bullet FR \bullet (T_{IG} - T_{OG}) \bullet t_V \quad (18)$$

where:

D_{air} = density of ambient humid air (kg/m^3),
C_{air} = specific heat of ambient air ($kJ \bullet kg^{-1} \bullet K^{-1}$), and
FR = ventilation flowrate (m^3/s).

MATERIALS AND METHODS

Test facility

The greenhouse is a "NORDIC" model constructed by Harnois Industries. Its characteristics are listed in Table I. The greenhouse is equipped with a thermal curtain that can also be used as a light shading device during summer. Two 2-speed ventilators, 610 mm in diameter, each with a maximum capacity of 2.12 m^3/s, were used to control the temperature when the experimental soil heat exchanger-storage system could no longer remove surplus heat fast enough. An auxiliary ventilator, 335 mm in diameter, with a capacity of 0.63 m^3/s, was used to control the ambient relative humidity. A standard oil heater, 36 kW in capacity, was used to heat the greenhouse. A drip irrigation system was used to irrigate and fertilize the crop, maintaining a relatively constant moisture level in the soil. The system was electrically controlled by three tensiometers connected in parallel. They activated a solenoid valve when the soil moisture level went below a preset level. Supplemental lighting was provided in winter by four 400 W HPS lamps mounted under the thermal curtain.

A detailed description of the experimental wet soil heat exchanger-storage system and data acquisition system is covered in Part I (Bernier et al. 1991).

Overall heat loss coefficient

Test runs were conducted at night without ventilation or artificial lighting, to evaluate the overall heat loss coefficient of the greenhouse for different wind conditions. The tests were performed with and without the thermal curtain and hoods on ventilation outlets. The hood forms an enclosure built around the ventilator outlet in order to reduce infiltration heat losses caused by the lack of airtightness of the louvers. These enclosures were installed in the fall and removed in late spring. To minimize the heat transfer between the soil surface and the surrounding air inside the greenhouse, the air temperature was maintained at the average soil surface temperature during those test runs.

Inside and outside air temperature and wind speed were measured over a period of a few hours during which steady-state conditions were assumed. Figure 1 illustrates the computation process.

Table I. Experimental greenhouse characteristics

Characteristic	Description
Structure	Gothic roof mounted on vertical walls
Covering	Hollow profile double skin, 6 mm thick polycarbonate
Orientation	Longitudinal axis running east-west
Insulation	North, west and east (partly) walls: polyurethane 76 mm thick; Night time: Thermal blanket made of a single sheet white diffusing plastic; Perimeter polystyrene 76 mm thick
Surface area	152 m^2
Floor Area	79 m^2 (12.1 m X 6.5 m)
Foundations	Reinforced concrete 1.4 m deep

Electrical energy consumption

The RMS voltages and currents were monitored for each electrical device to determine the average power requirements. Electrical energy consumption was calculated from these data and the operating time that was recorded by the data acquisition system.

Daily performance

Hourly averages of the following parameters were recorded:

i) inside and outside soil temperature,
ii) inside and outside air temperature,
iii) heater inlet and outlet air temperature,
iv) heat exchanger inlet and outlet dry and wet-bulb temperature,
v) inside global solar radiation on a horizontal plane,
vi) wind speed, and
vii) operating time for each piece of equipment.

The heat exchanger was operated under air-soil temperature differentials ranging from 0 to 10°C, and with and without active heat recovery at night. The flowchart presented in Fig. 2 illustrates the different steps involved in the computation of the daily performance parameters.

