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Energy Efficiency Analysis of Combined Heat Pump-PV-Solar Collector-Based Underground Thermal Storage Systems

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ABSTRACT

This paper presents a novel renewable energy system that can be used to deliver heating and electrical energy to buildings. The system consists of a thermal storage unit buried underground, PV panels with a cooling system, evacuated tube solar collector, heat pump and buffer tank. The waste heat from PV panels cooling is stored in a high-capacity storage tank installed underground. The solar collector unit is used to preheat the water, to maximize the solar energy transfer to coolant liquid. The underground tank is not insulated, so exchange the heat with the surrounding ground. Therefore, a large amount of heat can be effectively transferred from the tank to the ground. The ground is partially insulated (from the top, and the sides), to reduce the heat losses to surroundings. The idea of the system is to use the heat from the storage unit, to improve the COP of the heat pump and maximize the energy system performance. The heat pump is powered using the electric energy produced by PV panels and then stored in the grid. A mathematical model of the proposed energy system is developed, and the system performance is studied for Cracow city in Poland. The Finite Volume code written in MATLAB language is developed to study a transient two-dimensional temperature distribution underground, and to evaluate the heating energy stored.

1. INTRODUCTION

Building heating and cooling account for a significant part of our primary energy consumption and thereby is a key player in our transition to a more renewable-based energy future. Most of the renewable energy sources, however, face significant challenges for being intermittent and location-dependent (weather, wind speed, irradiation). Despite these inherent shortcomings, the low operational and maintenance costs as well as their lower greenhouse gas emissions, made renewable energy sources more popular in the past decades. Recently, EU countries planned to increase their Renewable Energy Sources share. The objectives encompass a reduction of greenhouse gas emissions by 20% compared to the 1990 year, a 20% coverage of renewable energy needs and a 20% increase in energy efficiency. Since the residential sector represents over 27% of global energy consumption and 17% of CO2 emission Vallati et al. (2019), the use of renewable energy systems in building heating is of high importance. One option is a heating system that utilizes a heat pump fed with the electricity generated from PV panels. Furthermore, the waste heat from PV (back-panel) cooling is stored in an external tank to be used during the heating period thereby reducing the load off the heat pump [2]. A similar system was studied experimentally in Zhou et al. (2019), where the authors proposed a single-stage compression RB-PVTHP system that consists of a novel RB-PVT unit using a refrigerant as a working fluid to generate thermal energy and electricity. The authors focused on the cogeneration performance of the system in northern China during summer. The results showed that the system works in a stable condition during the test period with considerable cogeneration performance. Dannemand et al. (2019) demonstrated a solar PVT assisted - heat pump system with a cold buffer storage tank on the source side of the heat pump and a hot storage tank for domestic hot water preparation. The authors performed nine months of measurements. The results showed that the hot water demand was almost completely covered by the thermal part of the PVT collector in sunny summer periods. In less sunny periods, the brine-water heat pump recharged the hot water tank after draw offs and discharged the buffer storage tank. More interestingly, the authors reported that the uninsulated PVT collector worked as an energy absorber and is able to extract heat from the ambient air and recharge the buffer storage tank when low solar irradiance was available. Furthermore, in the less sunny and colder periods, the PVT added a significant amount of energy to the cold storage tank. Lu et al. (2019) studied the performance improvement of solar PVT heat pump system in winter by using a vapor injection cycle. The authors developed a prototype and evaluated its performance for seven days in winter. The system performance was evaluated based on the average ambient temperature of −1.13 °C and solar irradiation of 164.03 W/m^2. Results showed that the total generated electricity, heat, and consumed power of the system were 0.51 kWh, 23.68 kWh, and 7.24 kWh, respectively. Moreover, the average heating coefficient of performance (COPth) and advanced coefficient of performance (COPPVT) of the PVT-VISHP system were 3.27 and 3.45, respectively. Bellos et al. (2019) conducted techno-economic analysis of four solar assisted heat pump heating systems to determine the most attractive solution. The use of PV collectors with air source heat pump is compared to that of FPC, PVT and FPC with PV coupled with a water source heat pump. The authors conducted a sensitivity analysis for the electricity cost because of the great variety of this parameter over the last years. It was concluded that for electricity cost up to 0.23 €/kWh the use of PV coupled with an air source heat pump is the most efficient while for higher electricity prices the coupling of PVT with a water source heat pump was recommended. Fine et al. (2017) presented a domestic water heating system with PVT solar collectors and two heat pumps. The objective of their analysis was to determine and compare the annual thermal energy output of the PVT cascade heat pump system with an evacuated tube and simultaneous consumption of a PVT single heat pump water heating system. The results showed that the PVT cascade heat pump system has an annual thermal energy output improvement over the evacuated tube heating system varied from 37% to 68%, depending on the selected simulation location. Putrayudha et al. (2015) studied PVT-GSHP (ground source heat pump) hybrid systems. The fuzzy logic control was applied to optimize the energy consumption of the system. The results showed that fuzzy logic control consumed 13.3% less energy annually for ground source heat pump when compared with traditional on-off controller. Moreover, PVT-GSHP is more interesting when the annual gain is 18.3% in favor of fuzzy logic control. Besagni et al. (2019) presented the results of a field study concerning a novel solar-assisted dual-source multifunctional heat pump, installed in a detached house in Milan. The system couples hybrid PVT panels with a multifunctional and reversible heat pump. Additionally, the heat pump was equipped with air-source and water-source evaporators, connected in series and operated alternatively based on the ambient conditions, system parameters and operating modes. The experimental results showed that the system can maintain high efficiencies in the different seasons and is able to use solar energy to support the production of domestic hot water.

