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Research Paper

Research Project - Experimental House EB2020

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ABSTRACT: *Research of combined building-energy systems with high potential for the use of renewable energy sources carried out since 2005 at the Department of Building Services, Faculty of Civil Engineering STU in Bratislava is focused not only on self-supporting panels used for construction of buildings with built-in active thermal protection (ATP), but also on the application of this technical solution as described, for example, in the patent document SK 284 751 (ISOMAX system) for existing, respectively for new masonry enveloping structures with one or two thermal barriers. The basic and original idea of using solar and geothermic energy is the combined building and energy system ISOMAX originating from Luxembourg (author: Krecké Edmond D .; Beaufort; LU), which, like TABS systems, uses thermally activated mass. During its operation, this system uses the heat obtained from solar radiation, which is stored in heat storages, to actively reduce heat loss through enveloping structures. During its operation, this system uses the heat obtained from solar radiation, which is stored in heat storage, to actively reduce heat loss through enveloping structures. During the heating season, water is supplied to the pipes from the ground heat storage, the average temperature of the heating water is in the range of 15°C to 20°C. Cold water from the ground pipeline register is used for cooling in the summer. In the research of combined building and energy systems at our workplace, doctoral students Ing. Martin Cvíčela, Ph.D. [12], (supervisor: Kalús, D.), Ing. Peter Janik, PhD. [13], (supervisor: Kalús, D.) and Ing. Martin Šimko, PhD. [14], (supervisor: Kalús, D.), have to a significant extent contributed to this research, who described the results of the research in their dissertations. Currently, experimental measurements in a mobile laboratory focused on the development of a compact heating/cooling unit in terms of utility model SK 5749 Y1: "Operation of a combined building and energy system of buildings and equipment" using renewable energy sources is performed by doctoral student Ing. Matej Kubica, [15], (supervisor: Kalús, D.).*

KEYWORDS: *Building structures with internal energy source, thermal barrier, large-area radiant low-temperature heating/high-temperature cooling, heat/cold accumulation in building structures, solar energy roof, large-capacity ground heat storage, solar energy, geothermic energy, recuperative ventilation, cooling circuit of a ground pipe register*

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I. INTRODUCTION

The technical solution of combined building-energy systems in the sense of the patent SK 284 751 (ISOMAX system) is based on the assumption that the only heat source is solar and geothermic energy. Solar energy is absorbed through a solar energy roof. This source appears to be unstable with insufficient absorption of sunlight. It can be used in the summer and partly during the transition period with sufficient heating of the heat transfer medium, i.e. temperature of the heat carrying medium is higher than the temperature in the long-term heat storage in the ground (ground heat storage). Geothermic energy is captured in the ground storage to an extent negligible for heating needs. **The ISOMAX system captures these energies only for direct use in the so-called thermal barrier without increasing energy efficiency e.g. by means of a heat pump or solar collectors.** The amount of energy is difficult to determine exactly due to the large number of unstable physical parameters affecting the capture of solar radiation. The captured energy is only applied to charge the long-term storage. The source is difficult to regulate and cannot cover sudden requirements for increasing the energy supply and cannot cover the year-round need for energy for heating, hot water, or ventilation. For example, the design of resources with the ISOMAX system is done only empirically - by estimation. **From the previous implementations, it is clear that a peak heat source is also needed.**

With the ISOMAX system, heat accumulation takes place only in the long-term ground storage, it is unstable, uneven. Ground storage is mostly constructed with an open surface at the bottom, which causes uncontrollable and immeasurable leakage of accumulated heat. The efficiency of such storage is several times lower than the efficiency of closed, insulated heat storage. The amount of stored energy and the length of charging of ground storage to a certain capacity are difficult to calculate due to a large number of changing physical parameters, such as ground moisture, its composition, groundwater level and its vertical movement and the like. Available for heating is always only the temperature of the heat transfer medium as is the average temperature of the long-term ground storage and the ISOMAX system cannot increase it in any way. The temperature of the heat transfer medium cannot be changed other than through the absorption of solar radiation. Calculation and design is done only by empirical - estimation method.

Heat transfer by the ISOMAX system is performed only to the heat barrier and serves only to reduce heat losses. The temperature of the heat transfer medium is limited by the temperature in the ground heat storage or in the cooling circuit and fluctuates according to the current temperature in these storages and cannot respond to sudden weather changes or needs for indoor climate change by higher or lower temperatures than available in the storage. Due to the fact that it is not possible to supply a heat transfer medium with a constant temperature to the thermal barrier during the entire period - this changes the heat transfer through the building structure and its thermal resistance. It is clear from the previous realizations that the thermal barrier constructed in this way cannot cover the heat losses of a building all year round.

The only source of cold for the ISOMAX system is ground cold storage at non-freezing depth. The coolant temperature depends on the changing soil temperature, it is limited and fluctuating and cannot respond to sudden changes in weather and needs with a colder substance than is available in the ground storage.

The ISOMAX system only solves preheating of hot water up to maximum temperature of 35 ^{0}C and only in summer when there is enough sunlight. The temperature of the ventilation air in the ISOMAX system fluctuates and depends on the temperature in the ground heat storage and in the ground cooling circuit and it is not possible to adjust it to temperatures different from that in the ground heat storage.

II. FOCUS OF RESEARCH

Due to the fact that the experimental house EB2020 was largely designed in accordance with the technical solution described in the patent document SK 284 751 (ISOMAX system), which seems to be a very promising idea for the construction of nearly zero energy buildings using renewable energy sources, but on the other hand, it has an unresolved mode of operation, which results in the shortcomings described in the previous chapter, the objectives of research in this area are aimed at proposing technical solutions to eliminate the shortcomings in question so that:

a) heat/cold sources for energy systems - heating, hot water preparation, ventilation and cooling were stable, independent of variable and unpredictable solar and geothermic energy accumulated in large-capacity, especially in ground heat storage,
b) the requirements were achieved for nearly zero energy buildings,
c) RES are used as much as possible and the best possible accumulation of heat/cold from these sources is ensured,
d) implementation of active thermal protection is simplified,
e) advantages of the contact thermal insulation system have been economically effectively combined with energy systems - thermal barrier, heating, cooling, storage and heat recovery, solar and environmental energy collection and the use of recuperation ventilation - in multifunctional energy constructions of buildings.
f) a compact heat station with a separate control system was designed to regulate, measure, and optimize the energy demand in the building,
g) a reliable exact calculation methodology was developed for the design, calculation, selection, and assessment of all components of the combined building and energy systems of the building.

The research project HZ PG73/2011 solved by the team of researchers from the Department of Building Services, Faculty of Civil Engineering STU in Bratislava in 2011-2013 focused on experimental measurements, analysis, and determination of the optimal use of RES for prototype family house EB2020 which is a nearly zero energy building (responsible researcher: Kalús, D.), [10], namely on:

- experimental measurements and evaluation of operation of the energy roof,
- experimental measurements and evaluation of the operation of the ground heat storage,
- experimental measurements and evaluation of operation of active thermal protection.

III. TECHNICAL SOLUTION OF THE EXPERIMENTAL HOUSE - EB2020

3.1 Construction solution of the experimental house - EB2020

The experimental family house is located 17 km from Bratislava, at an altitude of 128 m above sea level, in the village of Tomášov with a number of houses of about 700. It has two floors, specific area of 187.4 m^2, built-up volume of 590 m^3, and average construction height of 3.15 m Figure 1. Heat transfer coefficients (U) of individual structures: window 0,8 W/m^2K, wall 0,15 W/m^2K, floor 0,15 W/m^2K, roof 0,13 W/m^2K.

