# Simulation and Monitoring of PV Heat Pump System with Seasonal Storage

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**Abstract**

PV and heat pump system with a seasonal storage has been proposed and investigated. Specific components have been developed (ground-air source heat pump with variable speed compressor and desuperheater, combined storage tank with a division plate, low cost seasonal storage), built and installed in experimental family house. System simulations have shown a potential to achieve a very low need for external electricity from the grid and to reach strict requirements for nearly zero energy building. The long-term monitoring of the system has started in October 2017 and results representing the system functionality are presented.

*Keywords: heat pump, photovoltaic system, seasonal storage*

## 1. Introduction

European Directive on Energy Performance of Buildings (2010) has brought a clear vision and an opportunity to transform the building stock to nearly zero energy buildings (NZEB). There is a number of measures to increase the energy performance of modern buildings today. Space heating demand could be minimized to limits of technical and economical possibilities in case of passive houses (envelope insulation, triple glazing, ventilation with heat recovery, etc.). Domestic hot water systems could 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 the 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 an application of renewable energy sources. Heat pumps use the renewable energy from ambient environment, however they also need grid electricity to valorize the renewable heat to useful temperature level for space heating and hot water preparation. However, the 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 electricity in heating applications within the frame of building certification (primary energy factor *PEF* = 3.0).

To improve the balance, combination of the PV systems and heat pumps represents a trend to nearly zero energy buildings with minimized non-renewable energy demand. European Commission has recommended for oceanic climate area (also Czech Republic) specific values of non-renewable energy demand at level 30 kWh/m$^2$.a in annual energy balance (European Commission, 2016). Despite the fact that calculation of the non-renewable criterion is generally based on simple annual balance between imported and exported energy, it is an ambitious target. However, the export of local renewable electricity production to external grid has been already complicated in number of countries by significant reduction of feed-in tariffs. New PV installations focus on the local use of renewable electricity in buildings. Coupling of PV and heat pump system with low cost seasonal storage could significantly increase the local use of PV electricity in summer, reduce the electricity use from external grid in winter and achieve the target values of NZEB also with realistic evaluation of usability of locally produced electricity.


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Paper shows the results of simulation and monitoring of energy system which has been developed and demonstrated with the motivation mentioned above. The system combines the PV system and heat pump for family house to achieve high share of renewable energy for space heating and hot water, to increase the self-sufficiency and to meet the strict goals defined for NZEB.

## 2. Description of the system

The presented energy system for space heating and hot water preparation in a family house is based on the combination of PV system with an advanced heat pump, photovoltaic (PV) system and the low cost ground heat storage built within the foundation perimeter under the house. The system concept and function is shown in Fig. 1 with the main components used. The heat pump, in addition to usual components, has a variable speed compressor and desuperheater to use effectively heat from superheated refrigerant at high temperature. Heat pump in the case of sufficient PV power production in summer season adapts its power input to PV system power output and extracts the heat from the ambient air by heat exchanger (6) and rejects it to the building for hot water production with higher set-point in combined storage tank (overcharges the volume of storage tank to 55 °C) or to ground seasonal heat storage (at low condensation temperature 25 to 40 °C) while heat from the desuperheater (2) can be used for hot water preparation in the top part of water storage tank (hot water zone). Such a function of PV heat pump system could be achieved without any grid electricity input (see Fig. 1).

