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Air to Water Heat Pump Operation Improvement by Means of Heat Exchange in a Paraffin Tank

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Abstract: The global energy production has currently been characterized by a rapid transition driven by the increasing decarbonization process on one side and the development of renewable energy systems on the other. The commonly met difficulty with the planned solar energy utilization is its stochastic behavior. The solution for that problem may be the development of energy storage processes or hybrid systems. The paper discusses the application of a paraffin tank for solar heat accumulation with an air-to-water heat pump cooperation during the transition period of time for autumn/winter and winter/spring seasons. The hybrid system involves the external air temperature increase while discharging the heat storage tank. Thus, resulting in the heat pump COP improvement by 15% or 30% (November and February, respectively) as well as lower energy consumption costs in the building.

Keywords: heat exchange, heat accumulation, heat pumps, solar system, PCMs, hybrid systems

1. Introduction

In light of observed climate changes, the Energy Policy for Poland until 2040 requires the implementation of renewable energy sources (RES) for heating purposes (Stokowiec & Kotrys-Działak 2024, Liang 2024). Moreover, due to the fact that several of them are periodically available only (which concerns solar and wind energy), the heat suppliers are strongly encouraged to employ heat accumulation processes for RES applications. Furthermore, the intensity of accessible energy varies throughout the duration of the recipients' energy demand. This dependence is strongly observed in the case of heating purposes supplied with solar or wind energy. Thus, thermal energy storage plays a crucial role in terms of self-sufficient energy supplies as well as installation emergency status protection, including a lack of power supply.

Most commonly and most detailed literature reports analyze forms of energy storage related to the energy accumulation techniques aimed at avoiding low access to electricity. Such technologies are widely described and imply the cooperation of electric energy storage with a photovoltaic system. These works include reviews of participation of energy accumulation systems in the provision of the ancillary services in a microgrid (Kumar & Palanisamy 2020), thus enhancing both power quality and its reliability. Other research evaluates the energy storage system in terms of accumulation participation revision in the real-world microgrid (Fayek & Mohammadi-Ivatloo 2020). Using the optimum ratio of renewable energy sources fraction to the levelized energy cost (Al-Ghussain et al. 2020), the hybrid systems based on the RES share can be considered as the best economic benefit, since they present higher efficiency. In terms of technical feasibility and sustainability, a hybrid power system on a Greek island was analyzed with several economic indicators. It consists of a wind energy system and a battery (Fiorentzis et al. 2020).

In particular, the Energy Policy for Poland establishes the Polish energy transformation strategy aimed at zero energy heating sources. The aspect of green energy may include the concentration on new energy sources or carriers (Porowski et al. 2023). Moreover, the energy conservation and carbon reduction policies contribute to the higher interest among energy consumers in heat pump applications in heating systems. Therefore, several research projects address the air-to-water heat pumps with regard to energy saving potential that depends on the energy storage water tank size or heat pump size itself (Lyu et al. 2022). Nonetheless, other RES may contribute to lower particulate matter and gaseous emissions, e.g., the combustion processes of biomass. The emission of air pollutants is strongly dependent on the amount of combustion air and its redistribution (Holubcík et al. 2022). The pollutants' influence is a problem that requires mathematical modelling (Koshlak & Pavlenko 2020). To evaluate emissions and environmental impact of an air-to-water electric heat pump serving a university building, the Expanded Total Equivalent Warming Impact (ETEWI) has been proposed. In the scenario, the indirect term of ETEWI decreases by 47% within 18 years, with the calculations concerning the forecast of the carbon dioxide emission factors for electricity production (Ceglia et al. 2023). The reduction of pollutant emissions is significant for the natural environment, including tillage and crops (Alzaben et al. 2021, Stošić et al. 2021).

