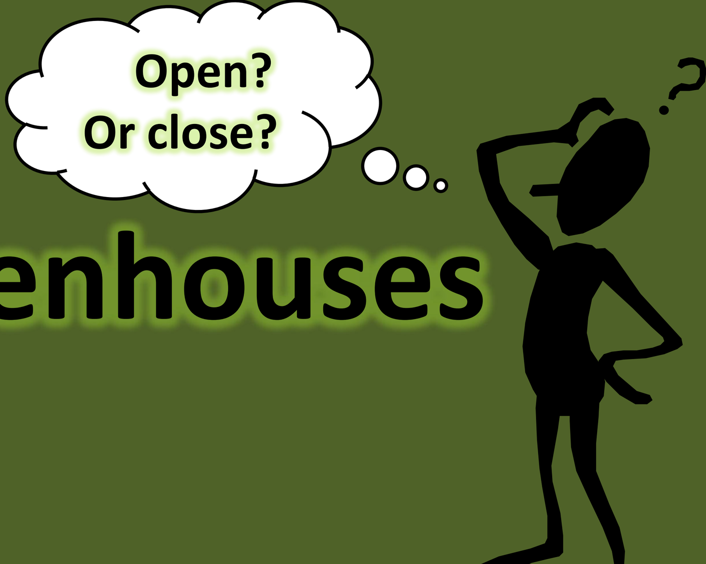

Cooling Capacity Assessment of Semi-closed Greenhouses

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Abstract

Energy and labor are the two largest expenditures of greenhouse operations. High energy cost and large CO_2 footprint associated with greenhouse heating have motivated research activities in the areas of energy conservation and alternative energy. Dutch researchers have demonstrated energy saving potential of closed greenhouse operation in the Netherlands. This study hypothesized that semi-closed operation was better suited for Ohio and other US northern climate regions. A decision support tool has been developed to assess energy recovery potential and other benefits of semi-closed operations. The results showed that a greenhouse can be closed 90% of the time using only 50% of the maximum cooling capacity required to keep a greenhouse closed 100% of the time. Also, heat recovered from cooling operations of a closed greenhouse in Ohio can contribute 23-98% of total annual heating needs. This study also found large disagreement when using a commonly used tool for heat loss calculation. The tool performed poorly with a 30% error under nighttime clear sky conditions. The evaluation suggested that accurate estimation of net solar radiation transmittance is important, e.g. a 5% change of the transmittance caused a 9% prediction performance shift. In addition to the originally designed functions, the decision support tool is extended to predict the performance of external shade curtains for cooling purposes. The development of this tool has established a solid foundation for the evaluation of greenhouse energy management strategies, including feasibility studies of alternative energy sources, and of sizing of greenhouse heating and cooling equipments.

1. Introduction

To improve energy efficiency of plant production, a closed greenhouse operation that reutilizes exhaust heat from cooling operations for later heating needs was proposed. The closed greenhouse operation in the Netherlands has demonstrated benefits including reductions of heating fuel, pesticide, water, CO_2 usage in elevated CO_2 environments, and increased crop yield and quality. This study hypothesized that semi-closed operation could better help Ohio and other northern regions of the US to achieve more economical operations, given larger weather variations and lack of accessibility to aquifers as heat storage compared to the Netherlands. Therefore, a decision support tool has been developed to assist users to evaluate the feasibility of closed operation at their locations by assessing energy recovery potential from cooling operations of a closed or semi-closed greenhouse, and other associated benefits, e.g. CO_2 and water savings. This tool can also assist users to decide the annual percentage of time that their greenhouses can be closed based on the sizes of their heating and cooling equipments. Since the overarching goal of this study was to assist growers in northern US regions in improving greenhouse plant production energy efficiency, the general approach to conduct this study was to design a decision support tool based on energy balance modeling in a greenhouse to calculate the operational requirements and potential benefits of a closed/semi-closed greenhouse. After the theoretical prediction was completed, the performance of the energy balance model was validated by field data. In the end, a user-friendly decision support tool allowing users to estimate potential benefits of a closed greenhouse at specific operations using user supplied information, such as greenhouse structure, glazing materials, climate data, temperature set point, net solar radiation transmittance and etc., was designed. In summary, the objectives were to:

1. estimate potential benefits and operational requirements of closed/semi-closed greenhouse,
2. validate greenhouse energy balance model, and
3. develop a user-friendly decision support tool.

