Ing. Michal BROUM[1)]
doc. Ing. Tomáš MATUŠKA, Ph.D.[2)]
Ing. Jan SEDLÁŘ[2)]
Ing. Bořivoj ŠOUREK Ph.D.[2)]

[1)] Regulus s.r.o.
[2)] CTU in Prague, University Centre for Energy Efficient Buildings

PV and heat pump system with a seasonal storage for nearly zero energy building

FV systém s tepelným čerpadlem a sezónní akumulací pro téměř nulovou budovu

The energy system consisting of a combined ground-air source heat pump, PV system and seasonal ground storage unit for an energy passive family house has been developed and analysed by computer simulation. The heat pump, during summer operation, transforms the ambient heat to charge the seasonal ground storage with the use of PV electricity only. Winter operation relies on the heat stored under the house and results in low grid electricity consumption. The simulation analysis has shown the significant decrease in the use of the grid electricity needed for the house (the system's SPF increased from 3.1 for the reference borehole system to about 6.0) and an increase in usability of the local PV electricity production for energy supply (space heating, hot water) in the house. In total, more than 80 % of the energy supply for the house is renewable energy and the specific non-renewable primary energy needs of the house is under 17 $kWh\cdot m^{-2}\cdot a^{-1}$ (for space heating, hot water and auxiliary energy).

Keywords: *heat pump, seasonal storage, PV coupled operation*

Pro energeticky pasivní rodinný dům byl vyvinut a počítačovou simulací analyzován energetický systém sestávající z kombinovaného tepelného čerpadla odebírajícího teplo ze země a vzduchu, FV systému a sezónního zásobníku tepla. Tepelné čerpadlo v letním období přeměňuje energie okolního prostředí pro nabíjení zemního sezónního zásobníku s využitím elektřiny pouze z FV systému. Zimní provoz spoléhá na teplo akumulované pod domem a výsledkem je nízká spotřeba elektrické energie ze sítě. Simulační analýza ukázala významný pokles potřeby elektrické energie ze sítě (sezónní topný faktor vzrostl z hodnoty 3.1 pro referenční případ se zemním vrtem a FV systémem na hodnotu okolo 6.0) a zvýšil využití produkce FV systému pro zásobování teplem v domě. Celkem více než 80 % energetické potřeby (vytápění, příprava teplé vody, pomocná energie) je dodáváno z obnovitelné energie a měrná potřeba neobnovitelné primární energie domu je menší než 17 $kWh\cdot m^{-2}\cdot rok^{-1}$.

Klíčová slova: *tepelné čerpadlo, sezónní akumulace, provoz svázaný s fotovoltaikou*

INTRODUCTION

The European Directive on the Energy Performance of Buildings [1] has brought a clear vision and an opportunity to transform the building stock to nearly zero-energy buildings (NZEB). There are a number of measures to improve the energy performance of modern buildings today. The space heating demand could be minimised to the limits of the technical and economical possibilities in the 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 runs, etc. Further savings can be expected with the use of heat recovery from waste water. Electricity demand has been continuously reduced with the introduction of appliances with energy class A and better and the implementation of modern daylighting principles together with proper control of LED artificial lighting.

The logical step ahead, in order to decrease the energy use in buildings, is the application of renewable energy sources. Heat pumps use renewable energy from the ambient environment, however they also need grid electricity to valorise the renewable heat to a 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 the 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 framework of building certification (primary energy factor *PEF* = 3.0). The non-renewable primary energy demand, as an integral quantity, has been adopted as the basis for comparison of a building's performance. Member states approach the definition with different strategies and different promptness. To define the target of a nearly zero-energy building, 30 $kWh\cdot m^{-2}\cdot a^{-1}$ has been set for the purpose of the presented study as a half value of the criterion for a passive house. Despite the fact that the calculation of the non-renewable criterion is generally based on the simple annual balance between the imported and exported energy, it is ambitious target comparable e.g., with Danish legislation [3]. However, the export of local renewable electricity production to a public grid has already become complicated in several countries (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 the reduction of 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 the public grid for space heating and hot water systems [4]. Such an approach also results in the need of the realistic evaluation of the locally produced electricity used in the system.