With the exception of ecology aspects, the electric air-to-water heat pumps are researched with regard to correlations for the mass flow rate of refrigerant through the electronic expansion valve (Kim et al. 2023). The conclusions based on the results of the study included a negligible effect of oil on the refrigerant mass flow rate of the system. Furthermore, several solar-assisted heat pumps applied in heating systems are analyzed. In terms of economy and thermal performance of a cooperation between an air-to-water heat pump and solar system, the heat pump's Coefficient of Performance was increased (Ma et al. 2023), resulting in lower costs and higher energy production. Direct Expansion Solar-Air Source Heat Pump presents high potential in water heating applications in hot regions (Chinnasamy & Arunachalam 2023). The research was conducted on energy and exergy performance characteristics evaluation and comparison during summer and winter days. Applications of RES in buildings may influence the thermal comfort in each room (Majewski et al. 2017).

The development of new and modern technologies for the improvement of energy consumption by means of renewable energy involves several modern techniques implementations for heat storage processes. Current research includes heat exchangers analysis (Križo et al. 2022) or enhancing their thermal performance with novel fin configurations (Yu et al. 2025). Other papers discuss waste heat implementation (Han et al. 2025). The most promising solution appears to be the seasonal energy storage employment (Weise et al. 2025) with Phase Change Materials (PCM) techniques. The advantages resulting from their applications include constant temperature during the discharge process or the possibility to accumulate the heat for more extended periods of time compared to sensible energy storage technologies. The recommended substances vary from organic to inorganic materials with a wide range of phase change temperatures and enthalpy (Selvam et al. 2025). The distinct thermodynamic parameter values of PCMs contribute to their application in heating, ventilation, and air-conditioning systems, including RES installations. In solar systems, PCMs require a suitable storage tank with isolation that reduces possible heat transfer to the ambient. Their impacts on the natural environment as well as the health issues are strongly evaluated for the wide range of installation interests (Nartowska et al. 2023). Other research includes PCM microcapsulation processes for thermal energy storage enhancement (Amanowicz & Turski 2025). However, PCMs are not only applied in RES systems. They are also highly recognizable in ventilating systems, aiming at the operation improvement of air heat exchangers that are used in decentralised façade ventilation units (Galiszewska & Zender-Świercz 2023). Phase Change Materials are also investigated in a passive cooling system for the cooling of photovoltaic panels (Agyekum et al. 2021) with 11.33% improvement of the system operation.

In several RES applications, the perspectives require not only the implications of heat accumulation technologies and their development but also heat enhancement solutions for heat exchangers. The application of various microstructures to the heat-exchanging surfaces increases heat fluxes exchanged at the same temperature difference in relation to the smooth surface with no coating adopted. The conducted research proves that the porous structures consisting of copper wires reinforced with carbon and glass fibers influence the thermal performance in the case of sintered heat exchangers (Orman & Chatys 2011). Other experiments discuss a phenomenon of substrates wetting with the use of various types of fluids associated with heat transfer (Wciślik & Mukherjee 2022).

The purpose of the paper is to analyze the cooperation of a heat accumulation tank filled with organic PCM (a paraffin wax) with an air-to-water heat pump during selected months. The Phase Change Material tank is aimed at the storage of solar energy. The hybrid system involves the external air temperature increase by means of accumulated thermal energy before flowing through the heat pump's evaporator, thus the heat pump COP value rises.

2. Materials and Methods

The analyzes involve a residential building equipped with an air-to-water heat pump that produces the heat for heating purposes in the building. In addition, the other renewable energy source present in the building is a solar system. Solar collectors aim to supply the domestic hot water system with cost-free heat, especially during the summer season. Moreover, in order to accumulate the energy excess, the solar system is equipped with a paraffin tank. The tank is isolated, and during the sunshine periods, heat is stored by means of a phase change process.

The transitional time of year, i.e., the beginning of winter or springtime, may not provide sufficient heat to obtain the required temperature at the domestic hot water inlet. Therefore, during these periods, the heat accumulator was assumed to operate in order to improve the heat pump operation. In other words, the energy stored may not increase the paraffin temperature to reach the phase change process. However, the heat gain is significant. According to the principle of the system operation, the external air temperature rise before flowing through the heat pump evaporator is assumed. Thus, allowing the limitations in additional heat source operation in case of proceeding with the process below the bivalent point. On the other hand, we obtain the air-to-water heat pump operation improvement. Summarizing, by means of cooperation with the paraffin tank, the coefficient of performance of the heat pump is to be increased.