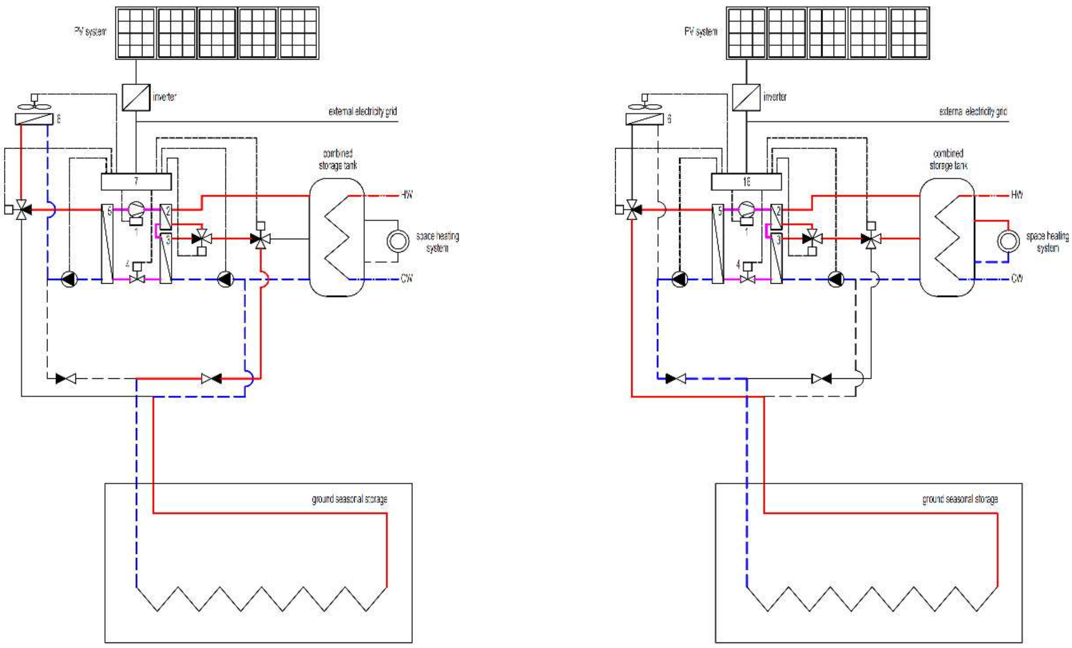


**Fig. 1: Scheme of the PV heat pump system concept: summer operation (left), winter operation (right)**

If the building requires the heat but PV system power has decreased under threshold electric power, i.e. during winter time or during the night, the electric demand for heat pump system operation is automatically covered from the external grid. Then, the heat pump extracts the heat stored in the seasonal ground storage at higher temperature (from 10 °C to 35 °C) than ambient air temperature or conventional ground borehole and thus system operates with higher efficiency (see Fig. 1, right).

This concept reduces the grid electricity use and simultaneously increases the usability of available PV system production within the whole year. Compared to conventional PV and heat pump systems the proposed energy system has a several advantages:

- application of desuperheater for hot water preparation at high temperature without increased electricity demand – increase of usable energy and effectivity of the heat pump;
- use of excess renewable electricity for heat pump system to charge the storage tank to higher setpoint and increase of stored heat to bridge the daily load peaks – coverage of hot water energy demand mostly by renewables in summer;

- use of excess renewable electricity to charge the ground heat storage by transformed ambient heat – increase of heat pump energy efficiency in winter season by use of stored heat at higher temperature;
- power input control for heat pump according to power output of PV system – operation of the heat pump completely without need of external electricity for a large part of the year;
- operation of ground heat storage with water instead of antifreeze mixture.

The energy system has been designed, simulated and demonstrated for a specific family house in Hamry (Hlinsko, 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 was designed in low energy house concept, *U*-values of individual envelope constructions meet the recommended values for such high performance buildings. Foundations has been realized by sacrificial formwork insulated by extruded polystyrene of thickness 160 mm. Base floor has been assembled from concrete slabs, upper insulation has been realized from extruded polystyrene with a thickness of 240 mm and floor heating system layer. Envelope brick system is based on cellular clay blocks filled with insulation and external mineral insulation system of thickness 180 mm. Saddle roof has a slope of 40° with south-north orientation and roof thermal insulation layer thickness is 240 mm.

Design heat loss of the house is 4.5 kW for design ambient temperature -15 °C. 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. The proposed system consists of the advanced heat pump with heat output 5.5 kW at B0/W35 (50 Hz) and combined storage tank of volume 900 l with internal heat exchanger with surface area 9 $m^2$. Investor considered the large PV system installation with peak power 6 $kW_p$ to increase the energy independency of the house operation.

During the construction stage the seasonal ground heat storage has been realized with use of pipe heat exchanger (see Fig. 2) with size of 14.4 m x 8.0 m within the foundations of the house, which are 1.5 m deep and thermally insulated at external surface. Internal perimeter of the ground storage volume is also thermally insulated but only to depth of 0.5 m in order to eliminate the thermal bridges from the charged storage to interior through the envelope and foundations. Heat exchanger is made of plastic piping DN32 burried in the trenches 300 mm deep filled with cement and silicate sand mixture to provide a good thermal contact between the pipe and ground. Distance of pipes in the heat exchanger is 0.6 m. Heat exchanger has been realized in two loops, each of length 100 m. Two loops have been designed to reduce the auxiliary demand of circulation pumps. Redundant thermal insulation with thickness 100 mm has been applied between the seasonal storage volume and the floor concrete slabs.

