

## DEVELOPMENT OF TECHNOLOGICAL PROCESS SOLUTIONS IN MODULAR SYSTEM OF SOLAR ELECTRICITY AND HEAT SUPPLY FOR GREENHOUSES

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**Abstract.** Considering the recent rapid increase of the energy costs for heating commercial greenhouses, solutions for more efficient use of the solar energy are needed. In this study there is investigated application of solar energy for greenhouse heating with a joint equipment, which consists of 8.0 kW solar photovoltaic panels (PV), coupled with a 5.0 kW air-to-water heat pump, 15.0 kW solar collectors (SC), a 10 kWh solar energy accumulator (SEA), and 1600 litre water heat accumulators (WHA). The tests of the joint equipment were made in a 50 m<sup>2</sup> experimental greenhouse (EG) in several stages: testing of heat accumulation in the water-based heat tanks, testing of the amount of the solar energy, produced by the photovoltaic panels, used for direct water heating and for the operation of the air-to-water heat pump with and without the solar accumulator; and in the periods with insufficient solar energy directly from the grid. Surplus heat from the system was used to heat the irrigation water or to drive the biomass dryer. The temperatures in various points of the heating system were measured and analysed together with average temperatures and the data about the heat and solar energy. The results of the 2022 study showed that in EG, at the average annual solar intensity of 1227.4 kWh·m<sup>-2</sup>, 6762.7 kWh of electricity was produced by PV panels, and 12385.2 kWh of heat energy by SC. In the industrial greenhouse (IG), where the total energy consumption during the period, when natural gas was used, was 17.95 m<sup>3</sup>·m<sup>-2</sup> or 163.73 kWh·m<sup>-2</sup>, causing climate change-promoting gas emissions (GHG) of 30.29 kg CO<sub>2</sub>·m<sup>-2</sup>; the experimental greenhouse (EG) emission factor was not detected. We concluded that, without a long-term energy storage system, covering several weeks of heat consumption, the solar energy system should be supplemented with external energy sources to cover the extended periods with insufficient energy supply at the beginning and the end of the vegetation season.

**Keywords:** solar energy, heat pump, solar collectors, greenhouse, heating.

### Introduction

The European Green Deal [1], where European Commission has adopted a set of proposals to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse GHG by at least 55% by 2030, will require broad changes in the energy across different sectors of economy. Being in the temperate climate zone, thermal energy production in Latvia is a significant source of GHG and air pollutants – 65.6% of total GHG emissions [2]. Agricultural sector is one of the sectors where the replacement of the fossil energy sources is the most difficult and challenging; at present agriculture produces 30-40% of all anthropogenic GHG emissions [3]. Latvian government, like other countries, promotes the use of renewable energy resources in various sectors [4]. The photovoltaic (PV) system is playing a significant role in providing clean and sustainable energy [5]. There are different ways of GHG free heating for a greenhouse such as using methane from the waste disposal sites, geothermal energy, burning biomass or cogeneration, or even the leftover heat from the nuclear power plants [6-8]. Complementary solution for the reduction of GHG could be the use of solar energy for the reduction of CO<sub>2</sub> emissions.

The annual global radiation on a horizontal surface in sunny regions can reach 2200 kWh·m<sup>-2</sup> [9]. Research has been carried out on the use of the PV panels for heat extraction by directly connecting the active resistance to them, for example, electric heaters for heating the tap water. In study [20] it was pointed out that many factors affect the productivity of solar panels, the most important of which are the power of solar radiation, received by the working surface of the panel and the temperature of the cell, and the PV element.

Several studies have indicated that the heat pump systems are very competitive with conventional heating, ventilation and air-conditioning (HVAC) systems in terms of cost, COP range and payback period [11; 12]. In some of the studies there is indication to the heating performance of the AWHP system with a storage tank for the greenhouse heating by calculating COP of the system [13]. Other researchers have carried out economic analysis of the AWHP system in the heating mode, where the results forecast an average COP of 4.5 and 70% reduction in the energy cost, when compared with a conventional air heating system [14]. The convenient installation and comparatively low cost of the air

source heat pumps makes them a viable option for energy to greenhouses [15]. Some studies have concluded that the use of an air source heat pump could be of great interest due to many of its other advantages, such as simple operation, low maintenance, and no pollution [15; 16]. The heat pumps use less energy to generate thermal outputs that are several times higher than ground source heat pumps (GSHPs) [17]. In our previous studies, we proposed an air-to-air heat pump (AAHP) model for greenhouse heating and cooling, where the energy efficiency, compared to the industrial facility, was approx. 8 times better, and the estimated CO<sub>2</sub> emissions were 8-16 times lower, compared to gas heating [18].

