USE OF HEATING PUMP TO REDUCE CARBON FOOTPRINT OF GREENHOUSE HEATING

Agris Auce[1], Adolfs Rucins[2], Aivars Jermuss[2], Indulis Arnis Horns[1], Ugis Grinbergs[3]
[1]University of Latvia, Latvia; [2]Latvia University of Life Sciences and Technologies, Latvia;
[3]Institute of Mathematics and Computer Science, University of Latvia, Latvia
a@aa.lv , adolfs.rucins@llu.lv, aivars.jermuss@llu.lv ,
indulis.horns@gmail.com , ugis@adsl.lv

Abstract. Heat pumps are highly efficient tools in reducing the CO_2 output in heating as compared to directly burning fossil fuels. However, their technical and economic characteristics are not well understood for greenhouse heating in Latvia climatic conditions. In this research, a commercially available regular air to water heat pump 5 kW (10 kW heat power) supported by solar panels (PV) 7.5 kW peak power and a solar hot water system 15 kW peak power were used to heat an experimental tomato greenhouse (50 m^2) located at a commercial production facility in South-East of Latvia. To reduce the capital expenses the DC output from PV panels was fed directly into the hot water boiler. The results obtained during late summer and during September 2021 are analyzed. While the climatic conditions were rather typical, the energy market for both natural gas and electricity (Nordpool prices) showed extraordinary variations with electricity prices striking record 1000 $EUR \cdot MWh^{-1}$ at some points. The results were compared with those of the industrial production facility that was heated by natural gas boilers. In periods of very low subzero temperatures and/or very high electricity prices, the heating with natural gas boiler was cheaper, while at temperatures close to zero and above the freezing point the heat pump outperformed the natural gas heating economically. At the climatic and market conditions of the second half of 2021 a heating system using natural gas or biomass boilers at periods of low air temperatures or high electricity prices and an air-to-water heat pump supported by PV panels and solar water heaters at periods of higher outdoor air temperatures and during low electricity prices has the best economic performance. We have estimated that using such hybrid system in greenhouse heating we can achieve 3-fold reduction of CO_2 emissions without increasing the heating costs.

Keywords: heat pump, greenhouse, heating, carbon.

Introduction

Greenhouse farming is an important part of agriculture that consumes thermal energy derived mostly from fossil fuels. The European Green Deal strategy calls for reduced use of fossil resources in the energy system, thus stimulating the technology of renewable energy sources [1]. The use of coal, natural gas, and oil for production of electricity and heat is the largest single source of greenhouse gases (GHG) and reaches up to 25% of global GHG emissions by the greenhouse industry [3]. With the rise of technological advances and energy costs, the heat pumps using ambient air heat are now as a competitive alternative of the thermal energy source [4; 5].

The air-to-water heat pump system in moderate winter of Australia showed about 16% savings of present LPG usage. In this case the air-to-water heat pump system payback period was less than six years. In terms of GHG emissions, the tested heat pump system produces almost the same level of CO_2 as the LPG system, so no environmental benefits were fixed of the heat pump system [6].

Reduction of CO_2 emissions from greenhouse heating require a lot of investment in new low energy facilities and therefore for prompt reduction of CO_2 emissions it is important to find ways to substantially reduce CO_2 emissions while using the existing facilities as much as possible. The air source heat pump does not require investment in specific heat exchangers buried in the ground or boreholes and similar costly installations. However, switching to a technology that is different from the currently installed there are additional investment costs associated with low-carbon technologies. Counting all equipment and building costs, it is one of the cheapest heating systems in terms of capital investment provided that there is adequate access to electricity [7]. Successfully used air to water heat pumps can heat originally built natural gas boiler greenhouses. It would provide very cost efficient and fast way of transforming the existing greenhouses and reducing CO_2 emissions in this area of agriculture. In this work the performance of the air-to-water heat pump (AWHP) as the replacement for natural gas heating for greenhouses was studied. Both CO_2 emissions and dependency of natural gas can also be reduced by using alternative heating methods. The most capital efficient way of reducing natural gas consumption in greenhouse heating is just to switch to another heat source and use the existing greenhouse. The coefficient of performance (COP) of AWHP depends on both the ambient air temperature and on the temperature of heating water. Since the greenhouse has its 24-hour temperature cycle the AWHP electricity consumption and the economic results of AWHP as compared to gas heating have to be evaluated by using data from a real greenhouse. In this work the AWHP energy consumption and running costs in the context of the heating requirements of the experimental greenhouse are analysed.