The perimeter structure consists of internal plaster, aerated concrete block (375 mm, λ = 0.104 W/m.K), adhesive mortar, facade polystyrene (100 mm, λ = 0.035 W/m.K) and external plaster. The active thermal protection ATP is formed by a plastic pipe between the aerated concrete masonry and the facade polystyrene and in the roof structure, Figure 2.

Figure 1: View of the experimental house EB2020 (Photo archive: Kalús) [10, 13]

In Figure 2 shows the temperature distribution in the perimeter structure without the use of active thermal protection ATP and with an average heat transfer medium temperature in the layer of 14°C and 20°C (at an outdoor temperature of -11°C). In the construction without ATP, the surface temperature will be 18.7°C and the temperature between the aerated concrete block and the thermal insulation will be 2.5°C. With the installation of ATO with a temperature in its location layer of 14°C, the surface temperature will be 19.6°C.

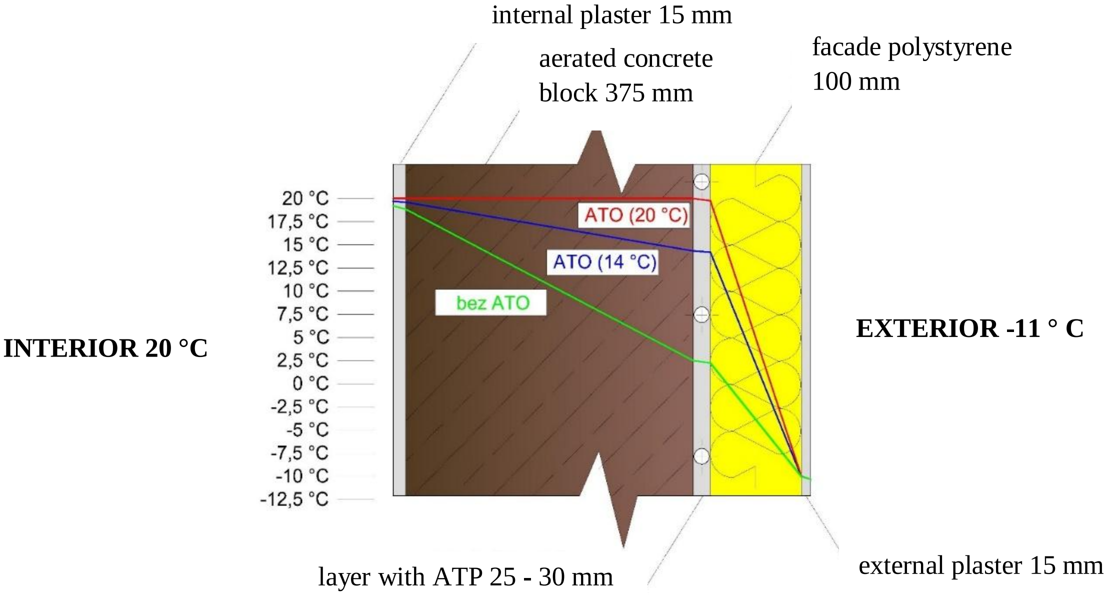


Figure 2: Sectional representation of a perimeter structure with temperature distribution without the use of ATP and with an average heat transfer medium temperature in the ATO layer of 14°C and 20°C [10, 13]

3.2 Description of the technical solution of energy systems

The source of heat is an energy roof formed by a plastic pipe placed under the roof tiles in circuits: 3 x 100 m, a fireplace insert and a gas boiler, Figure 3. In addition to the combined storage tank (V = 575 l for central heating and 180 l for DHW), the heat is stored in the ground storage, which is formed by a plastic pipe in the foundation slab in circuits: 5 x 100 m, Figure 4.

Figure 3: Energy roof consisting of plastic pipes under roof tiles, a low-temperature gas boiler and a fireplace with a hot water heat exchanger (Photo archive: Kalús) [10, 13]

Figure 4: View of the storage tank (V = 575 l for CH and 180 l for DHW), implementation and insulation of the ground heat storage with integrated pipes in the foundation slab (Photo archive: Kalús) [10, 13]

Active thermal protection (ATP) in a given building consists of a plastic pipe between aerated concrete masonry (375 mm) and facade polystyrene (100 mm) and in the roof structure in circuits: 20 x 100 m, Figure 5. With the help of ATO it is possible to reduce heat losses in the building through non-transparent structures, to heat the building and to cool the building in summer.

Figure 5: View of the ATO formed by a plastic pipe between aerated concrete masonry (375 mm) and EPS (100 mm) and in the construction of the roof in circuits: 20 x 100 m in the experimental house EB2020 (Photo archive: Kalús) [10, 13]

The source of cold is the cooling circuits, which are located at a non-freezing depth in the ground around the foundation strips of the building. They are formed by circuits of plastic ducts: 20 x 100 m, Figure 6.

Figure 6: View of cooling circuits, which are located in the non-freezing depth, in the ground around the foundation strips of the building in the experimental house EB2020 (Photo archive: Kalús) [10, 13]

Heat transfer in the building is also possible by underfloor heating on both floors, Figure 7. A ventilation unit with heat recovery is also installed, Figure 8.

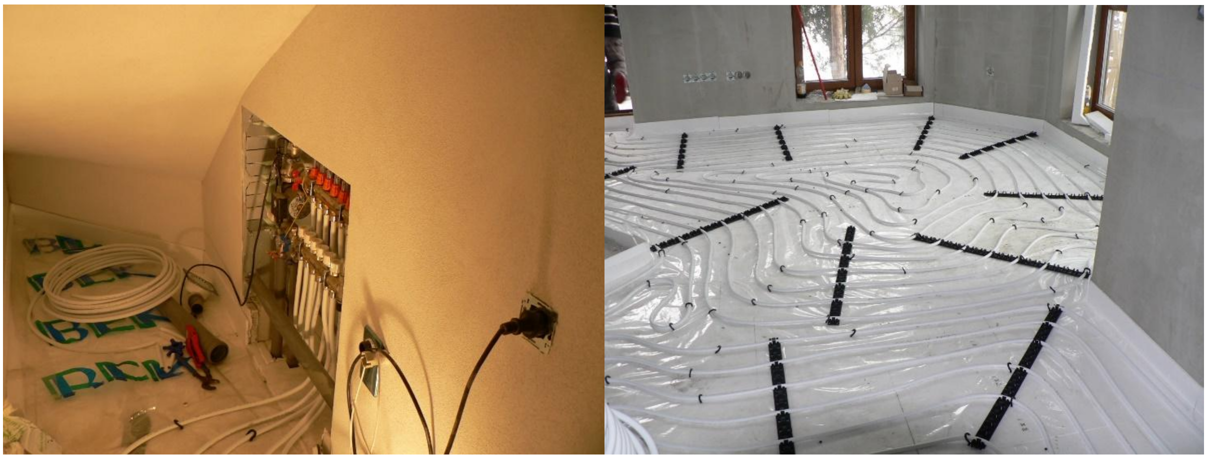


Figure 7: A look at the implementation of underfloor heating in the experimental house EB2020 (Photo archive: Kalús) [10, 13]

Figure 8: View of the implementation of recuperative ventilation in the experimental house EB2020 (Photo archive: Kalús) [10, 13]

3.3 Connection of energy systems in the experimental house EB2020

The connection diagram of the energy systems of the experimental house EB2020 is shown in Figure 9. It is clear from the diagram that the heat obtained from solar energy (energy roof) is stored in the ground storage, while under suitable conditions it can also be stored in the storage tank. A heat exchanger is installed between the primary side (in which a glycol-based antifreeze mixture circulates) and the secondary side. Heat to the ground storage can also be supplied by a fireplace insert, which is also a source of heat for the storage tank. A peak heat source for the storage tank is a low-temperature gas boiler. Low-temperature radiant floor heating is supplied from the storage tank. The m active thermal protection ATP can be supplied from the storage tank or directly from the ground heat storage.

