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Heat Pump Combined with PV for Single-Family House

Tepelné čerpadlo v kombinaci s fotovoltaikou pro rodinný dům

The simulation model of an energy system consisting of a ground-source heat pump combined with PV and thermal storage tanks for a single-family house was developed. The PV system is connected to the heat pump for the domestic hot water preparation and space heating. The energy system allows one to maximise the usage of the PV power by means of overcharging the volume of the storage tanks by the heat pump with the use of an adaptive control. Furthermore, a parametric analysis incorporating the different PV system power installed was carried out. With respect to the total electrical energy consumption of the heat pump, the annual grid consumption may be reduced up to 40 %.
Keywords: *heat pump, photovoltaics, nearly zero energy building, thermal storage*

Pro rodinný dům byl vytvořen simulační model energetického systému sestávajího z tepelného čerpadla země-voda kombinovaného s fotovoltaikou a akumulačními zásobníky tepla. Fotovoltaický systém je spojen s tepelným čerpadlem pro přípravu teplé vody a vytápění. Energetický sytém umožňuje maximalizovat využití výkonu fotovoltaiky přehříváním objemu akumulačních zásobníků tepelným čerpadlem prostřednictvím adaptivní regulace. Byla provedena parametrická analýza pro instalovaný výkon FV systému. Roční celková spotřeba elektrické energie ze sítě pro tepelné čerpadlo může být snížena až o 40 %.
Klíčová slova: *tepelné čerpadlo, fotovoltaika, téměř nulová budova, akumulace tepla*

INTRODUCTION

Implementation of the Directive on the Energy Performance of Buildings [1] into the national legislation has opened the question which energy systems for buildings could achieve the recommended figures for nearly zero energy buildings (NZEBs) [2]. As an ambitious target for the climate of the Czech Republic, the value of 20 kWh/m^2.a for non-renewable primary energy consumption can be set for space heating and hot water preparation.

The paper focuses on the heat pump system, which consumes electricity to transform low temperature heat into high temperature heat delivered in the building. Nevertheless, the electricity grid has a relatively high conversation factor for Europe in general and for the Czech Republic in particular ($PEF = 3$). Here, a combination of a heat pump system with photovoltaic (PV) technology is regarded as a logical step. On the one hand, feeding the energy produced by the local PV source into the grid has been complicated and has become less beneficial due to the negligible feed-in tariffs. Therefore, PV installations today are oriented to maximise its self-consumption. On the other hand, the time periods of the PV and heat pump's operation do not naturally match. The PV system generates electricity during the day and the summer season, the heat pump operates mostly during the winter, at night and in the morning/evening during the hot water load peaks.

From the available alternatives on how to overcome this mismatch (e.g., demand-side management), a load-shifting method was adopted in this paper. To arrive at the most cost-effective system operation, the surplus PV power is transformed by the heat pump and is stored in storage tanks by means of overcharging (charging a larger part of the tank volume at high temperature). Subsequently, such a strategy forces the heat pump to operate when the PV power is produced, i.e., it shifts the heat pump consumption towards the daylight hours.

HEATING SYSTEM

The energy system is represented by the heat pump operating with two storage tanks: 300 litres for the domestic hot water (DHW) preparation and 450 litres for the space heating (SH). Then, the heat for the space heating is distributed through the floor heating system with nominal heating water temperatures of 35/30 °C. The supply temperature to the floor heating system is set by the heating curve. The DHW demand profile is 206 l/day with a water intake temperature of 45 °C. The DHW heat demand is 3060 kWh/a, the SH demand is 4300 kWh/a.

The heat pump nominal output is 5.7 kW and the *COP* (coefficient of performance) is 4.6 at the B0/W35 condition. A simplified scheme of the heating system is shown in Fig. 1. The whole system has a controller logic as follows:

- the heat pump starts with respect to the conventional control signal (the temperature sensors are installed at the upper part of the tanks at 70 % of the tank's height), the strategy hereinafter is referred to as *non-PV-led* (see the upper part of Fig. 3);
- the previous signal is modified: the heat pump also starts when the PV power is higher than the threshold power and overcharges the storage tanks (additional sensors are installed at the bottom lower part of the tanks at 10 % of the tank's height), however, the sensor in the upper part still has the priority. The strategy hereinafter is referred to as *PV-led* (see the bottom part of Fig. 3);
- the threshold power was defined for the heat pump on a priori for the simulation of an on/off compressor.

As seen from the Fig. 1, two temperature sensors are employed for the control purposes. The setpoints for the DHW are 50 °C for the top sensor (standard operation) and 55 °C for the bottom sensor (overcharging operation). For the SH storage tank, the top sensor setpoint is the heating curve supply temperature plus 2 K, the bottom sensor setpoint is 55 °C.

