PV and heat pump system with a seasonal storage for NZEB house

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Abstract

Energy system consisting of combined ground-air source heat pump, PV system and seasonal ground storage for energy passive family house has been developed and analysed by computer simulation. The heat pump is equipped with a desuperheater to prepare hot water and variable speed compressor to adapt power to PV system production. Heat pump during summer operation transforms the ambient heat to charge the ground seasonal storage with use of the PV electricity only. Winter operation relies on the heat stored under the house and low grid electricity consumption. The simulation analysis have shown the significant decrease of the grid electricity needs for the house (system SPF increased from 2.9 for reference borehole system to 4.7) and increase in usability of local PV electricity production for energy supply (space heating, hot water) in the house. In total, 80 % of energy supply for the house is renewable energy and specific non-renewable primary energy need of the house is 22 kWh/m^2.a (for space heating, hot water and auxiliary energy).

Keywords: heat pump; seasonal storage; PV coupled operation

1. Introduction

European Directive on Energy Performance of Buildings [1] has brought a clear vision and an opportunity to transform the building stock to nearly zero energy buildings. 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 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 valorise 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 [2] 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 (primary energy factor *PEF* = 3.0). The non-renewable primary energy demand as an integral quantity has been adopted as a basis for comparison of the building performance. The similar approach historically originated in the field of passive houses certification, where one of the criteria is total non-renewable primary energy demand related to heated floor area. The maximum specific non-renewable primary energy demand for space heating, hot water preparation, parasitic energy and electricity for household appliances should not exceed 120 kWh/m^2.a. The Czech approach to passive house which originated from local climate conditions introduced requirement of 60 kWh/m^2.a but limited only to non-renewable primary energy demand for providing the indoor environment comfort and hot water load. Nearly zero energy buildings (NZEB) definition is not unified within EU [3]. Member states approach to definition with different strategy and different promptness. To define the target of the nearly zero energy building, 30 kWh/m^2.a has been set for the purpose of presented study as a half value of criterion for passive house. Despite the fact that calculation of the non-renewable criterion is generally based on simple annual balance between imported and exported energy, it is ambitious target comparable e.g. with Denmark legislation [3]. However, the export of local renewable 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. An interesting way to NZEB could lie in reduction of the grid electricity (and other energy carriers) use. Production of electricity by PV systems and use of electricity by heat pumps therefore seems to be an ideal combination to significantly reduce the external supply of electricity from public grid for space heating and hot water systems [4]. Such approach also results in realistic evaluation of usability of locally produced electricity.

Paper shows an analysis of proposed energy system under development which has been motivated by situation 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 even the strict goals defined for NZEB. On the other hand the system has to use common technology, optimized or low cost components because economic issue cannot be put aside.

2. System concept

The concept of the system being developed is based on combination of PV technology and advanced heat pump system to increase the use of local renewable energy for space heating and hot water preparation in the family house by use of simple and low-cost seasonal storage realized within the building foundations. The heat pump with variable speed compressor is coupled with PV system in order to adapt the heat pump power input to actual PV system power in operation. Target of the system concept is to reduce the annual external grid electricity demand for the house.

The system concept and function is shown in Fig. 1 with the main components used but without respecting of the heat transfer liquid here. Heat pump consists of evaporator (5), variable speed compressor (1), condenser (3) with separate desuperheater (2) to increase the usability of rejected heat and to increase the total effectivity, electronic expansion valve (4) and integrated controller (7). Power input of the heat pump compressor could be controlled by advanced algorithm using the external information on actual electric power of local PV system. Integrated controller uses a mathematical description of heat pump operation parameters and according to actual conditions predicts the power input of heat pump and causes change of compressor rotations.