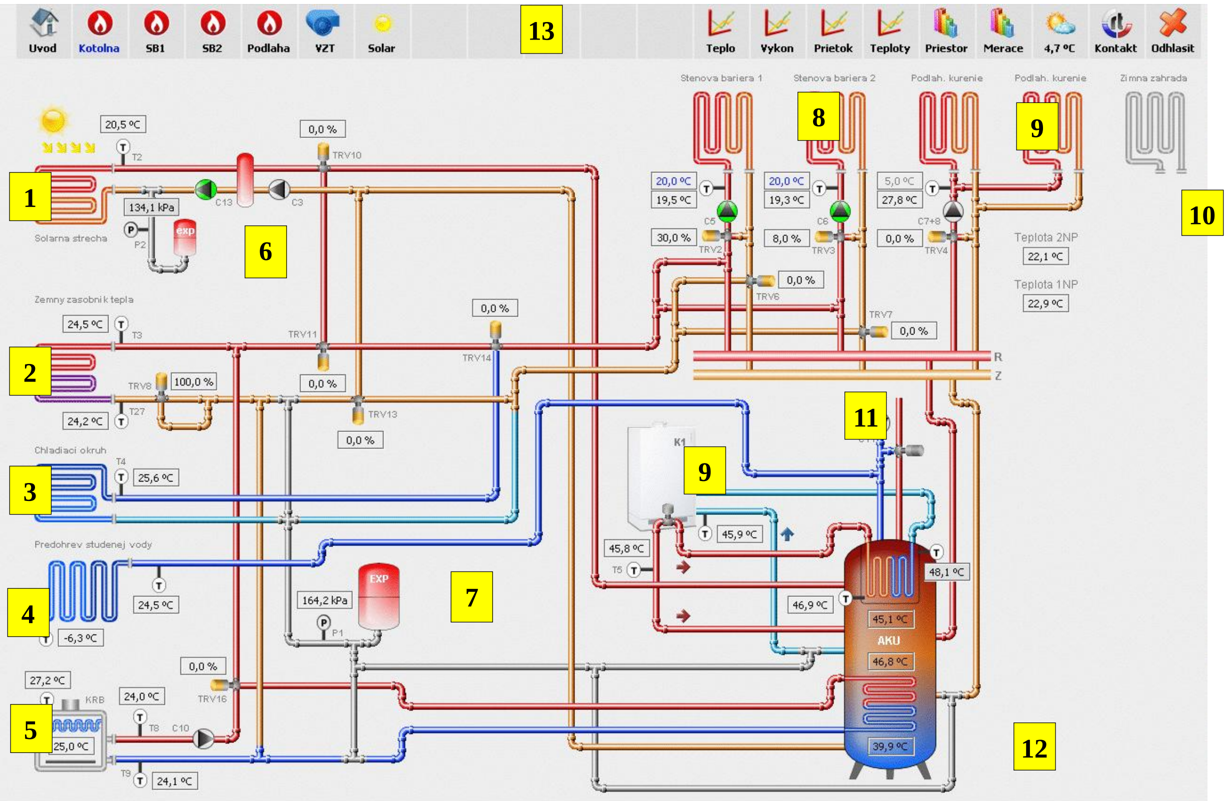


Figure 9: Connection diagram of energy systems in the experimental house EB2020 with the possibility of remote control via the Internet [10, 13]

1 - solar energy roof circuits, 2 - ground heat storage circuits, 3 - cooling circuit, 4 - hot water preheating circuit, 5 - fireplace with hot water heat exchanger, 6 - expansion vessel for solar roof, 7 - expansion vessel for heating system, 8 - active thermal protection circuits, 9 - low temperature gas boiler, 10 - preparation of *heating for a winter garden, 11 - hot water circuit with a circulation pump, 12 - storage tank, 13 - output from the building control system to the computer, control via the Internet*

Figure 10: A view of the connection of energy systems in the experimental house EB2020 (Photo archive: Kalús) [10, 13]

Figure 11: A view of the measurement and control station in the experimental house EB2020 (Photo archive: Kalús) [10, 13]

IV. EXPERIMENTAL MEASUREMENTS

In December 2011, the operation was started of the energy system with the use of active thermal protection and underfloor heating, while temporarily used from the heat sources were the low-temperature gas boiler and the hot-water fireplace insert. Different input temperatures to the active thermal protection ATP (wall barrier) and into the underfloor heating were set in order to find the optimal use of the energy system and evaluate the parameters of individual modes of operation. The measurement of the energy system with active thermal protection in the function of large-area wall cooling and thermal barrier and underfloor heating took place over two heating periods. Measurement of active thermal protection in the function of large-area wall cooling took place over one summer period (July to October 2012). The energy roof was put into operation in July 2012. The measurement of the energy roof and the charging of the ground heat storage in the charging cycle lasted one summer period.

4.1 Experimental measurements of the energy roof

The energy roof was put into operation on July 4, 2012. The obtained heat (GJ), flow volume (m3), flow rate (m^3/h), output (kW), and temperature on the supply and return pipes (°C) were measured - in Figure 12. marked as θ_2 and θ_3. These values were measured behind a plate heat exchanger. Also measured was the temperature of the working medium in front of the heat exchanger at the outlet of the energy roof, marked as θ_1. At that time, not measured was the temperature at the entrance to the energy roof, flow rate, flow volume, and heat on the primary side. The individual measuring points are not installed immediately in front of and behind the heat exchanger. Temperatures on the secondary side of the exchanger θ_2 and θ_3 were recorded at one hour intervals, the temperature on the primary side of the plate heat exchanger θ_1 at 5 minute intervals.

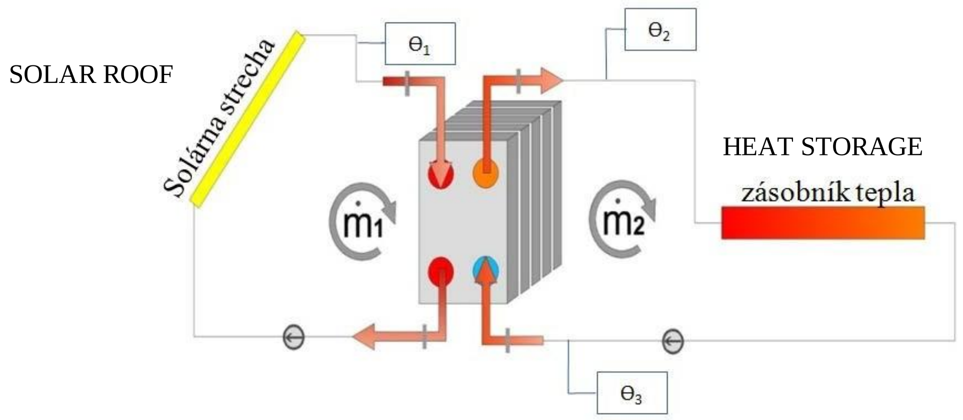


Figure 12: Scheme of measuring points of the energy roof in the family house [10, 13]

The circulation pumps are switched on in favorable conditions (with a suitable temperature difference in the solar roof and in heat storage). If the temperature in the combined water heat storage tank is lower than the temperature at the inlet from the solar roof, the heat is accumulated in this tank. Otherwise, the heat is accumulated in the ground storage. During the whole operation, the heat was accumulated in the ground storage. The first days of operation of the solar roof were not evaluated in the overall balance, as during this period a pressure test was performed and the operation of the system was tested. Values from 10 July 2012 were taken into the overall balance. Suitable conditions for the use of the energy roof were until 6 October 2012. In the periods from 8 to 15 August and from 7 to 14 September, maintenance work was carried out on the energy system, or there were faults on the server, when temperatures on inlet and return pipes, flow rates and outputs were temporarily not recorded. In view of these facts, the system was analyzed in more detail by month:

- July (considered from 10th to 31st),
- August (8th to 15th individual values were not temporarily recorded),
- September and October (individual values were not recorded from 7 to 14 September. After 19 September, the conditions for the use of the roof were no longer favorable in the given month, in October only the conditions favorable were on the 5th and 6th of the month).