The paper shows an analysis of a proposed energy system under development which has been motivated by the situation mentioned above. The system combines the PV system and a heat pump for a family house to achieve a 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, optimised or low-cost components because economic issues cannot be put aside.

SYSTEM CONCEPT

The concept of the system being developed is based on a combination of PV technology and an 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 realised within the building's foundations. The heat pump, with a variable speed compressor, is coupled with the PV system in order to adapt the heat pump power input to the actual PV system power output in operation. The target of the system concept is to reduce the annual external grid electricity demand for the house.

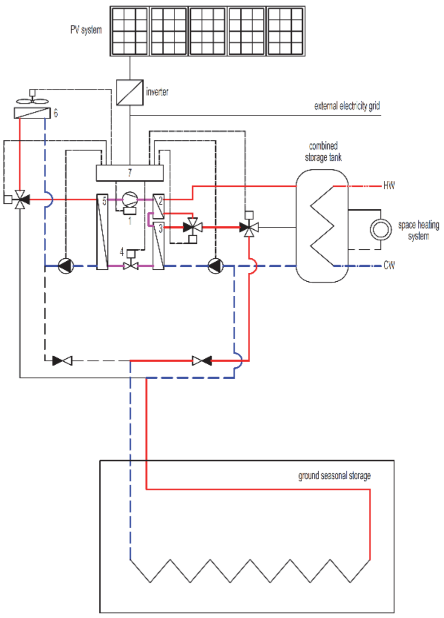

Figure 1 Diagram of the PV heat pump system concept: summer operation

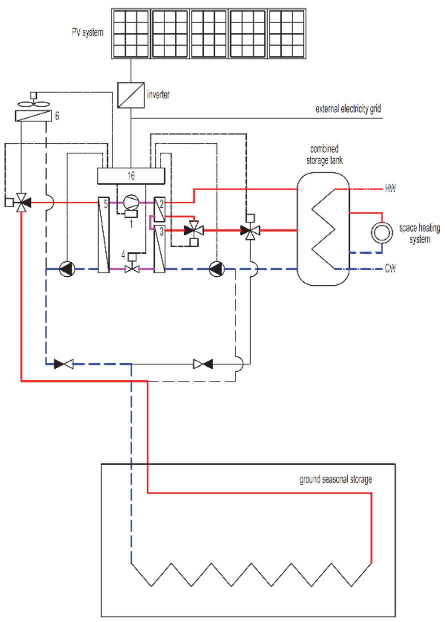

Figure 2 Diagram of the PV heat pump system concept: winter operation

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

A ground seasonal storage realised within the foundations under the house is an important component of the whole system. The heat pump, in the case of sufficient PV power production in summer season, adapts its power input to the PV system power and extracts heat from the ambient air by a heat exchanger / air cooler (6) and rejects it to the building for hot water production with a higher set-point in the combined storage tank (overcharges the volume of the storage tank) or to a 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 a temperature level of 50 to 60 °C in the top part of water storage tank (hot water zone). Such a function of the PV heat pump system could be achieved without any grid electricity input (see Fig. 1).

If the building demands the heat, but the PV system power has decreased under threshold electric power, i.e., during winter time or at night, the electric demand for the heat pump system operation is automatically covered from the grid. Then, the heat pump extracts the heat stored in the ground seasonal storage at a higher temperature (10 to 35 °C) than the ambient air temperature or conventional ground borehole and, thus, the system operates with a higher efficiency (see Fig. 2). This could reduce the grid electricity use and simultaneously increase the usability of the available PV system production over the whole year.

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

- use of a desuperheater for hot water preparation at high temperatures without an increase of compressor electricity use – an increase in heat pump operation effectiveness;
- a combined water storage tank for hot water preparation and space heating with an optimised internal heat exchanger surface area distribution for hot water production – a larger part of the surface area located in the hot water zone reduces the required temperature difference between the water tank volume and the hot water output which causes the high effectivity of the heat pump operation, even for hot water preparation;
- use of excess renewable electricity from the PV system for the heat pump to charge the combined storage tank to a higher temperature than the required set-point and, thus, increasing its storage capacity to overcome the hot water load peaks – a 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;
- the possibility to control the heat pump electric power according to the actual power output of the PV system (power adaptation) –

operation of the heat pump system without external grid electricity use during a significant part of the year.