Materials and methods

In the present paper we report the calculations of the performance of the heat pump in comparison to natural gas heating using the market prices for both electricity and natural gas and real temperature data during September 2021. The heat pump heating systems were studied in an experimental greenhouse 50 m^2 (B = 6.15 m, L = 8.30 m, H = 3.40 + 0.7 m roof part) that was detached from the main industrial facility at its northeast corner located in South-East of Latvia (latitude 56.50º N and longitude 25.77º E).

One Hitachi RWH-4.0VNFE air to water heat pump (AWHP) of 5.33 kW power (10 kW heat power) was installed. The heat pump system was combined with solar photovoltaic (PV) panels 7.5 kW peak power and a solar hot water system 15 kW peak power. The DC output from PV panels was fed directly into the hot water boiler for short term thermal energy storage. The harvested heat from these 3 sources was combined for use in heating the greenhouse and excessive heat was redirected to the ground water warming used for watering the plants in the production greenhouse. The existing industrial gas boiler heating system was disabled using 1 inch insulating foam. The use of electricity of the heat pumps was measured at the connection pool to the central electricity grid. The total amount of gas needed to heat one square meter was calculated from the industrial greenhouse facility that was used as the reference greenhouse.

The temperature sensors were installed to measure the temperatures of the heating water at different parts of the heating system. The outdoor and indoor air temperature at 3 different heights in the experimental greenhouse was measured as well. The reference measurements were made at the same heights in the industrial facility.

The temperature measurement system data accumulation and storage conformed to Linked Data concept. It refers to known events at the time and the spatial metadata. For particular research and exploitation goals are Real Time data. Layers for data storage were combined of the database storage and file system. The data managing system employed the open source relational database system PostgreSQL (PDB). The spatial extension of PDB PostGIS was chosen. There was a simple data model planned and implemented. It provided the following roles: 1) storage of data produced by temperature sensors; 2) storage of data provided by other data sources (researches) (future dev.); 3) management of data of activities or events (for future use); 4) geodata storage – contextual spatial data related location, field species etc.

The data management layer was built using API components for data exchange, analytics, and publishing purposes. Open source application service was deployed on the server. This component listed a particular socket for receiving data from the sensor unit provider, processed the received data packets and recorded the data in PDB storage tables employing HTTP API interface. MapServer published necessary contextual spatial data for visualization needs. Supplemental WEB application based on open source Python framework provided the main functionality of the system. To gather sensor data from the sensor node(s) and send it via defined API WEB server deployment a feeder service instance was built and coded. WEB server instance consists of web application and provided data model implemented in the PostgreSQL PDB with PostGIS spatial extension. The setup allowed to gather the data from the sensor units connected to a functional IoT computing node and transfer the data over public GSM connection. The temperature sensing device was based on industrial microchip DS18B20. Sensors for the research were specially designed to minimise thermal inertia by explicitly exposing chips to the air flow and by lowering the connected mass.

The tomatoes grew from the start of February till the first decade of October, but the analysed field data were recorded in the second half of 2021. Outdoor air temperatures of the reference period varied between -20.4 ºC and 24.2 ºC (Fig. 1).