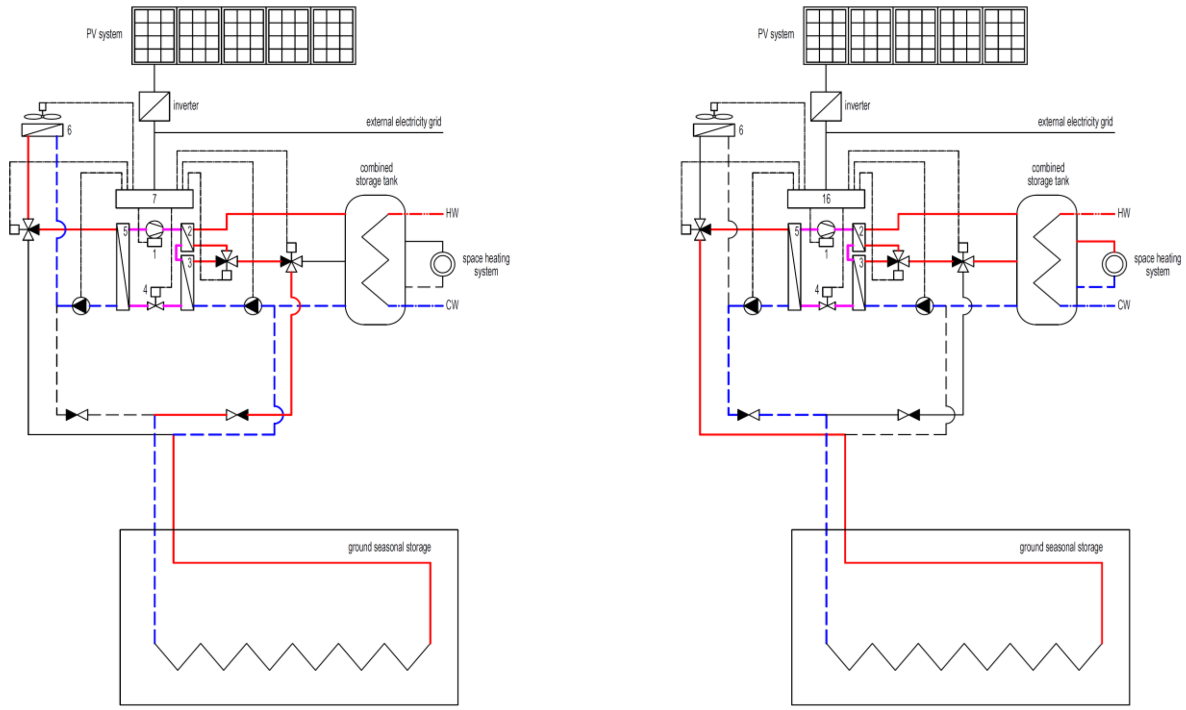

Fig. 1. Scheme of the PV heat pump system concept: summer operation (left), winter operation (right)

Ground seasonal storage realized within the foundations under the house is an important component of the whole system. Heat pump in the case of sufficient PV power production in summer season adapts its power input to PV system power and extracts the heat from the ambient air by heat exchanger / air cooler (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) or to ground seasonal heat storage, or the heat from the condenser can be stored in the ground at low condensation temperature 25 to 40 °C while heat from the desuperheater is used for hot water preparation at temperature level of 50 to 60 °C 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 left).

If the building demands 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 grid. Then, the heat pump extracts the heat stored in the ground seasonal storage at higher temperature (10 to 35 °C) than ambient air temperature or conventional ground borehole and thus system operates with higher efficiency (see Fig. 1 right). This could reduce the grid electricity use and simultaneously increase the usability of available PV system production within the whole year.

Compared to conventional solution based on the heat pump system with a ground borehole and parallel PV system the proposed system utilizes several innovative components and provides a number of advantages:

- use of desuperheater for hot water preparation at high temperatures without increase of compressor electricity use – increase of heat pump operation effectiveness;
- combined water storage tank for hot water preparation and space heating with optimized internal heat exchanger surface area distribution for hot water production – larger part of the surface area located in the hot water zone reduces the required temperature difference between water tank volume and hot water output which causes the high effectivity of heat pump operation even for hot water preparation;
- use of excess renewable electricity from PV system for heat pump to charge the combined storage tank to higher temperature than required set-point and thus increasing it storage capacity to overcome the hot water load peaks – significant increase of hot water demand coverage by renewable energy during the summer;
- use of excess renewable electricity for charging the ground seasonal storage – reduction of grid electricity use by the heat pump in winter season by the use of stored heat;

- possibility to control the heat pump electric power (20 to 100 %) according to actual power output of PV system (power adaptation) – operation of the heat pump system without external grid electricity use during the significant part of the year.

3. Family house

Energy efficient family house under construction (2016) has been chosen for an analysis of the proposed PV heat pump system under climate of Czech Republic (see Fig. 2). 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 passive 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.

