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Energy system for nearly zero energy family buildings — Experience from operation

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Abstract

Advanced concept of energy system for space heating, hot water preparation in new family buildings has been developed. Energy system consists of innovative heat pump (5.5 kW) extracting the heat from two environments: ground and ambient air. Heat pump is coupled with simple seasonal ground storage of heat built under the house and with photovoltaic system (6 kW_p) installed on the roof. In case of excess photovoltaic (PV) electricity in summer, the heat pump with variable speed compressor adapts its electric power to PV system power, extracts the heat from ambient air and transfers the heat into seasonal ground storage without external electric energy input. The ground storage is charged to 30 °C in upper level during the summer. In winter, heat pump uses the heat from ground storage and transfers it through the heat pump cycle for space heating with high effectivity. The experimental system has been installed in newly built house in Hamry (CZ) and it is operated for two seasons so far. Results from the monitoring show radical reduction of electricity use from external grid. System uses more than 80 % of energy from renewables. Specific non-renewable primary energy use for space heating, hot water preparation and auxiliary energy is about 15 kWh/m² per year.

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Keywords: Heat pump; Seasonal storage; Nearly zero energy building; NZEB

1. Introduction

In order to move the building stock to nearly zero-energy buildings (NZEB) in Europe according to EPBD recast [1], a radical increase in energy efficiency and high share of renewables in buildings are needed. At local perspective, solar and ambient heat can be used but coupled with seasonal storage to cover space heating in central Europe climate conditions. Seasonal storage of solar thermal energy has been proved and demonstrated many times and achieved high coverage of energy needs for space heating and hot water preparation [2]. On the other hand, seasonal storage of heat from solar thermal collectors for its direct use for building results in requirements for

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large collector areas and storage volumes [3]. Economic parameters of solar seasonal storage systems are not very positive, in case of family houses [4], especially with high share of renewable energy needed to meet the ambitious requirements of EPBD directive in real operation.

Seasonal storage volume can be reduced if heat pump is applied to transform low-grade heat to useable temperature level [5]. On the other hand, the grid electricity is consumed by heat pumps which can worsen the overall sustainability of the concepts, especially if grid electricity originates from fossil fuels. Increased trend of photovoltaic (PV) systems applications in family houses presumes the possible coupling of PV and heat pumps together with thermal storage [6].

The paper presents the new concept which steps even further by combining the PV system with a heat pump and seasonal ground storage. Theoretical possibility to use summer ambient heat for winter heat supply with use of excess summer PV electricity to achieve high share of renewable energy for space heating and hot water in family house, to increase the self-sufficiency and to meet the strict goals defined for NZEB has been investigated. The energy system has been designed and built. Results from monitoring of system operation in two seasons (2017 to 2019) are presented.

2. Experimental energy system demonstration

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 with heat output 5.5 kW at B0/W35 (50 Hz), photovoltaic (PV) system with peak power 6 kW_p and the low-cost ground heat storage built within the foundations perimeter under the house. The scheme of realized system is shown in Fig. 1 with the main components used. The energy system has been demonstrated for a family house in Hamry (Hlinsko, Czech Republic) which has two floors with a space volume 860 m³ and total living floor area 290 m². Family house was designed in low energy house concept. Design heat loss of the house is 4.5 kW for ambient temperature –15 °C. Low temperature space heating system has been used with design flow/return water temperatures 40/35 °C.

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. The heat pump in the case of sufficient PV power production in summer adapts its power input according to PV system power output, extracts the heat from the ambient air by heat exchanger (air cooler) 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 the heat from the desuperheater can be used simultaneously 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. If the building requires the heat but PV system power has decreased under a certain threshold value, i.e. during winter time or during the night, the electricity use 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 system thus operates with higher efficiency. Because of experimental nature of the system, there are additional components in the layout of realized system to back up the operation (back up ground loop, central water storage), see Fig. 1. Whole system has been connected to intelligent controller and monitoring system.

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. Foundations 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 the house interior through the building envelope and foundations. Heat exchanger is made of plastic piping DN32 buried in the trenches 300 mm deep and 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.