**Fig. 2: Realization of simple and low cost ground seasonal storage**

## 3. System simulation

The building and the system simulation has been performed in TRNSYS environment. The objective of the analysis was to proof the functionality of the system concept and to compare the performance with the conventional PV and heat pump system. Computer simulations have been performed with a time step of 2 minutes and always two years of operation have been simulated because of ground massive use in both proposed and conventional heat pump system. Results have been evaluated from the second year of simulation. Building model has been built also in TRNSYS based on construction plans and used for separate simulations to reduce the calculation time. Results for the space heating and hot water load have been used as inputs to system simulations. Space heating demand is 3400 kWh/a and hot water demand is 3060 kWh/a.

Conventional heat pump system with a borehole heat exchanger (75 m), standard combined water storage tank (900 l) and PV system (6 $kW_p$) has been modelled for given house as a reference case. Total grid electricity use of the conventional system is 2200 kWh/a and the system operates with seasonal performance factor *SPF* = 2.9. Monthly values of system *SPF* ranges around this value (see Fig. 3). The main reason of low operation effectiveness for the conventional reference case is large share of hot water heat demand in general combined with necessity of charging the hot water zone in the storage tank to temperature of 55 °C to eliminate the electric back-up heater operation. Despite the high installed power of PV system, there is high external electricity use and low utilization of PV electricity production by the heat pump system. The reason is the mismatch between hot water peak loads (morning, evening), space heating peak loads (winter season, night time) and PV electricity production (summer season, daytime). PV system covers annually only 420 kWh from total 2620 kWh system electricity demand, despite the installed power 6 $kW_p$ produces about 6020 kWh/a of electricity.

