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Solar and heat pump hybrid heated greenhouse in Latvia: energy storage and CO_2 reduction

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In the agricultural sector, heating greenhouses are one of the largest consumers of heat, and the cost of heat is a major part of total expenses. The volatile prices of fossil fuels and their negative impact on climate change make it necessary to find solutions for more efficient use of alternative energy sources. The aim of this study was to investigate possible solutions for converting an existing natural gas-heated greenhouse into a carbon-neutral greenhouse. This study investigates the use of solar energy to heat a 50 m^2 experimental tomato greenhouse (EG) with a hybrid module consisting of integrated installations of 8 kW solar photovoltaic (PV) panels combined with a 5.0 kW air-to-water heat pump (AWHP), 15.0 kW solar collectors (SC), a 10 kWh solar energy accumulator (SEA) and a 1600 L water heat accumulator (WHA). The interaction between the different parts of the heating system and the energy storage was investigated and compared with a reference industrial greenhouse (RG) on the same site. Excess solar energy was stored in a hot water storage tank (36 L m^{-2}) and in a battery (0.2 kWh m^{-2}). The energy storage requirement was determined to be 3-10 kWh m^{-2} for the tomato production season from March to October. For a day/night cycle, 0.2-0.3 kWh m^{-2} of electricity storage or 1 kWh m^{-2} of heat storage was found to be sufficient. The use of an air-to-water heat pump optimises the amount of energy to be stored and the cost of energy storage, while reducing CO_2 emissions by at least a factor of 8 compared to natural gas heating. The electricity cost of the hybrid module is estimated to 30 % lower than natural gas heating in the 2021 and 2022 seasons. The calculations are based on the Nordpool day-ahead electricity price and the natural gas market price.

Keywords: Solar energy, air-to-water heat pump, CO_2 reduction, greenhouse, Latvia, energy storage

INTRODUCTION

According to the FAO, an estimate of 405 000 ha of greenhouses are spread throughout the EU [1], a figure that includes both glass- and plastic-covered structures. In 2022, there were 62.2 ha of greenhouses in Latvia, of which 32.2 ha heated [2].

Greenhouse agricultural production is generally seen as one of the most intensive parts of agricultural production [3, 4] as compared to energy use in open-field agriculture [5]. However, the role of greenhouse agriculture in the European food systems is not well-documented [6], while a small number of studies have been conducted that document energy use in greenhouse production.

EU Green Deal [7] announced the need for broad changes in the energy in all sectors of the economy including agriculture. The production of thermal energy accounts for 65.6 % of the total greenhouse gas emissions in Latvia [8]. The heating energy demand represents about 70-80 % of the total greenhouse energy consumption [9].

Increasing fossil fuel prices [5], scarcity of fossil fuel resources [10], and the global warming problem resulted from the combustion gases emittance has prompted turning to alternative energy sources or enhancing the thermal efficiency of the existing heating systems [5, 11].

In this context, greenhouse cultivation is a significant energy consumer but there is relatively little data available and taking into account the implementation of EU climate targets and its farm-to-fork strategy in agriculture, it is apparent that there is a need to move towards sustainable production practices. To understand the future of greenhouse production in the EU and how they can contribute to a sustainable transformation of our agricultural systems, it is necessary to understand the energy use in greenhouses [12].

One of the most heat-intensive productions in agriculture in Latvia are greenhouses. Greenhouses in Latvia climatic conditions require heating during most of the year, the precise heating regime being dependent on the culture produced. Therefore, the transition of the greenhouses to CO_2-neutral heating systems is an important part of the overall efforts to reduce greenhouse gas emissions.

The velocity of the transition to new technologies can be made a very important factor as are the costs

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of transforming the greenhouse industry to low CO_2 emission model.