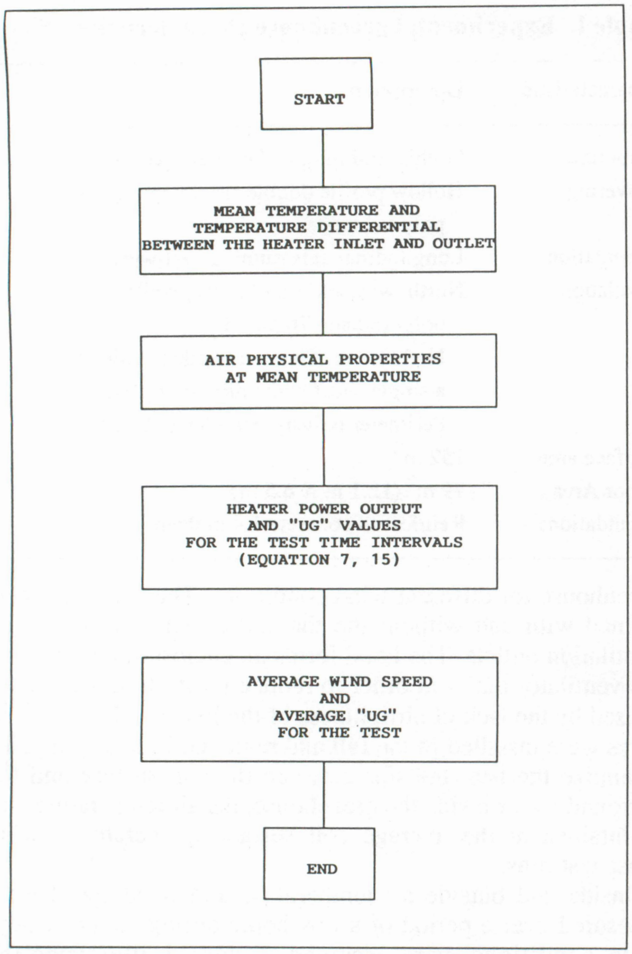

Fig. 1. Flowchart for the computation of the overall greenhouse heat loss coefficient.

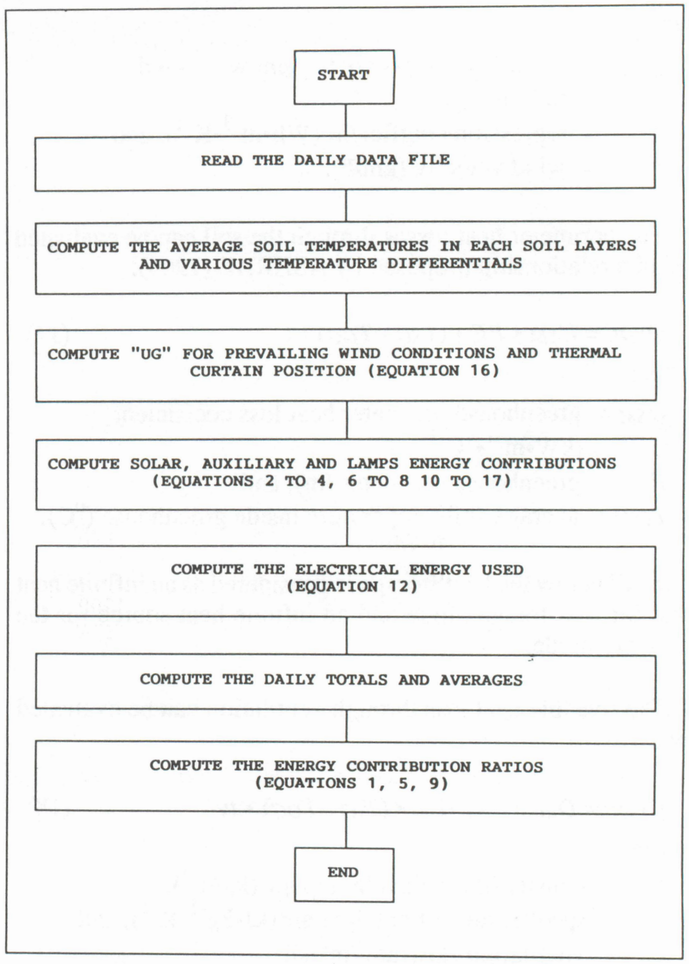

Fig. 2. Flowchart for the computation of the daily greenhouse energy ratios.

Payback estimation

The payback period for various scenarios was estimated using the procedure outlined by Perry and Robertson (1980). The cost estimates used, and the scenarios considered, are presented in Tables II and III, respectively. These scenarios involved different initial capital costs, auxiliary heating costs, operating costs and plant productivity for a 180 m commercial type greenhouse producing 3560 kg of tomatoes annually.