Input to heat storage Θ_2 External air temperature Θ_3. Figure 13 shows the average temperatures of the working medium: θ_1, θ_2, θ_3 and the average outside air temperature θ_e from the period when the circulation pumps were in operation. These values were not recorded on 8 - 15 August and 7 - 14 September. Also displayed is the total heat obtained and delivered to the ground storage, the average flow rate, and the flow volume on the secondary side. The values of supplied heat and total flow volume are included from the whole period. The values are displayed for individual months as well as for the entire period of operation for 2012.

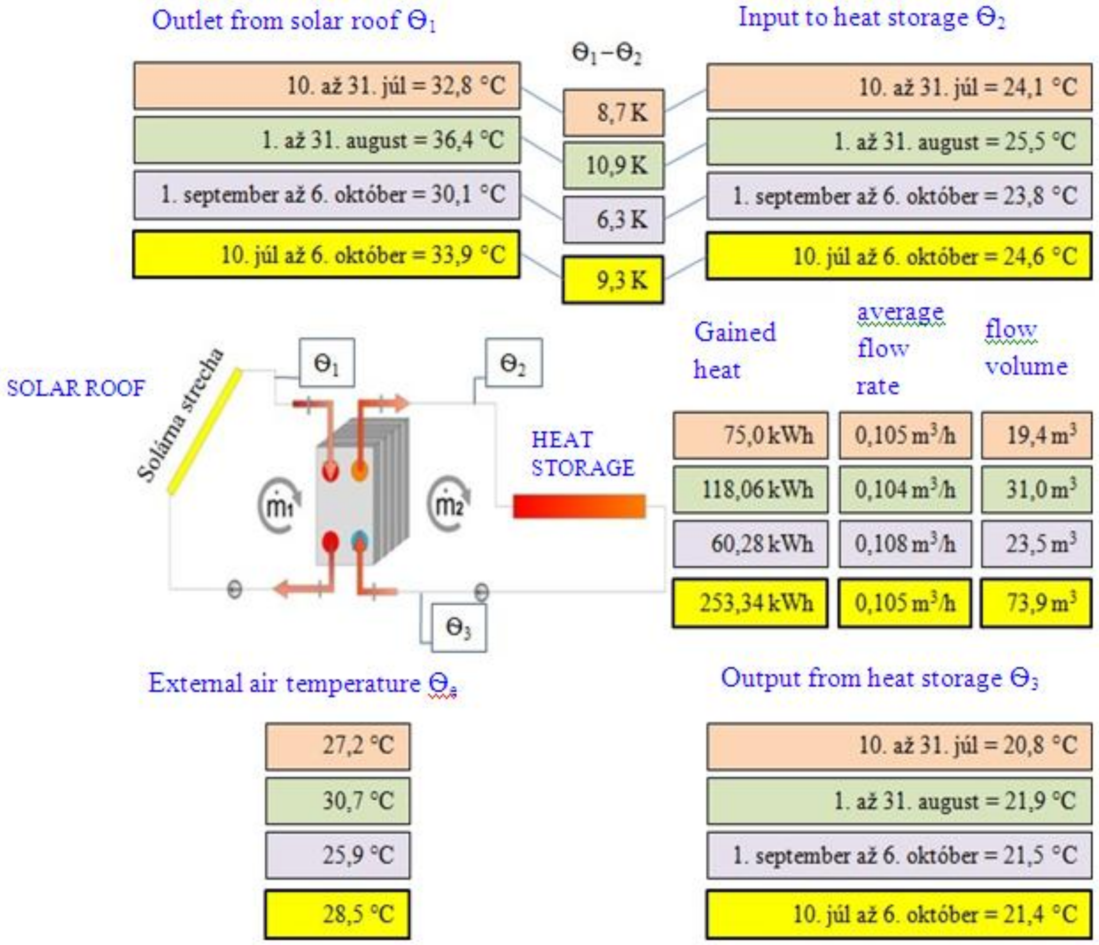


Figure 13: Summary of measured values from the operation of the energy roof **-** from 10 June to 6 October 2012: average temperatures of the working medium: Θ_1, Θ_2, Θ_3, average temperature of the outside air Θ_e (from the time periods when the circulating pumps were in operation), total heat obtained, average flow rate and flow volume on the secondary side [10, 13]

On the primary side of the heat exchanger, only the temperature at the outlet from the energy roof θ_1 was measured, the average value of which for the entire operation of 2012 was 33.9 °C. On the secondary side behind the heat exchanger, the average temperature was $\theta_2 = 24.6$ °C. The temperature difference is 9.3 K. The total heat obtained and stored in the ground storage is 0.912 GJ = 253.34 kWh. With the correct design or use of the heat exchanger, the amount of this heat could have been higher. The average flow rate on the secondary side was 0.105 m^3/h = 1.75 l/min. The average outside air temperature during energy roof operation $\theta_e = 28.5$ °C.

4.2 Experimental measurements of the ground heat storage

Experimental measurements of the ground heat storage took place during one charging season (values taken into account from 10 July, i.e. from the beginning of the operation of the solar energy roof) and one discharging season (one heating period). The heat source is the energy roof and a hot water fireplace insert. The energy roof is also a source of heat for the combined water tank for heating and hot water. However, since the temperature in the said combined storage tank was always higher than the temperature obtained from the energy roof, the heat from it was accumulated in the ground heat storage during the entire charging season. The fireplace insert is equally a source for both ground and water heat storage. The control of the system is set for primary heating of the combined water storage tank, whereby after it is heated to the required temperature, the heat is further accumulated in the ground heat storage.