In Latvia, a lot of the existing industrial greenhouse fleet use hot water central heating with natural gas. One of the ways for fast and relatively inexpensive transition is to replace the natural gas with another heat source leaving the rest of the technology intact. For example, to replace the gas boilers with biomass boilers. An alternative approach is by replacing natural gas with the combination of solar collectors (SC), electricity from photovoltaic (PV) panels and air-to-water heat pump. Their emission payback time is about one year but PV panels and solar collectors heating systems can be repaid in a short time period [13, 14].

The aim of this study was to investigate possible solutions for converting an existing natural gas-heated greenhouse into a carbon-neutral greenhouse. Particular attention was paid to requirements of heat storage for the greenhouse heated by a hybrid combination of solar energy and air-to-water heat pump.

An experimental greenhouse heated with the combination of SC, electricity from PV panels and air-to-water heat pump (AWHP) was designed and built to test the technology and the interaction between different heat sources. It is well known that the use of solar energy requires energy storage, and the affordability of proper energy storage facilities can be a limiting factor for the use of solar energy [15].

MATERIALS AND METHODS

The investigated 50 m^2 experimental greenhouse with beef type tomato *Solanum Lycopersicon* L. was detached from an industrial facility near the city of Jekabpils in South-East of Latvia (56.500197, 25.775123), 80 m high above sea level. The design, heating system and data acquisition system are detailed in [16, 17]. The warmest month in Jekabpils is July, its average air temperature is +18.1 ºC. On the other hand, the coldest months of the year with an average air temperature of -4 ºC are January and February. The last 10 years average in year intensity of solar radiation is 983 kWh m^{-2}, but the local weather station of the greenhouse recorded 1150 kWh m^{-2} of solar radiation intensity in 2022, 1900 hours of sunshine, 4400 hours of light and 4300 hours of darkness, Figure 1. The actual climatic data were obtained from the weather station of the industrial facility located near the experimental greenhouse.

A solar hot water heating system with 15 kW peak power (0.3 kW m^{-2}) and solar photovoltaic (PV) panels with 8 kW peak power (0.15 kW m^{-2}) optimized for spring/autumn were installed. 1600 L water heat accumulator system and 2 batteries of 5 kWh each were used, Figure 2.

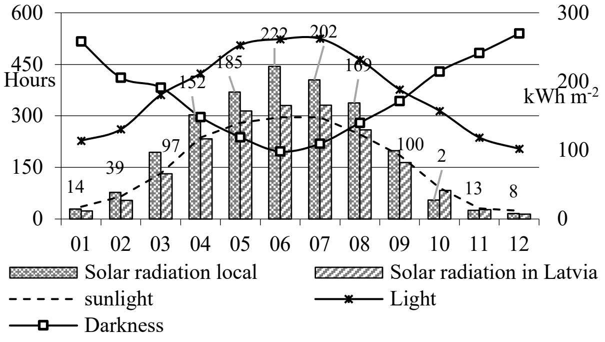

Fig. 1. Intensity of solar radiation in Latvia, 2022.

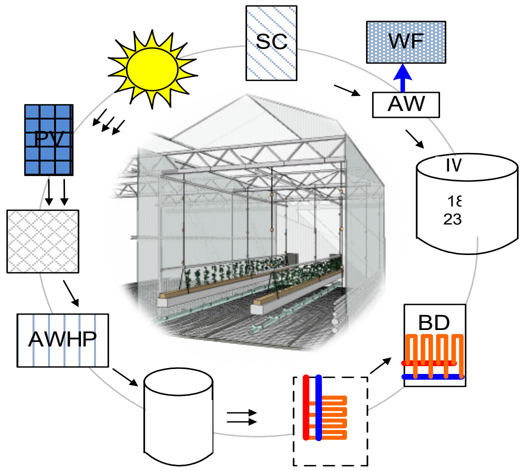

Fig. 2. Provision of heat supply of the experimental greenhouse with solar energy, a full-cycle scheme, where: PV - solar panels; SC - solar collectors; EA - storage battery for solar electricity; AWHP - air-to-water heat pump; WHA - water heat accumulator; GH - experimental greenhouse heating system; AW - irrigation water; WF - irrigation water filter; IWH - irrigation water heating; BD - drying of biomass; AW - Artesian well water, ~10°C.