RESULTS AND DISCUSSION

Greenhouse heat loss coefficient

Figure 3 shows the results obtained for the overall greenhouse heat loss test runs. The empirical equations obtained were used to compute the greenhouse heat loss coefficient for the occurring average wind speed. The use of a thermal curtain (UGC) reduces the heat loss coefficient (UG) by 28%. The use of enclosures (UGH) installed on ventilator outlets reduces the UG value by approximately 20% on the average. The enclosures improved the airtightness of the greenhouse and provided some added insulation. Both the thermal curtain and the enclosures were used at different periods during the experiment. An experimental error, likely caused by a faulty sensor, could explain the lack of linearity of the data obtained from the tests involving the use of both the thermal curtain and the enclosures (UGHC). Even though the correlation coefficient obtained for UGHC is not significant at the 0.05 probability level, the regression line based on the most likely representative data points indicates a reduction on the overall heat loss coefficient (UGHC) of 30% when compared to the greenhouse heat loss coefficient (UGH) obtained with the enclosures installed. This is consistent with the reduction of 28% obtained by using the thermal curtain (UGC) as discussed previously.

Contribution to the greenhouse heat load

Solar energy contribution to the greenhouse heat requirement is not as closely related to captured solar radiation by the greenhouse (Fig. 4) as initially expected. As solar radiation increases, the exchanger cannot extract all the surplus heat that becomes available and therefore, the ventilation system is activated to evacuate some of the heat, thus maintaining an acceptable temperature for the plants.

There is a closer relationship between the average soil temperature and the solar contribution to the greenhouse heat requirement (Fig. 5). Since the soil acts as a thermal mass, the warmer the soil, the more heat that can be recovered at night, resulting in more energy saving on heating. It seems that for the experimental conditions, a 100% solar contribution can be achieved when the average soil temperature gets above 21°C. Over 21°C, stored heat is not used efficiently, air temperature during night time will stay higher than the minimum level recommended for various crops.

Table II. Cost estimates for the payback period

Description		Cost* ($)
Material:	52 pipes twelve meters long, 0.70 $/m	440
	Plenum	160
	Two ventilators	400
	Two thermostats	200
	Inlet pipe	100
	Two dampers	200
	Connection to the electrical circuit (manpower, two hours)	100
	Total	1600
Installation:	Manpower for excavation 16 hours at 40 $/hour	640
	Manpower for installation 15 days at 80 $/day	1200
	Total	1840
Material plus Installation:		3440
Operation:	Electricity, 3080 kWh at 0.0396 $/kWh	122
	Maintenance over a ten year period	100
Heating:	Heat load 52,320 kWh	
Heat Source:	heating oil at 0.037 $k/Wh	1936
	natural gas at 0.029 $/kWh	1507
	wood chips at 0.008 $/kWh	419
Productivity:	5.2 kg/m^2 increase** in yield at 3.50 $/kg	3360

* 1986

** The increase in plant productivity is assumed to be 5.2 kg/m^2 based on the yields obtained in the experimental greenhouse for two tomato crops.

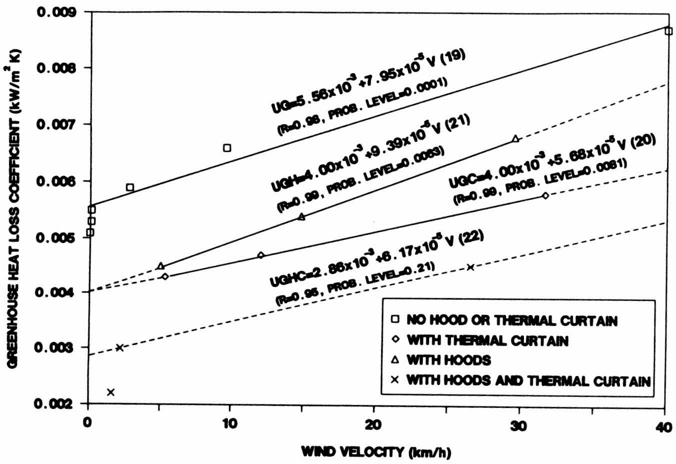

Fig. 3. Wind effect on the overall greenhouse heat loss coefficient.

