Combined photovoltaic and heat pump system for domestic hot water and space heating

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Abstract

The system combination of photovoltaic modules and heat pump is a very promising way of increasing renewable energy usage for domestic hot water preparation and space heating. The paper deals with analysis of ground-source heat pump connected to the customer domestic hot water and space heating load through the thermal energy storage. This combined system has been studied by means of numerical simulations. The challenging issue in the system is the controller setup. In this research, several ruler-based controller strategies are employed to maximize photovoltaic electricity usage on-site: by means of overheating the building or/and by means of overheating thermal energy storage. These approaches allow to store energy surplus generated by photovoltaics valorized by heat pump in the form of heat. Comparison between different system control setups and the reference case shows the absolute annual electricity savings and moreover, the results reveal advantages of proposed combined system and show the ways to maximize usage of the high volatile photovoltaic electricity. The simulation results for NZEB house with heating energy demand of 14 kWh/m^2.a indicate solar fraction raise up to 50 % , furthermore such combined systems are able to reach system seasonal performance factors in the level of 6.5

Key-words: PV; heat pump; NZEB; thermal storage

1. Introduction

The paper deals with heat pump application for domestic hot water preparation and space heating in single-family house. As Directive on Energy Performance of Buildings [1] obliges the European countries to build only Nearly-zero energy buildings (NZEB) from 2020 onwards, present study suggests measures of improving performance of an energy systems that incorporates heat pump. Coupling PV with heat pump has a bottleneck issue – controller setup. PV system as a highly volatile renewable energy source has production during hours with no heat pump electricity consumption. Thus, electricity generated by PV modules is barely used on-site, i.e. solar fraction is about 15 % (home electrical appliances are not considered in the scope of this study). In order to overcome this mismatch in electricity production and consumption the load-shifting approach has been used in this paper. The load-shifting method represents the way to store energy generated by PV and then valorized by the heat pump in form of heat. The paper investigates solutions to increase PV energy on-sight consumption by employing different control concepts. Our paper clearly has the limitation and does not consider home electrical appliances in the system balance, nevertheless current work can be solid framework for heat pump- and PV system analysis. As system control set-up plays a crucial role in the overall system efficiency Thus, three different approaches on how to store heat were applied:

- overheating thermal storages
- overheating building
- overheating thermal storages and building

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2. Heating system

The heating system is represented by the ground-source heat pump operating to heat up two storage tanks: for domestic hot water (DHW) preparation of 300 liters and for space heating (SH) of 450 liters. Then heat is distributed through the thermally activated building system (TABS) at 35/30 °C, which is floor heating system. The DHW demand profile is 206 l/day with water intake temperature of 45 °C. DHW heat demand is 3060 kWh/a, SH demand is 4180 kWh/a. Heat pump output is 5.7 kW and COP = 4.5 at B0/W35 and 50 Hz. The heating system is shown on the Fig. 1.

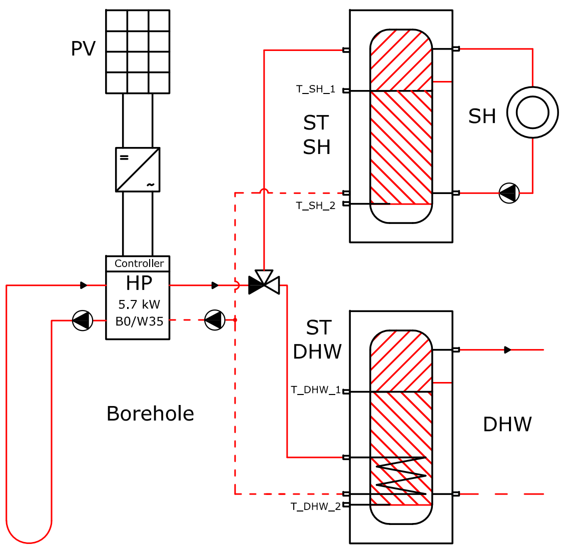

Fig. 1. *Scheme of PV heat pump system*

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

2.1. Family house

Single-family house (built in 2016) shown on the Fig. 2 has been employed in the research. The building is situated in Czech Republic and its design heating loss is 4.5 kW at -12 °C ambient temperature. Total leaving area is 286 m^2 while volume is around 1000 m^3. The floor heating system 35/30 ° is used to heat the building. Such low-temperature emission system was chosen due to the heat pump has better efficiency when operating at low condensation temperatures. The building is equipped with PV system of 6 kW_p, the roof slope (PV modules slope) is 40 °. Since the building has quite low energy demand for SH, internal heat gains start to play crucial role when calculating energy demand of the building. However, the simplistic approach was used for occupancy modeling, i.e. schedule occupancy presence from 17 to 8 hours with value of 130 W/person.