The schematic diagram of the system is proposed and presented in Figure 1.

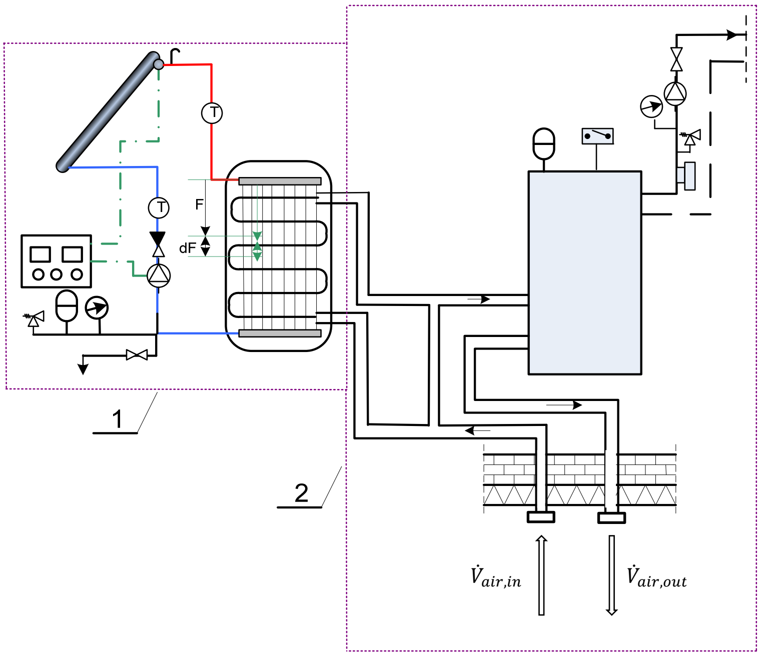

Fig. 1. Schematic diagram of the analyzed system; 1 – solar system with paraffin heat storage tank, 2 – air to water heat pump

In the analyzed building, the solar system consists of:

- A solar collector that receives the energy from the sun and transfers the heat to PCM (paraffin wax) by means of the heat exchanger inside the accumulation tank,
- pump station that is responsible for the glycol flow,
- all the required meters that measure pressure and temperature in the system,
- safety devices such as a safety valve and an expansion tank,
- electronic control system,
- and a Thermal Energy Storage (TES) tank filled with paraffin wax, where solar heat is stored and transferred to the lower heat source for the air-to-water heat pump.

The system that receives solar energy, which is accumulated by means of PCM, is an air-to-water heat pump situated inside the building. In addition, this system requires an external air intake situated at the external wall and air ducts. The air flows through them and passes directly to the heat pump's evaporator, or may be transferred through heat exchanger coils inside the PCM tank in order to increase its temperature. The air-to-water heat pump may transfer the heat for central heating needs or domestic hot water needs in a single-family residential building.

For the purpose of the presented research, two months (November and February) were analyzed, which represent the period of time with season changes. Heat gain and the paraffin temperature increase were calculated on the basis of the Hottel-Whillier-Bliss equation (Pluta 2006) with the parameters assumed as for the actual plate solar collector.

$$Q_u = A_p \cdot F_R \cdot \left[G(\tau\beta) - U_L \cdot \left(T_{w1} - T_a\right)\right] \tag{1}$$

where:

A_p – absorber surface, m^2
F_R – solar collector heat dissipation factor, –
$G(\tau\beta)$ – absorber solar radiation, W/m^2
U_L – absorber heat losses substitutive factor, W/(m^{2}K)
T_a – ambient temperature, °C
T_{w1} – solar fluid temperature, °C

The estimated solar energy value that may be absorbed was anticipated on the basis of meteorological data available for Poland (Pluta 2006), see Figure 2. The presented dependence provides information on the solar irradiance on a flat surface for particular hours of the day.