Heat pump installed in machinery room of the house extracts the heat from air cooler or central water storage to which the 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

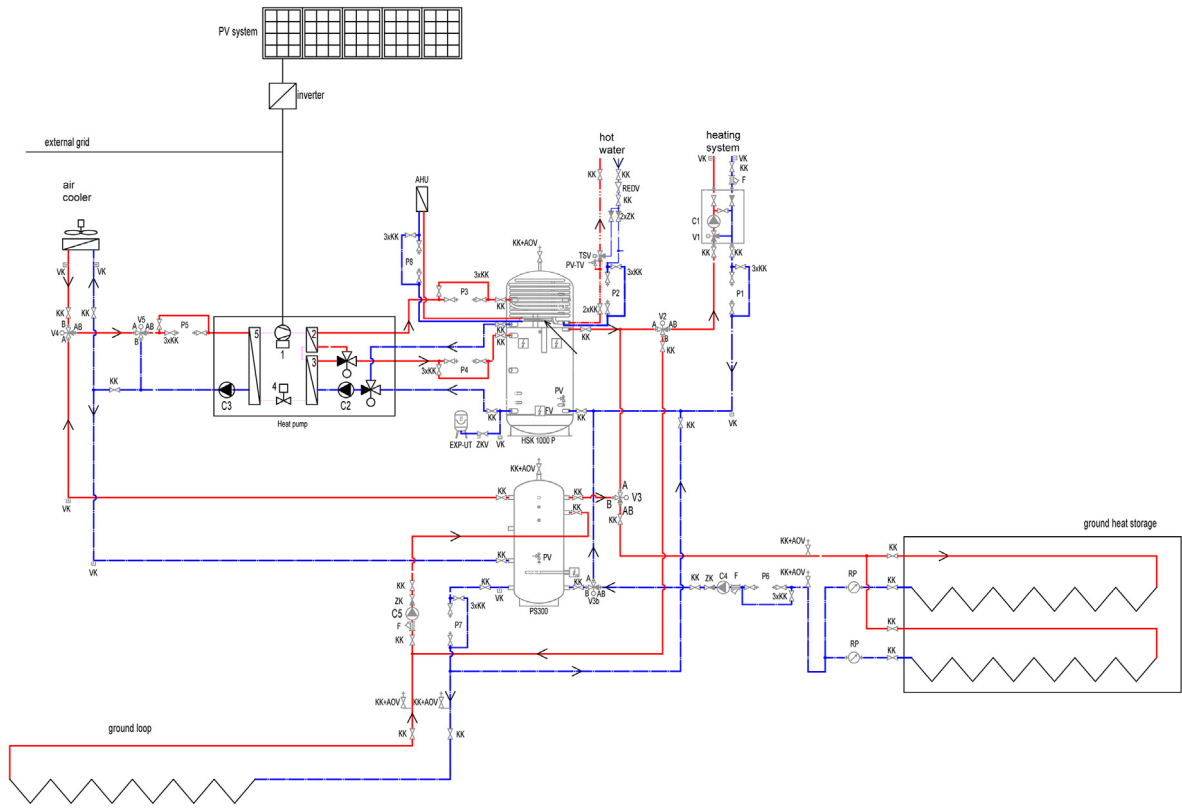


Fig. 1. Scheme of realized energy system.

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 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.

PV system has been commissioned in October 2017. Charging of seasonal ground storage has started late in 2017 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.

3. Monitoring of operation

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

hydraulic 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. 3 includes the graph with main quantities to show the functionality 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 the increase of operation temperature.

For the same day, Fig. 4 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.

To monitor the temperatures in the seasonal ground storage during operation 5 vertical borehole probes have been installed in experimental system. Each probe contains temperature sensors in 5 positions (depths, layers) under terrain with 1 m distance. The probe #1 is located in the centre of the ground storage. Timeline of temperatures in



Fig. 2. Realization of low-cost ground storage within foundations.