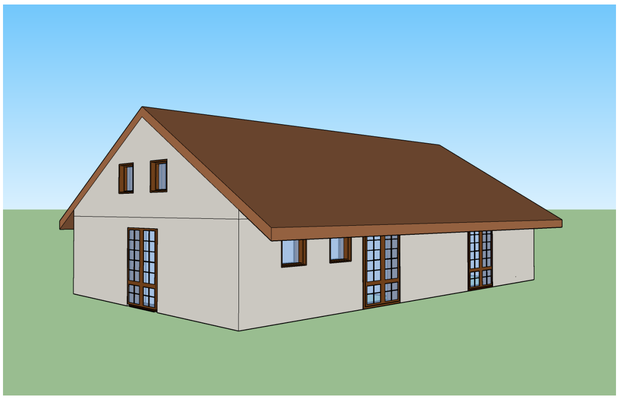

Fig. 2. *Family house used in simulations*

U-values of 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 condition used in simulations is typical meteorological year [2] for Prague.

2.2. Control concepts

The solution just to couple heat pump with PV is unsatisfactory under the conventional control strategy. By the conventional control authors refer the system control when the heat pump does not "see" the PV power generation. Thus, it runs according signals from temperature sensors at storage tanks only. The paper suggests new control approach – the heat pump can be run when there is surplus of PV power additionally to the conventional control signal. During these supplementary operating hours the heat pump can heat either storage tanks or building thermal mass, or both. Essentially, such control concept is storing PV surplus energy valorized by the heat pump in different thermal storages. The Tab. 1 is provided to summarize and to distinguish control approaches described above.

Table 1. *Control concepts*

Control concept	Description
ref	Reference control strategy (conventional)
ST	Storing energy in storage tanks by means of overheating them
SH	Storing energy in thermal mass of building by means of overheating it
SH_ST	Storing energy in both storage tanks and thermal building mass by means of overheating

As it was mentioned above the setpoint temperatures for thermal energy storage tanks (TES) was set at 50 °C for DHW, and according to the heating curve for the SH storage each with deadband of 4 K. This control approach is referred to as "ref" in Tab. 1. Temperature sensors are located at the top part of the TES (see Fig. 1: T_SH_1 and T_DHW_1). Further, ST is the concept of storing PV energy surplus in storage tanks which in its turn allows the heat pump to overheat DHW and SH storages, i.e. to heat up TES at higher temperature 55 °C. Moreover, temperature sensors used during overheating are moved to the bottom part of TES (see Fig. 1: T_SH_2 and T_DHW_2). SH control concept is described with heating the building at temperature of 26 °C instead of 21 °C. In the scope of this paper only one fixed room temperature for overheating is considered, i.e. 26 °C. The last control approach mentioned is SH_ST and it corresponds to the case when DHW TES has priority in overheating, then SH TES and building are overheated as well.

2.3. Simulation setup

All the system components were modeled with Modelica language and IDEAS library use [3]. Storage tanks are modeled considering stratification. DHW thermal storage has 200 l volume, the heat loss is characterized by overall UA-value of 1.58 W/K. SH storage has 450 l and it is characterized by overall UA-value of 2.0 W/K. Heat loss from TES is calculated as a heat loss to a boundary with a constant temperature of 20 °C. The heat pumps mathematical model is bi-quadratic curve fit for the heat output and electricity input. The curve-fit parameters were obtained for commercially available heat pump by least-square fitting [4]. During the modeling of the heat pump several restrictions have been imposed on heat pump operation, such as maximum and minimum condenser and evaporator operating temperatures, minimal standby time between start and stop of 10 min. Hot water load profile has been chosen from EU Commission Regulation 814/2013 on eco-design of water heaters [1]. Daily profile corresponding to the hot water consumption of single family of 4 persons was used in the simulations. Moreover, the load profile M was adjusted from delivering temperature of 55 ° to 45 ° temperature of water intake keeping the same amount of energy consumed. PV system is a detailed energy model that takes into account optical and electrical properties of the module [5]. The borehole was modeled as a constant temperature input t = 0 to the evaporator.

3. Simulations results

A heat pump system for SH and DHW was modeled with no PV installed. Such system has seasonal performance factor (SPF) of 3.5, total electricity consumption of the system is around 2000 kWh/a. If PV-system of 6 kW_p is added to the heating system, then SPF results in 4.2 (Tab. 2). PV-generated energy used for meeting the heat pump electricity input hardly approaches value of 300 kWh/a, even though PV modules generate annually 5420 kWh/a. Thus, solar usage is extremely low – around 6 %. Moreover, the specific non-renewable energy (nPE) demand results in value of 18 kWh/m^2.a.

