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Energy management in horticultural applications through the closed greenhouse concept, state of the art

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ABSTRACT

The commercial greenhouse has the highest demand for energy as compared to all other agricultural industry sectors. Here, energy management is important from a broad sustainability perspective. This paper presents the state-of-the-art regarding one energy management concept; the closed greenhouse integrated with thermal energy storage (TES) technology. This concept is an innovation for sustainable energy management since it is designed to maximize the utilization of solar energy through seasonal storage. In a fully closed greenhouse, there is no ventilation which means that excess sensible and latent heat must be removed. Then, this heat can be stored using seasonal and/or daily TES technology, and used later in order to satisfy the heating demand of the greenhouse. This assessment shows that closed greenhouse can, in addition to satisfying its own heating demand, also supply the demand for neighboring buildings. Several energy potential studies show that summer excess heat of almost three times the annual heating demand of the greenhouse. However, many studies propose the use of some auxiliary system for peak load. Also, the assessment clearly point out that a combination of seasonal and short-term TES must be further explored to make use of the full potential. Although higher amount of solar energy can be harvested in a fully closed greenhouse, in reality a semi-closed greenhouse concept may be more applicable. There, a large part of the available excess heat will be stored, but the benefits of an integrated forced-ventilation system are introduced in order to use fresh air as a rapid response for primarily humidity control. The main conclusion from this review is that aspects like energy efficiency, environmental benefits and economics must be further examined since this is seldom presented in the literature. Also, a variety of energy management scenarios may be employed depending on the most prioritized aspect.

Contents

1. Introduction

Sustainable energy management is one of the most important topics of research with global benefit. Here, energy consumption, environmental impact and cost efficiency are central aspects for achieving successful sustainable energy management scenarios. Sustainable horticulture[1] is one challenging task since the

Abbreviations: ACCFHES, Aquifer Couple Cavity Flow Heat Exchanger System; AHU, Air Handling Unit; ATES, Aquifer Thermal Energy Storage; CFD, Computational Fluid Dynamic; CHP, Combined Heat and Power; FiWihex, Fine Wire Heat Exchanger; HME, Heat and Moisture Exchanger; LMTD, Log Mean Temperature Difference; PCM, Phase Change Material; TES, Thermal Energy Storage

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[1] "Practice of growing plants in a relatively intensive manner" [Principle of horticulture, C.R. Adams, M.P. Early, Elsevier butterworth-Heinemana, ISBN: 0750660880].

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world-wide increase in population leads to a need for higher production yield in agriculture, which in turn leads to a rise in the energy demand of the agricultural industry. The average of European Union countries energy demand in the agricultural industry is 1.8 {MWh/ha-year} and in the Nordic countries, e.g. Sweden, it is higher at 3{MWh/ha-Year} [1]. Although it is small as compared to the total energy demand in many countries, it is significant in some countries such as the Netherlands where it represents almost 8% of total energy use in the agricultural industry [1]. One of the most energy consuming sectors in the agricultural industry is the greenhouse. The greenhouse has been implemented for centuries in order to increase yield and control growth in all climates. Analyses of the greenhouse technology started in the 1950s, with an increase in the late 1970s when many studies sought improvements in commercial greenhouses due to the oil crises [2,3]. In recent decades, the innovation idea of using closed greenhouse was formed in order to conserve water and energy [4]. A horticulture closed greenhouse can be used as a source of energy as well as for agricultural purpose. This should be considered e.g. in lieu of the statement by Hare et al. who declared that 70% of greenhouses are heated with a supplementary unit of which 90% of them use oil as fuel [5]. However, for Nordic conditions the oil consumption has recently been reduced by 50% while the use of the other energy sources such as biomass has increased 18% between 2005 and 2008 [6]. Fig. 1 presents the different energy sources used in the greenhouse sector in Sweden. From this graph it can be concluded that presently the overall policy in the horticultural industry regarding the energy consumption is to reduce fossil fuels and replace them with other renewable sources.