2. Materials and Methods

Estimate potential benefits and operational requirements of closed/semi-closed greenhouse:

When a greenhouse was maintained at set point conditions, operational requirements were:

Energy balance (Aldrich and Bartok, 1989):

Cooling requirement = Net solar radiation gain – Heat loss in convection, infiltration and ventilation.

Heating requirement = Heat loss in convection, infiltration and ventilation – Net solar radiation gain.

Water balance (Jolliet, 1994):

Dehumidification requirement = Plant transpiration – Water loss in condensation, infiltration and ventilation.

Potential benefits of closed/semi-closed greenhouse were:

Recoverable heat = Heat loss through active cooling operations.

Water savings = Water loss in active dehumidification.

CO_2 savings from cooling/dehumidification operation = CO_2 loss in ventilation cooling/dehumidification.

(When the greenhouse was enriched with CO_2 at certain level)

Validate greenhouse energy balance model:

Although water balance model was included in this tool, the main purpose of this study was to assess energy recovery potential for closed operation; Therefore, only the energy balance model was field validated. *Convection and infiltration heat loss:* During the night, when the greenhouse temperature was at equilibrium with the outside and ventilation was eliminated, the total energy used to heat the house to a higher temperature was compared with the total predicted heat loss when the temperature dropped from the higher point to the origin. *Ventilation heat loss:* Since the ventilation time was proportional to ventilation heat loss, during the day, the total measured ventilation time used to remove the excess heat from the house was compared with the total predicted ventilation time.

Develop a user-friendly decision support tool:

The tool was implemented on commonly used software, Microsoft Excel. The spreadsheet consisted of two sheets that allow users to input their greenhouse system details and climate data as well as one sheet to show the prediction results. The calculations sheets were hidden from users.

4. Conclusions and Discussion

This study found that semi-closed greenhouse could be beneficial for Ohio conditions. Proper sizing of cooling devices and heat storage was important to determine the feasibility of semi-closed operation. Nighttime heat loss predictions performed poorly under clear sky conditions, the possible explanation could be the significant effect of radiation heat loss from the greenhouse. Also, the daytime ventilation heat loss model evaluation showed the importance of using accurate net solar radiation transmittance for solar heat gain estimation. Overall, this tool performed well with less than 8% relative error and it has established a solid foundation for the evaluation of greenhouse energy management strategies.

3. Results

- A greenhouse can be closed 90% of the time using only 50% of the maximum cooling capacity required to keep a greenhouse closed 100% of the time. A smaller cooling device was preferable for economical consideration (Figure 1).
- Heat recovered from cooling operations of a closed greenhouse in Ohio can contribute 23% to 98% of total annual heating needs (Figure 2).
- Nighttime heat loss (convection and infiltration) assessment gave -30% prediction error under clear sky conditions (Figure 3).
- Daytime ventilation heat loss assessment gave 0.8 to -8% relative error. (Figure 4).
- A decision support tool: Greenhouse Energy Harvesting Analysis Tool (GEHAT) was developed (Figure 5, 6 and 7).

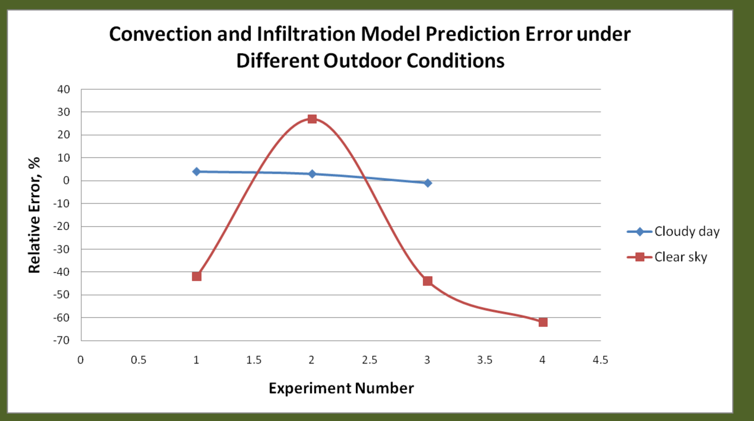


Figure 3: Performance of the nighttime greenhouse heat loss (convection and infiltration) prediction. 2% and -30% relative errors were found under cloudy and clear sky conditions, respectively.