One Hitachi RWH-4.0VNFE air-to-water heat pump (AWHP) of 5.33 kW electrical power (10 kW heat power) was installed. The energy from the grid made up the difference when there was insufficient energy form the solar system. The need for energy accumulation for the day/night cycle was calculated to be 0.2-0.3 kWh m^{-2} for electrical power storage or 1.0 kWh m^{-2} for the heat power storage. These power storage requirements are economically affordable and are comparable to the cost of the PV cells. As for the heat power storage, usually, industrial greenhouses already have this capacity installed as a part of the existing heating system. In the experimental greenhouse a computerized temperature measurement system with 23 temperature sensors was used to control the temperature in the different parts of the heating system and in the greenhouse itself, as well as in the reference greenhouse. Particular attention was paid to measuring the temperature of the heating water in different parts of the heating system. This was considered important because the coefficient of performance (COP) of the heat pump strongly depends on the temperature of the heating water. Using producers COP data at 4 outdoor temperature points and 2 heating water temperatures we interpolated the COP of the heat pump for all outdoor and heating water temperature combinations. The temperature measurement system read the data from the sensors with 30 second interval and the data were stored in a server that was accessible online for data downloads and analysis.

The study was done from the summer 2021 till winter 2023. Because of the huge volatilities of the energy prices (for both electricity and natural gas) the timing of the experiment was unfortunate for the economic analysis of the performance of the experimental system.

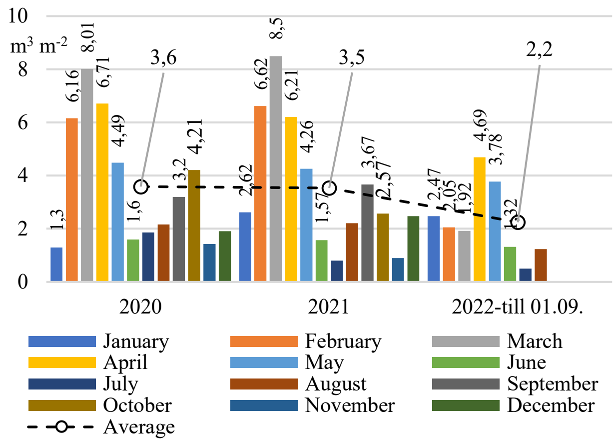

Fig. 3. Gas consumption and price in the reference greenhouse.

Due to the start of the war in Ukraine the energy prices for year 2022 were too extreme in Latvia to be used in any meaningful economic estimates. Therefore, the 2021 Nordpool day ahead electricity prices and the market prices of natural gas were used for the economic analysis, Figure 3.

RESULTS

In Latvia climate condition the greenhouse should be heated almost all the year with exception of sunny warm weather in summer. The greenhouse we studied – both the experimental greenhouse and the industrial reference greenhouse, were used for the part of the year with winter reserved for the servicing needs with minimal heating and thus minimal energy consumption during the winter time. Obviously, the highest need for heating energy is at the early spring and the late autumn. Due to the climatic conditions in Latvia and the dynamics of the industrial production, the end of the season is the most important factor defining the requirements for the energy storage as the stored energy defines how long the productive season can be extended in autumn.

In this research the experimental greenhouse was heated with the combination of solar collectors and heat pump while the PV panels were used in two setups – in direct DC heating of hot water boiler to test a low-capital investment setup without DC/AC conversion and in a second mode with PV output converted to AC and used to drive the heat pump.