This study is aimed to find a more optimal solution for heating greenhouses by applying solar energy with a joint integrated equipment, which consists of PV panels with an energy storage battery, coupled with AWHP, SEA, WHT and surplus heat use for heating irrigation of water, or to run the biomass dryer. An economic alternative for converting greenhouses into low CO<sub>2</sub> industries is to find a new low CO<sub>2</sub> heating source for the existing greenhouse infrastructure.

**Materials and methods**

EG was created by separating 50 m<sup>2</sup> from IG, located in the Southeast of Latvia (56.500197, 25.775123). The design, the heating system and the data acquisition system are described in detail in [19]. In this research we analyse the performance of the EG heating system (Fig. 1), consisting of Hitachi RWH-4.0VNFE AWHP of 5.0 kW power (10.0 kW heat power) and a solar hot water system, calculated for 15 kW power. The PV panels with 8.0 kW peak power could be used either directly for water heating in a water boiler in the DC mode, connected to the greenhouse heating system, and/or via the inverter supplied electricity to AWHP. The accumulation system of the heat energy consisted of three hot water boilers with a total volume of 1860 litres, each boiler connected to a separate energy generation system – AWHP, SC and connection to the PV panels in DC mode.

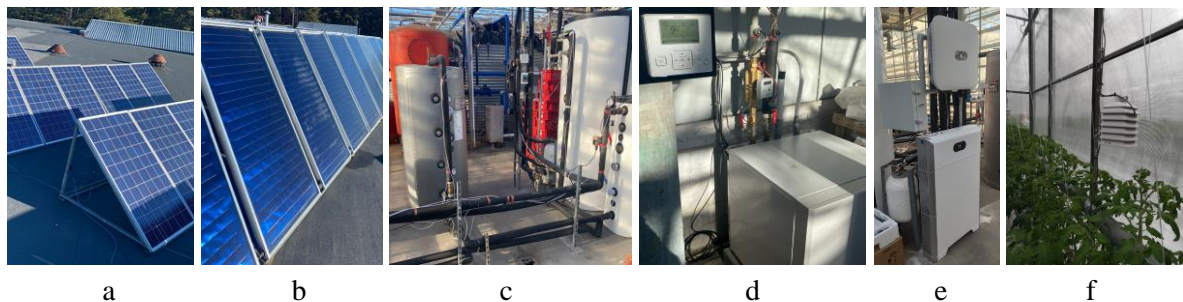


Fig.1. Heating system with joint integrated equipment: a) PV panels; b) SC; c) hot water boilers; d) AWHP; e) SEA with an inverter; f) EG

The total heating power was chosen to fit the heating requirements, corresponding to a productive season, starting at 19.04.2022 and continuing till 25.10.2022, and a servicing period during the winter period when the temperature should be maintained low but above zero.

According to the Global Solar Atlas meteorological data [9] in the existing location the solar radiation has comparatively low intensity. Figure 2 for the last 10 years shows that the average in year intensity of solar radiation is 983 kWh·m<sup>-2</sup>, but the local weather station of the greenhouse recorded 1150 kWh·m<sup>-2</sup> of solar radiation intensity in 2022, 1900 hours of sunshine, 4400 hours of light and 4300 hours of darkness.

