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. 33:99-105. 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 flow rate of 0.91 m³/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 ondule 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 m³/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) 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:

\[ SF = \frac{Q_{THL} - Q_{AUX}}{Q_{THL}} \]  

(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:

\[ Q_{THL} = Q_{GHL} + Q_{SHL} + Q_{VHL} \]  

(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:

$$Q_F = PF \cdot t_F \tag{6}$$

where:

$PF = $ 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:

$$PF = DA_F \cdot VAH \cdot AI \cdot CA_F \cdot (TOH - TIH) \tag{7}$$

where:

$DA_F = $ density of humid air in heater (kg/m$^3$),
$VAH = $ air velocity of heater inlet (m/s),
$AI = $ heater air inlet cross sectional area (m$^2$),
$CA_F = $ specific heat of air in heater (kJ·kg$^{-1}$·K$^{-1}$),
$TOH = $ average air temperature at heater outlet ($^\circ$C), and
$TIH = $ average air temperature at heater inlet ($^\circ$C).

Combining Eqs. 6 and 7 gives:

$$Q_F = DA_F \cdot VAH \cdot AI \cdot CA_F \cdot (TOH - TIH) \cdot t_F \tag{8}$$

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:

$$Q_L = PF \cdot t_L \tag{10}$$

where:

$Q_L = $ heat produced by high pressure sodium (HPS) lamps (kJ),
$PF = $ 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:

$$Q_{LE} = PF \cdot t_F \tag{11}$$

where:

$Q_{LE} = $ excess heat produced by the HPS lamps (kJ), and
$t_F = $ 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:

$$Q_{GHL} = UG \cdot AG \cdot (T_H - T_OG) \cdot t = PF \cdot t_F \tag{13}$$

where:

$UG = $ overall heat loss coefficient (kW·m$^{-2}$·K$^{-1}$),
$AG = $ greenhouse walls and roof surface area (m$^2$),
$T_H = $ inside air temperature ($^\circ$C),
$T_OG = $ outside air temperature ($^\circ$C), and
$t = $ time interval between data points (s).

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

$$UG = \frac{DA_F \cdot VAH \cdot AI \cdot CA_F \cdot (TOH - TIH) \cdot t}{AG \cdot (T_H - T_OG) \cdot t} \tag{14}$$

If $t_F = t$, then:

$$UG = \frac{DA_F \cdot VAH \cdot AI \cdot CA_F \cdot (TOH - TIH)}{AG \cdot (T_H - T_OG)} \tag{15}$$

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:

$$UG = UGO + C \cdot V \tag{16}$$
where:

\[ UGO = \text{overall heat loss coefficient with wind (kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}), \]
\[ e = \text{regression coefficient (Wh}\cdot\text{m}^{-3}\cdot\text{K}^{-1}), \]
\[ V = \text{wind velocity (km/h)}. \]

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

\[ Q_{SHL} = U_SM \cdot PE \cdot (T_{SG} - T_{CG}) \cdot t \]  
(17)

where:

\[ U_SM = \text{greenhouse perimeter heat loss coefficient (kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}) \]
\[ PE = \text{greenhouse perimeter (m), and} \]
\[ T_{SG} = \text{average soil temperature inside greenhouse (°C)}. \]

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:

\[ Q_{VHL} = D_{air} \cdot C_{air} \cdot FR \cdot (T_{IG} - T_{CG}) \cdot tv \]  
(18)

where:

\[ D_{air} = \text{density of ambient humid air (kg/m}^3\text{)}, \]
\[ C_{air} = \text{specific heat of ambient air (kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}), \]
\[ FR = \text{ventilation flow rate (m}^3\text{/s)}. \]

### 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, 50 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.

### 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,
vi) 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.
RESULTS AND DISCUSSION

Fig. 2. Protocol for the computation of the daily greenhouse heat load.

Fig. 1. Flowchart for the computation of the overall greenhouse heat loss coefficient.
Table II. Cost estimates for the payback period

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material: 52 pipes twelve meters long, 0.70 $/m</td>
<td>440</td>
</tr>
<tr>
<td>Plenum</td>
<td>160</td>
</tr>
<tr>
<td>Two ventilators</td>
<td>400</td>
</tr>
<tr>
<td>Two thermostats</td>
<td>200</td>
</tr>
<tr>
<td>Inlet pipe</td>
<td>100</td>
</tr>
<tr>
<td>Two dampers</td>
<td>200</td>
</tr>
<tr>
<td>Connection to the electrical circuit</td>
<td>100</td>
</tr>
<tr>
<td>(manpower, two hours)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1600</strong></td>
</tr>
<tr>
<td>Installation: Manpower for excavation</td>
<td>640</td>
</tr>
<tr>
<td>16 hours at 40 $/hour</td>
<td></td>
</tr>
<tr>
<td>Manpower for installation</td>
<td></td>
</tr>
<tr>
<td>15 days at 80 $/day</td>
<td>1200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1840</strong></td>
</tr>
<tr>
<td>Material plus Installation:</td>
<td>3440</td>
</tr>
<tr>
<td>Operation: Electricity, 3080 kWh at 0.0396 $/kWh</td>
<td>122</td>
</tr>
<tr>
<td>Maintenance over a ten year period</td>
<td>100</td>
</tr>
<tr>
<td>Heating: Heat load 52,330 kWh</td>
<td></td>
</tr>
<tr>
<td>Heat Source: heating oil at 0.037 $/kWh</td>
<td>1936</td>
</tr>
<tr>
<td>natural gas at 0.029 $/kWh</td>
<td>1507</td>
</tr>
<tr>
<td>wood chips at 0.008 $/kWh</td>
<td>419</td>
</tr>
<tr>
<td><strong>Productivity:</strong> 5.2 kg/m² increase in yield at 3.50 $/kg</td>
<td>3360</td>
</tr>
</tbody>
</table>