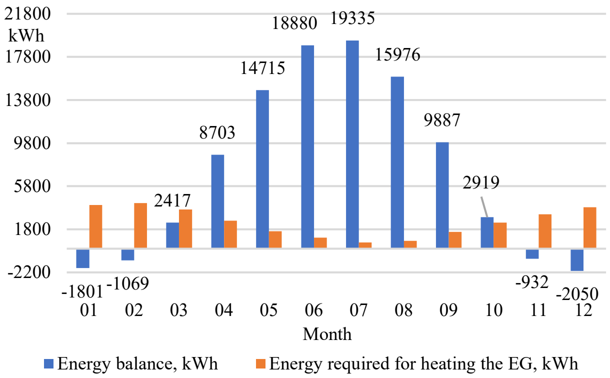

Fig. 4. Energy balance and required energy for heating, 2022, kWh.

In the combined regime of heating the experimental greenhouse with solar collectors and air-to-water heat pump the energy consumption of the heat pump was studied as it defines the potential need for the electricity storage or alternatively the costs of the electricity from the grid to supplement the renewables. The heat pump used on average 0.3-0.5 kWh m^{-2} a day during May-August, 0.7-0.8 kWh m^{-2} a day during April and August/September and 1-1.2 kWh m^{-2} a day during October and March, Figure 4.

Availability of solar energy is out of phase with the need for heating both during the day/night and the seasonal cycles. Figure 5 shows the monthly distribution of the total energy used for heating by AWHP and the total energy produced by solar PV and solar collectors as the percentage of the total energy over the whole period.

The amount of the electrical energy for the heat pump depends on its COP that in turn is related to both heating water temperature and outdoor air temperature. COP can be increased designing the greenhouse in a way that minimizes the heating water temperature but, in this work, the experimental greenhouse was built to replace the existing industrial greenhouse heating system - fitted to gas boiler and using relatively high heating water temperatures of up to 60 ºC by colder weather.

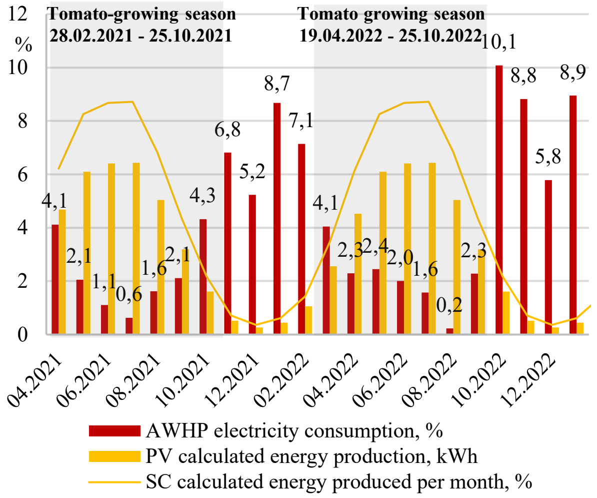

Fig. 5. Monthly energy distribution from various heating and energy sources. Grey area is the active tomato growing season. Energy represented as a part of total energy used in each of the months expressed as a percentage of the total energy over the whole period.

COP of air-to-water heat pump varies between 2 and 6.5 in the outdoor temperature range between -7 °C and +7 °C while difference in COP between heating water temperatures of 35 °C and 55 °C can be up to 30 %. During the warm season, from April to October, outdoor air heat pumps operate with a high COP. This means that for every unit of energy used to run the heat pump, we get 3 to 5 units of heat energy. As the temperature of the outdoor air decreases, the efficiency of use decreases. Our findings showed that the average COP in 2022 is 4.3, while it is 5.6 in the warm season from April to October and 2.8 in the hot season. The measurements of heating water temperatures in the experimental greenhouse stated that heating water temperatures are not directly related to the outdoor air temperatures as can be seen in Figure 6. There are a number of other factors like daily indoor temperature changes and solar irradiation that influence the heating water dynamics in the greenhouse [18]. As the COP of the AWHP depends on the heating water temperatures, a performance of heat pump cannot be calculated using only outdoor temperature data because heating water can have any temperature for a given outdoor air temperature. In our work we used the theoretical performance of AWHP from the experimentally measured heating water temperatures in the experimental greenhouse. Using the heat pump's factory-specified COP and comparing energy expenses – prices of electricity for AWHP in the experimental greenhouse and gas for the gas boiler in the reference industrial greenhouse we estimated that the heat pump is economically a twice more efficient way of heating greenhouse than natural gas until the end of September 2021.