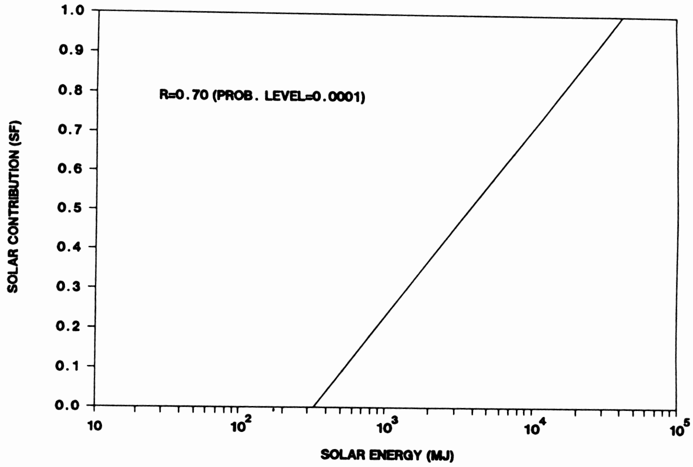

Fig. 4. Effect of solar energy on the solar contribution to the heat requirement.

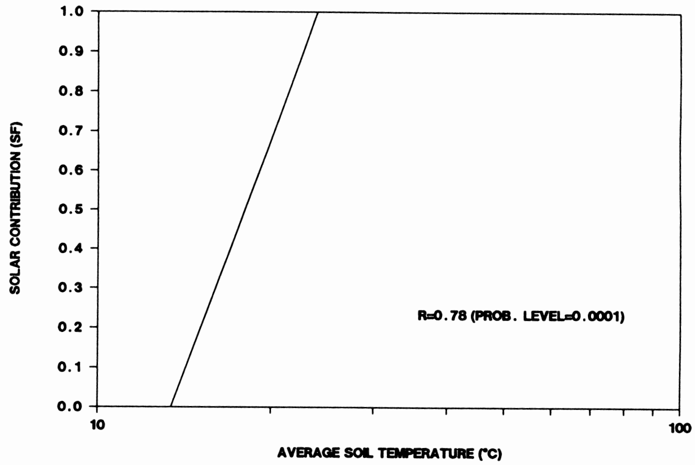

Fig. 5. Effect of soil temperature on the solar contribution to the heat requirement.

Figure 6 shows that from March 1986 to July 1986, solar energy contributed from 50% to 100% of the heat requirement, while it decreases from 90% to 30% during the fall. From February 1986 to June 1986 and from September 1986 to December 1986, the overall solar contribution has been estimated at 58%. For the same period, the four HPS lamps and the heater contributed 7% and 35%, respectively. Assuming that a conventional low thermal mass greenhouse could get 25% of its heat requirement from passive solar energy (Van Die 1981), the system could have provided a 33% energy saving. Detailed data are presented in Bernier (1987).

Payback period

Payback period estimates computed according to different scenarios are presented in Table III. It can be seen that the payback period is strongly influenced by the capital cost involved and by the system impact on plant productivity. The system is less cost effective when installation costs are involved and when the system does not enhance plant productivity, as would be the case for plants grown on benches for example. On the other hand, a greenhouse owner installing the system himself could get a payback period of approximately two years or less

Table III Payback period estimation[1]

Scenario #	Auxiliary heat source	Initial capital cost ($)	Operating cost ($)	Higher plant productivity considered	Payback period (years)
1	Heating oil	1593[2]	0[4]	No	2.2
2	Heating oil	3433[3]	0	No	4.6
3	Heating oil	1593	222	No	2.6
4	Heating oil	3433	222	No	5.5
5	Heating oil	3433	222	Yes	0.9
6	Natural gas	3433	222	Yes	0.9
7	Wood chips	3433	222	Yes	1.0

[1]All costs are in Canadian dollars estimated in 1986.
[2]The greenhouse owner buys and installs the material required for the heat exchanger-storage system.
[3]The greenhouse owner buys the material and pays for the installation of the heat exchanger-storage system.
[4]The heat exchanger-storage system blower replaces the standard fan jet normally found in a plastic covered greenhouse.