We present a novel heating system for buildings. The system combines the PV panels with cooling, evacuated solar collector and water to the water heat pump. Additionally, a storage tank, buried underground, is used to store the waste heat from PV panels cooling, and also the thermal energy produced by the solar collectors. Both PV panels and solar collectors are assembled with a sun-tracking system, to achieve the highest possible solar energy gain. The tank is intentionally not insulated so that it will exchange heat with the ground; heating it in summer so the increased soil temperature heats the tank and, worst case scenario, acts as a natural insulator, with a slow time response, during winter when the tank is discharged. This study analyzes how the heat pump COP changes over the heating season, as well as how much of seasonal heating demand can be covered by using the proposed system.

2. MATERIALS AND METHODS

The proposed heating system utilizes the heat from the PV panels cooling, and from the evacuated solar collectors. To increase the solar energy gain, the PV panels and evacuated solar collectors are equipped with the sun tracking system. The heating system (Fig. 1) consists of the following components: PV panels equipped with sun-tracking system and cooling radiators, solar collector (evacuated tubes), water to water heat pump and an underground storage tank (heat accumulator). The waste heat from the cooling of PV panels is stored in the ground during the heating period (spring-summer). The glycol-water mixture is used to cool down the PV pannels. During winter, the thermal energy from the solar collectors is also supporting the thermal storage unit. The heat pump source fluid is a glycol-water mixture, and load fluid is water with a temperature of 40 ^{o} C which can be applied in floor heating system commonly installed in new build houses in Poland. In wintertime, the heat stored in the ground is transferred to the storage tank to compemsate for the water temperature drop during the discharge. Additionally, by applying the evacuated tubes solar collectors in wintertime, it is possible to obtain extra heat gain to charge the storage unit.