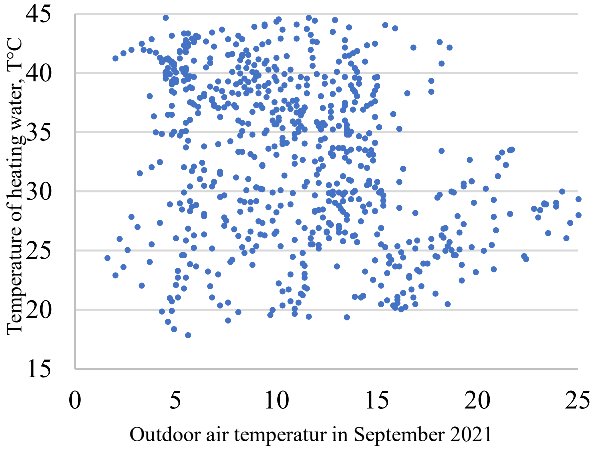

Fig. 6. The temperature of incoming heating water in the experimental greenhouse as function of outdoor air temperature.

2021 energy price data were used because of the war in Ukraine and the following energy price shock in the Baltic States. The 2022 price data were not suitable for analysis. As can be seen in Figure 7. the energy cost of AWHP was considerably (more than twice) lower than the cost of natural gas heating. The fluctuations in the cost ratio in Figure 7. are due to day/night electricity price differences in Nordpool day ahead market.

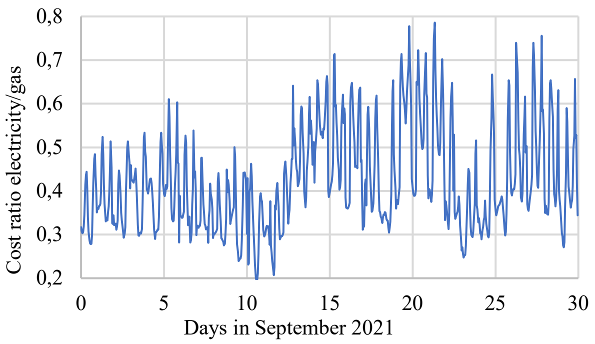

Fig. 7. Calculated cost ratio between grid electricity for AWHP and gas for boiler in September 2021.

Hourly electricity consumption was calculated from interpolated COP values for hourly outdoor and heating water temperatures. The amount of natural gas to produce the same amount of energy was calculated using COP of 0.94 for the natural gas boiler installed at the reference industrial greenhouse.

Energy Storage

Several time intervals – intraday, day/night and finally the longer cold cloudy weather periods that should be covered by the energy storage, were identified. Intraday storage should accumulate the heat energy for cloudy periods of the day that might last several hours. Day/night cycle is further complicated by the dynamics in the indoor temperature regime for the plants. The indoor temperature is some centigrades lower during night time that shifts heating energy consumption for some time delaying the need for heating in the evening and requiring more energy in the morning. The need for energy accumulation for the day/night cycle was calculated to be 0.2-0.3 kWh m^{-2} for electrical power storage or 1 kWh m^{-2} for heat power storage. These power storage requirements are economically affordable and are comparable to the cost of the PV cells. As for the heat power storage, industrial greenhouses already have this capacity installed as a part of the existing heating system.

In Latvia, the cold, cloudy periods may last up to 7–10 days or even longer. Some research has reported that changes in the polar vortex can bring longer periods of both warm and cold weather [19, 20]. Dunkelflaute's studies, e.g. [21] will bring more insight into this climatic condition. We estimate that the requirements for the energy storage are defined by the requirement that the greenhouse heating system should be able to withstand at least 10 days' cloudy cold spell during the productive season.