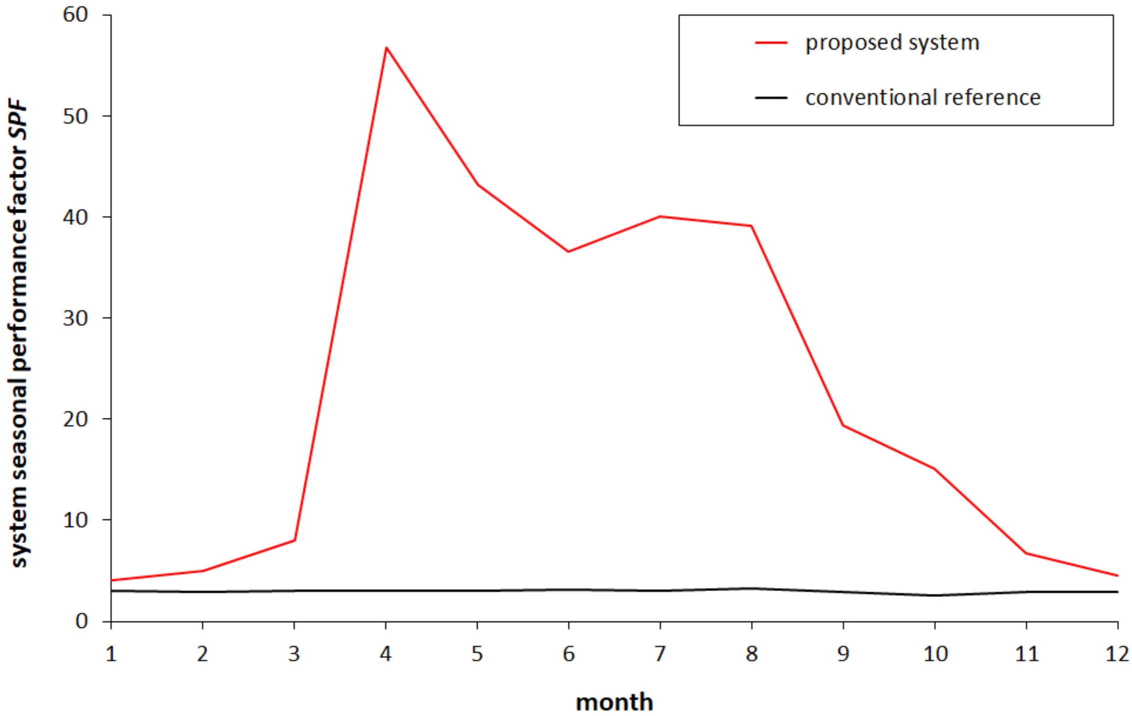


**Fig. 3: Seasonal performance factor of the proposed system compared with conventional system**

The developed system concept has been modelled with use of both newly developed models (variable speed heat pump with desuperheater) and standard models (storage tank, seasonal storage). The models of critical system components have been calibrated by results from testing. Total electricity demand (heat pump, circulation pumps, auxiliary heater, external air cooler) with subtracted PV production used for system is 1069 kWh/a and the system operates with seasonal performance factor *SPF* = 6.1. The system operates with very low energy demand outside the heating season and monthly *SPF* values are above 30 (see Fig. 3). Advanced control of compressor allows the operation of system completely with use of PV electricity for charging of combined storage tank and for charging of ground storage. Coverage of energy demand for system operation by renewable energy achieves about 83 %. Thus the specific demand of non-renewable primary energy for the space heating and hot water preparation for given family house is under limit of 20 $kWh/m^2.a$ and house reaches reliably NZEB requirements for oceanic climate zone. Moreover, this value results from realistic balance of energy utilization, not from fictive balance of PV electricity export to the external electric grid and annual electricity import.

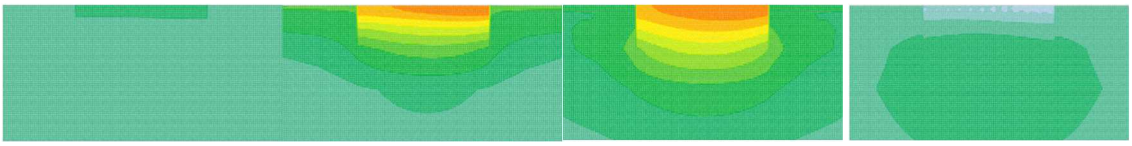

**Fig. 4: Charging and discharging of ground seasonal storage during the year (March, June, September, December)**

Fig. 4 shows the simulation results for the ground storage charging/discharging during the year. The highest temperature in the ground storage occurs in September, lowest in December. The thermally insulated foundations are clearly visible in the figures. Fig. 5 shows the course of average temperature in the ground storage mass within foundations during the year.