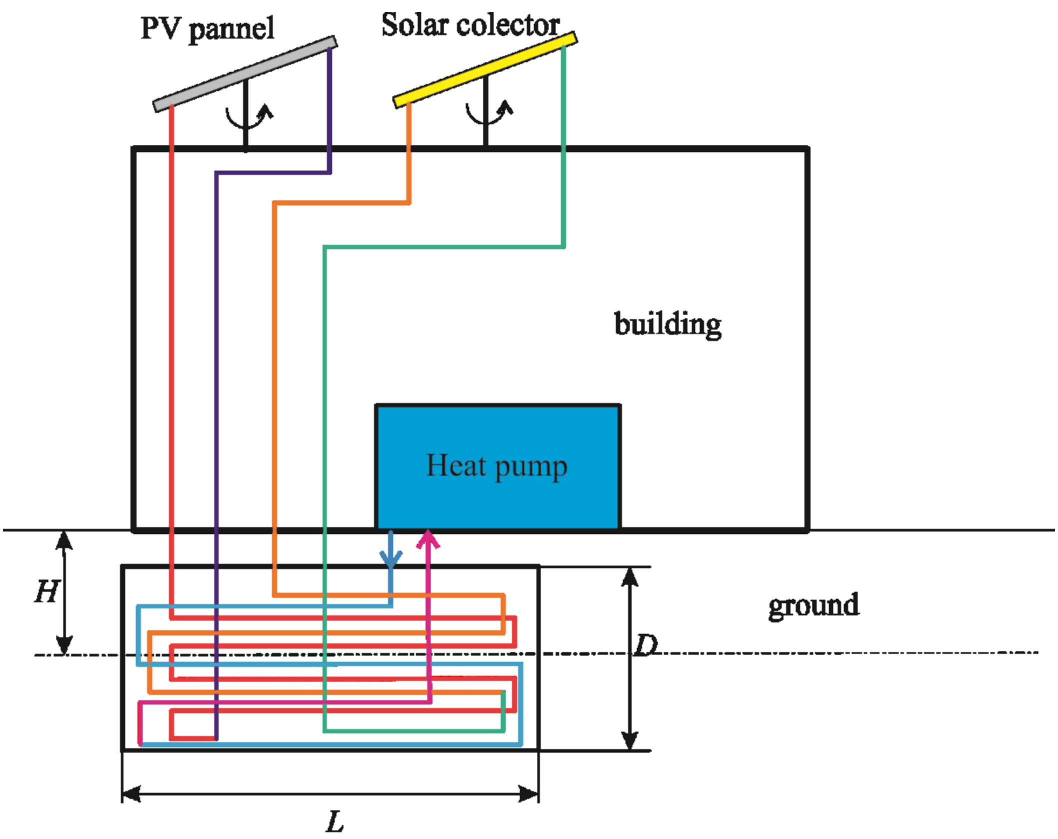

Figure 1: schematic description of our proposed design.

We offer a numerical model to test the merits of our proposed design. Hence, the results are limited to a case study only. In what follows the governing equations and the appropriate boundary conditions are presented and discussed. The major component of the heating system is a storage tank. The tank temperature T_{tank} can be determined from the following differential equation:

$$\rho_w c_w \frac{\pi D^2}{4} L \frac{dT_{\mathrm{tank}}}{d\tau} = Q_{solPV} + Q_{solSC} - Q_{HP} + Q_{ground} \tag{1}$$

where T_{tank} , ρ_w, c_w , $Q_{sol,\,PV}$, $Q_{sol,\,SC}$, L and D, are water temperature in storage tank, density and specific heat of water, solar heat flow from PV panels cooling, solar heat flow from solar collectors, length of the tank (10 m), and tank diameter (3 m), respectively. Solar heat flows, $Q_{sol,\,PV}$ and $Q_{sol,S.C.}$, are calculated as:

$$Q_{solPV} = qA_{PV}\eta_{PVt} \tag{2}$$

$$Q_{solSC} = qA_{SC}\eta_{SC} \tag{3}$$

where $A_{PV} = 259$ m^2 and $A_{SC} = 54.4$ m^2 is the surface area of PV panels and solar collectors respectively, $\eta_{PVt} = 0.45$ and $\eta_{SC} = 0.75$ are the PV panels and solar collector solar-thermal energy conversion efficiency, q is monthly averaged solar daily irradiation. Table 1 presents the values of q and irradiation hours assumed in computation for the location of Cracow in various months of the year.

Table 1. Monthly averaged daily solar irradiation flux and irradiation hours, assumed in the calculation.

Month	Monthly averaged daily solar irradiation flux (q, W/m^2)	Irradiation hours
Jan	400	2.8
Feb	400	3.6
March	500	4.8
April	600	7
May	800	7.7
June	800	7.9
July	900	8.8
Aug	900	7.5
Sept	700	6.1
Oct.	500	4.8
Nov.	400	3.4
Dec.	400	2.5

Heat transferred through the heat pump to the building is calculated as:

$$Q_{HP} = Q_b(1 - 1/COP) \tag{4}$$

where Q_b is a building heating demand calculated as:

$$Q_b = UV_b(T_{set} - T_{ext}) \tag{5}$$

Thermal transmittance of the building is estimated as UV_b = 960 W/K. T_{ext} is the variable daily temperature, and T_{set} is a set temperature given as 20°C. Coefficient of Performance (COP) of the heat pump is calculated as:

$$COP = \eta_{cycle}\frac{T_L}{T_L - T_S} \tag{6}$$

where the temperature at the hot side of heat pump T_L = 40 °C, and the temperature at the cold side of heat pump T_S is either 20 °C when the T_{tank} is higher than 20 °C or is equal to T_{tank} otherwise. Heat pump cycle efficiency η_{cycle} is assumed to be equal to 0.4. Ground heat transfer to the tank is calculated as:

$$Q_{ground} = h_1\pi DL(T_g - T_{\text{tank}}) \tag{7}$$

Where h is the equivalent heat transfer coefficient from the fluid to the ground, T_g, is the area-averaged ground temperature along the tank circumference calculated from ground heat transfer model:

$$\rho c \frac{\partial T_g}{\partial \tau} = k \frac{\partial^2 T_g}{\partial x^2} + k \frac{\partial^2 T_g}{\partial y^2} \tag{8}$$

with boundary conditions:

$$\begin{aligned} &\frac{\partial T_g}{\partial x}(W, y) = 0 \\ &\frac{\partial T_g}{\partial y}(x, H_1) = 0 \\ &\frac{\partial T_g}{\partial y}(x, H_t) = U_g\left(T_g - T_{g,av}\right) \end{aligned} \tag{9}$$