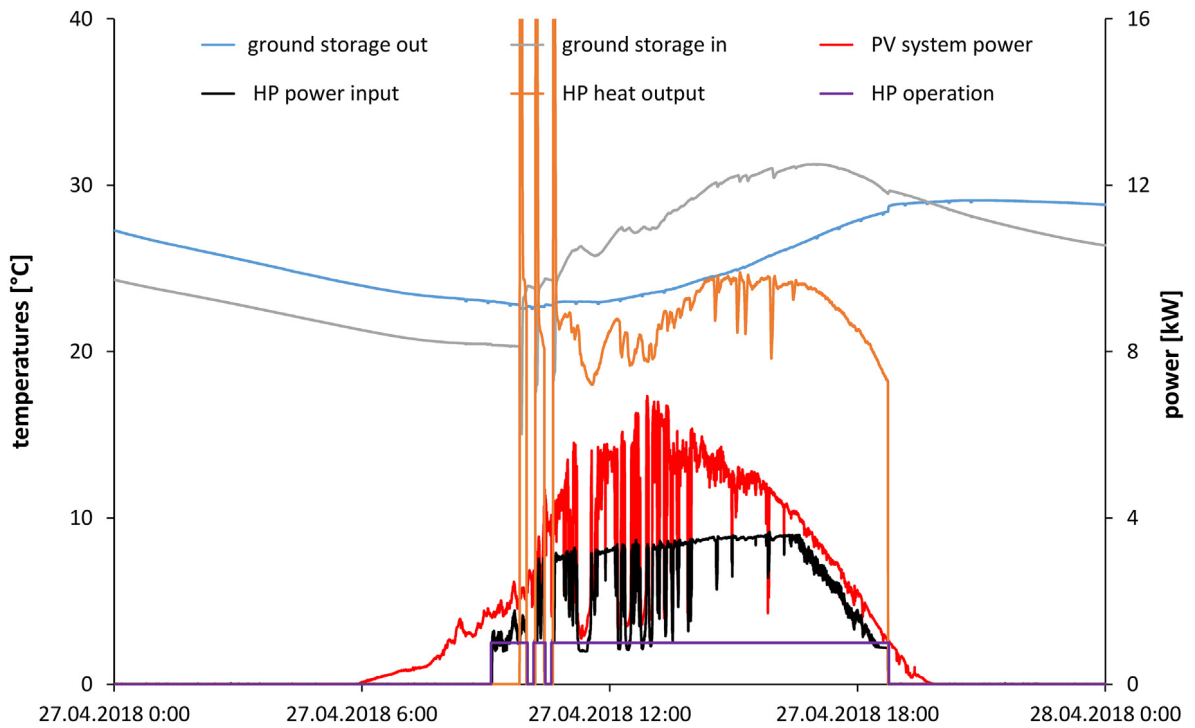


Fig. 3. Adaptation of heat pump power input according to PV system output during ground storage charging.

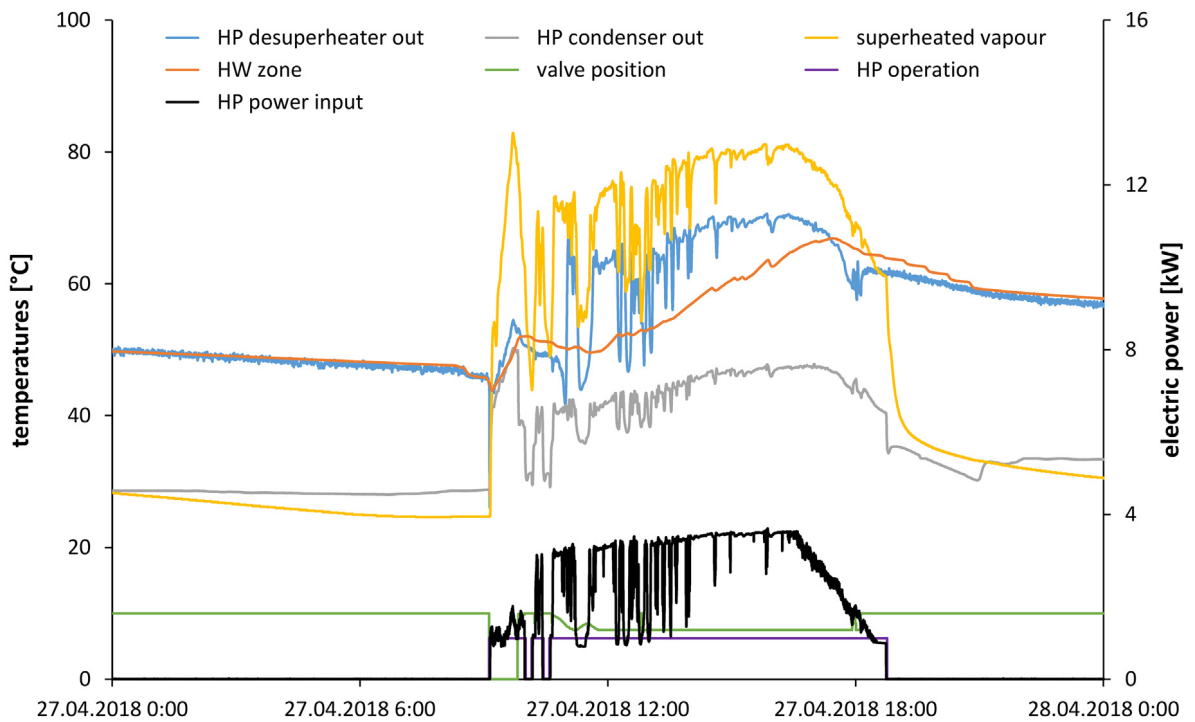


Fig. 4. Desuperheater function for hot water preparation during the charging of ground storage.