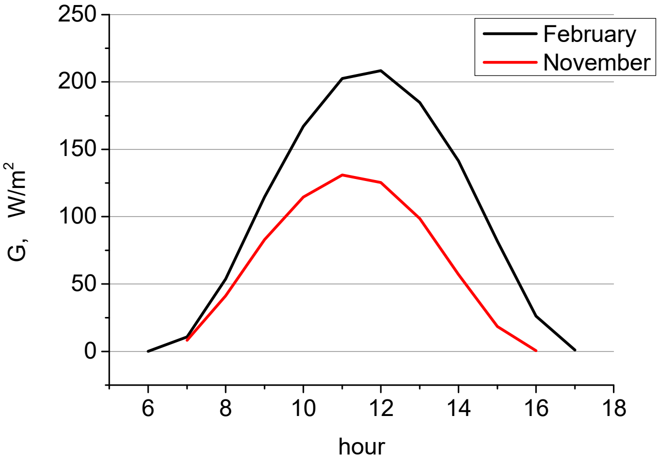

Fig. 2. Total amount of solar radiation on the flat surface depending on the hour of the day (Pluta 2006)

Figure 2 illustrates the solar energy incident on a flat surface for both months, with the enhanced possibility of heat accumulation more visible in February compared to November.

The storage tank is filled with paraffin as a PCM material with the characteristic of melting/solidifying temperature of 64°C. In the analyzed months, the phase change temperature is not reached, but the heat accumulation by means of paraffin occurs. For February and November, the PCM possible temperature achieved is respectively 45°C or 33°C with the appropriate solar operation included. The complete calculation methodology was described in (Orzechowski & Stokowiec 2016).

3. Results

In order to calculate the paraffin temperature as well as the temperature of flowing air, the heat storage tank discharging process requires its description by means of an energy balance. Thus, the equation for temperature distribution along the heat exchanger length was proposed:

$$\frac{\partial T_1(t,F)}{\partial F} = \frac{U}{m_1 \cdot C_{p1}}\left[T_2(t) - T_1(t,F)\right] \tag{2}$$

After the formula transformation and integration, the temperature dependence is obtained. Equation (3) was applied in the following calculations:

$$\frac{T_2 - T_{1in}}{T_2 - T_{1out}} = e^{\frac{U \cdot F_w}{m_1 \cdot Cp_1}} \tag{3}$$

where:
T – temperature, °C
U – heat transfer coefficient, W/(m^{2}K)
F_w – heat transfer area, m^2
m – mass flow, kg/s
Cp – specific heat, J/(kgK)
indexes:
1 – air,
2 – paraffin,
in – at the inlet,
out – at the outlet

The heat transfer process is described by means of three factors: the heat transfer coefficient, strongly dependent on the paraffin characteristics during the discharging process, the parameters of the fluid receiving the accumulated heat in a storage tank, and the geometry of the heat transfer elements themselves. The research on estimating heat transfer coefficient value was proposed (Orzechowski & Stokowiec 2016), and the results enabled further calculations concerning the simulations for hybrid systems that involve cooperation of an air-to-water heat pump with a solar system additionally equipped with energy accumulation technology.

Due to the assumption of the solar system operation for all the months of the year, the analysis conducted in the paper included the solar collector location at an angle of 55°. The air flow rate was assumed to be 2.5 m/s for the air intake, since the air flows through the heat accumulation tank from the inlet point before reaching the heat exchanger in the heat pump (evaporator). The air temperature at the inlet to the heat exchanger of the paraffin tank was considered on the basis of the average temperature for the particular month obtained from the meteorological data available for Kielce, Poland – see Table 1 (https://meteobox.pl/kielce/statystyki).

Table 1. Estimated mean external air temperature for the selected months (https://meteobox.pl/kielce/statystyki)

Month	February	November
Mean external air temperature (Te)	-2°C	3°C

The results of the calculation are presented in Figure 3. The diagram curves represent both paraffin and air temperature changes during the discharging process of the heat accumulation tank. The PCM temperature decrease over time is illustrated with black (T_2), whereas air temperatures are shown with a red line (T_{1out}). The given air temperatures were calculated at the outflow from the heat exchanger in the TES tank, which are equal to the temperature of the air reaching the evaporator. The calculations were conducted until the limit value for PCM temperature (10°C) was reached.