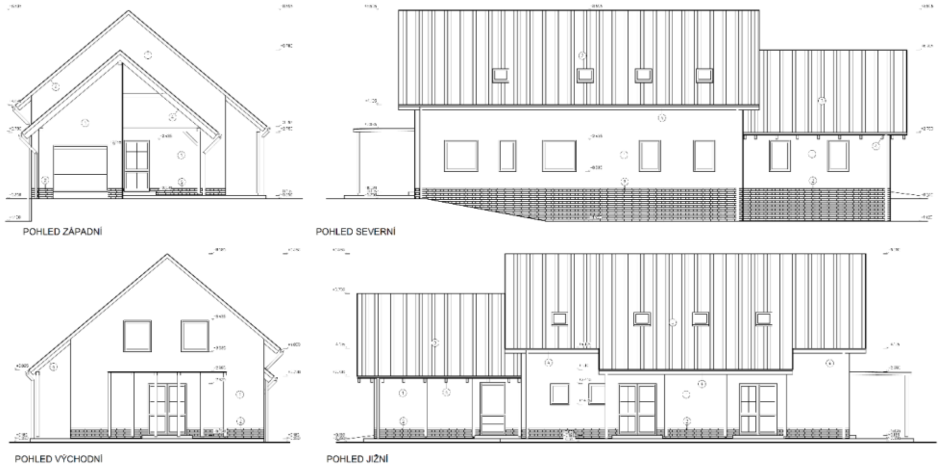

Fig. 2. Family house Hlinsko used for the PV heat pump system analysis

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.

Fig. 3. Realization of simple and low cost ground seasonal storage

During the construction stage the ground seasonal storage has been realized with use of pipe heat exchanger (see Fig. 3) 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 (see Fig. 3). 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.

4. Simulation analysis

Computer simulation analysis of the proposed PV and heat pump system has been performed in TRNSYS environment [5]. 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. To model the components of the system both the available TRNSYS models and own specifically developed TRNSYS models have been used. Tab. 1 presents the description of applied models for the main components of the 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. Properties of the ground massive have been defined as follows: thermal conductivity 2 W/m.K, density 2100 kg/m^3 and specific capacity 840 J/kg.K.

Table 1. Description of component models

Component	TRNSYS model	Description
Heat pump	type 250	Model developed at UCEEB CTU [6] which allows modelling of heat pump with multiple heat exchangers (desuperheater, subcooler). Simplified compressor control has been introduced by change of refrigerant flowrate.
Combined storage tank	type 340	Multiport storage tank model developed at ITW Stuttgart [7] allows to couple the defined number of heat sources and defined number of heat exchangers. Model includes the stratification behaviour of the storage tank with possibility of division of the volume to defined number of

		layers.
Ground seasonal storage	type 997	Model of ground storage heat exchanger with defined number of pipes with liquid flow (component of TESS libraries). Type allows to model the behaviour of ground storage volume limited by perimeter insulation and adjacent insulated zone (building). Temperature distribution in the storage volume is modelled in 3D matrix with use of hexadral network by method of finite differences.
Ground borehole	type 451	Model of ground borehole with possibility to define number of borehole heat exchanger parameters [8].
PV system	type 50b	Model for PVT collector which allows the simplified parametrization of PV module by efficiency at standard testing conditions (STC), packing factor, gross module area and power temperature coefficient.

Building model has been built 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.

5. Results

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 *SPF* ranges around this value (see Fig. 6). 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 electricity use and low utilization of produced PV electricity 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), see Fig. 4. 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.

The proposed system has been modelled with advanced heat pump with desuperheater and variable speed compressor for adaptation of power input to PV system power production combined with a ground seasonal storage of ambient heat extracted by air cooler in summer and used as a source for the heat pump in winter. Total grid electricity (heat pump, circulation pumps, back-up heater, ambient air cooler minus PV electricity used) is 1370 kWh/a and the system operates with seasonal performance factor *SPF* = 4.7. Fig. 5 shows the energy balance of the whole system. It has been shown that very low grid electricity use resulted in the period of year outside the heating season. Monthly system seasonal performance factors reach the values above 10. However, monthly values of *SPF* ranges between 3.5 and 4.7 (see Fig. 6) even within the most severe months in the heating season due to favourable temperature conditions in the ground storage (see Fig. 7). Fig. 8 shows the process of charging of the ground storage under the house in the course of year (second year of simulation).