for the tank:

$$\frac{\partial T_g}{\partial r}(r_i, \phi) = h_1\left(T_g - T_{\text{tank}}\right) \tag{10}$$

where W, H_t, H_1, h_1, h_2, k, c_p, ρ, $T_{g,av}$, r_i, are the width of the domain, assumed as 10 m, the total height of the domain assumed as 13 m, a tank burial depth assumed as 3 m, the heat transfer coefficients from tank 1 and tank 2, thermal conductivity (1.8 W/mK), specific heat capacity (1800 J/kgK), and density (1400 kg/m^3) of the ground, the yearly average ground temperature, assumed to be equal to 7.5 ^{o}C for Cracow, the outer radius of the tank equal to 1.5 m, respectively. The ground is insulated at the top and the left side of the domain. Therefore, the system is expected to maintain the heat for a long time period.

Figure 2 shows the computational mesh used in the calculations:

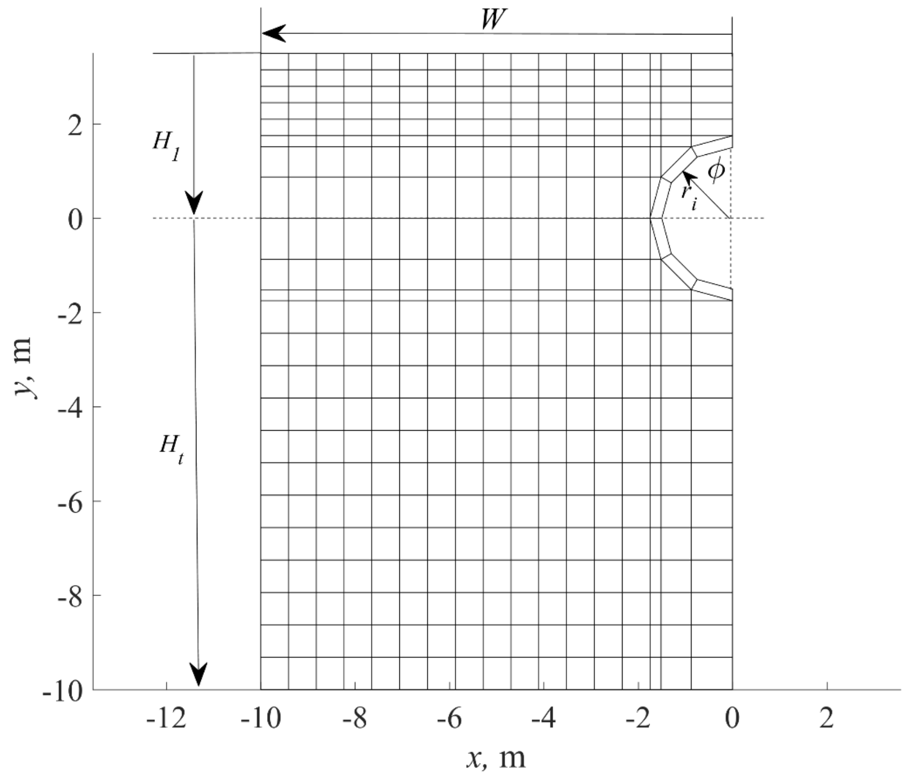

Figure 2: Mesh used for calculation of the ground temperature.

The heat conduction within the ground domain is considered to be two-dimensional and transient. Transient heat conduction equation is discretized using an explicit control volume method. An in-house MATLAB code is developed to calculate the temperature distribution in the ground leading to ground heat transfer rate Q_{ground} which is then substituted into Eq. (1) for calculating the tank water temperature. The solar collectors and PV panel heat gains are subsequently determined as well as the building heat demand.

3. RESULTS AND DISCUSSION

It is assumed that the system set-up is carried out in May, and the storage tank is charged by the heat from PV panels and solar collectors until the water temperature reaches 45 °C; see Figure 3. As the heating demand increases in winter, the storage tank is discharged with a drop in its temperature. If the glycol temperature drops below 3 °C the system cannot be further used and external heat source (for example ground heat exchanger, or a backup boiler) should be used. As seen, with the application of evacuated tubes, even in winter the storage unit can be charged effectively and the tank water temperature can be maintained above 3 °C for more than 75% of the operational time of the heating system.

Figure 4 shows the transient distribution of heat pump COP. It is possible to observe, that the COP value is decreased during the heating period from November to Feb, to the value slightly less than 4. However, in the case of the October-November period, and February-March its value is higher than 4. The averaged value of COP over the year is calculated as 5.26. The overall heating demand covered by the proposed system is calculated as 76.5%, which is a very promising value.