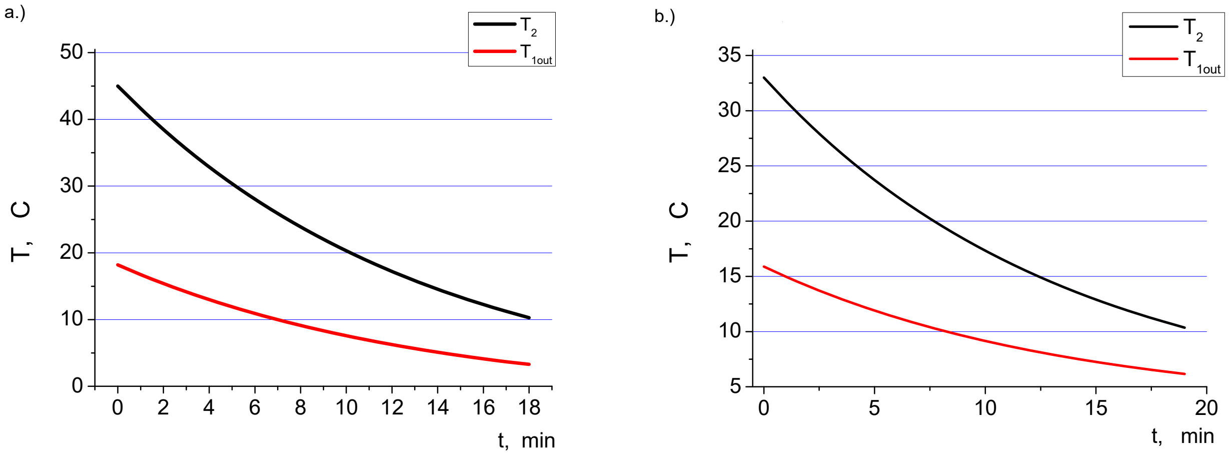

Fig. 3. The paraffin (T_2) and air (T_{1out}) temperature distribution inside the heat storage tank during the discharging process: a) February, b) November

As presented in the figure above, the time required to reach the limit temperature of the paraffin inside the storage tank during the discharging process is below 20 minutes. Nevertheless, during that period of time, the increase in air temperature is significant in comparison with the external air temperature. In case of no cooperation with the PCM tank, the air temperature at the inlet to the heat pump would be the external air temperature for the particular day. For February, the temperature of the air reaching the heat pump's evaporator is even 20°C higher than the average temperature of the external air in this month (-2°C). Due to the lower solar operation for November (Fig. 2), the air temperature reached for that month is more than 5 times higher while analyzing the cooperation with a paraffin tank than the average temperature outside of the building (3°C).

4. Discussion

The effective operation of the heat pump is described by means of the Coefficient of Performance (COP). The factor discusses the electric energy consumption for compressor operation in relation to the building heat demand, equal to the condenser performance. For air-to-water heat pumps, COP is proportional to the external air temperature (Te), enabling the lower energy consumption to be constrained by higher temperatures of air reaching the evaporator.

In order to investigate the energetic benefits of the proposed system, the actual values of COP were analyzed. They were included on the basis of data available for monoblock-type air-to-water heat pump operating on the thermodynamic fluid R32 (https://kaisai.com/pl/split-arctic). The temperature of the hot water supplying the heating system in the building was assumed to be 45°C. The heat pump features the A++ energy class. For the presumed parameters, the COP dependence on the external air temperature was read from the tables provided by the producer and presented in Figure 4. The green identifiers shown in the diagram correspond to February, whereas the red identifiers correspond to November.