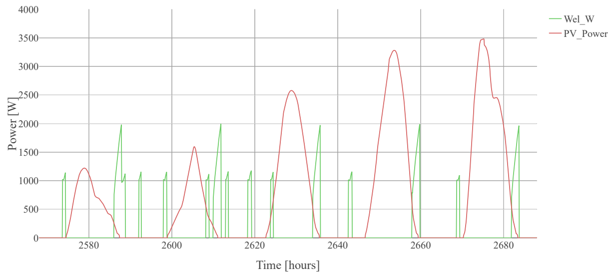

Fig. 3. *Reference control concept*

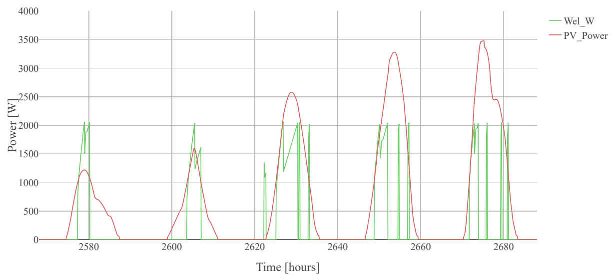

Fig. 4. *ST control concept*

The graph above (Fig. 3) indicates that reference setup results in mismatch between PV energy production and heat pump energy consumption. This comes naturally from user behavior – DHW and SH load occurs when there is almost no energy generated by PV. On the contrary, Fig. 4 presents the shift in heat pump electricity input due to ST control concept. Here the major part of heat pump electricity input is met by PV output. Thus, this concept reveals potential for PV self-consumption on the site.

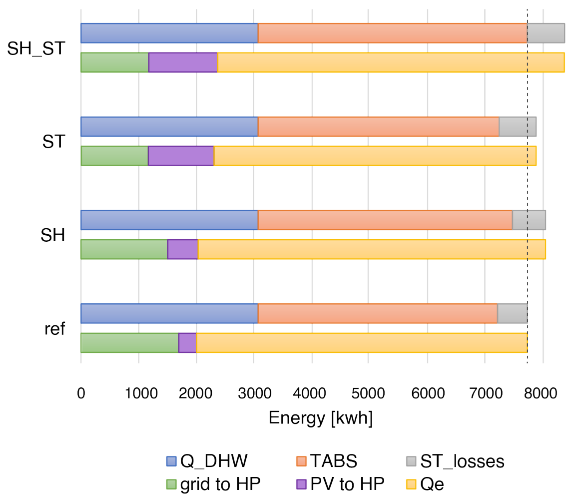

Fig. 5. *Energy balances for various control strategies*

The results of applying various control concepts are apparent from Fig. 5. The energy demand and energy supply are indicated as top and bottom bars, respectively for each of the control concept. First, the reference case resulted in total energy consumption of 7900 kWh/a, every other concept caused the total energy demand increase, due to the supplementary heat pump operation. Consequently, the PV-power consumption by the heat pump has raised from 300 kWh/a for reference case up to 1210 kWh/a for SH_ST, which corresponds to solar fraction increase from 15 % up to 51 %, respectively.

Such improvement in system performance can be seen from the system seasonal performance factor(SPF) as well, which is given in the Tab. 2. The system SPF is evaluated as follows:

$$SPF = \frac{Q_{DHW} + Q_{SH}}{W_{el,HP} + W_{el,aux} + W_{el,BH}} \qquad (1)$$

The heat pump performance is highly influenced by the operating temperatures of primary and secondary sides. Thus, overheating thermal storages causes the heat pump to run at high condenser temperatures, which subsequently results in low coefficient of performance (COP) of heat pump. Next, when overheating building the supply temperature to TABS is comparatively low and heat pump has high COP. Therefore, SH control concept has huge potential for system performance increase. However, the current system setup indicates the system benefited from ST concept more than from SH.

Huge improvement in performance is seen when ST strategy is applied. This is attributed not by capacities magnitude of thermal storages versus building, but the priority in control signals: DHW TES has priority. On the other hand, building absorbs solar gains during the day, in particular the floor temperature raises limiting overheating capacity of the SH strategy. This accounts for low gains in system SPF when SH and ST concepts compared to reference case, i.e. 4.9 and 6.2 versus 4.2 (see Tab. 2).

Table 2. *Control concepts*

Parameter	noPV	ref	SH	ST	SH_ST
Specific electricity demand [kWh/m^2.a]	7.0	6.0	5.4	4.1	4.2
Specific nPE demand [kWh/m^2.a]	21.0	18.0	16.1	12.3	12.5
System SPF [-]	3.6	4.2	4.9	6.2	6.5
Solar fraction [%]	-	15	26	50	51
Solar usage [%]	-	6	10	21	22

4. Conclusion

The present paper deals with heat pump combined with PV system application for DHW and SH in single-family house. As reported above the control strategy has a crucial impact on the system performance. If the heat pump is adjusted to the PV power then solar fraction can be increased up to 50% as well as system SPF can be increased up to 6.5. The investigations are quite optimistic, however the results came from numerical simulation study only. Current work has led us to conclude that heat pump combined with PV can be an elegant solution for heat pump application for NZEB.

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