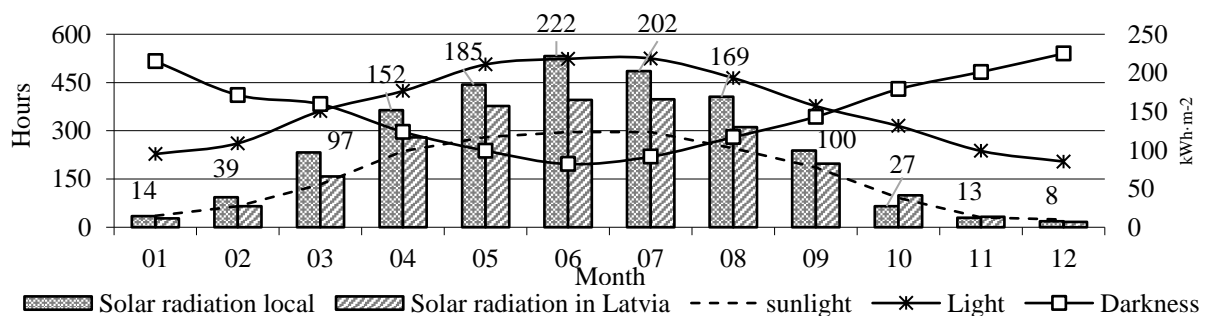


Fig. 2. Intensity of solar radiation

Figure 2 shows that a significant amount of solar energy per day can be obtained in the period from March to September, inclusive. A small amount of solar energy, obtained per day in EG location, is usually in the period from November to March.

The solar power used directly for water heating by PV in a water boiler in the DC mode, produced during the day, was theoretically calculated as a function of time,  $P = f(t)$ , using the mathematical function *ABS* and formula (1) [10].

$$P_i = \frac{\left(\frac{U_{Hi}}{k}\right)^2}{R_{si}}, \quad (1)$$

where  $P_i$  – registration time of the solar panel, W;  
 $U_{Hi}$  – value of voltage, V;  
 $k$  – partition coefficient of the voltage divider,  $k = 0.06$ ;  
 $R_{si}$  – numerical value of the load resistance, connected to the respective solar panel,  $\Omega$ .

The quantities of the produced electric energy are calculated, using the mathematical function *SUM* formula (2, 3) [10].

$$\eta_p = \frac{P_p}{P_{st} L_p}, \quad (2)$$

where  $P_p$  – power, produced by the solar panel, W;  
 $P_{st}$  – power of solar radiation,  $\text{W m}^{-2}$ ;  
 $L_p$  – working surface of the solar panel,  $\text{m}^2$ .

$$\eta_q = \frac{Q_p}{Q_{st} L_p}, \quad (3)$$

where  $Q_p$  – energy, produced by the solar panel, Wh;  
 $Q_{st}$  – value of the solar radiation energy,  $\text{Wh m}^{-2}$ ;  
 $L_p$  – working surface area of the solar panel,  $\text{m}^2$ .

For heating water for the plants the performance of the heat pump was calculated, using the outdoor air temperature and the heating water temperature data (4, 5) and AWHP COP data, provided by the producer of AWHP [6].

$$T_{W,35^\circ\text{C}} = 0.0006T_o^3 - 0.0121T_o^2 + 0.193T_o + 4.8632, \quad (4)$$

$$T_{W,55^\circ\text{C}} = 0.00007T_o^3 - 0.00055T_o^2 + 0.175T_o + 3.2284. \quad (5)$$

where  $COP$  – coefficient of performance;  
 $T_o$  – outdoor air temperatures of the reference period,  $^\circ\text{C}$ ;  
 $T_W$  – heating water temperature,  $^\circ\text{C}$ .

Calculation of the required amount of energy for the experimental greenhouse was made, using the formula (6) [20]:

$$Q = \frac{A(T_i - T_o)}{R}, \quad (6)$$

where  $Q$  – heat loss, kWh;  
 $A$  – area of the greenhouse surface,  $\text{m}^2$ ;  
 $R$  – resistance to the heat flow (a characteristic of the material);  
 $T_i, T_o$  – air temperature differences between the inside and the outside temperatures.

Calculation of the amount of energy, required for heating water for watering was made, using formula (7)

$$Q = mc\Delta T, \quad (7)$$

where  $Q$  – amount of energy, required to heat water for irrigation (watering) (kW);  
 $m$  – mass in kilograms (1 litre of water  $\approx$  1 kg);

$c$  – heat capacity  $\text{Wh} \cdot (\text{kg} \cdot \text{K})^{-1}$  (for water  $c \approx 1.16 \text{ Wh} \cdot (\text{kg} \cdot \text{K})^{-1}$ );  
 $\Delta T$  – difference between the temperatures of cold and hot water ( $T^\circ\text{C} = 20$ , 350 litres per day) (K).