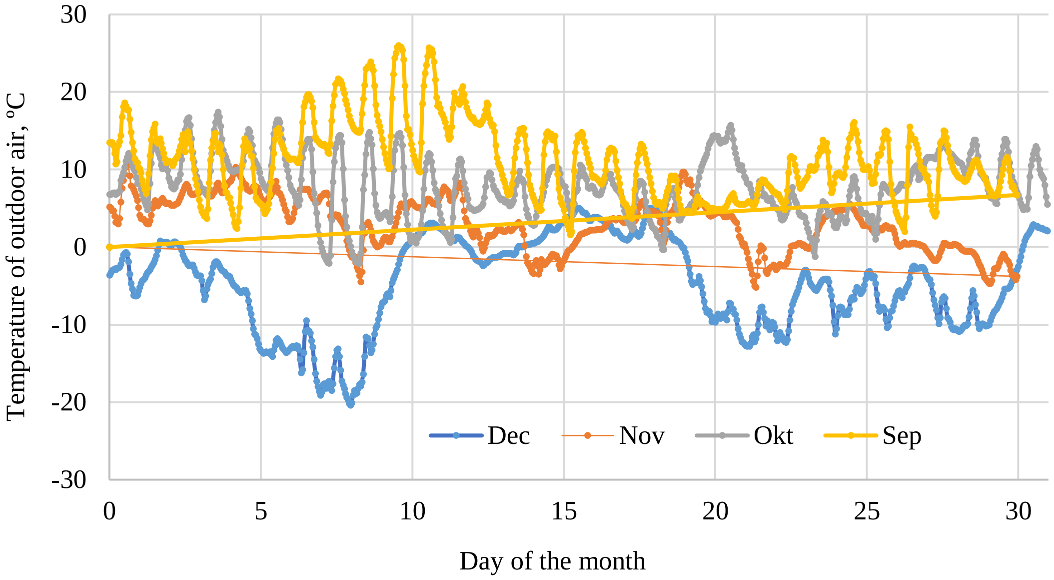

Fig. 1. **Outdoor air temperature during the second half of 2021 at Ltd Ritausma production facility**

For optimal growth of tomato plants in the greenhouse the temperature had to be kept at 21 ºC during the day and 16-17 ºC during the night depending on the daily time and plant development stage (Fig. 2).

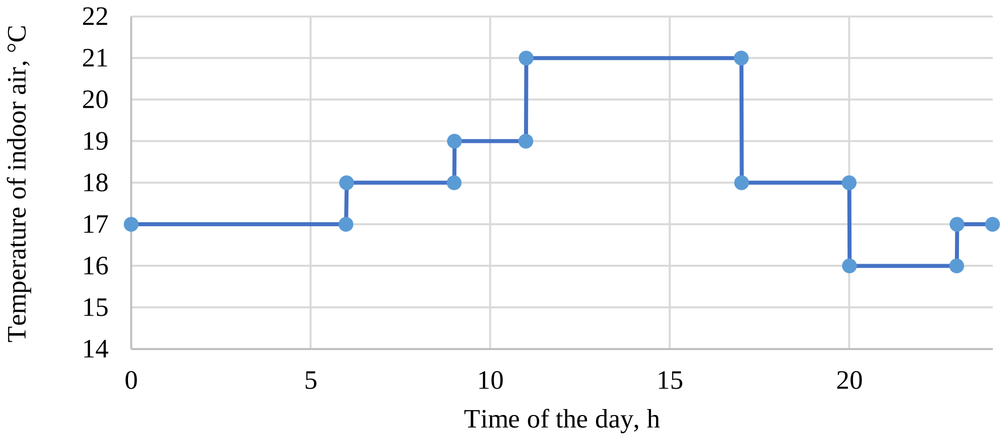

Fig. 2. **Temperature requirements for tomato plants during the productive part of the season**

Beef type tomato *Solanum lycopersicum* L. variety Admiro was grown in four rows with 1.2 m distance between the rows. The transplants were planted into bags filled with coconut fibre at five to six leaf stage. All nutrients were dissolved in water and circulated past the tomato roots in each row. The nutrient solution level was controlled by determining the concentration of hydrogen ions and electric conductivity of irrigation water. The feeding system of the experimental greenhouse was incorporated into an industrial – reference greenhouse system. Ventilation and shading were connected to the general system.

The producer of the heat pump provides the COP at 4 different temperatures: -7, 2, 7 and 12 ºC and also at 2 different heating water temperatures 35 ºC and 55 ºC. In this work the COP of AWHP at any outdoor and heating water temperature combination measured in the experimental greenhouse was calculated by first fitting the COP as a function of the outdoor temperature using the 3rd degree polynomial least square method. Then the obtained values where interpolated assuming the linear dependency of COP on the heating water temperature.