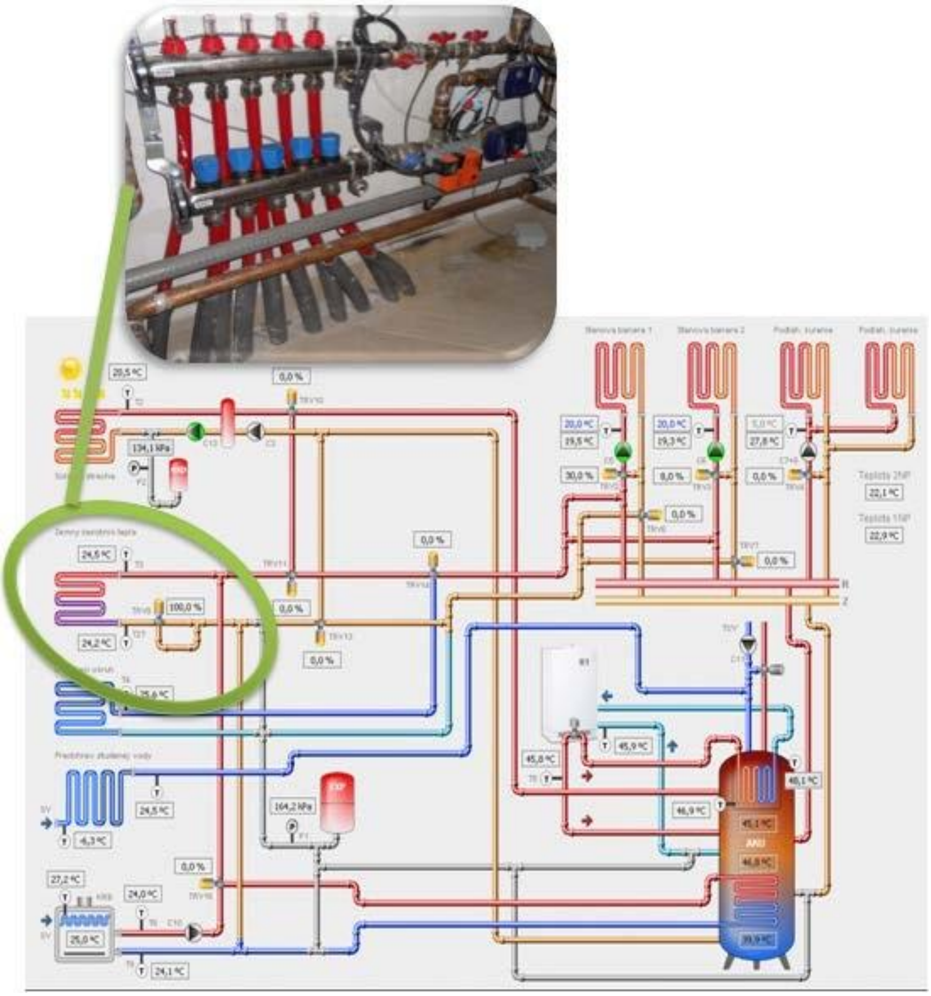


Figure 14: Diagram of the energy system in the family house and display of compact heat meters connected by a by-pass at the ground heat storage [10, 13]

A compact heat meter is fitted to the ground heat storage (heat, flow rate, total flow volume, temperatures and output are measured). A second compact heat meter is fitted via a by-pass. One meter is used for measuring when heating (charging) GHS, the other when taking heat from GHS (discharging). Heat meters with the bypass are shown in Figure 14.

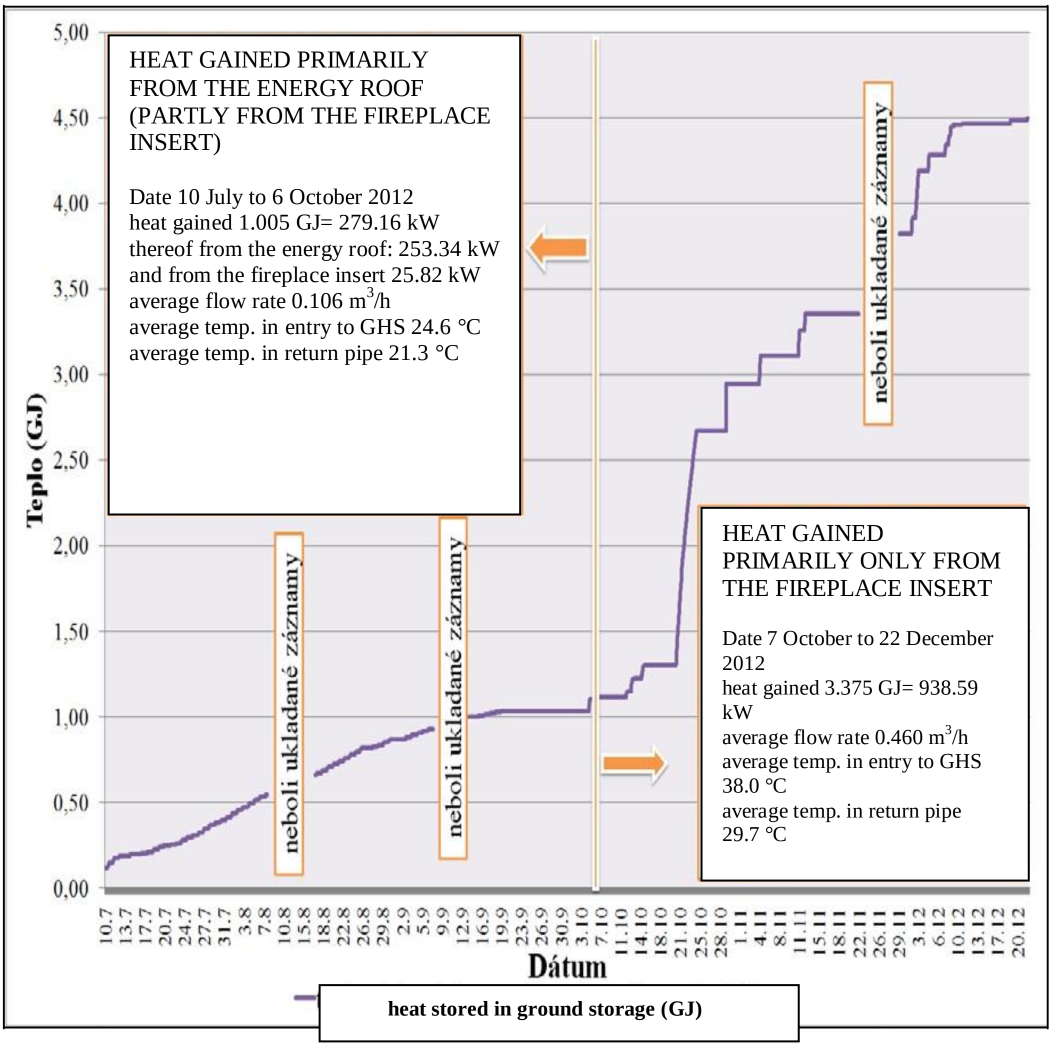
Compact heat meters are also fitted to the energy roof and fireplace insert. Heat from the energy roof could be accumulated in the combined water heat storage as well as in the ground heat storage. At the time of measurements during the entire operation, it was accumulated only in the ground heat storage. Heat from the hot water fireplace insert was accumulated both in the combined water heat storage tank and in the ground heat storage. This means that it is possible to find out the values on the heat meter at the fireplace insert, but further, the values behind the three-way valve are not recorded - towards the combined water heat storage tank and towards the ground heat storage.

4.2.1 Experimental measurements when charging the ground heat storage

Figure 15 shows the heat stored in the ground heat storage in GJ for the period 10 June to 22 December 2012 with marked average flow rates and average temperatures of the working medium at the inlet to the ground heat storage and in the return pipe (at the outlet from the GHS). The chart is divided into two periods: "A" and "B". The limit is the time when the energy roof is no longer used. After 6 October 2012, the conditions for its use were no longer suitable.

- period "A" – 10 July to 6 October 2012 - heat to the GHS was stored mainly from the energy roof, only partially from the hot water fireplace insert,

- period "B" 7 October to 22 December 2012 **-** heat was stored in the GHS only from the hot water fireplace insert.



HEAT GAINED PRIMARILY FROM THE ENERGY ROOF (PARTLY FROM THE FIREPLACE INSERT)

Date 10 July to 6 October 2012
heat gained 1.005 GJ= 279.16 kW
thereof from the energy roof: 253.34 kW
and from the fireplace insert 25.82 kW
average flow rate 0.106 m^3/h
average temp. in entry to GHS 24.6 °C
average temp. in return pipe 21.3 °C

HEAT GAINED PRIMARILY ONLY FROM THE FIREPLACE INSERT

Date 7 October to 22 December 2012
heat gained 3.375 GJ= 938.59 kW
average flow rate 0.460 m^3/h
average temp. in entry to GHS 38.0 °C
average temp. in return pipe 29.7 °C

Figure 15: Heat stored in the ground heat storage (GJ), period: 10 July to 22 December 2012 with marked flow rates and temperatures [10, 13]

Figure 16 shows the flow rate during charging of the ground heat storage and at the same time the temperature difference at the inlet to the GHS and the outlet (in the return pipe). The boundary between periods "A" and "B", i.e. the time when the energy roof ceased to be used, is separated by an orange line. At the time of operation of the fireplace insert, the heat was primarily supplied to the combined water storage tank, and after it was heated, the heat was further used to supply the ground heat storage. The fireplace insert was used irregularly by the inhabitants. After 22 December 2012, in the heating season 2012/2013, the fireplace insert was no longer used to supply heat to the ground heat storage.