An electrical battery of 10 kWh capacity was coupled to the inverter and the PV panels, and used to supply AWHP. The heating water temperature was measured at critical points of the heating system and also in EG and outdoors. IG was used as reference. For the solar irradiation and other metrological measurements the data from the IG meteorological data collection system was used.

**Results and discussion**

The heating power was sufficient to ensure optimum temperatures, required for tomato production at the greenhouse. During the productive season the temperature had to follow a 7-step daily cycle with minimum of 16 °C at night and maximum of 21 °C during the day, slightly adjusted to the growth stage of the plants.

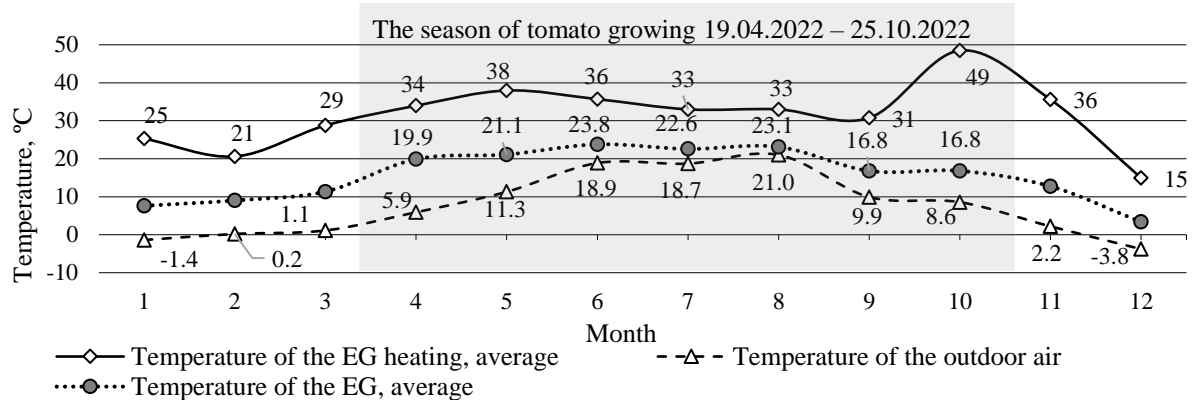


Fig. 3. Temperature conditions in EG

The heating system was built so that the heat from all the sources was combined to the hot WHA, and then the temperature of the hot water, flowing into EG, was regulated to ensure the optimum temperature there. In this way the experimental heating system was compatible with the existing heating system for IG with a natural gas boiler heating system via the selection of a hot water source.

