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Heat Pump System Performance with PV System Adapted Control

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Abstract

Combination of heat pumps with PV systems could significantly reduce the use of grid electricity from external supplier for space heating and hot water application. The paper presents an analysis of using PV adapted control for heat pump operation in two different alternatives and compares such advanced approach with conventional static approach. Both alternatives of the adapted control for the heat pump system achieve high solar fraction about 39 % compared to conventional approach (16 %) and more than 30 % higher seasonal performance factors.

Keywords: *heat pump, PV system, adapted operation*

1. Introduction

There is a number of measures to increase the energy performance of modern buildings today. Space heating demand has been minimized to limits of technical and economical possibilities in case of passive houses (envelope insulation, triple glazings, ventilation heat recovery, etc.). Domestic hot water systems use energy saving showers, insulation of hot water piping, time and temperature control of hot water circulation run, etc. Further savings can be expected with use of heat recovery from waste water. Electricity demand has been continuously reduced with an introduction of appliances with energy class A and better and implementation of modern daylighting principles together with proper control of LED artificial lighting.

Logical step ahead to decrease the energy demand in buildings is application of renewable energy sources. Heat pumps use the renewable energy from ambient environment, however they also need grid electricity to valorise the renewable heat to useful temperature level for space heating and hot water preparation. Grid electricity in Europe in general has high primary energy conversion factors (Molenbroek, 2011) dependent on the share of renewables in the grid in each country. The grid electricity in Czech Republic originates from non-renewable fuels (brown coal and nuclear power plants) which disqualifies the use of such electricity in heating applications within the frame of building certification. Simultaneously, the associated high CO_2 emission factor for electricity (Ecometrica, 2011) has a direct impact on the environmental assessment of the heating systems in subsidy schemes. Both implications lead to the effort of minimizing grid electricity use as an energy carrier for space heating and hot water preparation, despite the fact that costs of electric heating systems are the lowest.

Current trend in increasing the effectiveness of electricity use by the heat pumps is complemented by local production of renewable electricity by PV systems. The supply of local electricity production to a public grid has been complicated in several countries already (huge administration, negligible feed-in tariffs) and new installations are focused on the local use of renewable electricity from PV systems integrated into buildings. Production of electricity by PV systems and use of electricity by heat pumps seems to be an ideal combination to significantly reduce the external supply of electricity from public grid for space heating and hot water systems (IEA, 2014). However, the reality is not that simple as can be evident on first sight. The paper shows the potential of conventional state-of-art heat pump systems to use local PV electricity to increase the effectiveness of space heating and hot water preparation.

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2. Family house

Energy efficient family house under construction (2016) has been chosen for an analysis of potential to combine the heat pump and PV system under climate of Czech Republic. Family house has two floors with a space volume of 935 m^3 and total living floor area 190 m^2. Family house has a passive house concept, *U*-values of individual envelope constructions meet the recommended values for such high performance buildings. Saddle roof has a slope of 40° with south-north orientation. Design heat loss of the house is 4.5 kW. Low temperature floor space heating system has been used with design flow/return water temperatures 40/35 °C. Ventilation is provided by air handling unit with maximum flowrate 275 m^3/h using a heat recovery.

Ground source heat pump unit has been designed for the heat supply to house. Investor considered the PV system installation to increase the energy independency of the house operation. Analysis of different size of PV system and different control of heat pump operation has been performed by computer simulation to provide maximum use of electricity production from PV system to cover the heat pump needs and thus to minimize external supply from public grid. System simulations have been performed in TRNSYS with use of detailed mathematical models of building (type56), storage tank (type340) and heat pump (type250) with a borehole (type451). Simulation has been performed with time step of 2 minutes to evaluate the match between the the electricity load by heat pump and electricity production by PV system properly. Two subsequent identical years of system operation have been simulated to provide the balance in the ground source, only second year has been used for evaluation.

3. Conventional static approach

Conventional solution for the improvement of energy effectivity for heat supply in considered passive house has been based on combination of ground source heat pump of capacity 5.5 kW without speed control and PV system. PV system has been considered in different alternatives of installed nominal power without any advanced system control to adapt the operation of the heat pump according to available PV production. Heat pump is hydraulically connected to combined water storage tank with volume 900 l. Bottom part of the storage is connected to space heating system (SH zone) and is charged to required flow temperature according to outside air temperature (OTC control). Storage tank involves the integrated tube heat exchanger with surface area 6 m^2 for hot water preparation. Top part of the storage tank is dedicated to water heating (HW zone) and maintained at required temperature at minimum required set-point the whole year.