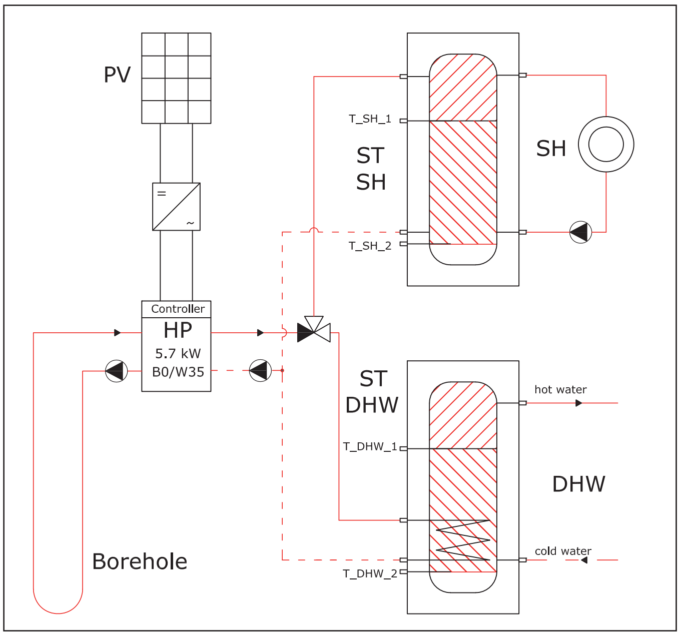

Fig. 1 The scheme of the PV heat pump system

FAMILY HOUSE

The single-family house (built in 2016) shown in Fig. 2 has been employed in the research. The building is situated in the Czech Republic and its design heating loss is 4.5 kW at -12 °C ambient temperature. The total heated area is 286 m^2 while the volume is around 1000 m^3. The building is heated by a floor heating system. The building is equipped with a PV system of 6 kW$_p$, however, a series of the installed PV power was studied, i.e., 1, 3 and 6 kW$_p$. The roof slope (PV modules slope) is 40°.

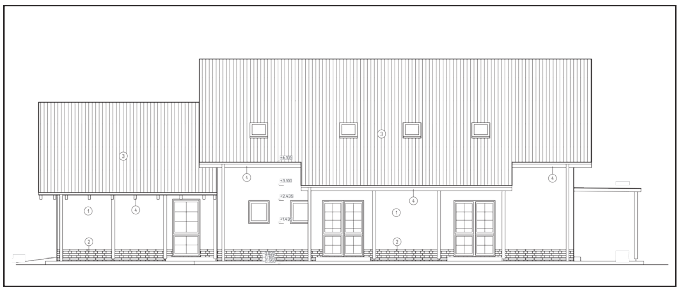

Fig. 2 The family house used in the case study

SIMULATION ANALYSIS

The PV heat pump system was described with the Modelica language and Buildings library use [3]. The heat pump model used is a grey model which considers a simplified compressor cycle. The storage tanks are modelled considering stratification. The PV system is a 5-parameter model that takes the optical and electrical properties of the module into account. The borehole is 75 m deep [4] in the ground with average properties (conductivity 2 W/m.K). The building envelope was described using the IDEAS library [4], the U-values of the constructions are as follows:

- Walls – 0.12 W/m^2.K;
- Floor and ceiling – 0.15 W/m^2.K;
- Windows – 0.7 W/m^2.K.

The weather conditions used in the simulations are those typical for meteorological year [5] in Prague.

RESULTS

A heat pump system with a borehole for the SH and the DHW was modelled as a reference case. Such a system has a seasonal performance factor (*SPF*) of 3.73, the total electricity consumption of the system is 1976 kWh. If the PV system of 6 kW$_p$ is added to the heat pump system then the *SPF* results in 4.9 (Tab. 1). The PV-generated power used for covering the electricity hardly approaches a value of 470 kWh even though the PV modules generate 5420 kWh annually. Thus, the PV power usage is extremely low – around 9 %. Moreover, the specific nPE demand results in a value of 24 kWh/m^2.a, thus, it is still above the target set. The following research f°Cuses on the measures for the specific nPE demand decrease in the respected energy system.

Furthermore, the same system was studied with a conventional control strategy with respect to the PV power (non-PV-led) and with an advanced control strategy (PV-led) with a series of PV installed power of 1, 3 and 6 kW$_p$. The results are presented in Tab. 1 and Tab. 2.

Tab. 1 – The simulation results for the conventional control strategy (non-PV-led)

Parameter	**w/o PV**	**1 kW$_p$**	**3 kW$_p$**	**6 kW$_p$**
Electrical power need [kWh/a]	1976	1874	1673	1504
System *SPF* [-]	3.73	3.94	4.41	4.90
Solar fraction f_{PV} [%]	-	5	15	24
Solar usage r_{PV} [%]	-	12	11	9
Specific nPE consumption [kWh/m^2.a]	31	30	26	24

Each installed power of the PV system results in its own optimum threshold power level – the value of the PV system generating power above which the heat pump is started to overcharge the storage tanks. In addition, the results are presented in Fig. 4 as a graph of the external electricity grid needed versus the power threshold. Based on these results, it is worth noticing that the grid electricity needed for the system studied is also in high dependence on the thresh-