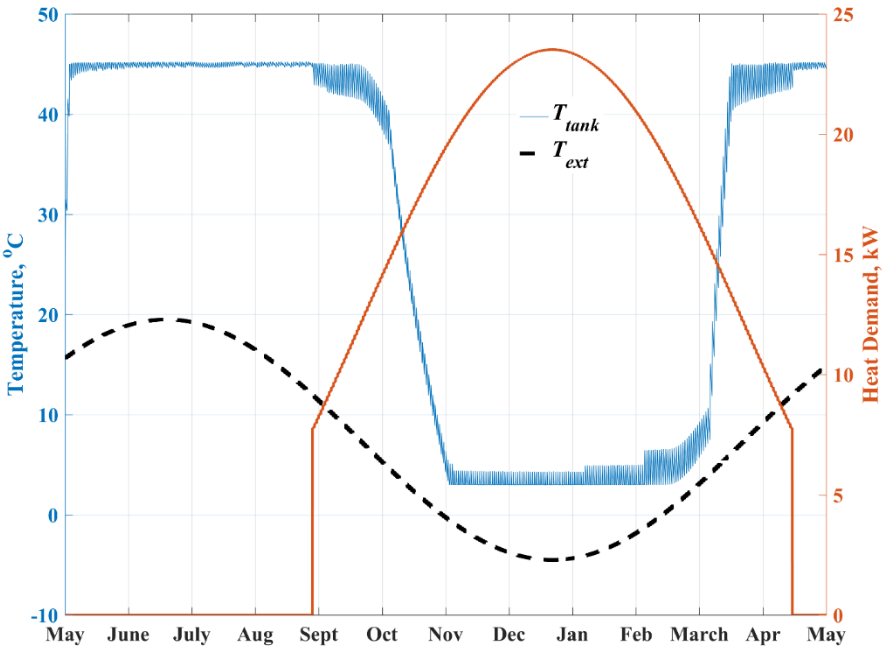

Figure 3: Transient temperature distribution: tank water temperature (T_{tank}) and the daily averaged air temperature (T_{ext}), as well as the heating demand Q calculated for 1 year period of time.

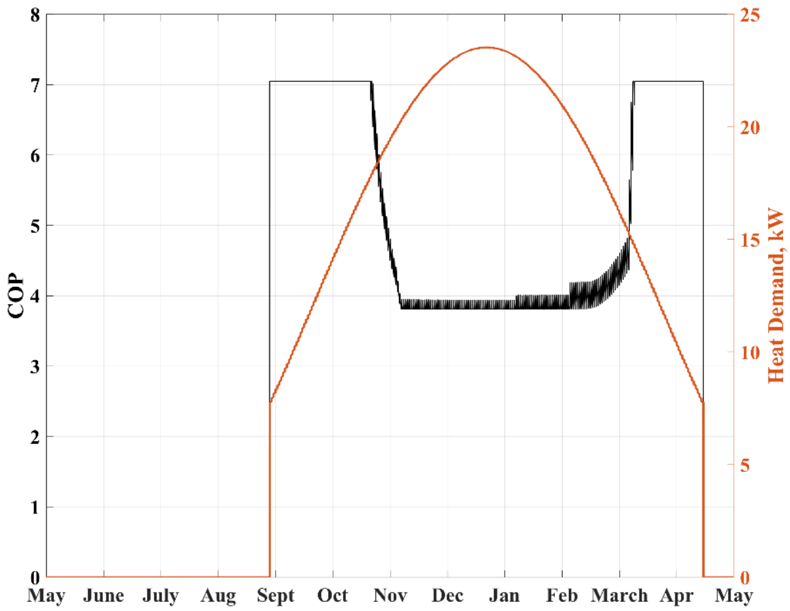

Figure 4: Transient distribution of heat pump COP calculated for 1 year period of time.

Figure 5-11 shows how the temperature distribution in the ground varies after each month of the simulation. One can observe, that at the beginning of the heating period in October (Fig. 5), the ground temperature near the storage tank is high, and reaches 35 °C, thanks to the significant heat gains in October with relatively low heating demand. Therefore, the water temperature drop (in the tank) is negligibly small.