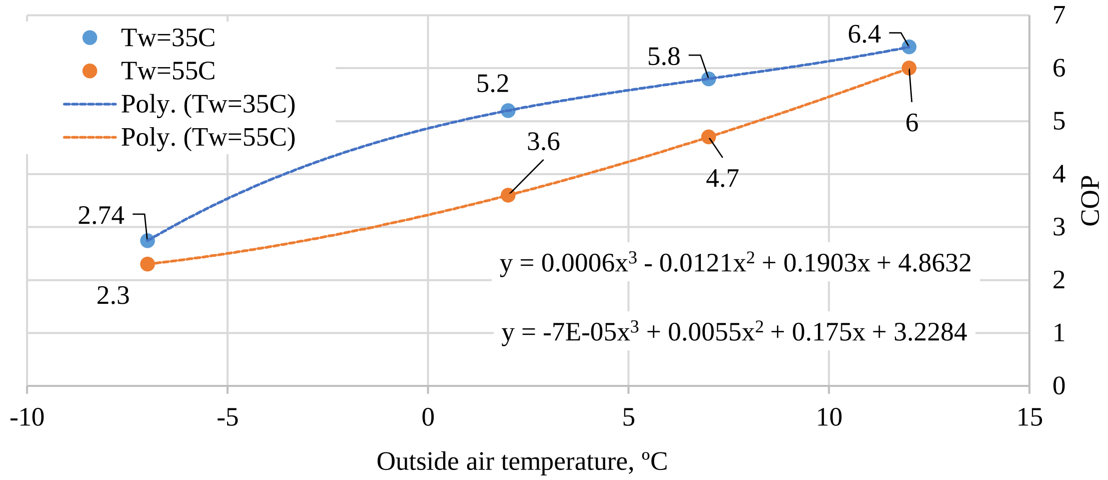

Fig. 3. **COP of AWHP as the function of outdoor air temperature as provided by the producer**

For the economic analysis the Nordpool day ahead electricity price was used for the electricity and the commercial gas price at Ritausma Ltd production facility was used for the gas. Since the heat generated by AWHP was combined with other heat sources and then diverted not only to the experimental greenhouse but also for heating of water for the plants, the performance of the heat pump was calculated using the outdoor air temperature and heating water temperature data (1, 2) and AWHP COP data provided by the producer of AWHP.

$$T_{W,35^\circ C} = 0.0006T_o^{\,3} - 0.0121T_0^{\,2} + 0.193T_o + 4.8632, \quad (1)$$

$$T_{W55^\circ C} = 0.00007T_o^{\,3} - 0.00055T_0^{\,2} + 0.175T_o + 3.2284 \quad (2)$$

where *COP* – coefficient of performance;
T_o – outdoor air temperatures of the reference period, °C;
T_W – heating water temperature, °C.

Results and discussion

The actual energy consumption per 1 m^2 of the reference greenhouse was taken from the production data of the production facility. Then the corresponding amount of electricity needed to achieve the same heating effect by AWHP was calculated using the COP established from the measured heating water temperatures and outdoor air temperatures. Due to the 24-hour temperature cycle of tomato plants and different conditions of solar irradiation, wind, rain and other factors, there was no simple relation between the heating water temperature and outdoor air temperature as can be seen in Fig. 4.

The declared efficiency of the gas boiler at the production facility was 0.94. Hourly cost comparison between AWHP and the gas boiler was calculated. For the cost of the electricity the Nordpool day ahead prices for Latvia with all compulsory payments – like transmission costs and special electricity taxes were used. The actual gas price at the production facility was used.

The resulting ratio of AWHP and gas heating costs are shown in Fig. 5. The heating by AWHP was at least twice cheaper than gas heating for the most of the time during September 2021.

The second half of 2021 was extraordinary in terms of very high prices of electricity and gas. The electricity prices rose sharply and were extremely high, particularly in November and December. In September 2021 the average monthly Nordpool price for Latvia was 123.96 EUR MWh^{-1} while the price for gas for the production facility was fixed at 52.53 EUR MWh^{-1}. One of the advantages of the heat pump is that most of the heating energy is needed during the night when the electricity is much cheaper. This advantage is partially offset by the lower outdoor air temperatures and thus lower COP during the night. It was reported [8] that in the climatic conditions of the Central Europe the use of 24 h outdoor air temperature prediction for control of AWHP increased COP of HP up to 23%. This increase in COP conforms to reduction of about 20% of a year based power consumption.