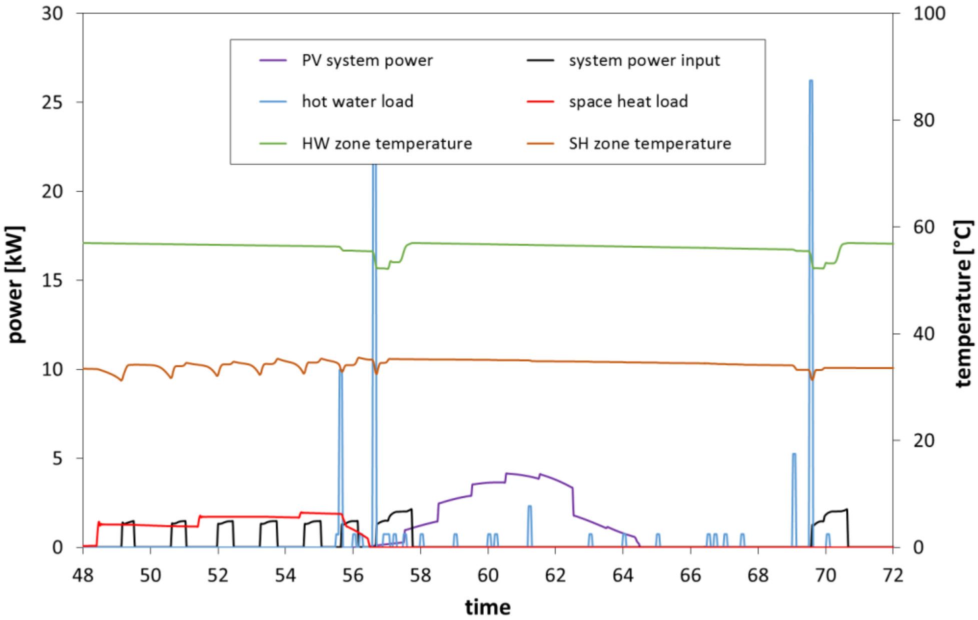

Fig. 4. Detailed comparison of production and load profile of the PV heat pump system in winter for conventional system