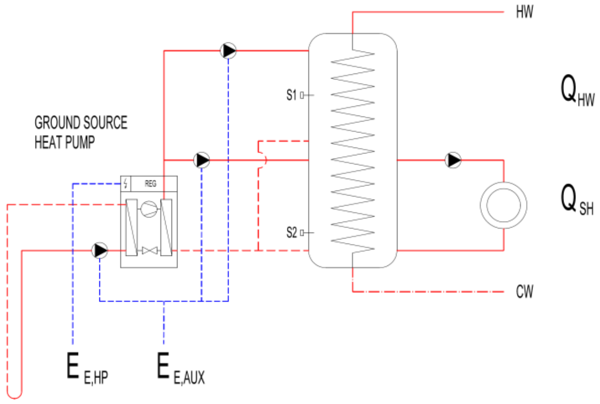

Fig. 1: Scheme of the conventional ground source heat pump system

The heat pump system delivers 3429 kWh/a of heat for space heating and 3063 kWh/a of heat for hot water to satisfy the energy demand of house. The heat loss of the storage tank amounts more than 550 kWh/a which degrades the performance of the whole system. Electricity use of the heat pump system is 2446 kWh/a, i.e. system seasonal performance factor *SPF* is 2.7. This is a value common for heat pump applications in passive houses because annual effectiveness is significantly influenced by high ratio of hot water preparation demand (47 % in given case) to be supplied at high required temperature 45 °C at any part of the year. Such temperature available at integrated heat exchanger output results in hot water set-point for HW zone permanently 55 °C.

Improvement of the system performance could be achieved by a combination with PV system. The PV electricity production can partially cover electricity use of the heat pump system. Tab. 1 presents the results of computer simulation in TRNSYS for different alternatives of PV system size: 1 kW_p, 3 kW_p and 6 kW_p. Except the grid electricity use and *SPF* the parameters monitored and evaluated were solar fraction f_{PV} (coverage of electricity use by PV system) and degree of PV electricity utilization r_{PV} (ratio of used PV electricity to produced PV electricity). The results show that installation of PV system slightly improves the total effectiveness of heat supply, however utilization of PV electricity is very low, at level of several percents. The explanation can be shown in two profiles of the electricity load and production including the temperatures in the storage tank for two typical weeks, first for summer season (see Fig. 2) and second for winter season (see Fig. 3).

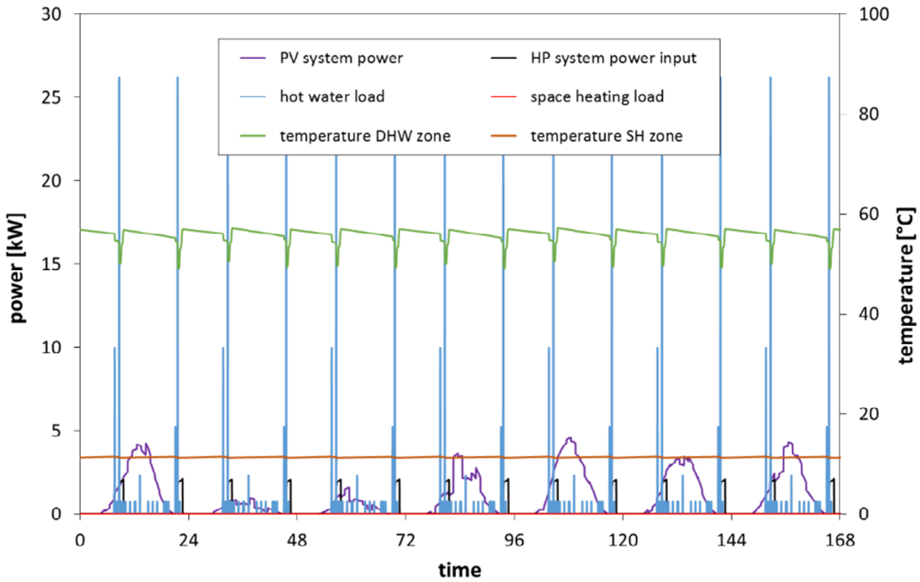

Fig. 2: Production and load profile of the conventional PV heat pump system in summer (6 kW_p)