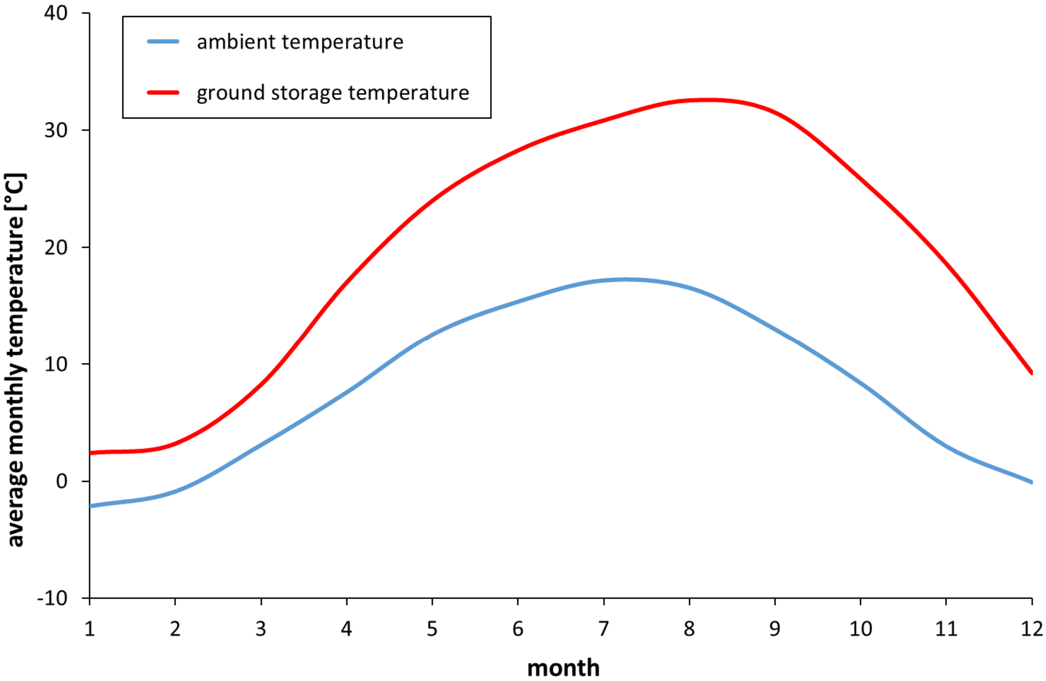


**Fig. 5: Temperature in the ground storage during the year**

## 4. Demonstration and monitoring

The main components of the energy system: heat pump with desuperheater and varable speed compressor, combined storage tank with division plate and underground storage have been developed, built, tested and installed in respected family house in Hamry (Hlinsko, CZ) during season 2016 / 2017. Whole system has been connected to intelligent controller and monitoring system. With a respect to demonstration nature of the energy system, specific components were installed in addition to proposed system to allow the experiments, further development and optimization of critical components. Central water storage tank and back-up ground loop has been applied. Scheme of realized demonstration system is shown in Fig. 6.

Heat pump installed in machinery room of the house (see Fig. 7) extracts the heat from air cooler or central water storage to which heat from seasonal ground storage and back-up loop (in case of insufficient temperature in ground storage) is delivered. Controller automatically runs the ground heat sources according to priority and set temperature difference (winter season). Surplus electricity production from PV system is converted to heat by a heating element in central water storage in summer season and heat is be delivered to evaporator of heat pump or to ground storage. Simultaneously, the heat from ambient air can be pumped through combined storage tank to charge the seasonal ground storage. Space heating, ventilation and hot water heating loops are connected to combined storage tank. Heat pump is connected to combined storage tank by 4 pipes for separate charging of hot water zone and space heating zone. Controller allows charging of the space heating zone by condensation heat while hot water zone is charged by heat from desuperheater to high temperature (more than 60 °C). Controller evaluates required setting of compressor speed according to measured PV system power and power input of the compressor, in order that heat pump is not consuming any external grid electricity during the ground storage charging. Similar strategy is used in case of overheating of combined storage tank above standard set-point in case of sufficient PV power.