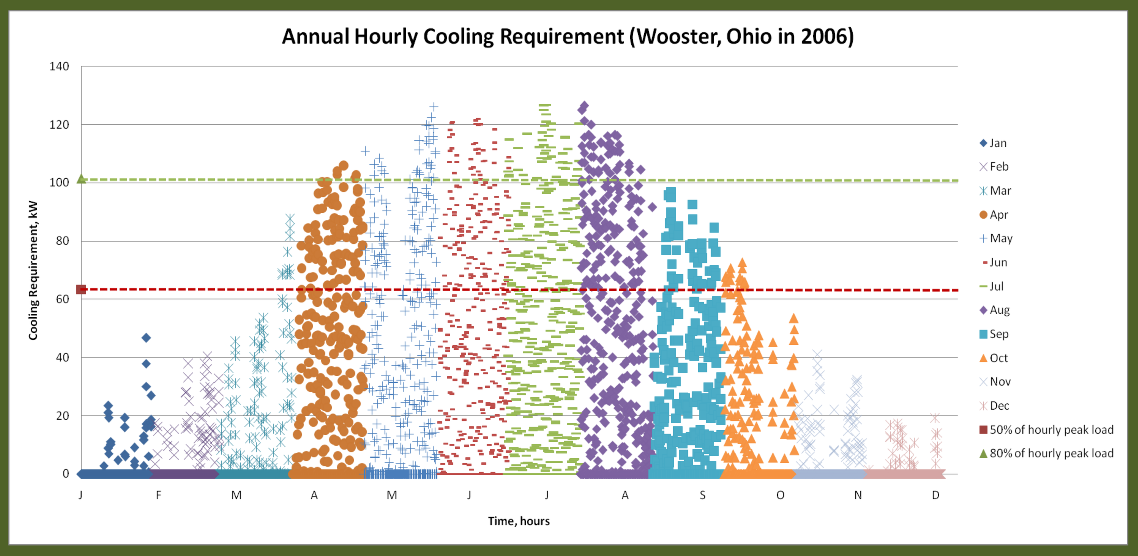


Figure 1: Annual hourly cooling requirement of the greenhouse in Wooster, Ohio in 2006 from January (J) to December (D). The 50% and 80% peak cooling requirements were indicated with the lower and higher dotted horizontal lines, respectively.

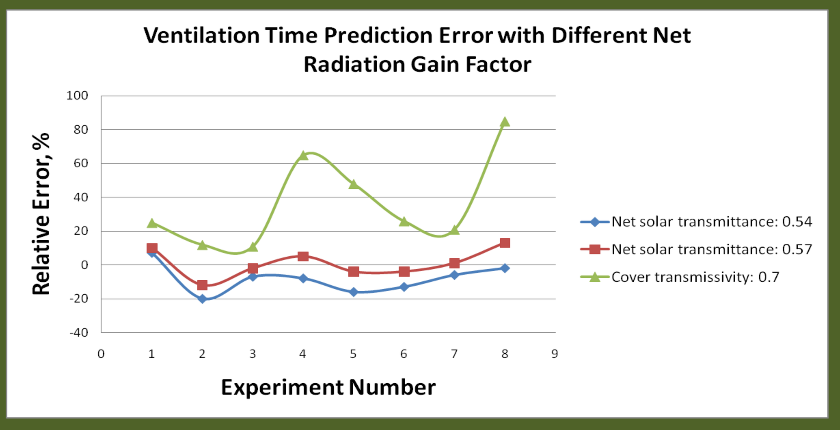


Figure 4: Ventilation time prediction error with 0.54 and 0.57 net solar transmittances as well as 0.7 cover transmissivity. The average prediction errors were -8%, 0.8% and 37%, respectively. Results showed the importance of accurate measurement of net radiation gain factor.