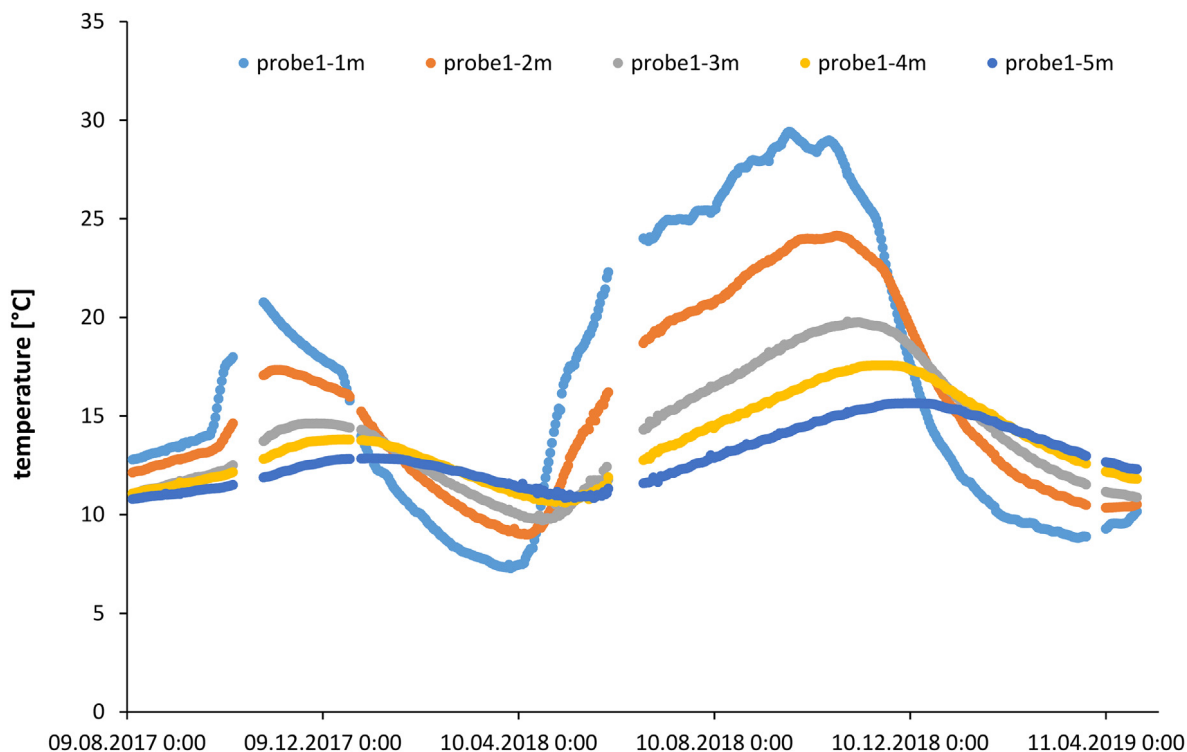


Fig. 5. Timeline of temperatures (different depths) in the central part of ground storage (monitored).

different depths is presented in Fig. 5 for two seasons of operation. Due to late commissioning of the PV system the ground storage was not charged to proposed temperature at the beginning of the first heating season (2017–2018). Back-up ground loop and seasonal storage were the heat sources for the heat pump during winter. But from April 2018, the normal operation and charging the ground storage has started. The temperature at depth 1 m under floor slab was about 30 °C at end of September 2018. Heat extraction from the ground storage in winter induces drop in temperature in upper layer and consequently in the layers below as well. The figure shows thermal momentum of ground storage, the heat extraction from deeper layers is shifted in time and intensity. There are also visible the fallouts of the monitoring.