FAMILY HOUSE

The energy efficient family house under construction (2016-2017) has been chosen for the analysis of the proposed PV heat pump system in the climate of the Czech Republic (see Fig. 3). The family house has two floors with a space volume of 935 m^3 and a total living floor area 190 m^2. The family house was designed in a passive house concept, the *U*-values of the individual envelope constructions meet the recommended values for such high-performance buildings. The foundations have been realised by a sacrificial formwork insulated by extruded polystyrene with a thickness of 160 mm. The base floor has been assembled from concrete slabs, the upper insulation has been realised from extruded polystyrene with a thickness of 240 mm and a floor heating system layer. The envelope brick system is based on cellular clay blocks filled with insulation and an external mineral insulation system with a thickness of 180 mm. The saddle roof has a slope of 40° with south-north orientation and the roof thermal insulation layer thickness is 240 mm.

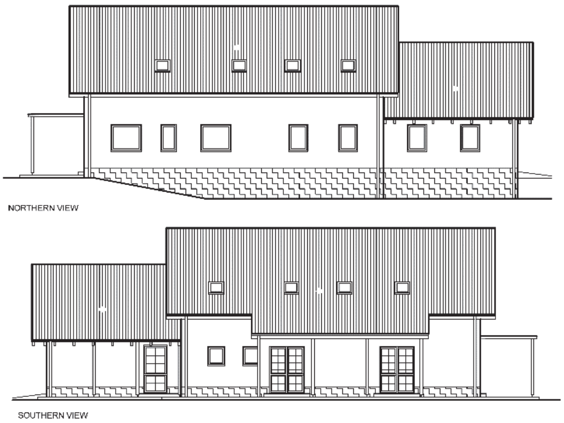

Figure 3 Family house used for the PV heat pump system analysis

The designed heat loss of the family house is 4.5 kW for ambient air temperature -15 °C. The low temperature floor space heating system has been used with design flow/return water temperatures 40/35 °C, respectively. Ventilation is provided by an air handling unit with a maximum flowrate of 275 $m^3 \cdot h^{-1}$ using heat recovery. The proposed system consists of an advanced heat pump with a heat output of 5.5 kW at B0/W35 (50 Hz) and a combined storage tank of volume 900 l with an internal heat exchanger with a surface area 9 m^2. The investor considered the large PV system installation with a peak power of 6 kW_p to increase the energy independency of the house operation.

During the construction stage, the ground seasonal storage has been realised with the use of a pipe heat exchanger (see Fig. 4) with a size of 14.4 m x 8.0 m within the foundations of the house, which are 1.5 m deep and thermally insulated on the external surface. The internal perimeter of the ground storage volume is also thermally insulated, but only to a depth of 0.5 m in order to eliminate thermal bridges from the charged storage to the interior through the envelope and foundations (see Fig. 4). The heat exchanger is made from plastic piping DN32 buried in the 300 mm deep trenches filled with cement and silicate sand mixture to provide a good thermal contact between the pipe and the ground. The distance between the pipes in the heat exchanger is 0.6 m. The heat exchanger has been realised in two loops, each 100 m in length. Two loops have been designed to reduce the auxiliary demand of the circulation pumps. Redundant thermal insulation with a thickness of 100 mm has been applied between the seasonal storage volume and the concrete floor slabs.

Figure 4 Realisation of a simple and a low-cost ground seasonal storage unit

SIMULATION ANALYSIS

The computer simulation analysis of the proposed PV and heat pump system has been undertaken in the TRNSYS environment [5]. The objective of the analysis was to prove 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 our own specifically developed TRNSYS models have been used [6-8]. The computer simulations have been completed with a time step of 2 minutes and two years of operation has always been simulated because of the ground massif use in both the proposed and conventional heat pump system. The results have been evaluated from the second year of the simulation. The properties of the ground massif have been defined: thermal conductivity of 2 $W \cdot m^{-1} \cdot K^{-1}$, density of 2100 $kg \cdot m^{-3}$ and specific capacity of 840 $J \cdot kg^{-1} \cdot K^{-1}$.