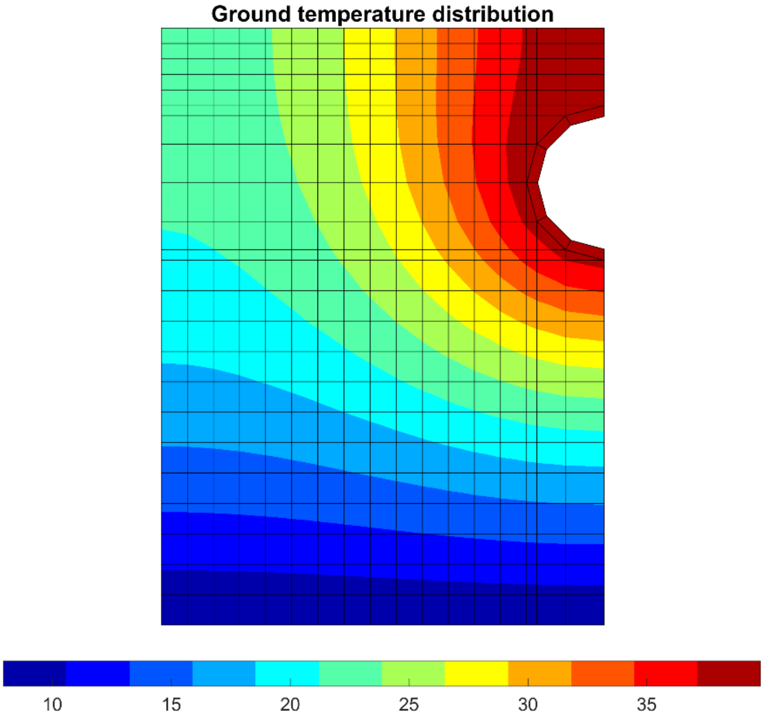

Figure 5: Ground temperature distribution on the last day of October.

At the end of November (Figure 6), due to the increased heating demand, the water temperature in the tank drops. However, still the ground temperature near the tank is relatively high, and the heat transfer from the top of the domain to the tank can be noted.

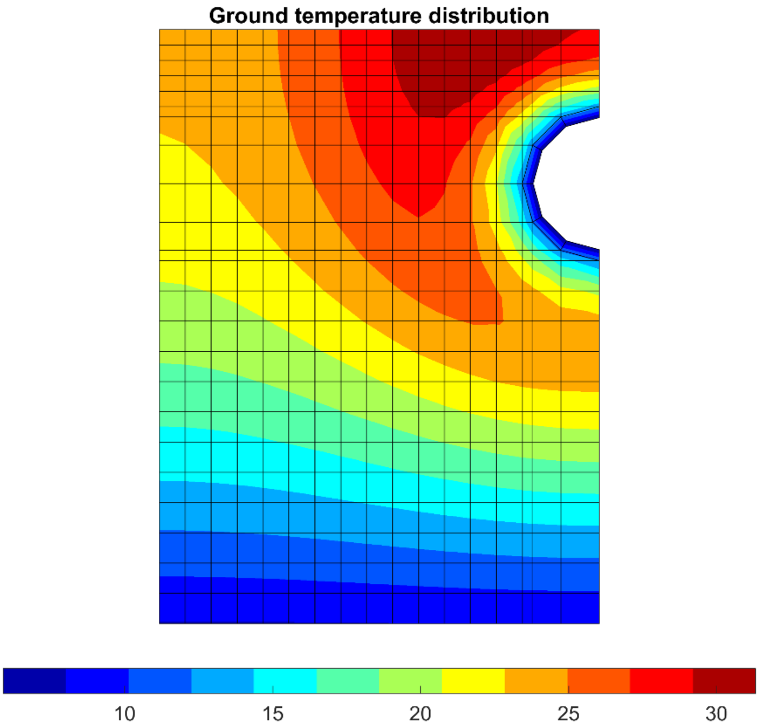

Figure 6: Ground temperature distribution on the last day of November.

After the December, it is possible to observe the ground temperature change. From over 33 °C at the end of November down to 25 °C. The reason is that the temperature of the water in storage tank is low, and therefore, due to the heat transfer from the ground to the tank, the ground temperature decreases.