4. Energy balance

The energy flows in technical system have been monitored with 10 s time step, especially PV power, house load (space heating, hot water), heat balance of ground storage (heat extraction, heat supply) and electric consumption of different technical subsystems (heat pump, ventilation, appliances). Fig. 6 shows the monitored energy balance of the operated system in 2018. PV system produced 6250 kWh of electric energy. Annual heat use of the house for space heating and hot water preparation in 2018 was 8900 kWh. To cover the heat use, only 1400 kWh of electricity has been taken from external grid which results in total seasonal performance factor (*SPF*) of the system 6.3. Use of renewable energy sources (RES) to cover the energy use of technical systems in the house was about 84 %.

Assuming the primary energy factor for electricity $PEF = 3.0$ valid for Czech Republic (2018), specific annual use of non-renewable primary energy for space heating, hot water and auxiliary energy (pumps, control) was about 15 kWh/m².a which is about one quarter of the requirement for passive houses (excluding appliances). Because the energy balance is based on monitored values with realistic usability of PV power in the house, the result meets the very ambitious requirements for nearly zero buildings (NZEB).

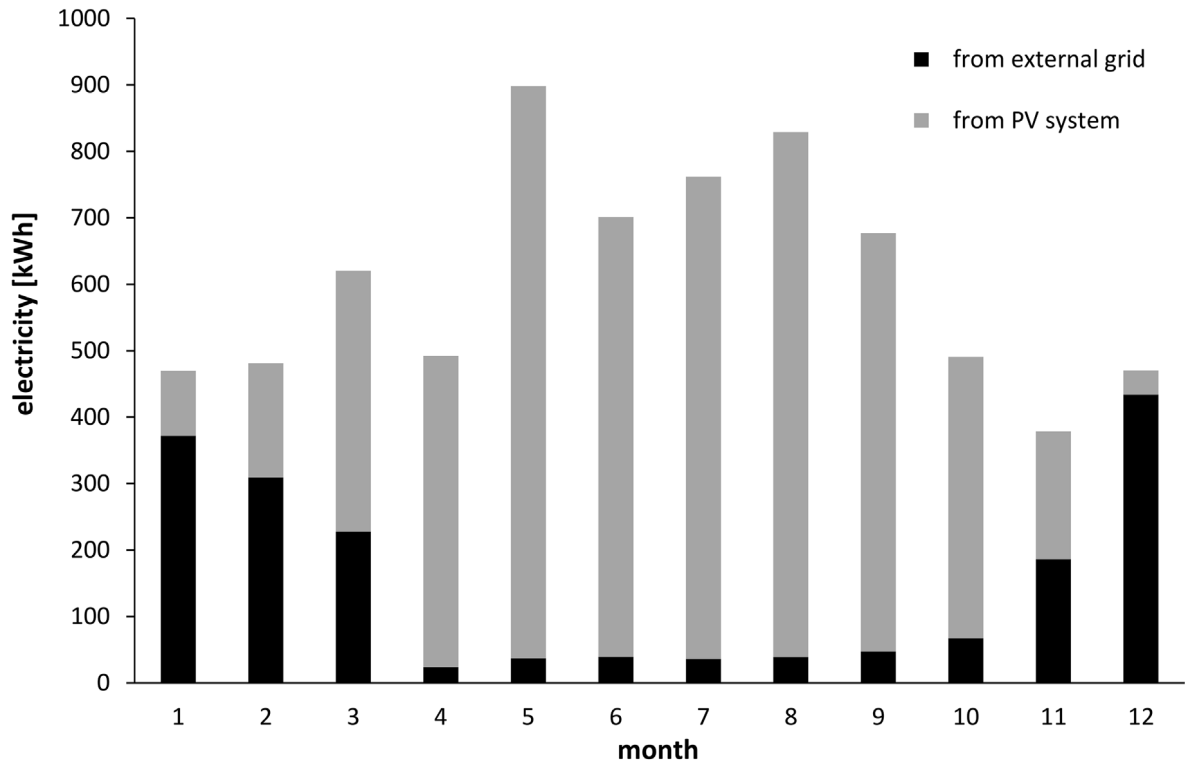


Fig. 6. Energy balance of the system.

5. Conclusion

The energy system combining the advanced heat pump, PV system and low-cost seasonal ground storage under the house has been designed, built and experimentally investigated for two seasons in central Europe climate. The system in real operation has demonstrated functionality. Results from operation and monitoring have shown significantly reduced electricity use from external grid. Coverage of energy use for system operation by renewable energy achieves about 84 %. Specific use of non-renewable primary energy for the space heating and hot water preparation for given family house falls far under passive house requirement and opens the significant potential to meet ambitious targets for nearly zero energy buildings.

Acknowledgements

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