The building model has been built in TRNSYS based on the construction plans and used for separate simulations of space heating load to reduce the calculation time. The results for the space heating and hot water load have been used as inputs for the system simulations. The space heating demand is 3400 $kWh \cdot a^{-1}$ and the hot water demand is 3060 $kWh \cdot a^{-1}$.

RESULTS

A conventional ground source heat pump system with a borehole heat exchanger (75 m), a standard combined water storage tank (900 l) and a PV system (6 kW_p) has been modelled for the given house as a reference case. The total grid electricity use of the conventional system is 2061 $kWh \cdot a^{-1}$ and the system operates with a seasonal performance factor *SPF* = 3.1. The monthly values of the *SPF* range are around this value (see Fig. 7). The main reason of the low operation effectiveness for the conventional reference case is the large share of hot water heat demand in general combined with the necessity of charging the hot water zone in the storage tank to a temperature of 55 °C to eliminate the operation of the electric back-up heater. Despite the high installed power of the PV system, there is high electricity use and low utilisation of the produced PV electricity with the heat pump system. The reason is the mismatch between the hot water peak loads (morning, evening), space heating peak loads (winter season, night time) and PV electricity production (summer season, daytime), see Fig. 5. The PV system annually covers 420 kWh from a total 2620 kWh system electricity demand only, despite the installed 6 kW_p power produces about 6020 $kWh \cdot a^{-1}$ of electricity.

The proposed system has been modelled with an advanced heat pump with a desuperheater and a variable speed compressor for adaptation of the power input to the PV system power production combined with a seasonal ground storage of ambient heat extracted by an air cooler in the summer and used as a source for the heat pump in the winter. The total grid electricity use (heat pump, circulation pumps, back-up heater, ambient air cooler minus the PV electricity used) is 1078 $kWh \cdot a^{-1}$ and the system operates with a seasonal performance factor of *SPF* = 6.0. Fig. 6 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. The monthly system seasonal performance factors reached the values far above 10 from spring to autumn. However, the monthly values of *SPF* ranges between 3.5 and 4.7 (see Fig. 7) even within the most severe months in the heating season due to favourable temperature conditions in the ground storage (see Fig. 8). Fig. 9 shows the process of charging and discharging of the ground storage under the house in the course of year (second year of simulation).

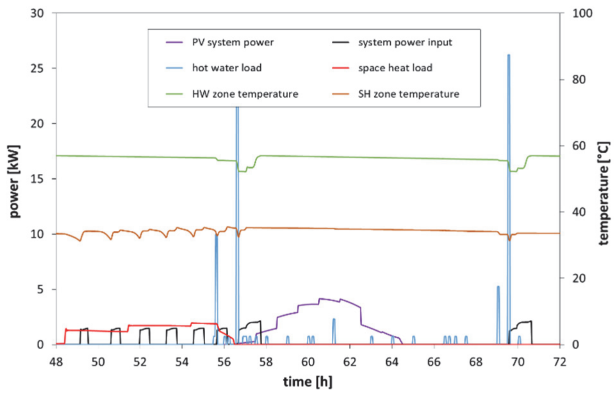

Figure 5 Detailed comparison of the production and load profile of the PV heat pump system in winter for the conventional system

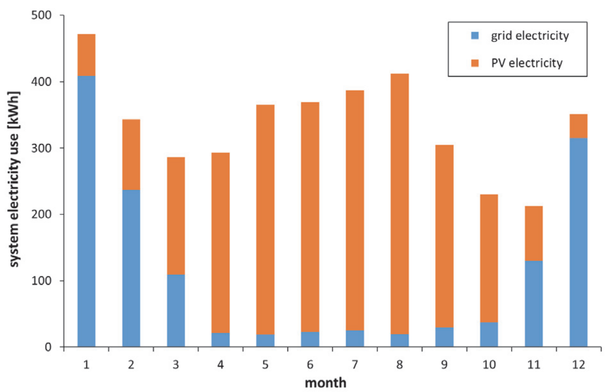

Figure 6 Electricity balance of the proposed PV heat pump system

The results have shown that the proposed system uses 83 % 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 be around 17 $kWh \cdot m^{-2} \cdot a^{-1}$. This is, finally, almost half of the original focused target. Moreover, this value results from the real balance of energy utilisation, not from a fictive annual balance of the PV electricity export to the external electric grid.