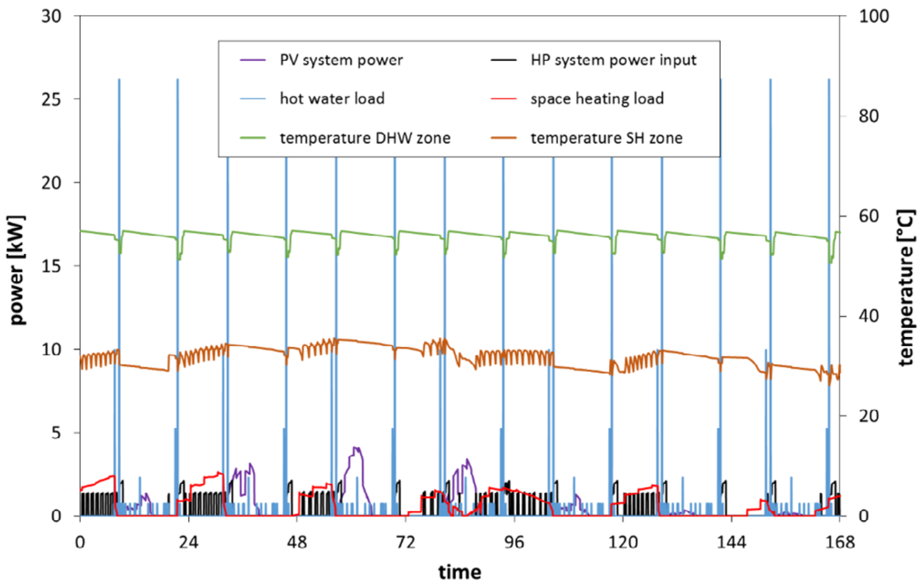

Fig. 3: Production and load profile of the conventional PV heat pump system in winter (6 kW_p)

As shown in Fig. 2 for summer season, the heat pump starts and uses electricity if temperature in HW zone decreases due to hot water load. Hot water load has the morning peak and the evening peak. Match between time of PV electricity production and electricity load by heat pump happens only partially during the HW zone charging by heat pump after morning peak of hot water load (in optimum case).

Tab. 1: Results of TRNSYS simulation of PV heat pump system with conventional approach

Parameter	Reference alternative (no PV)	Alternative 1 kW_p (4 modules)	Alternative 3 kW_p (12 modules)	Alternative 6 kW_p (24 modules)
Electricity from grid W_{el} [kWh/a]	2446	2370	2217	2061
System *SPF* [-]	2.7	2.7	2.9	3.1
Solar fraction f_{PV} [%]	-	3	9	16
PV utilization r_{PV} [%]	-	8	8	6

From the point of the match between heat pump electric load and PV system electricity production (see Fig. 3) the situation is not more favourable in winter. Heat pump for space heating starts and uses electricity if temperature in SH zone decreases due to space heating load. The space heating in passive house occurs practically only during the night because the heat loss of the passive house is effectively compensated by solar heat gains during the day. Morning and evening hot water peak loads occur mostly within the time periods with no PV production.

4. Advanced approach – PV adapted operation of heat pump

An adaptation of heat pump operation to time period of PV system production ca be used in order to increase the utilization of PV electricity to cover heat pump electricity use. If the PV system actual power overcomes at given time a certain power threshold, algorithm of the system controller shifts the set-point for charging the storage tank and thus forces the heat pump to start. It practically means that in case of sufficient PV electricity production the heat pump is started, heats up the defined volume of storage tank to higher temperature than the required set-point (zone overcharging). The heat produced by the heat pump is stored in the combined storage tank for later use. The question of optimization process is the value of the power threshold for adapted operation of the heat pump system to minimize the annual electricity demand of the system. There were two alternatives for the control by set-point shift considered:

- PV-HW – alternative where the control shifts the required temperature 55 °C to 60 °C (considering the temperature limit of the heat pump) in the hot water zone of storage tank and sensor S3 is used as relevant temperature sensor (see Fig. 4 left) to enlarge the heated volume of the HW zone in storage tank;
- PV-SH – alternative where the control shifts the required temperature to 50 °C in the space heating zone of storage tank (see Fig. 4 right).