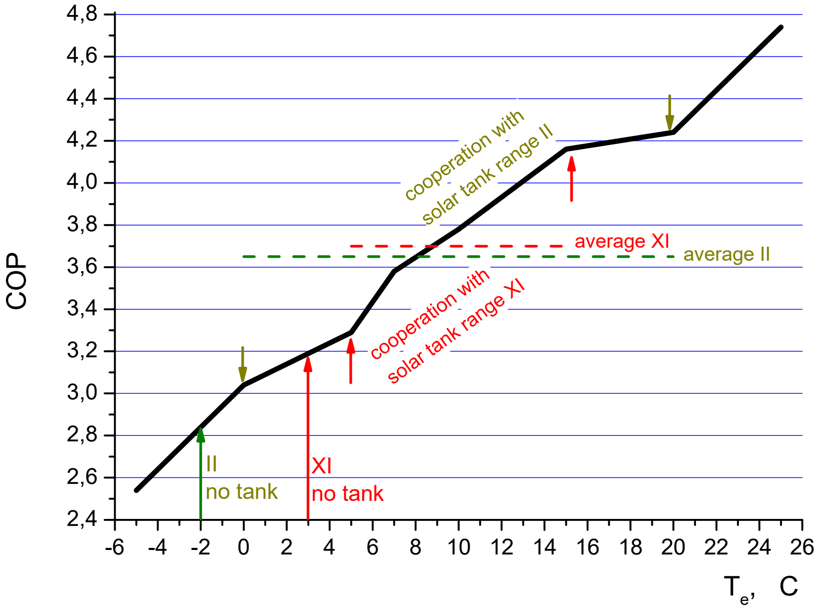

Fig. 4. Heat pump Coefficient of Performance comparison for selected months

Assuming the reference temperature for each month as the average temperature of external air (Table 1 embodying the meteorological data), we can read the diagram and learn the COP values for temperatures given as 2.8 and 3.2 for February (-2°C) and November (3°C), respectively. The values are presented with a green arrow at the diagram marked as 'II no tank' for February and a red arrow marked as 'XI no tank' for November.

Moreover, the diagram presents the increase in the COP value during the heat storage tank discharging process. These are signed as 'cooperation with solar tank range' with a given month of the year and marked with short arrows. All the data given for February is signed in green color, whereas for November, it is in red color. In case of late winter period (February), we observe the COP value rise from 3.0 to 4.2 (short green arrows) according to the air temperature reaching the evaporator (see Fig. 3) with the average value of 3.65 (green dashed line – "average II"). As for November, the middling value of COP is 3.7 (red dashed line – "average XI") with the increase in the range of 3.3 to 4.1 (short red arrows). The calculations present a 30% increase in COP value in the case of February and 15% for the November analysis.

The measurable effect of the addition of a heat storage tank to the system is a reduction of expenses for the system owner. For the calculations proceeded in the economic aspect, the assumption is that the solar system and air-to-water heat pump system are already installed in the building. Only the energy accumulating tank will be an additive component of the system. When considering the actual paraffin prices, the installation cost is about 1,800 euros. In February, the expenses reduction will amount to 58 euros, with the cost decrease in November totaling 28 euros. The calculations concerned the electric energy present costs and were conducted assuming the cooperation during the months of the year that were analyzed in the paper: for February or November only.

The studies prove that the simple payback period for February and November is 2.5 and 5.3 years, respectively, for the analyzes of the transition period only. The value verifies the short period of time necessary to recover the expenses by means of compressor energy consumption reduction. However, the solar energy storage tank will not only accumulate the energy during those two examined months. Therefore, the payback period would be even shorter, with studies concerning the whole year.

5. Conclusions

The cooperation of a solar system equipped with a heat energy storage tank and an air-to-water heat pump during the transition period of time (for autumn/winter or winter/spring seasons) presents the quantifiable outcomes. The energy accumulation system absorbs the solar energy by means of a phase change material: paraffin. The external air flows through the heat exchanger inside the tank in order to increase its temperature before reaching the heat pump's evaporator. The temperature rise, in the months analyzed in the paper, November and February, is 15 times to more than 20 times greater than the average external air temperature, respectively. The results demonstrate COP improvement of the heat pump by 15% to 30% (November and February, respectively), which gives a significant reduction in the heat pump system operation cost. Only for the analyzed months, the conducted profitability analysis, characterized by means of the simple payback period value below 3 years (February) and 6 years (November). The rate would be even lower if the solar heat accumulation throughout the entire year were included. The economy of the system was therefore verified through the studies. A Thermal Energy Storage tank equipped with a paraffin wax is an effective solution to develop the RES system in the building, already consisting of solar and an air-to-water system.

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