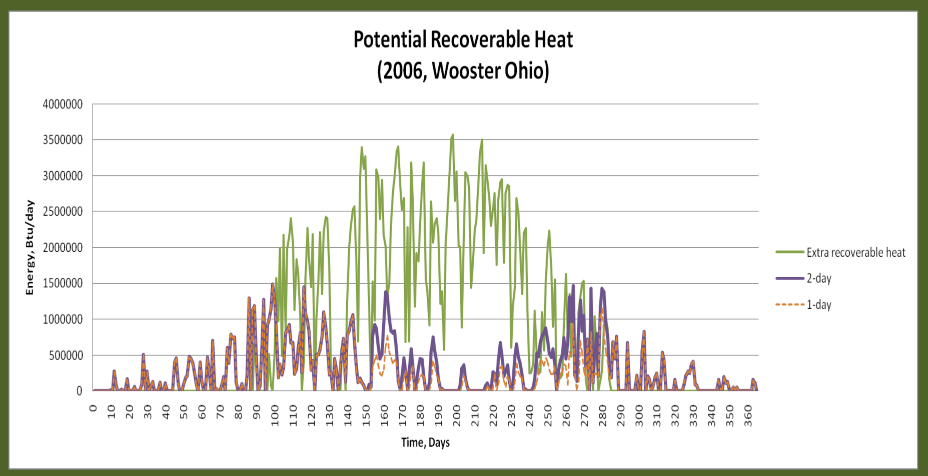


Figure 2: Potential recoverable heat with 1-day and 2-day storage can contribute 23% and 25%, respectively, heating needs in Wooster, Ohio in 2006. Also, 98% heating needs can be met with extra recoverable heat.

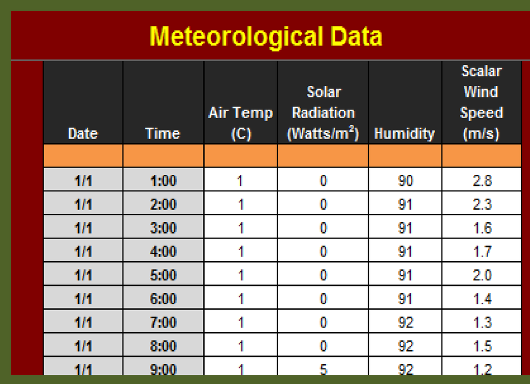
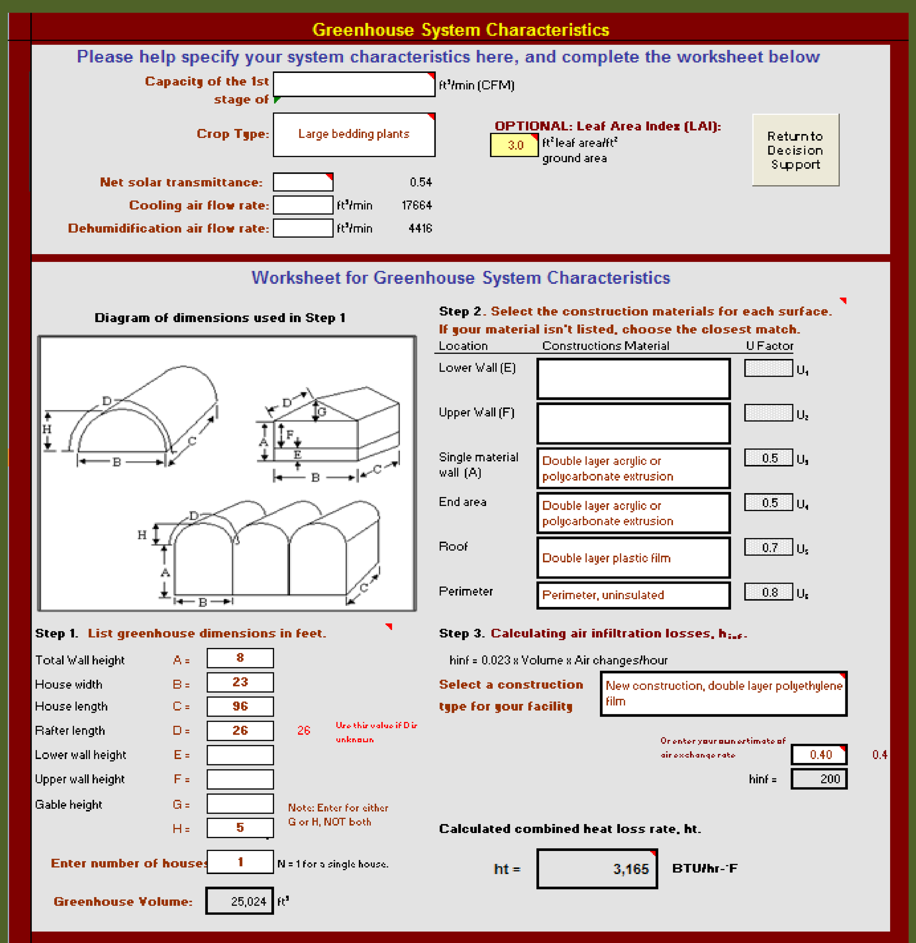