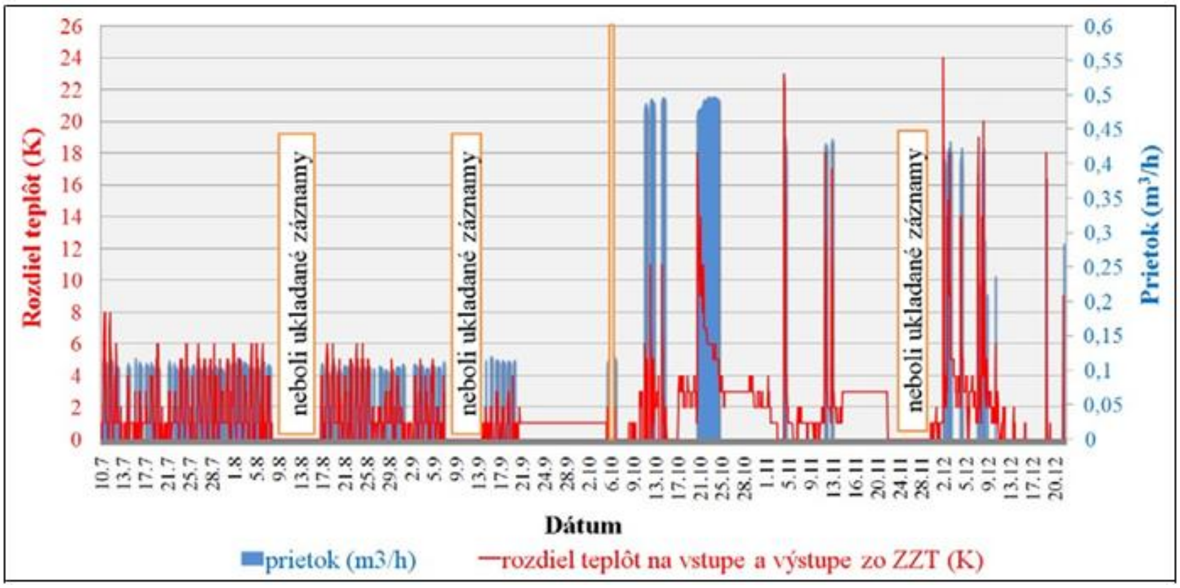


Figure 16: Flow rate during DHW charging (m3/h) and temperature difference at the inlet to the DHW and outlet (in the return pipe): 10 July to 22 December 2012 [10, 13]

During the period "A" (10 July to 6 October 2012) heat was stored in the GHS: 279.16 kW, of which a substantial part = 253.34 kWh was supplied from the energy roof. The hot water fireplace insert supplied heat to the GHS on 19 and 20 September and October 5 and 6. Total heat supplied to the GHS from the fireplace insert from this period = 25.82 kWh.

During the period "B" (7 October to 22 December 2012), a total of 938.59 kWh was stored in GHS. This heat was supplied only from the hot water fireplace insert. Heat from the period before July 10 2012 is obtained during testing of heat meters, pressure test of the system, and initial inspection of the system = 29.72 kWh. The heat obtained from the energy roof for the entire charging period is 253.34 kWh, the heat obtained from the hot water fireplace insert is 964.41 kWh.

4.2.2 Experimental measurements of discharging the ground heat storage

The main idea in the design of projects with ground heat storage is the long-term accumulation of low-potential heat and its subsequent use in a low-temperature heating system, or active thermal protection. Figure 17 shows the heat taken from the ground heat storage in GJ from the period 29 November 2012 to 25 February 2013 with the marked average flow rates and average temperatures of the working medium at the outlet from the ground heat storage and in the return pipe. After February 25, 2013, no heat was removed. A total of 0.020 GJ = 5.56 kWh of heat was taken from the GHS for the ATO. The average flow rate was 0.021 m^3/h = 0.33 l/min. The average temperature at the outlet from the GHS was 20.2°C, the average temperature in the return pipe to the GHS was 18.4°C. In the chart it is possible to distinguish two main periods when heat from GHS was used. The first period is marked in green in the chart. This heat was removed during the charging cycle of the GHS.

Precisely half of the total heat taken, i.e. 0.010 GJ = 2.78 kWh, was taken from 7 February to 25 February 2013. This period is marked in burgundy in the chart. During this period, the input temperature to the ATP was set to 20°C, so the conditions for its supply from the ground heat storage were suitable. In this period from 7 February until 25 February 2013, the average flow rate was 0.021 m^3/h = 0.33 l/min, the average temperature at the outlet from the GHS was 19.2°C and the average temperature in the return pipe to the GHS was 17.6°C. Even after 25 February 2013, the ATO was supplied with inlet temperature of 20°C, but there was no longer enough heat in the GHS to supply it. As only 5.56 kWh of heat was taken in total, of which only 2.78 kWh after the end of the charging cycle, temperatures and flow rates will no longer be displayed graphically.