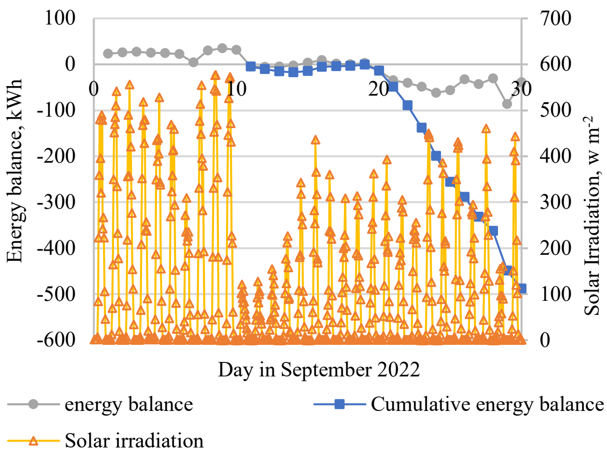

Fig. 8. Solar irradiation and both daily and cumulative energy balance in greenhouse in September 2022.

Clear sky conditions at the beginning of September come together with larger daily day/night temperature differences and the need for energy storage to cover heating for colder nights and surplus electrical energy produced by PV. Cloudy weather with more stable outdoor air temperatures in mid-September demonstrates conditions with energy balance close to zero. Solar irradiation and both daily and cumulative energy balance in the greenhouse in September 2022 are shown in Figure 8. With lower temperatures and partially cloudy skies the cumulative energy deficit starts to rise fast in the 2nd half of September and it cannot be covered by energy storage in an economically feasible way. Electricity from the grid or other heat source like biomass or natural gas boiler should be used to cover the periods when there is not enough solar and stored energy.

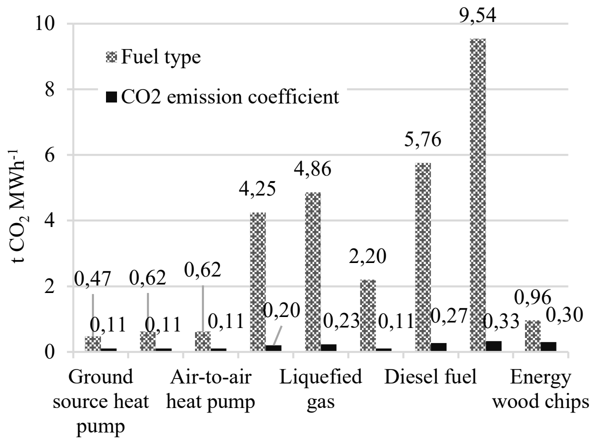

Fig. 9. CO_2 emissions associated with the EG heating.

When estimating CO_2 reduction in a hybrid heated greenhouse as compared to traditional natural gas heated greenhouses (Figure 9) an assumption should be made about the ratio of CO_2-free electricity in the grid. In Latvia, the electricity from the grid is approximately 75% CO_2-free, the overall effect of using the electricity from the grid is at least 5-8-fold reduction in CO_2 emissions as compared to gas.

CONCLUSIONS

Hybrid system using solar power by solar collectors and PV-driven air-to-water heat pumps can be used for greenhouse heating in Latvia, but it can't cover the beginning and the end of the productive season of greenhouses and the current energy storage technologies do not allow heating with solar energy only.

Energy storage for the day/night cycle was calculated to be 0.2-0.3 kWh m^{-2} for electrical power storage or 1.0 kWh m^{-2} for the heat power storage. The costs for such storage facilities are economically affordable.

Grid-connected solar collector and PV driven air-to-water heat pump heating system for greenhouses reduces CO_2 emissions at least 8-fold as compared to natural gas heating. The cost of heat pump was lower than the cost of gas heating for temperatures above –3 °C at 2021 energy prices.

A topical issue for further research is the possibility of storing the excess energy produced by the system over a longer period of time in an ecologically and economically safe manner.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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