Figure 5: Meteorological data input sheet of GEHAT.



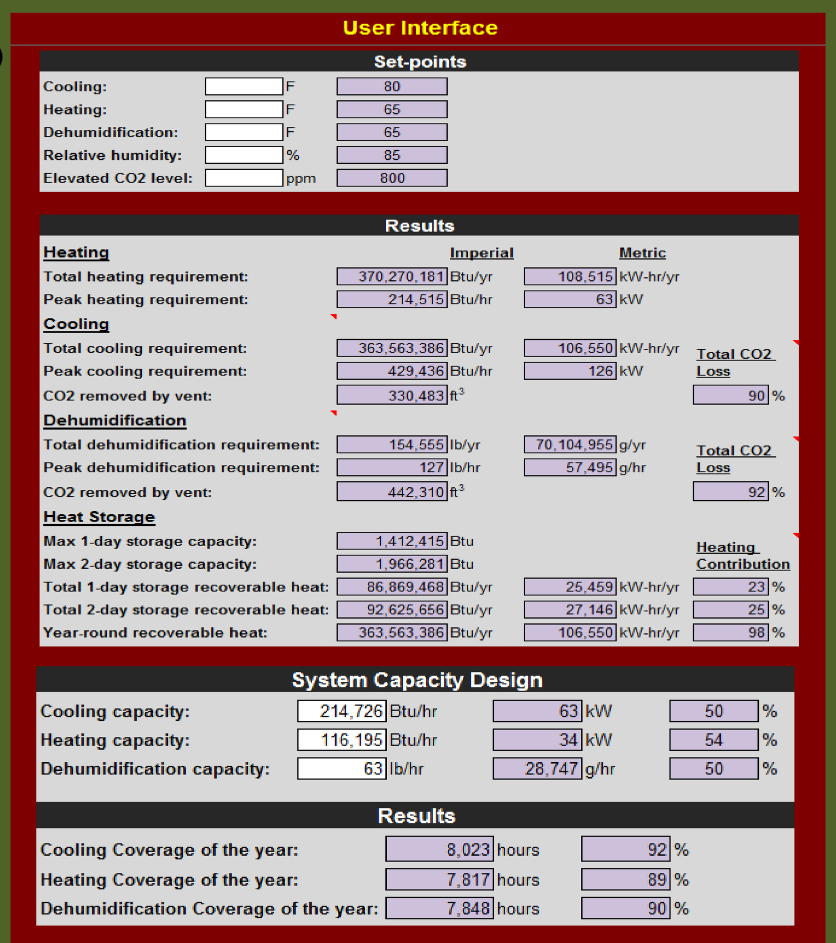


Figure 6: Greenhouse system characteristics input sheet of GEHAT.

Figure 7: User Interface with prediction results sheet of GEHAT.

References:

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Jolliet, O. (1994). HORTITRANS, a model for Predicting and Optimizing Humidity and Transpiration in Greenhouses. J. Agricultural Engineering Research , 57:23-37.

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