As compared to conventional greenhouse technology, the closed greenhouse can in principle be independent of fossil fuel since it is designed to maximize the use of solar energy through seasonal thermal energy storage (TES). Using the concept, the greenhouse also becomes independent of the weather situation and can then in principal be used all over the world. However, limiting conditions depend on the geology of the ground since underground seasonal storage is presently the only cost-effective option, the type of heating and ventilation system implemented inside the greenhouse, and the rate of solar radiation. In the predominately hot and arid region it should still be possible to use a closed greenhouse although the water temperature in the storage system must be maintained low enough for cooling. Although closed greenhouses may require a higher capital investment as compared to conventional greenhouses, there is still a possibility to cost-effectively implement the concept [7]. Cost competitiveness of closed greenhouses is dependent on size, as well as the type of TES used and other installations. This paper presents a state-of-the-art assessment of the closed greenhouse concept, with the objective of setting the stage for further advancement of this very promising concept for energy management and sustainability. Specifically, advantages and challenges of the closed greenhouse concept in comparison with conventional open greenhouse concept are discussed. In addition, appropriate climate control strategies and technologies for the closed greenhouse concept are described, with special attention given to various types of TES systems to be implemented. Finally, this information is used to discuss the energy management potential through the closed greenhouse concept.

2. The closed greenhouse concept

Since the closed greenhouse concept is not a widely implemented concept there is no specific definition available in the literature. However, one reference described it as follows:

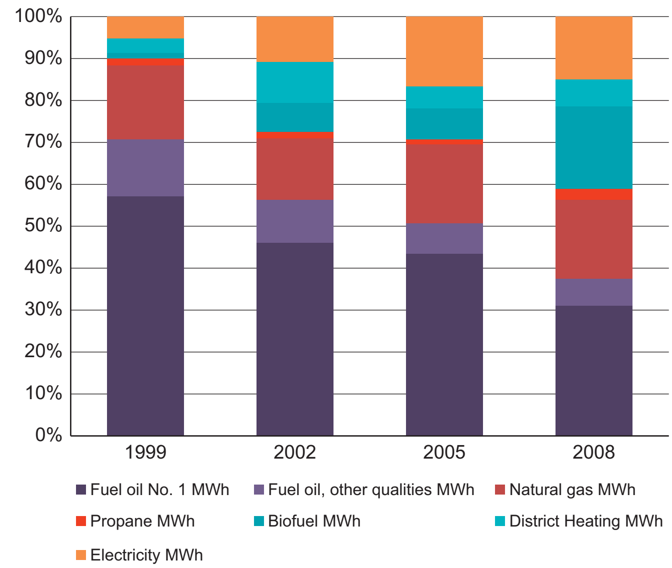

Fig. 1. Portion of the energy sources which has been utilized in the horticultural industry between 1999 to 2008 [6].

> "A greenhouse, which is completely closed, no windows to open to release excess humidity or to cool the house when it is too warm" [4].

As previously mentioned, provided that TES is effectively integrated, the closed greenhouse can be independent of fossil fuel and weather. The closed greenhouse can supply heat for itself and other nearby buildings. However, in practice an auxiliary system may be employed to supply part of the peak energy demand. If this system is based on biomass, then all of the supplied energy is of renewable origin. The greenhouse can be considered as a large solar collector. It can collect around 80% of the incident solar irradiation which is around 2.5 GJ/m^2-year for north of Europe [8]. Solar energy is transformed into heat inside the greenhouse. Since this amount of heat is more than required in hot and sunny days, it should be captured and stored in a TES system for re-use whenever the greenhouse needs to be heated. One concept proposed is underground thermal storage systems [9]. For example, the aquifer storage can be integrated with a heat pump system for heating and cooling a closed greenhouse.

In a simple design, which is presented schematically in Fig. 2, the heating and cooling processes rely on storage TES system, heat pump and heat exchanger. In the heating mode (Fig. 2a) the greenhouse will be heated using a heat pump. Warm water is then extracted from the TES and delivers low temperature heat to the heat pump while being cooled. Then, the cooled water is returned to the TES-system and thus charges the cold side of the TES. The heat pump provides the hot water. The hot water will charge a short-term buffer storage which is used to level the daily/hourly load in the closed greenhouse. In the cooling mode (Fig. 2b), cold water from the cold TES is pumped directly into the greenhouse and removes heat via a heat exchanger system. Then, the warm water is brought to the warm TES charging it for the winter. There are many other options for managing the heating/cooling demand and they will be described in the following sections.

2.1. Advantages and applications

Agricultural technology is faced with three important aspects: energy consumption, environmental impact, and economical constraints [2,7,10–12]. All these aspects should be considered