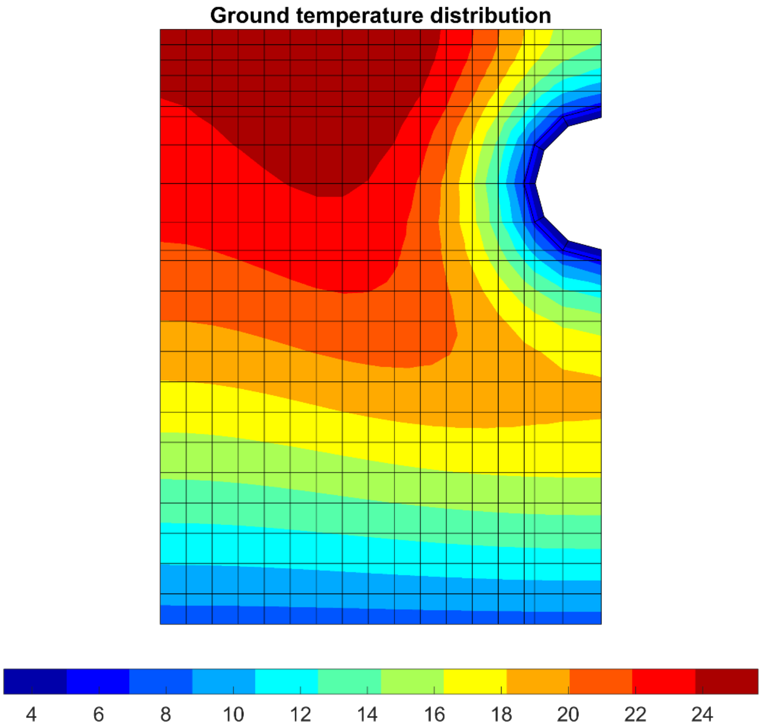

Figure 7: Ground temperature distribution on the last day of December.

At the end of the January, a weak heat transfer from the ground to the storage tank can be noted. The ground layers around the tank are at the temperature between 8 °C and 12 °C.

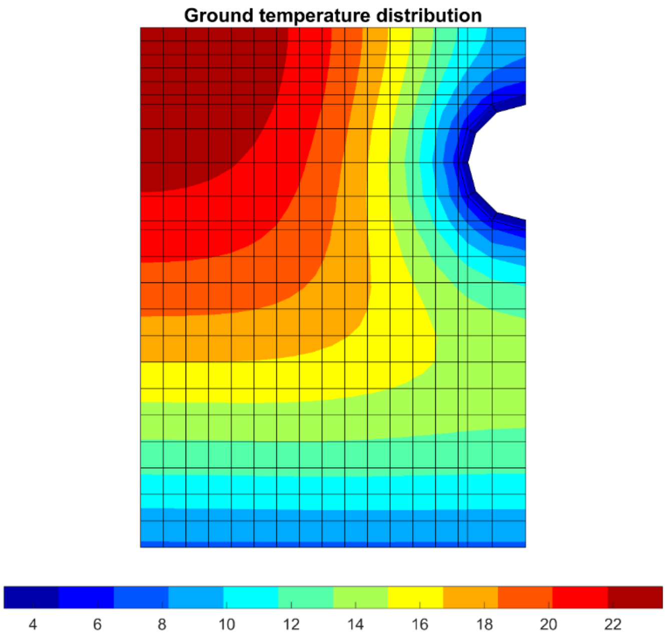

Figure 8: Ground temperature distribution on the last day of January

A similar ground temperature distribution is observed at the end of February, where the highest heating demand is expected to nearly drain the heat in the ground leaving almost no heat to be transferred to the tank.

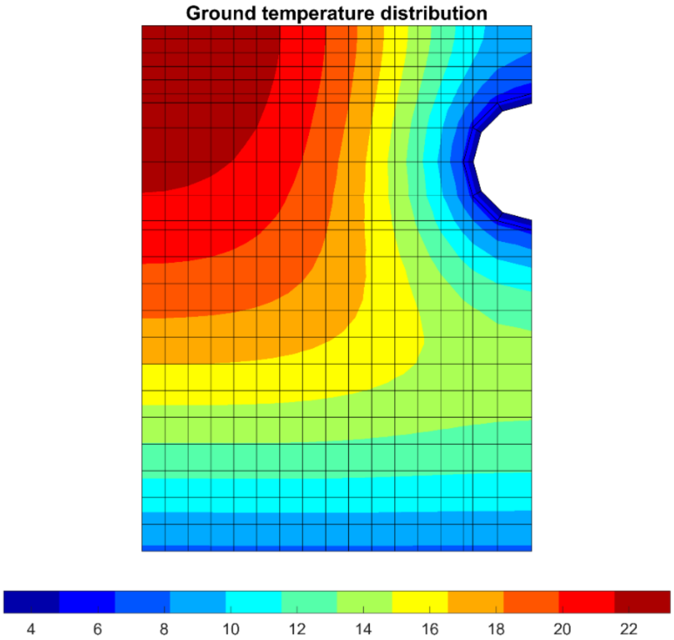

Figure 9: Ground temperature distribution on the last day of February.

In March, however, the solar heat gain is improved while the decreased heating demand is lowered. Hence, the tank water temperature increases as per Figure 10.