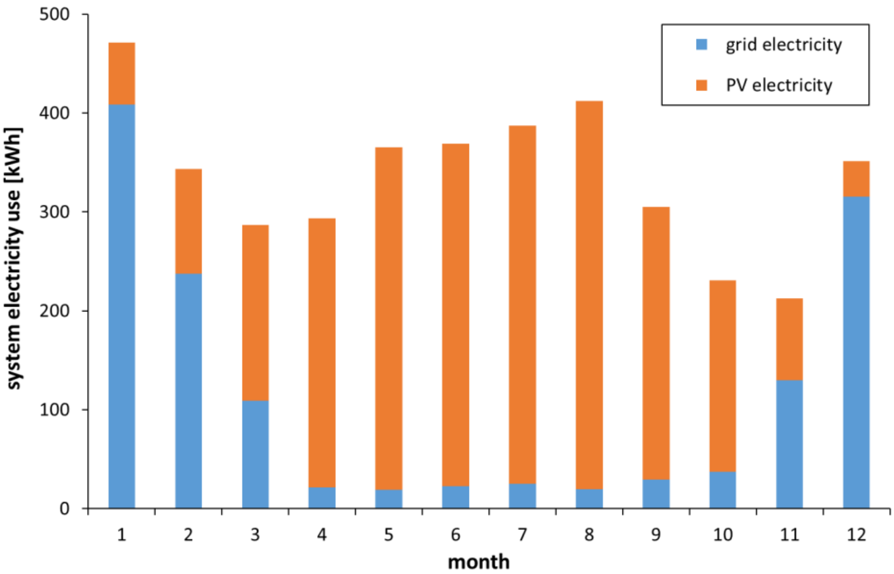

Fig. 5. Electricity balance of the proposed PV heat pump system

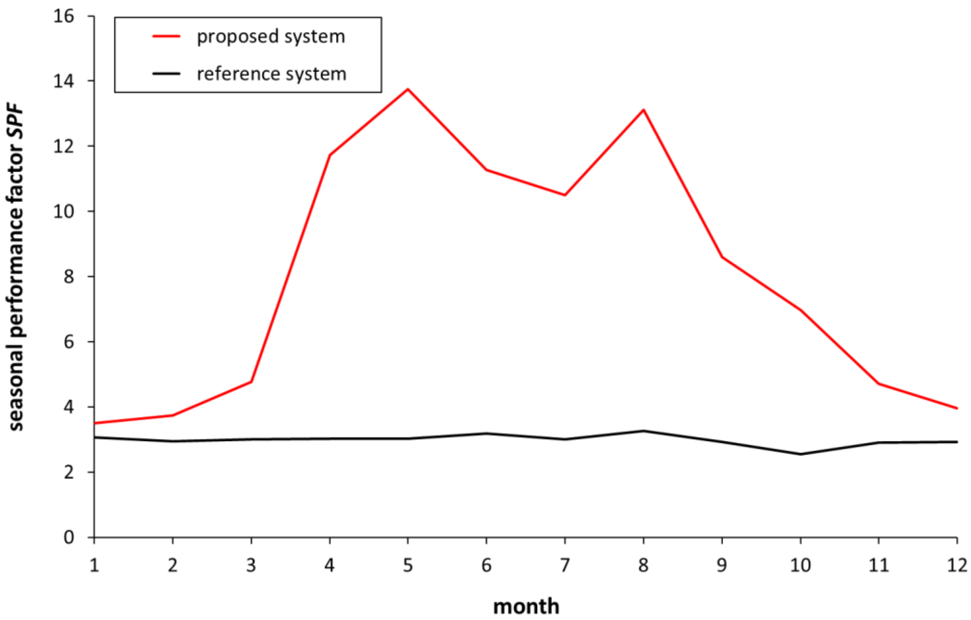

Fig. 6. Comparison of monthly seasonal performance factors for reference and proposed system