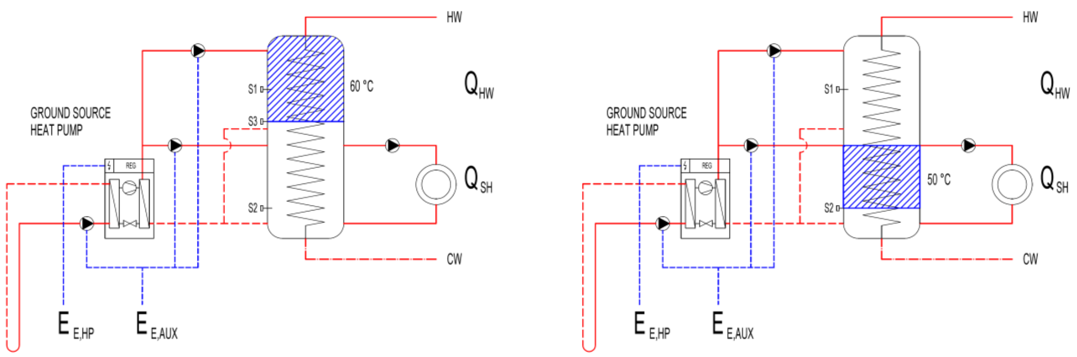

Fig. 4: Alternatives of adaptive control for heat pump system: PV-HW (left) and PV-SH (right)

To find an optimum power threshold for both adapted control alternatives a parametric analysis has been performed. The results are shown in Fig. 5 and Fig. 6. While the system power input in regime of overheating the storage to high temperatures 50 to 60 °C overcomes the value of 2 kW, the optimum threshold found for both alternatives ranges around 1.0 kW for 3 kW_p PV system and around 1.25 kW for 6 kW_p PV system. Analysis for PV system with installed power 1 kW_p wasn't considered.