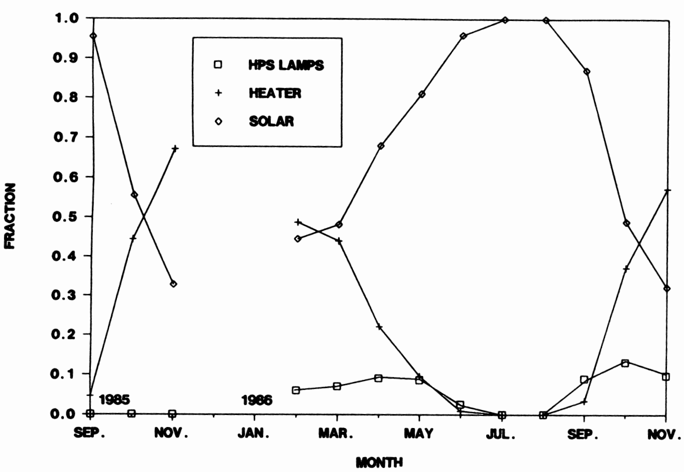

Fig. 6. Contributions of solar, HPS lamps, and heater to the heat requirement.

CONCLUSIONS

Several conclusions may be drawn from the results of this study.

1) Solar energy contribution to the greenhouse heat requirement is more closely related to soil temperature than to captured solar energy. For the prevailing conditions, soil temperatures above 21°C produced close to 100% solar contribution.

2) From February to June and from September to December 1986, the overall solar energy contribution to the heat requirement has been calculated as 58%. Assuming a passive solar contribution of 25% for a conventional low thermal mass greenhouse, the soil heat exchanger-storage system has provided an estimated 33% energy saving.

3) A simple economic evaluation indicates a payback period ranging from 0.9 to 5.5 years depending on the costs and plant productivity.

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NOMENCLATURE

A_G greenhouse walls and roof surface area (m^2)
A_I heater air inlet, cross sectional area (0.162 m^2)
c regression coefficient ($Wh\bullet m^{-3}\bullet K^{-1}$)
C_{AF} specific heat of air in the heater ($kJ\bullet kg^{-1}\bullet K^{-1}$)
C_{air} specific heat of ambient air ($kJ\bullet kg^{-1}\bullet K^{-1}$)
D_{AF} density of humid air in the heater (kg/m^3)
D_{air} density of ambient humid air (kg/m^3)
FF heater contribution to the greenhouse heat requirement
FR ventilation air flowrate (m^3/s)
LF lighting system contribution to the greenhouse heat requirement
PE greenhouse perimeter (37.2 m)
P_F heater power averaged on an hourly basis (kW)
P_L power of the HPS lamps (1.9 kW)
Q_{AUX} auxiliary heat used by the greenhouse (kJ)
Q_F heat supplied by the heater (kJ)
Q_{GHL} greenhouse structure heat loss (kJ)
Q_{IR} heat gained by the soil from the irrigation water (kJ)
Q_L heat produced by the HPS lamps (kJ)
Q_{LE} excess heat produced by the HPS lamps (kJ)
Q_{LU} usable heat produced by the HPS lamps (kJ)
Q_S solar heat gained by the greenhouse (kJ)
Q_{SHL} greenhouse soil perimeter heat loss (kJ)
Q_{THL} greenhouse total heat loss (kJ)
Q_{VHL} sensible heat loss by ventilation (kJ)
SF solar energy contribution to the greenhouse heat requirement
t time interval between data reports (s)
t_F heater operating time (s)
T_{IG} inside air temperature (°C)
T_{IH} average air temperature at the heater inlet (°C)
t_L HPS lamps operating time (s)
T_{OG} outside air temperature (°C)
T_{OH} average air temperature at the heater outlet (°C)
t_V ventilation system operating time (s)
T_{SG} average soil temperature inside the greenhouse (°C)
UG overall heat loss coefficient ($kW\bullet m^{-2}\bullet K^{-1}$)
UGC overall heat loss coefficient with thermal curtain ($kW\bullet m^{-2}\bullet K^{-1}$)
UGH overall heat loss coefficient with hoods on ventilator outlets ($kW\bullet m^{-2}\bullet K^{-1}$)
$UGHC$ overall heat loss coefficient with hoods and thermal curtain ($kW\bullet m^{-2}\bullet K^{-1}$)
UG_O overall heat loss coefficient without wind ($kW\bullet m^{-2}\bullet K^{-1}$)
U_{SM} greenhouse perimeter heat loss coefficient (0.00112 $kW\bullet m^{-1}\bullet \$C^{-1}$, Lawand et al. 1985)
V wind velocity (km/h)
V_{AH} air velocity at the heater inlet (4.96 m/s)