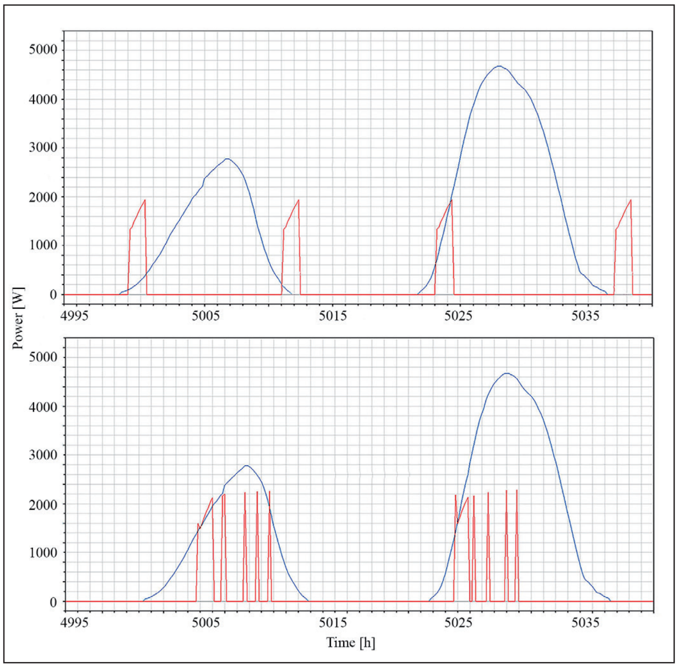

Fig. 3 The simulation results for the non-PV-led system (on the left) and the PV-led system (on the right) (the PV power is in blue and the heat pump power is in red)

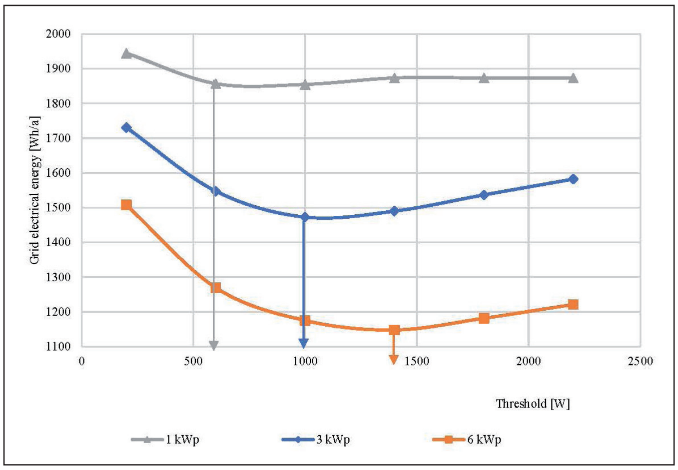

Fig. 4 The optimum power threshold levels for the given PV peak power installed

old, which also takes place with the heat pump-PV system for the DHW preparation only. Nevertheless, the optimum threshold values can be derived from the graph: as the PV power installed increases the threshold, the level increases as well (see Fig. 4): for 1 kWp, the threshold was found at 600 W, for 3 kWp at 1000 kWp and for 6 kWp at 1400 W. The results in Tab. 1 and Tab. 2 are given considering these optimum values for the the threshold power.
During the extensive number of simulations, the heat pump operated under the on/off controller only and the results in Tab. 1 - 2 are given for the on/off heat pump.

As follows from Tab. 2, the specific nPE system consumption can be reduced up to 18 kWh/m².a by introducing a PV-led control approach. With this improvement, the specific nPE demand meets the set target of 20 kWh/m².a.

CONCLUSION

Overall, there are several approaches aimed to reach the NZEB target energy demand. In parallel to these approaches, a clear and sustainable way is to use a heat pump combined with the PV and PV-led strategy employed. This paper investigates the operation of the energy system consisting of a ground-source heat pump combined with PVs and a thermal storage for a single-family house. Furthermore,

Tab. 2 – The simulation results for the advanced control strategy (PV-led)

Parameter	w/o PV	1 kW_p	3 kW_p	6 kW_p
Electrical power need [kWh/a]	1976	1857	1473	1148
System *SPF* [-]	3.73	3.97	4.96	6.41
Solar fraction f_{PV} [%]	-	8	30	46
Solar usage r_{PV} [%]	-	19	23	18
Specific nPE consumption [kWh/m².a]	31	29	23	18

the specific nPE need of the house is 18 kWh/m².a (for the SH, DHW and auxiliary energy) which is in good accordance with the target NZEB demand set in this article. The study brought the benefits of a heat pump-PV system to light, consequently the nPE demand is reduced up to 42 % with 6 kW_p PV compared to the reference system. Moreover, the PV-led strategy decreases the electricity grid demand by 12 % and by 24% compared to the conventional (non-PV-led) control approach for the 3 and 6 kW_p PV systems, respectively.

ACKNOWLEDGMENTS: The authors would like to acknowledge the financial support received for this research from SGS16 / 212 / OHK2 / 3T / 12 – Modelling, control and design of environmental technology equipment and Technology Agency of the Czech Republic (TACR) under the programme National Centres of Competence I.

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