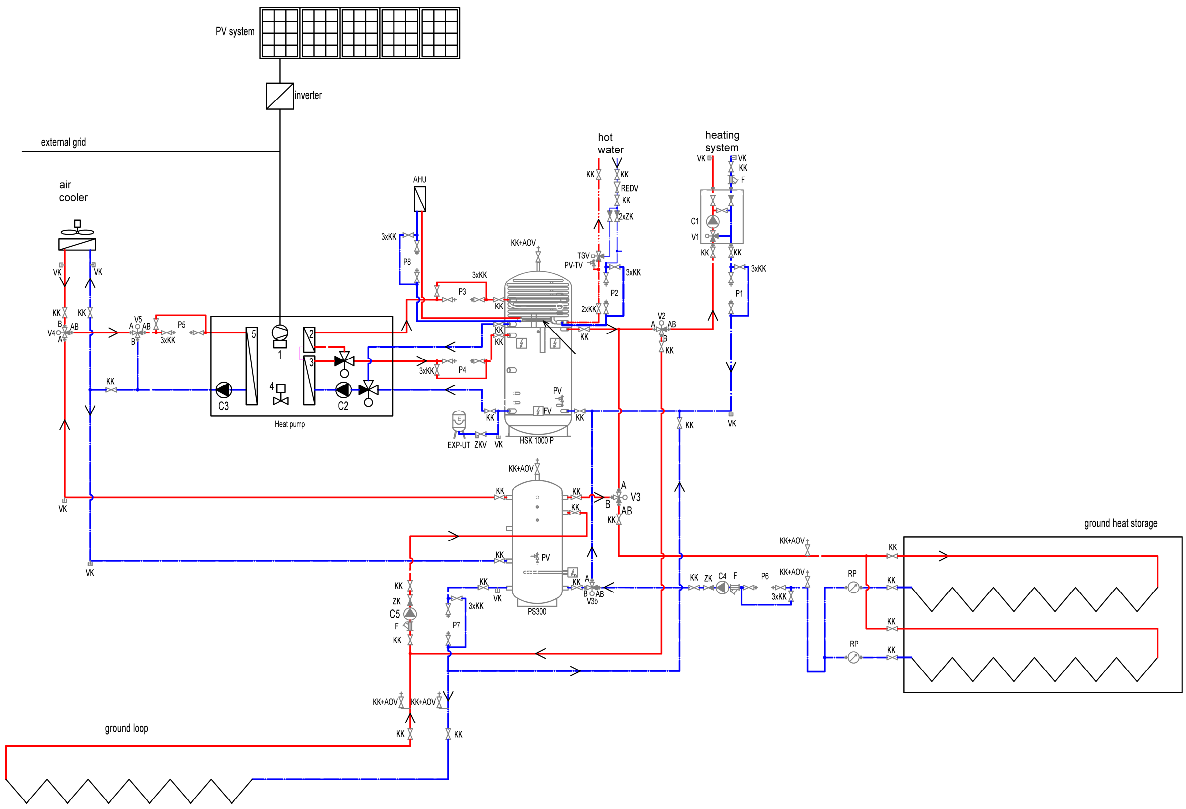


**Fig. 6: Scheme of realized demonstration system**

PV system has been commissioned in October 2017. Charging of seasonal ground storage has started late and it was not possible to reach sufficiently high temperature for winter operation. Therefore the system was running during winter in emergency regime with use of back-up ground loop periodically alternating with seasonal ground storage. Because both the back-up loop and loops for ground storage are operated with water (not antifreeze), controller precisely evaluates operation temperatures at evaporator and central water tank, in order not to go under freezing temperature. Controller starts the heat pump with minimum rotations 20 Hz to avoid sudden cooling-down at evaporator.


**Fig. 7: Heat pump, storage tanks and external air unit for heat pump**

The whole energy system is monitored and evaluated. The monitoring system includes the energy balance of PV system, heat pump, hot water and space heating system. Flowrates and temperatures are monitored in each of operation loops and storage tanks. Temperature field in seasonal ground storage is monitored by 5 vertical borehole probes with temperature sensors in 5 heights with 1 m distance. The probe #1 is located in the centre of the ground storage. Moreover, the heat pump has own monitoring of internal refrigerant loop. Measured data are saved and accessible via webserver of Regulus company for the research purposes.

Fig. 8 includes the graph with main quantities to show the function of ground storage charging by heat pump during one selected day (April 2018). Heat pump delivers heat into combined storage tank, from which it is extracted and fed into ground storage. From the comparison of PV power and heat pump power input during charging, there is an evident speed control of the compressor and adaptation of compressor power input to PV power output with a certain provision, that the heat pump will never use external grid electricity when charging the ground storage by extracted ambient heat. Electric power input of the heat pump slightly increases during the charging, which is associated with increase of operation temperature.