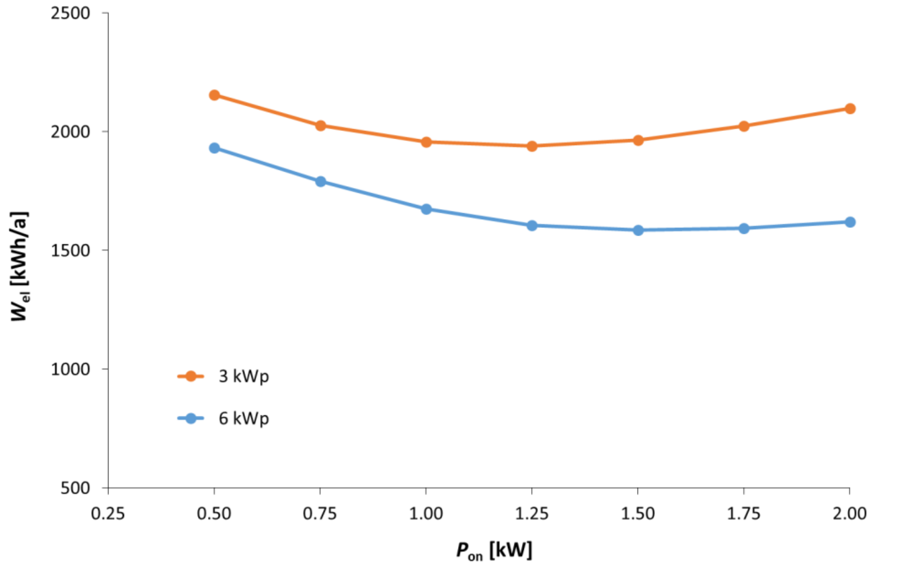

Fig. 5: Optimum value of power threshold for alternative PV-HW

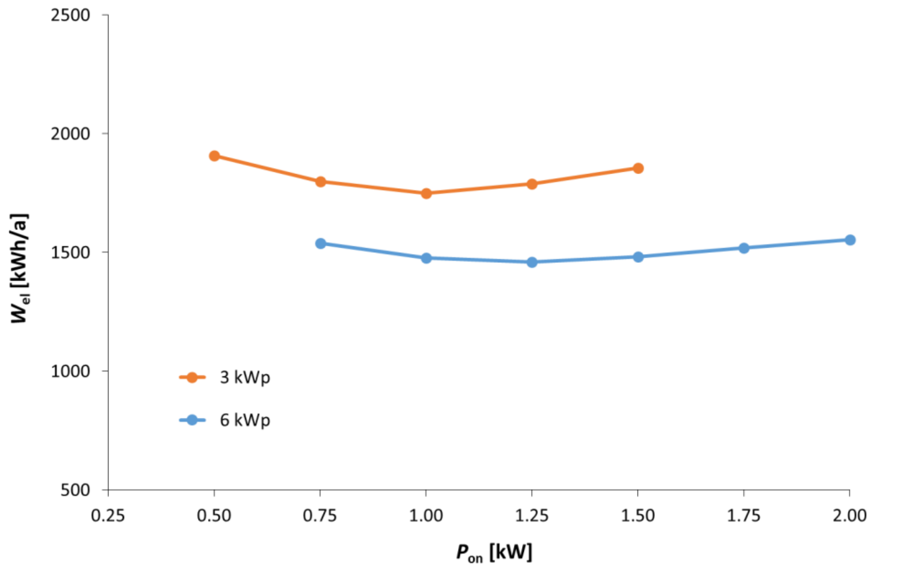

Fig. 6: Optimum value of power threshold for alternative PV-SH

Results of simulations with optimized thresholds are presented in Tab. 2 for both alternatives of the adaptive control and PV systems with nominal power 3 kW_p and 6 kW_p. Fig. 7 and 8 shows the profile of the electricity load and production, including the temperatures in the storage tank for adaptive system alternative PV-HW in the identical two typical weeks as it has been shown for reference system with PV system of nominal power 6 kW_p. Compared to the reference (shown in Fig. 2), there is obvious shift of heat pump operation to the daytime with PV electricity production due to adaptive control in summer season (see Fig. 7). Increased temperature and larger heated volume has a direct consequence that despite the evening and morning hot water peak load from the storage, the temperature in the HW zone of the storage (required temperature sensor) doesn´t decrease under the standard set-point value and the heat pump doesn´t start out of the daytime. Only the days without available power of PV system sufficient to forced starting the heat pump show the decrease of required temperature in the HW zone in the evening hours and operation of the heat pump consuming the grid electricity. Similar function can be seen within the winter season (see Fig. 8 and compare it with Fig. 3), but with respect to lower PV system production the charging of HW zone in the storage tank to higher temperatures is not so frequent.

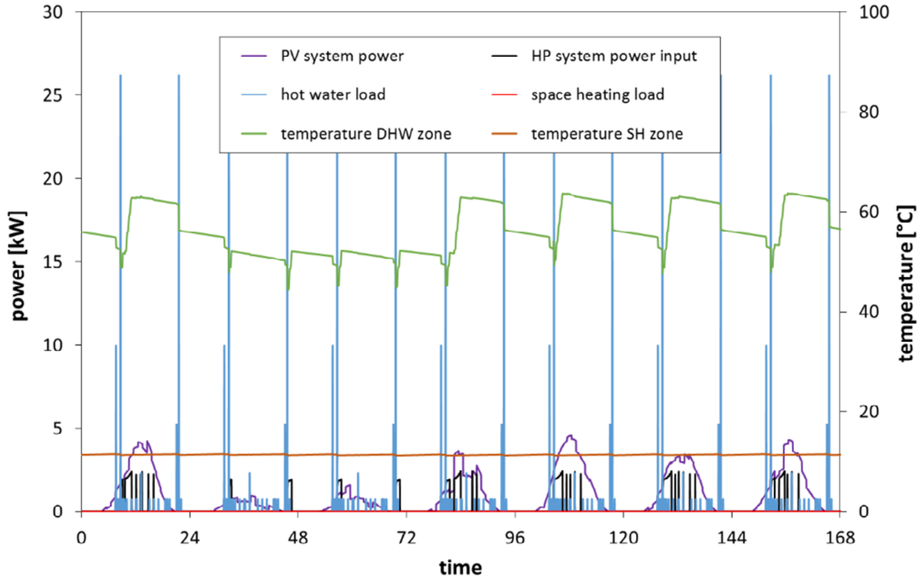

Fig. 7: Production and load profile of the PV heat pump system in summer (6 kW$_p$) – alternative PV-HW