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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

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Auxiliary heat source</th>
<th>Initial capital cost ($)</th>
<th>Operating cost ($)</th>
<th>Higher plant productivity considered</th>
<th>Payback period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heating oil</td>
<td>1593&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0&lt;sup&gt;4&lt;/sup&gt;</td>
<td>No</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>Heating oil</td>
<td>3433&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0</td>
<td>No</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>Heating oil</td>
<td>1593</td>
<td>222</td>
<td>No</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>Heating oil</td>
<td>3433</td>
<td>222</td>
<td>No</td>
<td>5.5</td>
</tr>
<tr>
<td>5</td>
<td>Heating oil</td>
<td>3433</td>
<td>222</td>
<td>Yes</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>Natural gas</td>
<td>3433</td>
<td>222</td>
<td>Yes</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>Wood chips</td>
<td>3433</td>
<td>222</td>
<td>Yes</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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

**ACKNOWLEDGEMENTS**

The authors express their gratitude to the Institut de technologie agro-alimentaire (La Pocatière, PQ) and Employment and Immigration Canada for their financial assistance, and to the Corporation des Agronomes du Québec (La Pocatière region) and the Fondation François Pilote Inc. for their support and encouragement. Appreciation is also extended to Louise Lizotte and Angèle Bernier for their help in preparing this paper.

**REFERENCES**


## NOMENCLATURE

- **AG**: greenhouse walls and roof surface area (m²)
- **AI**: heater air inlet, cross sectional area (0.162 m²)
- **c**: regression coefficient (Wh·m⁻³·K⁻¹)
- **CAF**: specific heat of air in the heater (kJ·kg⁻¹·K⁻¹)
- **Cair**: specific heat of ambient air (kJ·kg⁻¹·K⁻¹)
- **DAF**: density of humid air in the heater (kg/m³)
- **Da**: density of ambient humid air (kg/m³)
- **FF**: heater contribution to the greenhouse heat requirement
- **FR**: ventilation air flowrate (m³/s)
- **LF**: lighting system contribution to the greenhouse heat requirement
- **PE**: greenhouse perimeter (37.2 m)
- **PF**: heater power averaged on an hourly basis (kW)
- **PL**: power of the HPS lamps (1.9 kW)
- **QAUX**: auxiliary heat used by the greenhouse (kJ)
- **QH**: heat supplied by the heater (kJ)
- **QGH**: greenhouse structure heat loss (kJ)
- **QIR**: heat gained by the soil from the irrigation water (kJ)
- **QL**: heat produced by the HPS lamps (kJ)
- **QLE**: excess heat produced by the HPS lamps (kJ)
- **QLU**: usable heat produced by the HPS lamps (kJ)
- **Qs**: solar heat gained by the greenhouse (kJ)
- **QSHL**: greenhouse soil perimeter heat loss (kJ)
- **QTHL**: greenhouse total heat loss (kJ)
- **Qvhl**: sensible heat loss by ventilation (kJ)
- **SF**: solar energy contribution to the greenhouse heat requirement
- **t**: time interval between data reports (s)
- **TF**: heater operating time (s)
- **TIG**: inside air temperature (°C)
- **TlH**: average air temperature at the heater inlet (°C)
- **IL**: HPS lamps operating time (s)
- **TOG**: outside air temperature (°C)
- **TOH**: average air temperature at the heater outlet (°C)
- **LV**: ventilation system operating time (s)
- **TSG**: average soil temperature inside the greenhouse (°C)
- **UG**: overall heat loss coefficient (kW·m⁻²·K⁻¹)
- **UGC**: overall heat loss coefficient with thermal curtain (kW·m⁻²·K⁻¹)
- **UGH**: overall heat loss coefficient with hoods and thermal curtain (kW·m⁻²·K⁻¹)
- **UGHC**: overall heat loss coefficient with hoods and thermal curtain (kW·m⁻²·K⁻¹)
- **UGO**: overall heat loss coefficient without wind (kW·m⁻²·K⁻¹)
- **USM**: greenhouse perimeter heat loss coefficient (0.00112 kW·m⁻¹·°C⁻¹, Lawand et al. 1985)
- **V**: wind velocity (km/h)
- **VAH**: air velocity at the heater inlet (4.96 m/s)