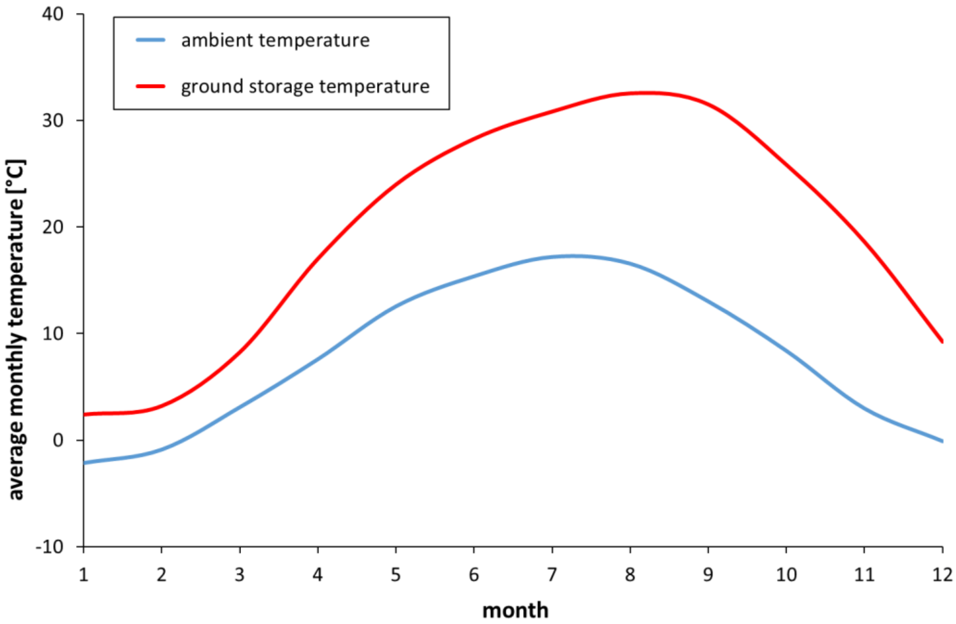

Fig. 7. Development of temperature in the ground seasonal storage

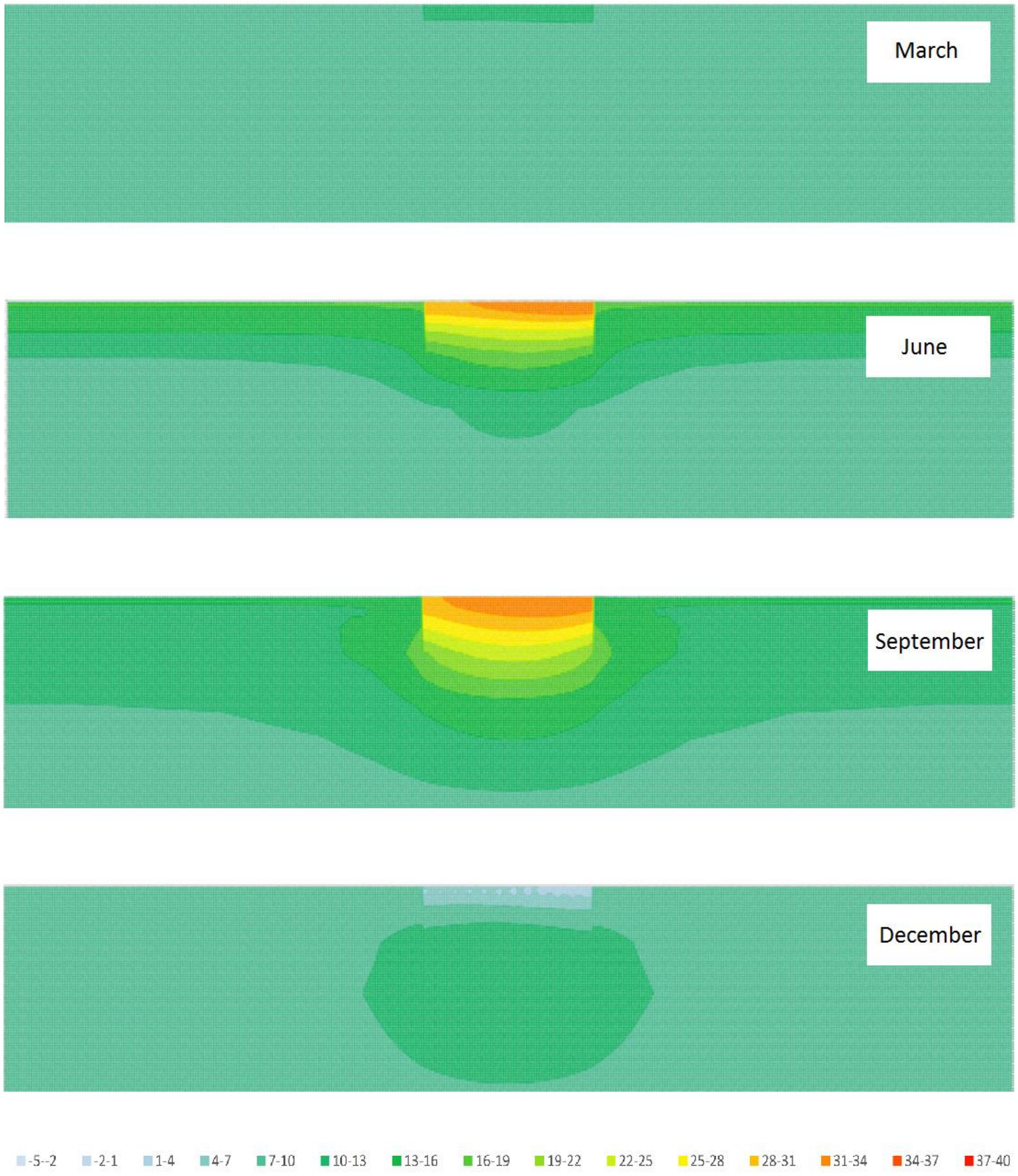

Fig. 8. Charging and discharging of the ground storage during the year

Results have shown that the proposed system uses almost 80 % of renewable energy for space heating, hot water preparation and auxiliary consumption (parasitic system energy). If a strict non-renewable primary energy factor value of 3.0 for electricity is applied the specific primary energy demand for space heating, hot water and auxiliary energy will result 22 kWh/m^2.a. This is finally one third lower value than the focused target. Moreover, this value results from real balance of energy utilization, not from fictive balance of PV electricity export to the external electric grid.

6. Conclusion

Energy system consisting of combined ground-air source heat pump, PV system and seasonal ground storage for energy passive family house has been presented and analysed by computer simulation in TRNSYS. The simulation analysis have shown the significant decrease of the grid electricity needs for the house (system SPF increased from 2.9 for reference borehole system to 4.7) and increase in usability of local PV electricity production for energy supply (space heating, hot water) in the house. In total, 80 % of energy supply for the house is renewable energy and specific non-renewable primary energy need of the house is 22 kWh/m^2.a (for space heating, hot water and auxiliary energy). This is in line with the strict criteria for nearly zero energy buildings.

Acknowledgements

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