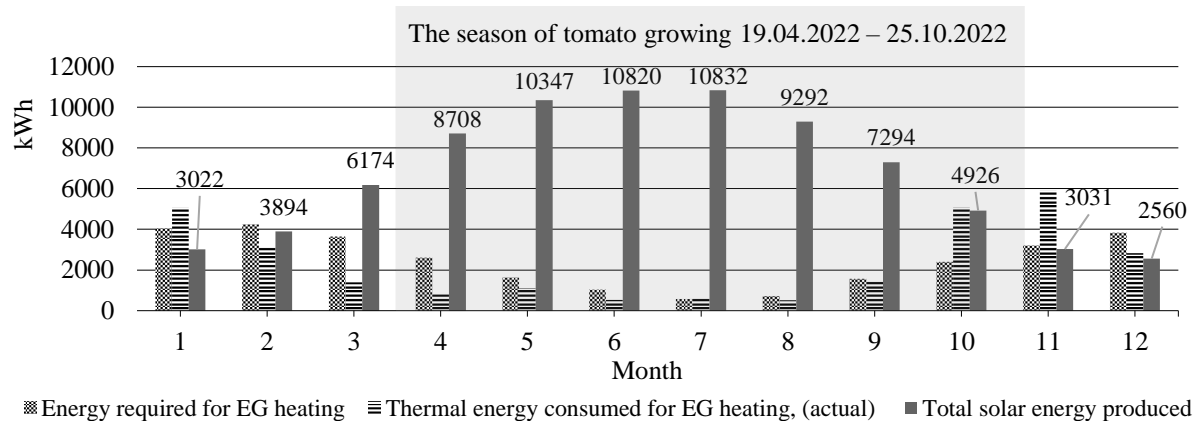


Fig. 4. Balance of the produced, consumed energy

A limiting factor for the fraction of the greenhouse energy, supplied by solar energy is energy storage for colder periods without direct sunshine. Several studies [17; 21] found that electrical energy storage will allow the use of electricity in renewable-sourced grids with the same demand centric perspective that is provided today from fossil fuel sourced grids. The energy capacity required is likely between 4 and 12 hours of average power demand. Some research [22] showed that all the issues can be addressed at low economic cost and the worst-case, conservative technology choices (such as dispatchable capacity for the peak load, grid expansion and synchronous compensators for ancillary services) are not only technically feasible, but also have costs which are a magnitude smaller than the

total system costs but more cost-effective solutions that use variable renewable generators intelligently are also available. The practical viability of 100% renewable energy systems is controversially discussed mainly because of the extensive storage requirements to ensure supply and grid stability [22]. The excess solar energy – either in form of heated water or electricity – should be stored for later use. The requirements for energy storage and the cost of energy storage determine what fraction of the total greenhouse energy consumption can be covered by solar energy.

In our experimental setup we found that intraday heating, lasting for up to 50% of the day, can be conveniently covered by hot WHA and SC, or any other heat source. Usually for the intraday heating the heat requirements for the heat accumulators are 0.05-0.2 kWh·m<sup>-2</sup>, depending on the time of the year. The heat storage requirements for the day-night cycle are up to 1 kWh·m<sup>-2</sup> or even 2 kWh·m<sup>-2</sup>, depending on the time of the year (Fig. 5). The longer the season, the higher the heat storage requirements due to the colder and longer nights. As a rule, March would be the most demanding month in the day/night cycle where temperatures could be as low as -10 °C, and even lower.

The heat storing requirements for the day/night cycle of the system would be set by the start of active production season in spring. Typically, all the existing greenhouses, heated by fossil fuel, have hot WHA with the capacity, exceeding the requirements for both the intraday and the day/night heating cycle.

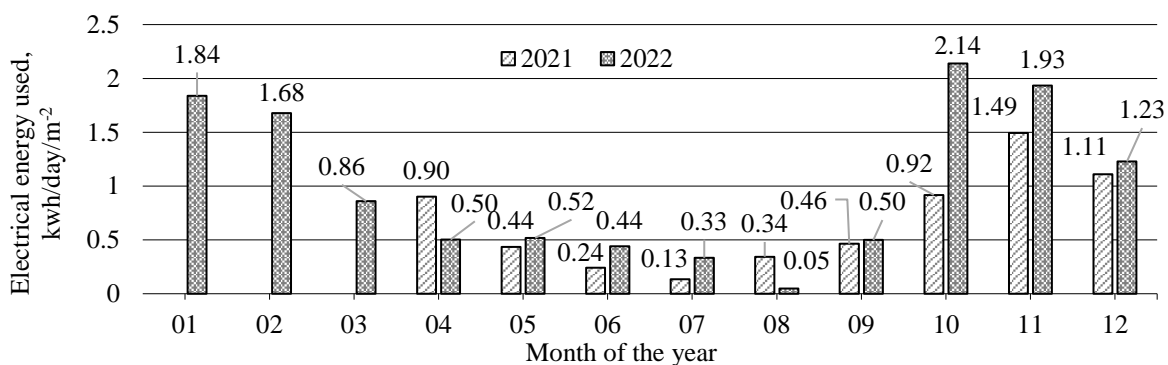


Fig. 5. Daily averaged electrical energy, used by AWHP in kWh per square meter of the greenhouse in month

The cold, cloudy periods of local weather conditions may last up to 7-10 days. The climate studies and recent reports indicate that the changes of the polar vortex and increased perturbations in the borders of the vortex can bring longer continuous periods of both warm and cold weather in Latvian latitudes [23; 24]. This can change the climate pattern and distribution of cold and warm days without big changes in average temperatures and solar irradiation (radiation). Our estimate is that the greenhouse heating system should be able to withstand at least 10 days' cloudy cold spell in any of the seasons. The studies of the dunkelflaute phenomena, related to requirements of wind and solar electricity generation [25] will bring more insight into this climatic condition, requiring long continuous heating periods for the greenhouses.