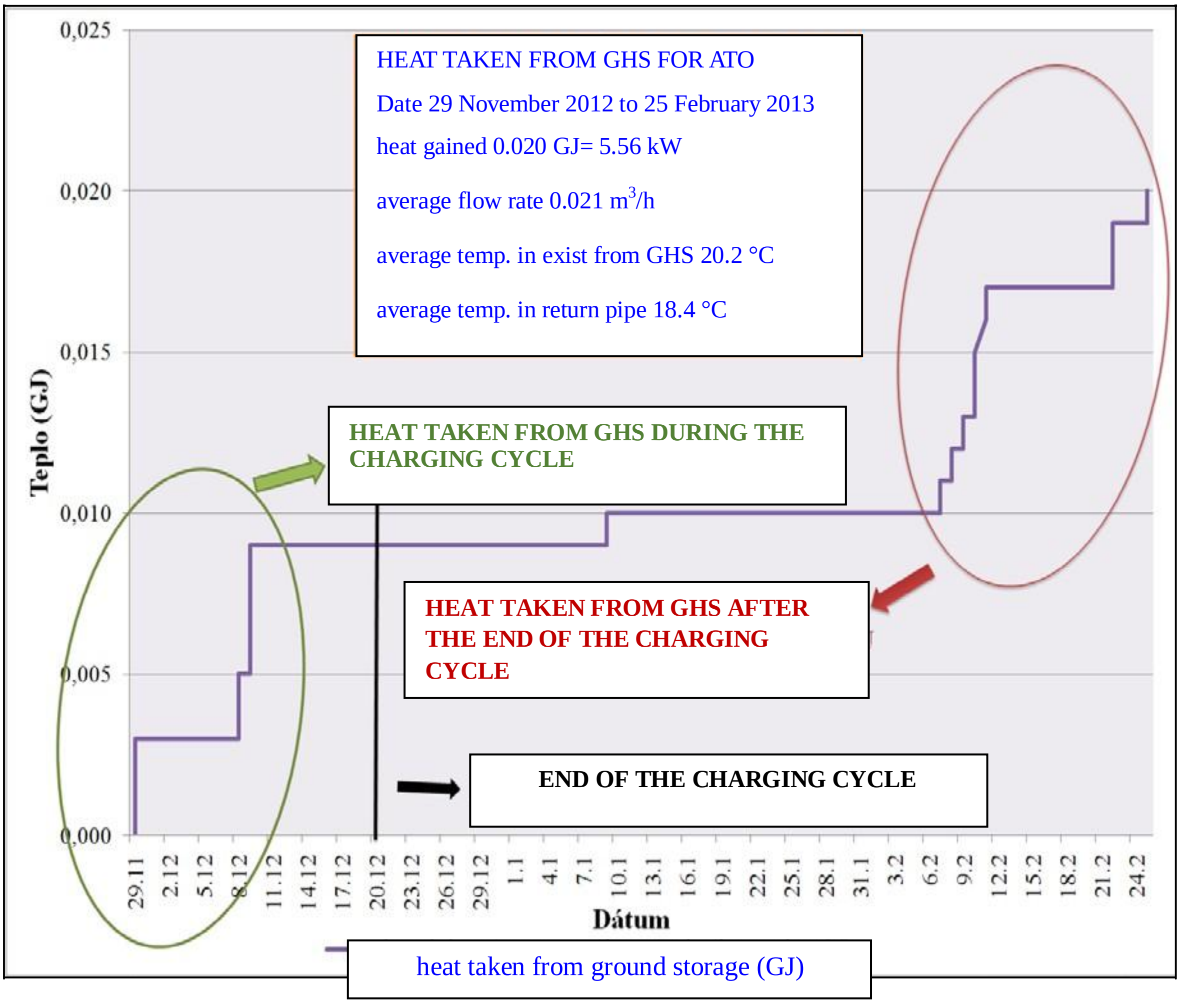


Figure 17: Heat taken from the ground heat storage (GJ), period: 7 February to 25 February 2013 with marked flow rates and temperatures [10, 13]

4.3 Experimental measurements of active thermal protection (ATP)

The aim of the measurements was a comprehensive evaluation of the system, focusing on the energy and economic aspects, evaluation of the environmental impact and measurement of the internal environment of the building. In order to be able to draw relevant conclusions of the system, it was necessary to compare the system with another operation. The system was therefore tested in various operations - with the use of active thermal protection ATP and without the use of ATP. Different inlet temperatures of the working medium into ATP (wall barrier) and to the underfloor heating were set in order to find the optimal use of the energy system. Comparing different operations of the energy system in one building is more efficient than measuring different operations in several buildings. In one building there are the same structural and technical boundary conditions, the same number and behavior of inhabitants.

The first objective of long-term measurements was to determine whether it is meaningful to operate the energy system with active thermal protection as a thermal barrier and wall heating (referred to as a "wall barrier" in energy system diagrams). As already mentioned, the active thermal protection ATP consists of 20 circuits, which are connected via two circulating pumps.

In the circuit diagram in Figure 9, the branches are designated as "wall barrier 1" and "wall barrier 2".

Two measuring periods were analyzed in more detail, where each period lasted 360 hours (full 15 days) and the building was fully inhabited:

"A" - simultaneous operation of underfloor heating and ATO,

- feed temperature of the working medium entering the PDL: 26°C,
- feed temperature of the working medium entering the ATO: 20°C.

"B" - underfloor heating operation without ATO,

- feed temperature of the working medium entering the PDL: 30°C.

4.3.1 Measuring period "A" - simultaneous operation of underfloor (UFH) heating and ATP

In the measuring period "A" (10 January 2012, 10:00 to 25 January 2012, 9:00), large-area radiant underfloor heating and active thermal protection were in operation at the same time. During underfloor heating, the inlet temperature of the working medium was set at 26°C (return temperature was approximately 25 °C). The inlet temperature of the working medium entering the ATP was set at 20°C (the return temperature was approximately 17 °C). It is important to note that the given temperatures were not set at the beginning of the evaluation period. The system worked stable with the given temperatures for several days before the beginning of the evaluated period. Figure 18 shows the output (kW) of ATP and underfloor heating. The average output of the ATP - the sum of "wall barrier 1" and "wall barrier 2" was 1.526 kW, the average output of the UFH was 1.262 kW. The heat supplied to the ATP in the given period was 1.970 GJ (547.21 kWh), the heat supplied to the UFH: 1.607 GJ (446.38 kWh). It is clear that both the ATP output and the delivered output are significantly higher compared to the PDL, despite the lower inlet temperature of the working medium.

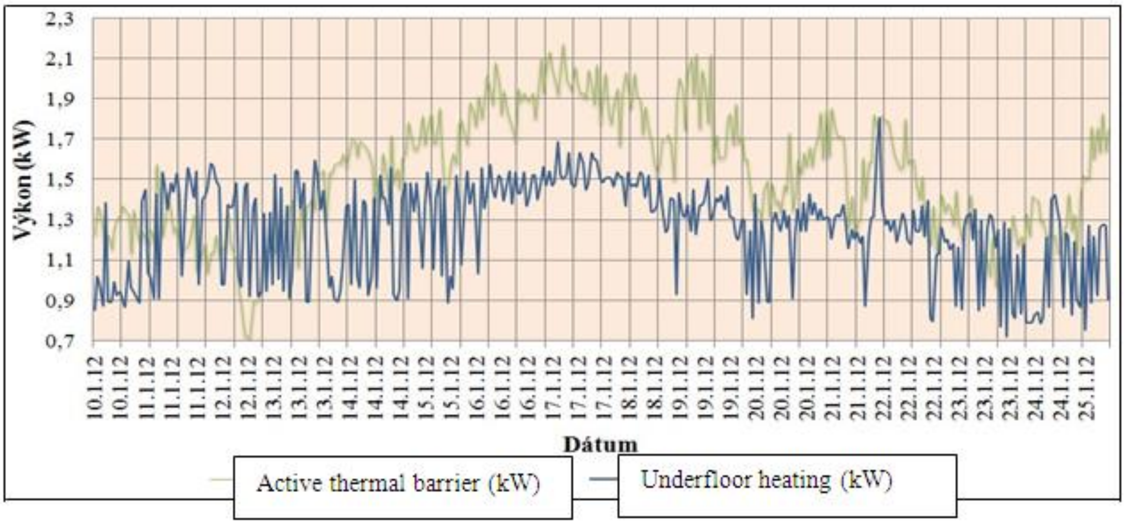


Figure 18: Output curve (kW) of ATP and underfloor heating (10 January 2012 – 25 January 2012) [10, 13]

4.3.2 Measuring period "B" - underfloor heating (UFH) operation without ATP

In the measuring period "B" (8 January 2013, 19:00 to 23 January 2013, 18:00) only large-area radiant underfloor heating was in operation. The inlet temperature of the working medium was set at 30 °C (return temperature was about 28 °C). Figure 19 shows the power output (kW) of the underfloor heating. The average output of underfloor heating was 2.776 kW. Heat supplied to the underfloor heating in the given period: 3.550 GJ (986.08 kWh).