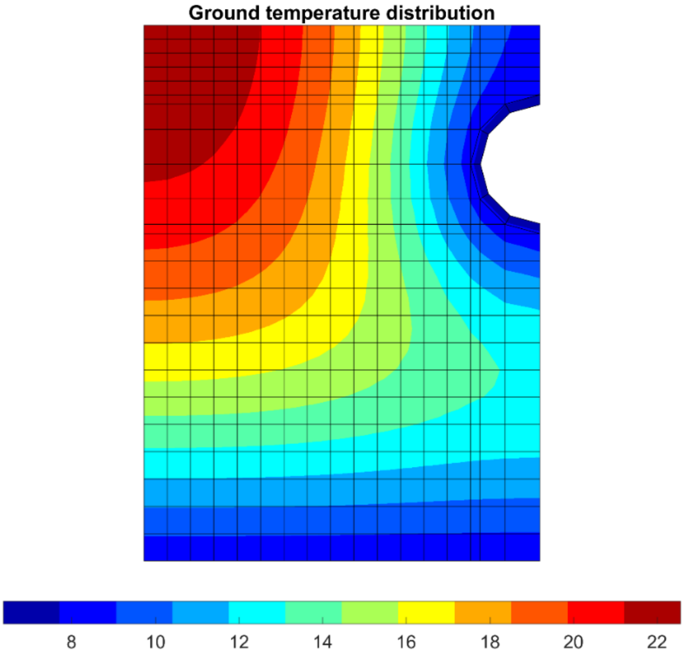

Figure 20: Ground temperature distribution on the last day of March.

At the end of April, the water temperature in the tank is heated up to 40 ^{o}C thereby augmenting the heat transfer from the storage tank to the ground and increasing the ground temperature.

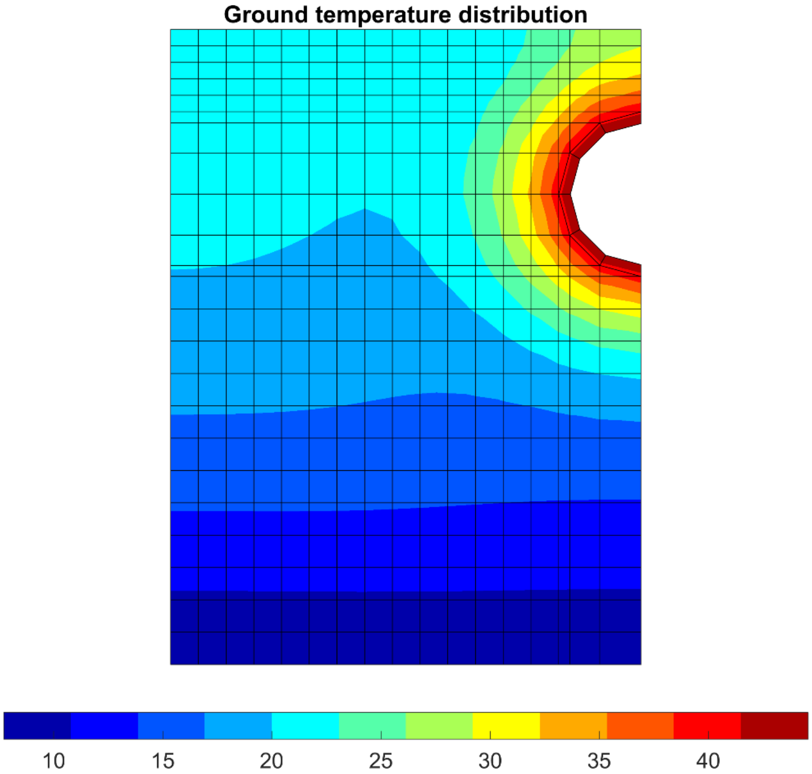

Figure 13: Ground temperature distribution in the last day of April.

Finally, the ratio of thermal Energy produced by the system to total heating demand is calculated to be equal to 76.5%, what is very promising for Poland.

4. CONCLSUION

This paper presents a novel system for building heating. The water to water heat pump is coupled with PV panels cooling system and evacuated tube solar collectors through the thermal storage unit (water heat accumulator). The thermal storage unit is not insulated, therefore it transfers the heat to the ground during the summer period, and in the winter period, the heat accumulated in the ground is transferred back to the storage tank. The application of evacuated tube solar collectors allows to achieve the heat gains even in wintertime and to increase the tank water temperature. The numerical model of the system operation is developed, considering the transient and two-dimensional heat transfer in the ground domain. The Control Volume method is used to discretize the heat conduction equation for the ground domain. The calculations are performed for the entire one-year period of system operation, and the temperature of storage tank water and heat pump COP histories are presented. The results showed, that for the considered building it is possible to cover 76.5 % of heating demand by using the proposed system. The remaining part shall be covered by using the additional heating system (for example ground heat exchanger or condensing boiler). Also, the average heat pump COP during the heating period is equal to 5.25, therefore electrical energy used by the heat pump can be lower than for the typical heat pump operation.

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