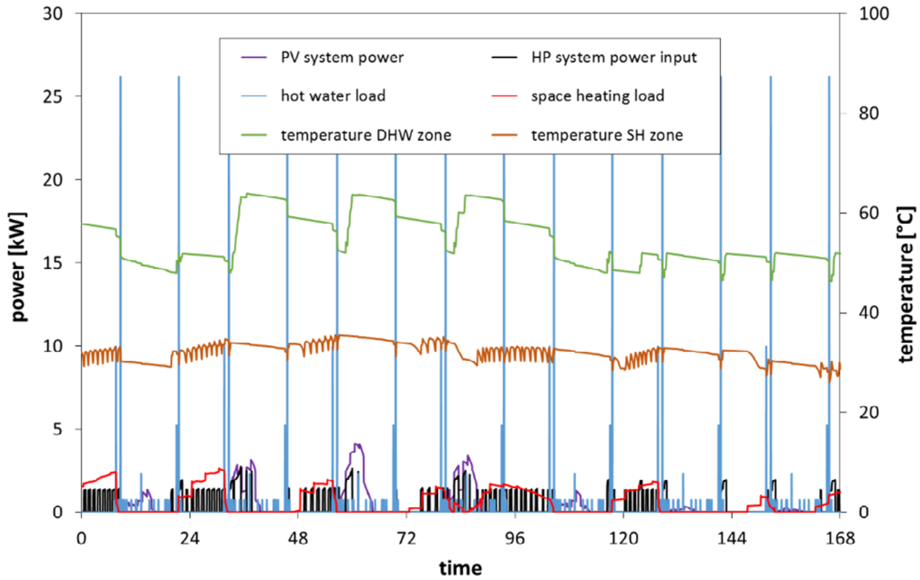

Fig. 8: Production and load profile of the PV heat pump system in winter (6 kW$_p$) – alternative PV-HW

Similar trend in system operation can be monitored also in adaptive control alternative PV-SH. Heat pump charges the SH zone of the storage tank to 50 °C whole year if the sufficient PV power is available. Hot water is preheated by integrated tube heat exchanger already in the SH zone. Therefore the temperature in HW zone doesn´t decrease significantly during the hot water loads (see Fig. 9 and 10). A very detailed comparison is shown in Fig. 11 where the PV system power and electric power input of the system for selected sunny winter day are presented for a conventional alternative without adaptation (above) and for PV-SH alternative with adapted control (below). Use of the PV electricity for overcharging of the storage tank by heat pump can shift significant amount of "night demand" of grid electricity to daytime and cover it from PV system. Temperatures shown in graphs belongs to temperature sensors positions dedicated to control of storage tank charging in both zones (HW, SH).

