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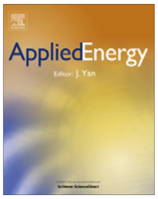

Energy analysis and thermoeconomic assessment of the closed greenhouse – The largest commercial solar building

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HIGHLIGHTS

- An energy analysis in the greenhouse has been assessed using the TRNSYS tool.
- The annual heating and cooling demand has been studied in four configurations.
- The energy conservation ratio has been indicated by "Surplus Energy Ratio" (SER).
- The potential for storing heat in an ideal closed greenhouse is 164 kW h m^{-2}.
- The design load has the main impact on the Payback time however the glazing and ventilation ratio have a minor impact.

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ABSTRACT

The closed greenhouse concept has been studied in this paper. The closed greenhouse can be considered as the largest commercial solar building. In principle, it is designed to maximize the utilization of solar energy by use of seasonal storage. In an ideal fully closed greenhouse, there is no ventilation window. Therefore, the excess heat must be removed by other means. In order to utilize the excess heat at a later time, long- and/or short-term thermal storage technology (TES) should be integrated. A theoretical model has been derived to evaluate the performance of various design scenarios. The closed greenhouse is compared with a conventional greenhouse using a case study to guide the energy analysis and verify the model. A new parameter has been defined in this paper in order to compare the performance of the closed greenhouse concept in different configurations – the Surplus Energy Ratio showing the available excess thermal energy that can be stored in the TES system and the annual heating demand of the greenhouse. From the energy analysis it can be concluded that SER is about three in the ideal fully closed greenhouse. Also, there is a large difference in heating demand between the ideal closed and conventional greenhouse configurations Finally, a preliminary thermo-economic study has been assessed in order to investigate the cost feasibility of various closed greenhouse configurations, like ideal closed; semi closed and partly closed conditions.

Here, it was found that the design load has the main impact on the payback period. In the case of the base load being chosen as the design load, the payback period for the ideal closed greenhouse might be reduced by 50%. On the other hand, glazing type, ventilation ratio, and the closed area portion have a minor impact on the payback period.

1. Introduction

Sustainable agriculture is a challenging area for global ambitions towards sustainability for future generations. Three important aspects are at the centre of attention: energy utilization, environmental impact and cost-efficiency. Growth in population and the increasing development of new production technology leads to a rise in the energy demand of the agricultural industry. The annual average EU-27 energy usage in the overall agricultural industry is 188 W h/m^2 and in the Nordic countries, such as Sweden, it is higher, at 299 W h/m^2 [1]. Although the energy use in the agricultural industry is small as compared to the total energy demand in many countries, it is substantial in some countries like the Netherlands where it represents 8.1% of total energy use [1]. For increased yield and controlled growth in all climates, the greenhouse is used and it is one of the most energy demanding sectors in the agricultural industry [2]. In order to conserve energy, the idea of using a closed greenhouse was formed [2–5]. The closed greenhouse can be considered as one large commercial solar building. In principle, it is designed to maximize the utilization of solar energy through seasonal storage. In a fully closed

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Nomenclature

Cp	specific heat in constant pressure ($J\,kg^{-1}\,K^{-1}$)
K	empirical constant coefficient (–)
L	heat of vapourization ($kJ\,kg^{-1}$)
M	moisture capacitance (kg)
Q	energy transfer in terms of heating or cooling (W)
T	temperature
V	volume (m3)
W	water amount ($kg\,day^{-1}$)
X	total indoor greenhouse humidity ratio (kg (H2O) kg^{-1}(dry air))
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)

Symbols

ρ	density ($kg\,m^{-3}$)
v	wind velocity ($m\,s^{-1}$)
γ	multiplication factor (–)

Subscript

ET	evapotranspiration rate ($kg\,day^{-1}$)
a	greenhouse air
adj	adjacent zone
cplg	coupling zone
d	drained out from the greenhouse
eff	effective
gc	convective gain
i	zone i
in	inside
inf	infiltration
ir	due to irrigation system
lat	latent heat
o	outdoor
p	due to plant
set	set point
surf	surface
vent	forced ventilation term
w	water vapour

Abbreviations

COP	coefficient of performance
SER	Surplus Energy Ratio
EU-27	European union 27 countries
PCM	phase change material
ppm	part per million
TES	thermal energy storage

greenhouse, there is no ventilation window. Therefore, the excess heat must be removed by other means. In order to utilize the excess heat at a later time, long- and/or short-term thermal storage technology (TES) should be integrated. From previous studies, it has been shown that a closed greenhouse, in addition to satisfying its own heating/cooling demand, can also supply heating and cooling to neighbouring buildings [6–9]. Advantages of the closed greenhouse concept are increased energy and water conservation and increased production yield due to the controlled growth environment obtained in a closed greenhouse [2,8–14]. The cost benefit of the concept depends on many parameters such as primary energy cost and total production yield, with the increased yield being the most important added value [11,15]. Montero et al. addressed the three largest operational costs in the Dutch commercial greenhouse which are labour costs (27%), energy costs (18%) and capital cost (18%) [3]. One study has shown that the closed greenhouse concept has the potential to increase production yield up to 20% while the total primary energy demand will be reduced by 30–40% based on the technology utilized [5,16]. Therefore, although the closed greenhouse concept may have high investment cost, it can still be cost effective due to the higher yield as well as the lower energy cost [2,11–13,16–20]. Economy of scale in the commercial greenhouses can be considered as a solution in order to increase the economic yield and cutting costs simultaneously [3].

In order to assess the technical potential of a variety of design concepts as well as the cost-effectiveness, proper modelling is essential. Although there are numerous R&D programs on the closed greenhouse concept being run in many countries (e.g., the Netherlands, Canada, Finland and Turkey) a general and complete closed greenhouse system model has still not been reported in the literature. However, there are many developed models based on specific projects but they cannot be considered general enough to evaluate and compare energy management scenarios for optimal design [18,20–28]. Therefore, for the present research a general greenhouse energy analysis model has been developed using the TRNSYS software [29]. With this, a variety of closed greenhouse configurations have been assessed with regard to opportunities for advancement through R&D.

The objective of this study is to present a comparative study on energy conservation for various closed greenhouse configurations and a conventional greenhouse design. Therefore, using theoretical modelling as outlined above, the annual heating and cooling demand is analyzed, and based on these loads, strategies for closing a greenhouse are examined techno-economically. The model has been bench-marked against a case study – Ulriksdal greenhouse located in Stockholm, Sweden, in order to verify the results.

2. Energy analysis and greenhouse modelling

Both the conventional greenhouse and the closed greenhouse concept have to be analyzed in order to evaluate their relative performance. Here, TRNSYS has been chosen to model the annual system performance of several configurations. In this section, the system model is described with regard to the components, system configuration, and major assumptions made.

2.1. Greenhouse energy layout and system modelling

There are analytical and empirical equations in previously developed models considering the greenhouse, and they are described in the literature [20,21,23,25,27,30]. These models describe the mass and energy balance for the greenhouse. The principle energy balance equations for the greenhouse can be divided into three main categories [30]:

- Greenhouse plants.
- Greenhouse structure.
- Greenhouse indoor climate.

The energy equations for the plant lead to an estimation of the sensible and latent heat absorbed by the plant surfaces [11]. The greenhouse structure energy equations calculate the rate of thermal energy received and lost by the structure and the ground. Finally, with regard to the greenhouse indoor climate, a model is needed to describe how the energy is transferred by the plants