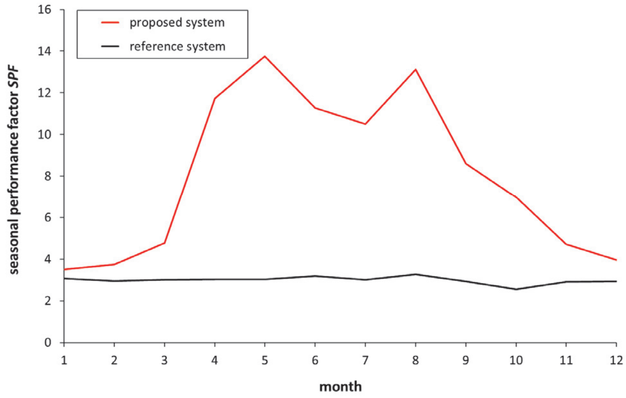

Figure 7 Comparison of the monthly seasonal performance factors for the reference and proposed system

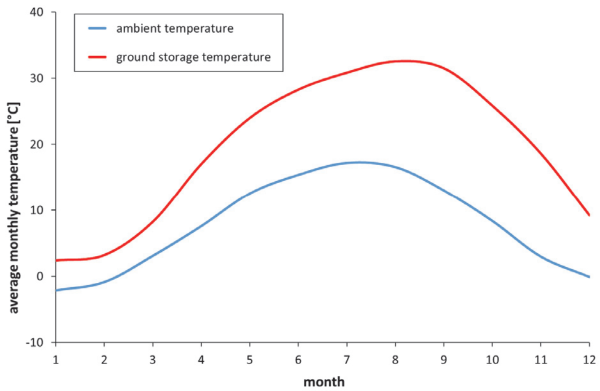

Figure 8 Development of the temperature in the seasonal ground storage

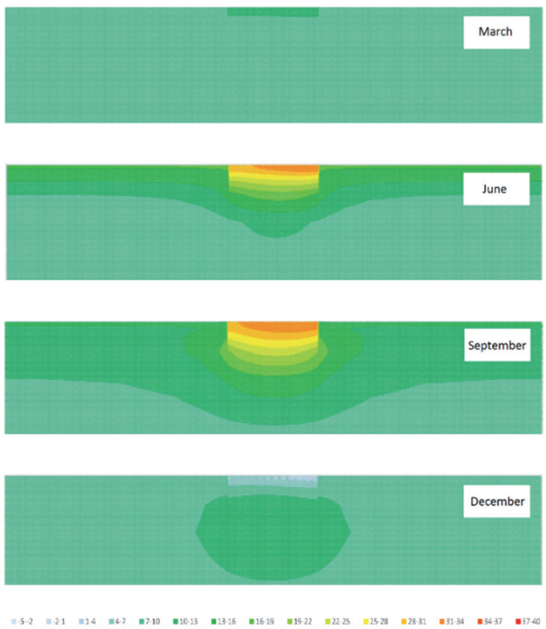

Figure 9 Charging and discharging of the ground storage during the year

CONCLUSION

The energy system consisting of a combined ground-air source heat pump, a PV system and a seasonal ground storage unit for an energy passive family house has been presented and analysed by computer simulation in TRNSYS. The simulation analysis has shown a significant decrease of the grid electricity needs for the house (the system's *SPF* increased from 2.9 for the reference borehole system to 6.0) and an increase in usability of the local PV electricity production for energy supply (space heating, hot water) in the house. In total, 83 % of the energy supply for the house is renewable energy and the specific non-renewable primary energy need of the house is lower than 20 $kWh \cdot m^{-2} \cdot a^{-1}$ (for space heating, hot water and auxiliary energy). This is in line with the strict criteria for nearly zero-energy buildings.

ACKNOWLEDGMENT

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