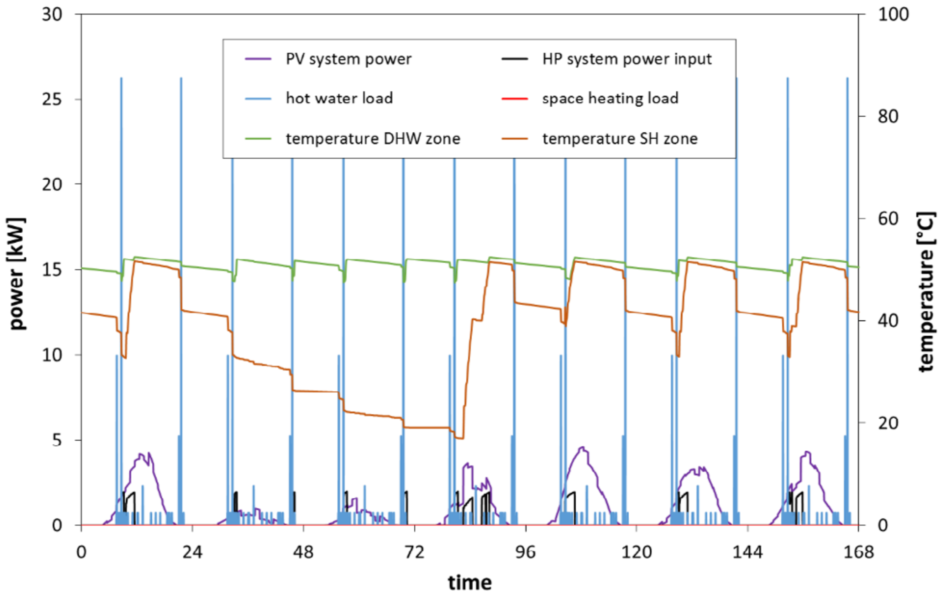

Fig. 9: Production and load profile of the PV heat pump system in summer (6 kW$_p$) – alternative PV-SH

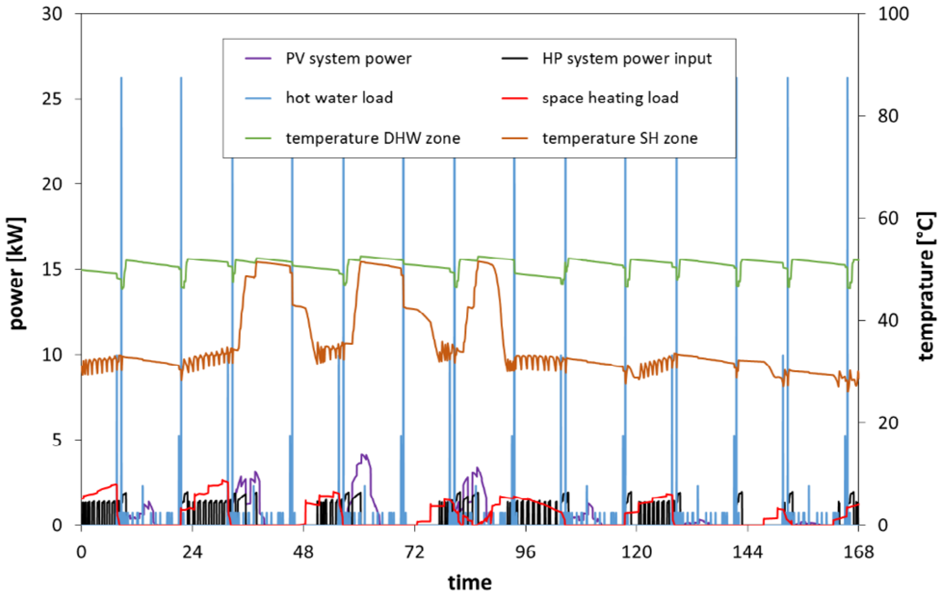

Fig. 10: Production and load profile of the PV heat pump system in winter (6 kW$_p$) – alternative PV-SH

Tab. 2: Results of TRNSYS simulation of PV heat pump system with adaptive control

Parameter	Alternative PV-HW		Alternative PV-SH	
	3 kW$_p$	6 kW$_p$	3 kW$_p$	6 kW$_p$
Electricity from grid W_{el} [kWh/a]	1941	1586	1749	1459
System *SPF* [-]	3.3	4.1	3.7	4.4
Solar fraction f_{PV} [%]	26	41	32	44
PV utilization r_{PV} [%]	22	19	27	19