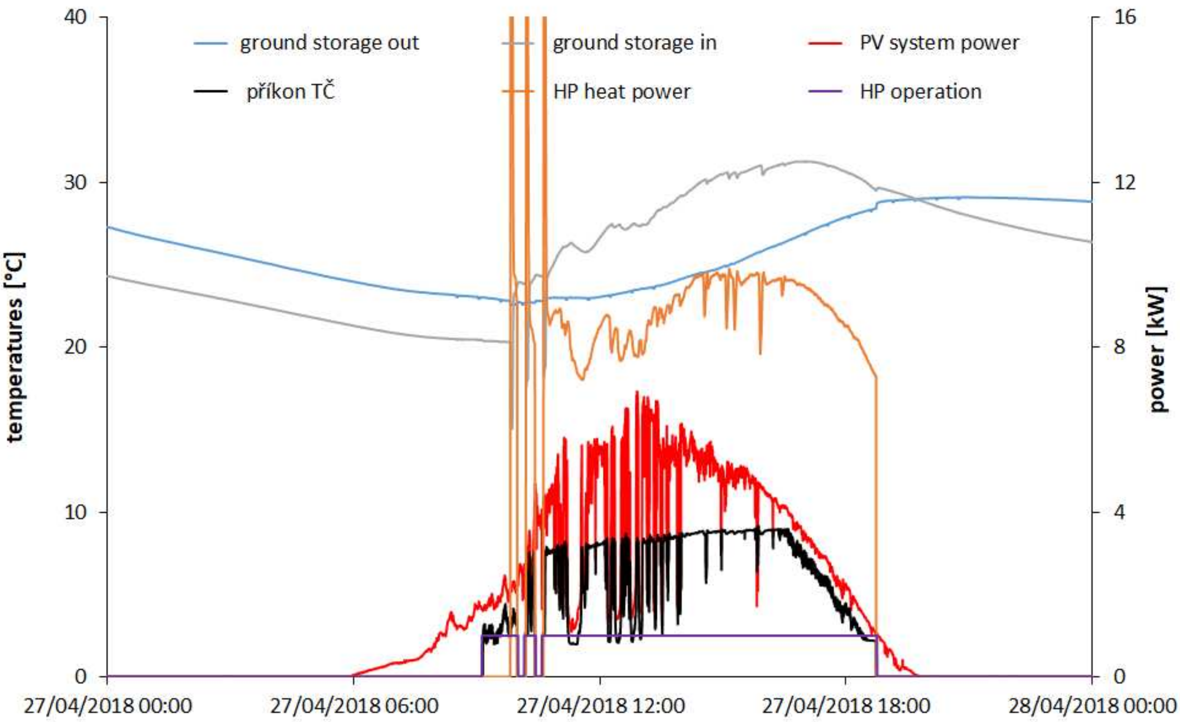


**Fig. 8: Adaptation of heat pump power input according to PV system output during ground storage charging**

For the same day, Fig. 9 shows the function of desuperheater. While condenser output temperature during the ground storage charging is maintained at low value close to condensing temperature, three-way valve integrated in the heat pump controls the flowrate from condenser output to desuperheater by PID algorithm. Output from desuperheater has then significantly higher temperature than the condenser output. While condenser output is supplied into ground storage through space heating zone of combined storage tank, desuperheater output is led into hot water zone of storage tank. Temperature of the water in hot water zone is about 65 °C at the end of heat pump operation.

The graph in Fig. 10 represents the time course of the temperatures in seasonal ground storage in period of October 2017 to end of August 2018 for a borehole probe #1 located in the central part, in the layers of 1, 2, 3, 4 a 5 meters under the base slab. While the temperature is varying during charging and discharging in the upper layer with installed pipe heat exchanger, the temperature increase is supressed in deep layers. There are also visible the fallouts of the monitoring during the season. Temperature in upper layer of seasonal ground storage has decreased down to 7 °C. Back-up ground loop and seasonal storage was a heat source for the heat pump during winter. From the beginning of March 2018 the charging of the seasonal storage has been started again and achieve at the end of August almost 30 °C, which is in good correlation with a simulation.