In our research we have estimated that the heat storage requirements for the long cold cloudy periods under the Latvia climatic conditions are 3–10 kWh·m<sup>-2</sup> of heat energy or even up to 15 kWh·m<sup>-2</sup>, depending on the time of the year. This is several times more than a typical hot WHA, installed in the existing greenhouses.

The requirements for the storage of electricity to drive AWHPs are more difficult to estimate since COP of the heat pump depends on the outdoor air temperature and can vary between 1.5 and 5 in the temperature range that can be expected for a cold, in the time period from the end of February to the beginning of November.

Requirements to AWHP and the solar energy system are set by the condition at the beginning and end of the productive season. During the rest of the season the solar energy is more available and the higher outdoor air temperature means much better COP for the heat pump leading to much lower costs of heating. In this work we concentrate more on the energy storage requirement for the extension of the productive season in September and October.

In Figure 5 there is daily electrical energy used by AWHP in greenhouse heating averaged over one-month period in kWh per square meter of the experimental 50 m<sup>2</sup> greenhouse. AWHP was part of the heating system and was activated only in cases when there was insufficient amount of the heat from SC with the installed capacity of 0.3 kW m<sup>-2</sup>. The difference between 2021 and 2022 is mainly due to PV panels being coupled to DC direct heating in 2021 and used to power the heat pump in 2022. The heat pump requires some energy to run on a standby mode and in a more careful power management system it would be switched off when not in use. In our experiment for the purposes of research it was not switched off.

The primary heating source was SC, and the heat pump was automatically starting heating only when heat from SC was insufficient for heating. As it can be seen in Figure 5, there is a clear deficit of solar energy in April and September.

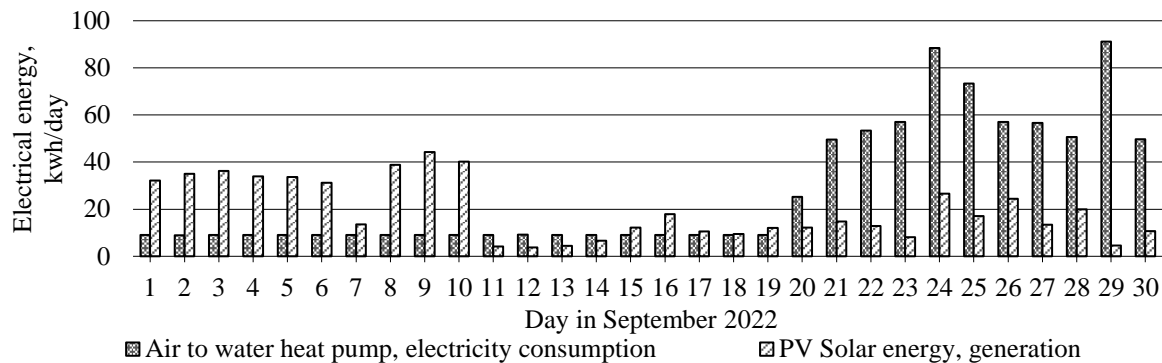


Fig. 6. Electricity balance in heating of EG in September 2022

The daily energy consumption by the heat pump to heat 50 m<sup>2</sup> EG and daily generation of electrical energy by the solar panels with 8.0 kW installed power. AWHP worked as a secondary heating source in cases when the primary heating source, consisting of 0.3 kW m<sup>-2</sup> installed power SC, could not deliver the energy needed for the greenhouse.

As it can be seen in Figure 6, AWHP electricity consumption was on flat standby mode until the 19th of September 2022 with SC providing almost all the needed heating energy. After the 19th of September a sudden deficit of solar energy started. For the extension of season after the 19th of September either an energy storage with sufficient capacity or the electricity from the grid is required.