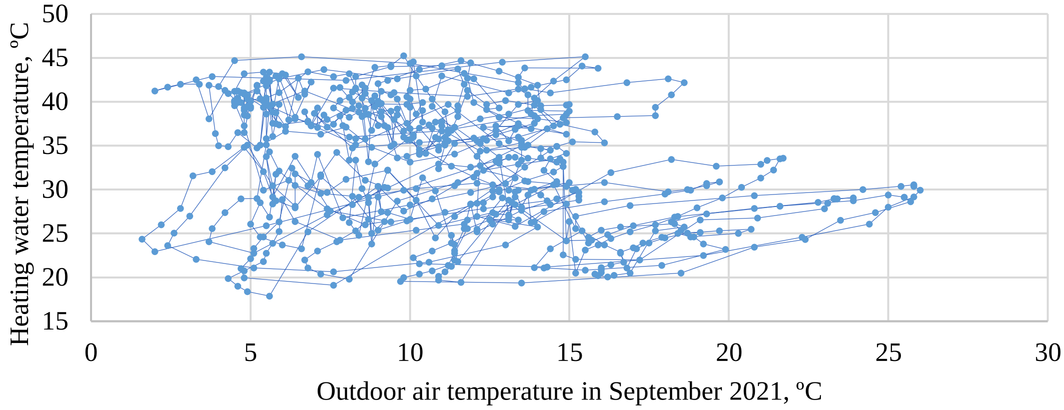

Fig. 4. **Heating water temperature as a function of outdoor air temperature and time, the dots on the line are separated by one hour from each other**

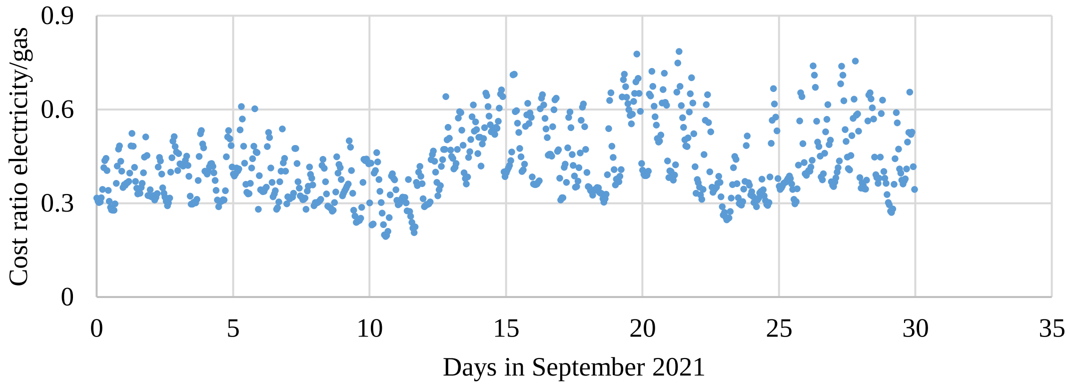

Fig. 5. **Ratio between electricity costs of AWHP and gas heating calculated for every hour in September 2021**

The reduction of CO_2 emission by using AWHP depends on how the electricity has been produced. Water, wind and nuclear energy that are among the main sources of electricity used in Latvia are associated with very low CO_2 emissions. For the estimate of CO_2 reduction by AWHP we assumed that 50% of electricity was produced in CO_2 free manner and the rest was produced by burning natural gas. This approximately corresponds to electricity generation in Latvia. Under this assumption we calculated that in September 2021 AWHP used in greenhouse heating would have only 20% of the CO_2 emissions as compared to gas heating. Our previous test results show that air-to air heat pumps reduced up to 8-16 times CO_2 emissions compared to natural gas boiler heating [9]. It was reported [10] that a system with a ground heat pump with a shallow pipe heat exchanger and low soil thermal conductivity provided the desired air temperature, except during the winter season. In our experiment the heat pump was able to sustain the needed temperature even at serious sub-zero temperatures since air is a heat reservoir with unlimited heat capacity. Another research showed that a ground heat pump reduced CO_2 emissions by 56% to 79% compared to a greenhouse kerosene heater maintained at around 16 ºC while the outside air temperature ranged between -5 ºC and 6 ºC and the energy cost was lower in the ground heat pump. These results indicate that the heat pump system is found to be more efficient than the kerosene heating system and economically feasible for greenhouse heating [11]. Our air to water heat pump requires significantly less investments to install as compared to the ground heat pump.

Conclusions

The effect of using the air to water heat pump in heating the tomato greenhouse in south east Latvia in September 2021 was calculated to be a 5-fold reduction in CO_2 emissions and at the same time halving the cost of heating as compared to heating by a natural gas boiler. At climatic and market conditions of the second half of 2021, a heating system using natural gas or biomass boilers at periods of low air temperatures or high electricity price and the air-to-water heat pump supported by PV panels and solar water heaters at periods of higher outdoor air temperatures and during low electricity price has comparable performance while five times reducing CO_2 emissions.

Acknowledgements

This research was funded by European Regional Development Fund (ERDF) 2014-2020 for Operational Groups, project No. 18-00-A01620-000023.

Author contributions

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

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