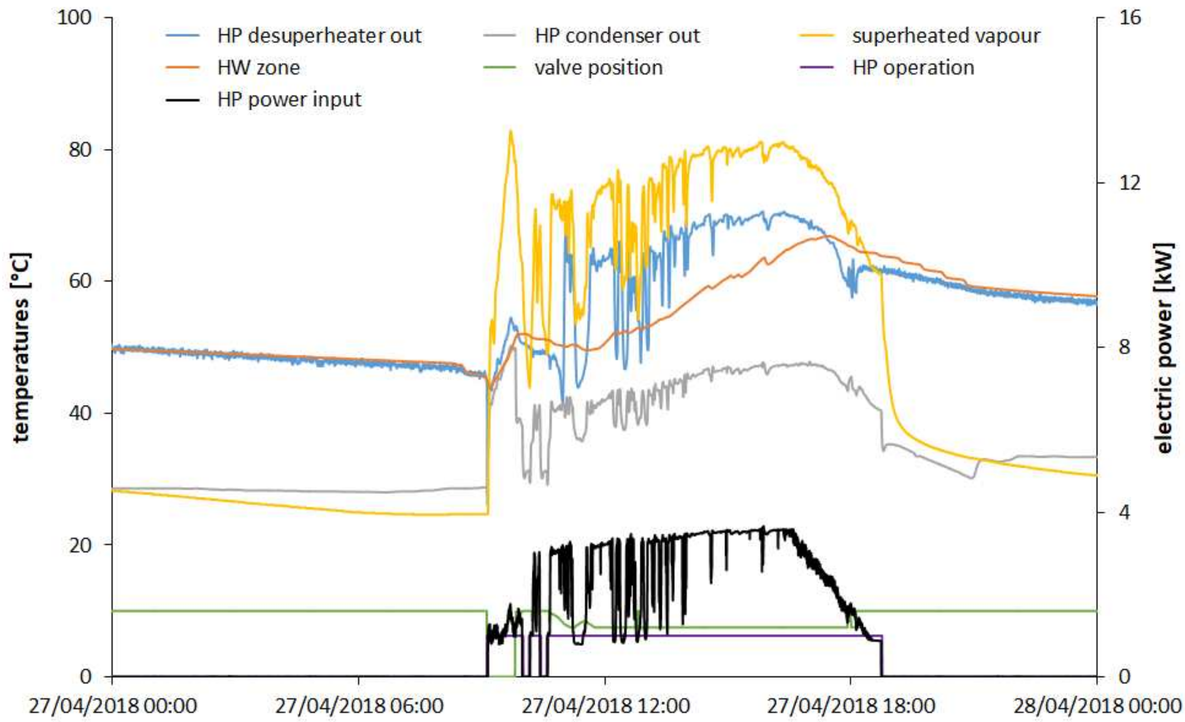


**Fig. 9: Desuperheater function for hot water preparation during the charging of ground storage**

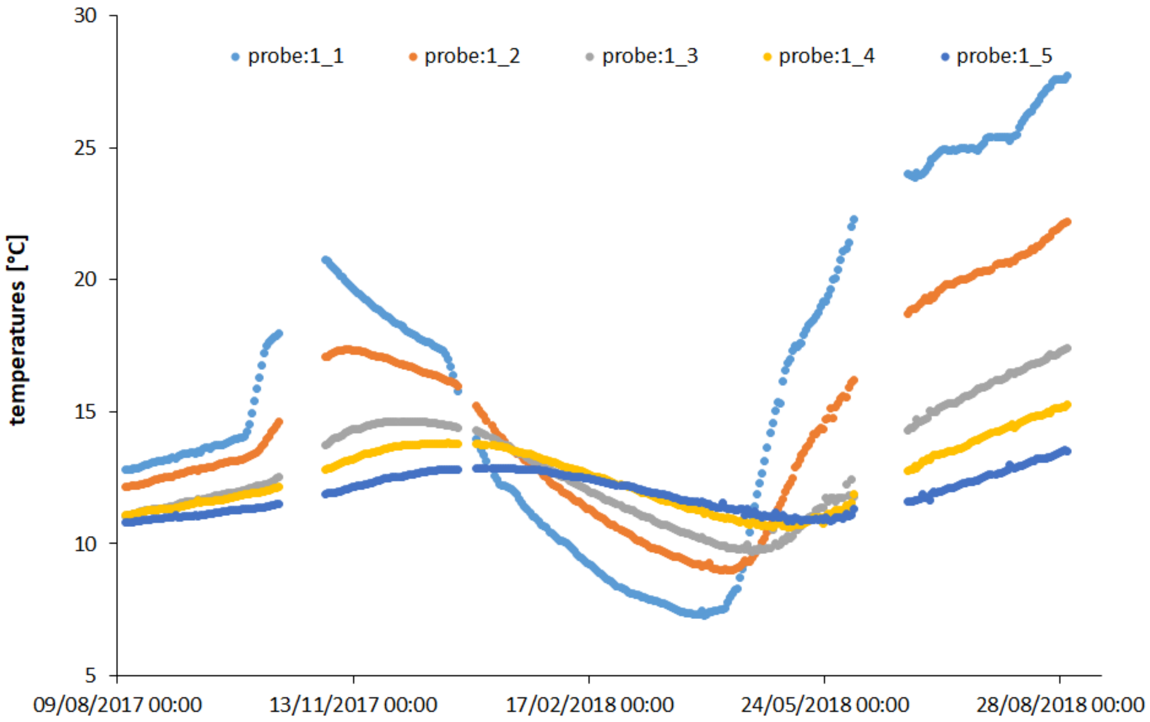


**Fig. 10: Temperatures in the central part of the ground storage**

## 5. Conclusion

The energy system combining the advanced heat pump, PV system and low cost seasonal ground storage under the house has been proposed. The simulations have shown significantly reduced electricity demand from external grid. Coverage of energy demand for system operation by renewable energy achieves about 83 % and the specific demand of non-renewable primary energy for the space heating and hot water preparation for given family house fall far under NZEB requirements.

The system has been demonstrated and the monitoring of functionality runs for the first season. The system has been operated in “emergency” mode during the first winter because ground storage was insufficiently charged due to late installation of PV system. However, the experience was positive, the ground water loops delivered enough energy for the house without freezing even in the climate area of highlands. The new charging cycle has started in spring 2018 and at the end of August almost reaches the predicted value (about 2 K lower). Results of monitoring has also shown the function of advanced components as charging of the ground heat storage by heat pump with adapting of power input to PV system power output or use of desuperheater for hot water preparation in storage tank at high temperatures without increase of electricity consumption.

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