The results of the 2022 study showed that in EG, at the average annual solar intensity of 1227.4 kWh·m<sup>-2</sup>, 6762.7 kWh of electricity was produced by the PV panels, and 12385.2 kWh of the heat energy – by SC.

Figure 7 shows the relative CO<sub>2</sub> emissions associated with the heating of EG 50 m<sup>2</sup>, Δt = 20°C.

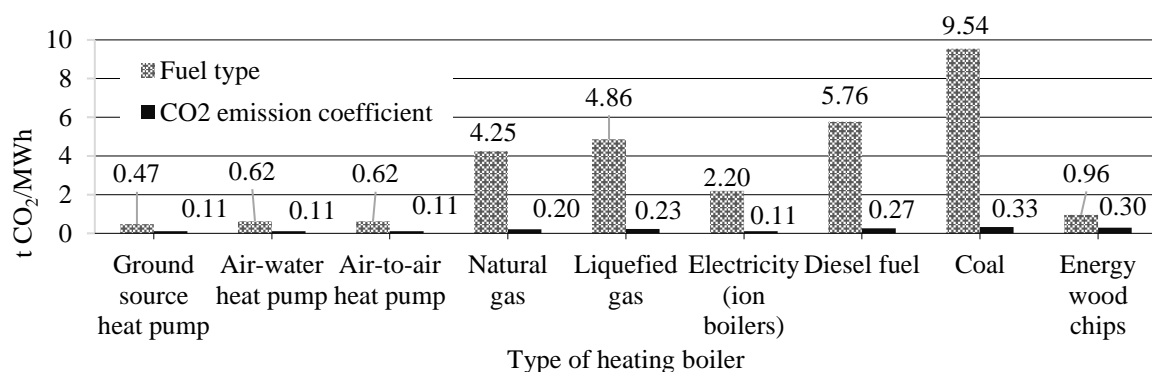


Fig. 7. CO<sub>2</sub> emissions associated with EG heating

In IG, where the total energy consumption during the period when natural gas was consumed, was 17.95 m<sup>3</sup>·m<sup>-2</sup>, or 163.73 kWh·m<sup>-2</sup>, was causing climate change–promoting GHG of 30.29 kg CO<sub>2</sub>·m<sup>-2</sup>. The CO<sub>2</sub> emissions from EG can be attributed to the electricity, used by the heat pump. With the nominal COP of the air to the water heat pump between 2.5 and 5 during the productive season, we estimate that at least 10-fold reduction of CO<sub>2</sub> emissions is achieved by using the hybrid heating system while simultaneously lowering the operating costs.

## Conclusions

1. A modular hybrid heating system, consisting of SC, solar panels (PV) and the air to water heat pump is compatible with the existing gas heated greenhouse heating systems and can be installed gradually by adding new modules to increase the fraction of the CO<sub>2</sub> energy in the greenhouse heating.
2. The use of solar energy for greenhouse heating requires storage of heat. The heat storage requirements for the day-night cycle are up to 1 kWh·m<sup>-2</sup> or even 2 kWh·m<sup>-2</sup>, depending on the time of the year (season). Solar energy should be supplemented by electricity from the network. For economic reasons during very cold meteorological conditions with temperature below -10 °C the air to water heat pump should be substituted by the biomass or gas burning heating system if possible.
3. In our experimental greenhouse with 0.3 kW·m<sup>-2</sup> SC, 0.15 kW·m<sup>-2</sup> solar panels (PV) and 0.2 kW·m<sup>-2</sup> air-to-water heat pump was achieved at least 7-fold CO<sub>2</sub> emission reduction while lowering the operating costs, the calculation made with 2021 market prices.

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## Author contributions

Conceptualization, A.A. and A.J.; methodology, A.A. and A.R.; data validation, I.A.H. and U.G.; formal analysis, S.I.; investigation, A.A., A.R., S.I., U.G. and A.J.; writing – original draft preparation, A.A.; writing – review and editing, A.J. and A.R.; project administration, S.I. All authors have read and agreed to the published version of the manuscript.

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