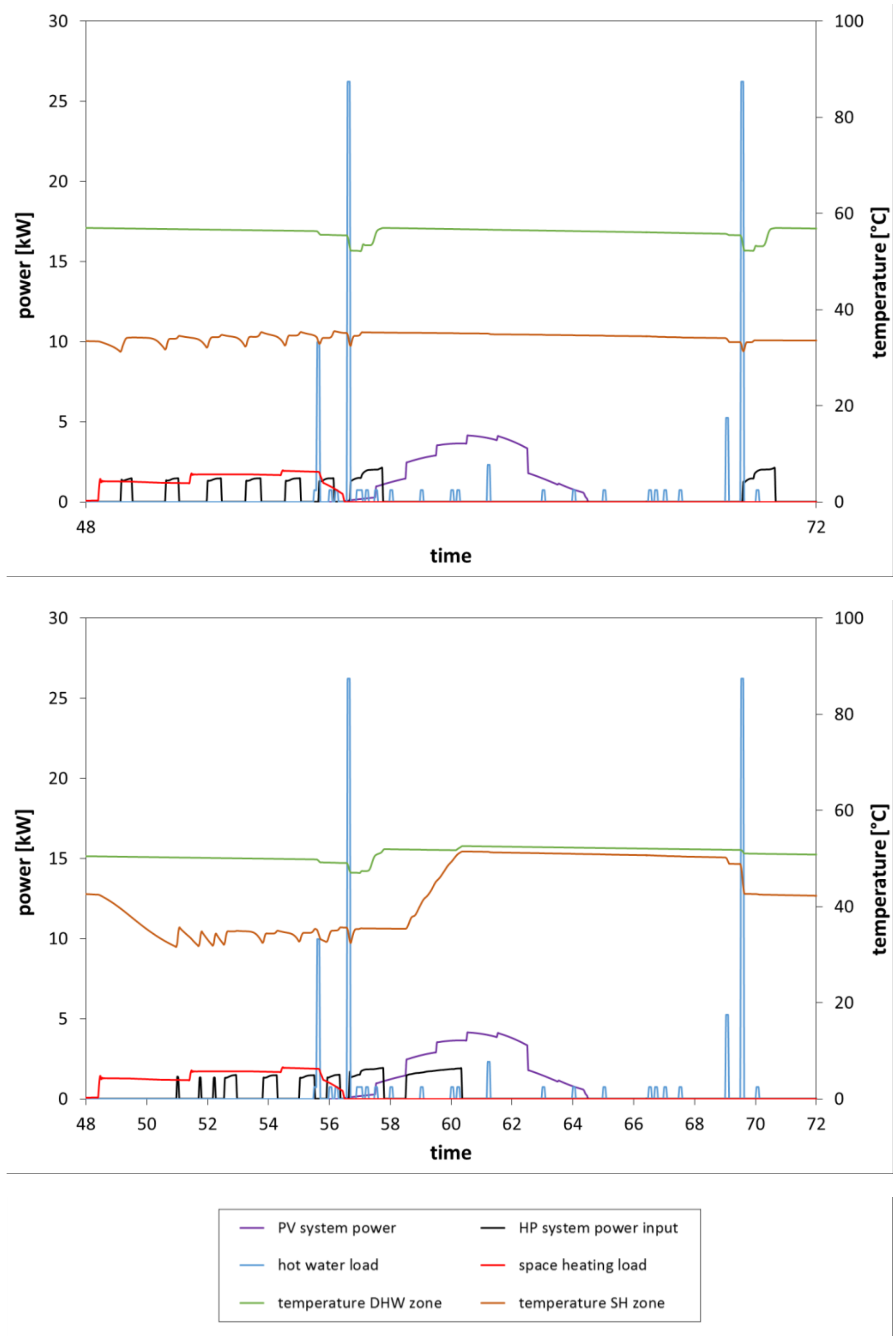

Fig. 11: Detailed comparison of production and load profile of the PV heat pump system in winter for conventional alternative and adapted PV-SH alternative (6 kW_p)

Computer simulations have shown that both alternatives of adapted control can significantly reduce the grid electricity use of heat pump system combined with PV system. The alternative PV-SH with overcharging the SH zone of the storage tank is more favourable thanks to lower annual use of grid electricity and higher seasonal performance factor *SPF* of the system for both PV systems with installed power 3 kW_p and 6 kW_p. Heat pump system alone works more effectively in time of using PV electricity due to charging the storage volume to lower temperature (50 °C) and finally the larger volume of the storage tank which is charged due to natural convection too.

5. Conclusions

Paper has indicated possibility of combination of heat pump and PV system by means of advanced adaptive control which already appears on the market. Computer simulation in TRNSYS has shown the benefits in energy performance of the PV heat pump systems for space heating and domestic hot water preparation. Simple adaptive control allows a significant increase in solar PV fraction and reduction of grid electricity use when compared with static control of conventional system. I has been shown that power threshold for adapted operation of heat pump to PV system lies significantly lower than maximum power input of the system. PV-SH control alternative with overcharging of space heating zone in storage tank has shown better results for the energy performance of the system at conditions of given passive house than alternative with overcharging of the hot water zone.

6. Acknowledgment

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7. References

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