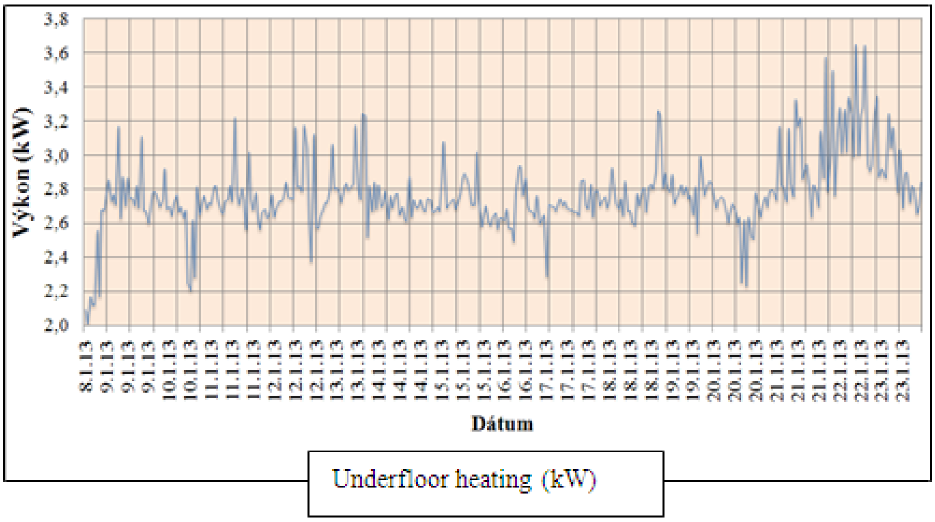


Figure 19: Output curve (kW) of underfloor heating (8 January 2013 – 23 January 2013) [10, 13]

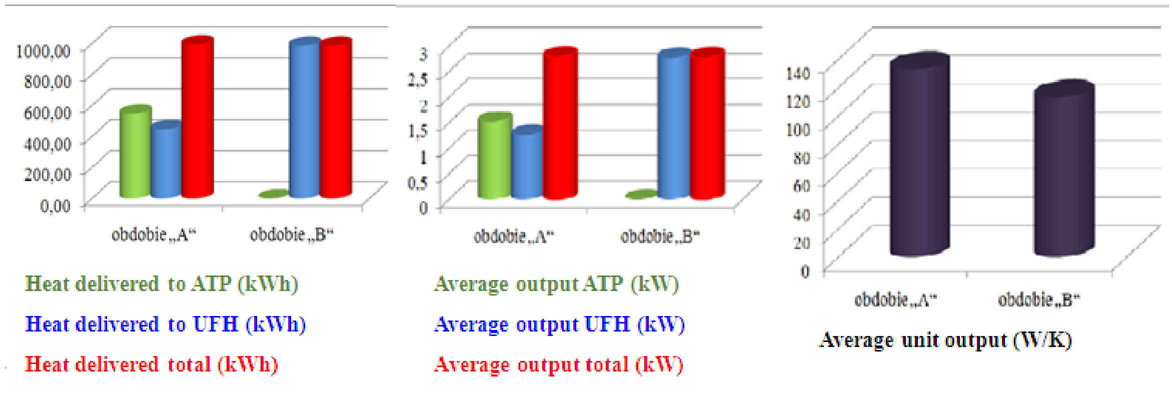
4.3.3 Evaluation of measuring periods "A" and "B"

Two periods were selected with the same boundary conditions. The same building is assessed, with the same heat source, in both cases without the operation of the fireplace, with the same number of inhabitants, with full occupancy. In addition, the choice of period is not random. The total heat supplied and the average output is approximately the same in the measuring period "A" and "B". The difference is in indoor and outdoor air temperatures. In period "B" the temperature difference was larger, therefore the average specific output was calculated per 1 K (divided by the total output and the average temperature difference between interior and exterior). This allows for better comparisons of measurement periods. The average specific output is 17% higher in the simultaneous operation of ATP and underfloor heating (period "A") at given temperature gradients compared to operation without ATP (period "B"), due to greater heat losses from the ATP to the exterior. Tabular and graphical comparison of measuring periods is shown in Table 1 and Figure 20.

TAB.1 Comparison of measuring periods "A" and "B"

	Delivered heat (kWh)	Average outout (kW)	Average temerature (°C)	Temperature difference (K)	Average unit output (W/K)					
	ATP	UFH	Together	ATP	UFH	Total	Int	Ext		
„A“	547.21	446.38	993.58	1.526	1.262	2.788	23.2	2.2	21.0	133
„B“	-	986.08	986.08	-	2.776	2.776	22.5	-2.0	24.5	113

The average specific output and the specific heat supplied to the system are thus higher during the simultaneous operation of ATP and UFH (underfloor heating) with a permanent heat supply. A certain advantage seems to be the fact that the system was supplied with a lower temperature, due to the use of the entire building envelope (heat supplied to the floor, walls and ceiling on the 2nd floor). This allows better use of the low-potential heat source. Another advantage for the inhabitants of the building is the elimination of cold walls. It is also important to note the fact that ground heat storage is situated under the house, which reduces the total heat loss of the building. As already mentioned, the system was permanently supplied with heat and the storage capacity of the walls with ATP and the total operating time were not taken into account. From the point of view of regulation, it is necessary to focus on setting the switching off of the heat source (or circulating pumps, if the system is supplied from the ground heat storage) and let the accumulated building structures act. The heat supplied to the ATP will be smaller, due to the shorter operating time. With a permanent heat supply, the total energy supplied also increases - electricity must be included for the operation of the circulation pumps. Two Grundfos Alpha2 15-60 130 pumps with stepless speed control are installed for the ATP1 and ATP2 circuits. When considering a power input of 25 W, the electricity consumption with a permanent heat supply of 15 days is 21600 Wh = 21.60 kWh = 0.0778 GJ.



a) **b)** **c)**

Figure 20: Comparison of measuring periods "A" and "B" [10, 13]
a) heat supplied to the ATO (green), PDL (blue) and together (red) (kWh),
b) average heating output of the ATO (green), PDL (blue) and together (red) (kW),
c) Average specific heating output in measuring periods "A" and "B"

V. SUMMARY OF EXPERIMENTAL MEASUREMENT RESULTS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Combined building-energy systems with applied active thermal protection with the use of solar energy with long-term heat accumulation can be more efficient than conventional construction with conventional heating systems only with the correct design and proper operation. Theoretical calculations, experimental measurements and analysis have identified important facts that need to be taken into account in the calculation, design, assessment, and planning of buildings with combined building and energy systems, and they also show the need for further research in this area, as these technical solutions have a high the potential to make significant use of RES and, in accordance with Directive 2018/844/EU, to meet the requirements for *nearly Zero Energy Building (nZEB).*

Several system optimizations and recommendations for further research can be suggested:

- The application of an energy roof requires lower investment costs than conventional solar collectors, but experimental measurements have shown that the energy gain and the achieved temperatures of the working medium at the outlet are significantly lower. For higher efficiency, it is worth considering installing dark roofing and installing more circuits with a suitable division according to cardinal directions. This may be the subject of further research.
- For theoretical calculations of an energy roof it is necessary to know the solar radiation in hourly averages for a specific inclination - it is appropriate to install a solar radiation meter on the roof and connect to a measuring and recording control panel, or to install a flat solar collector with a given roof slope for direct comparison of heat and outlet temperatures.
- For a more detailed evaluation of the energy roof, it is advisable to install a compact heat meter on the primary side as well - in front of the plate heat exchanger (already performed).
- The use of an energy roof for low-temperature heating or the supply of active thermal protection can only be realized with a suitable heat storage solution. When preparing hot water, the energy roof can only be used for preheating. It is appropriate to consider its use in the operation of heat pumps, where in the summer it could serve as a heat exchanger in the preparation of hot water or in pool management.
- Whenever it is possible to supply the active thermal protection ATP directly from the energy roof without heat accumulation, consider using the energy roof to preheat hot water.
- In summer, the active thermal protection ATP was used as a wall cooling from July to September, with the inlet temperature to the ATP set at 20°C and the return temperature ranging from 20°C to 23.5°C. The supply was carried out from cooling circuits, which are located in the ground around the foundations of the building - a passive cooling system. The soil temperature has warmed up here and another low-temperature storage has been created - it is appropriate to consider its use for the supply of ATP in the transition and winter period. The cooling circuits are directly connected to the ATP.
- With large-area wall cooling, a separate cooling source is not required with the correct design. The thermal conductivity of the material in front of the ATP pipes and the material in which the ATP tubes are located is essential.
- The use of ATP as a wall heating and cooling function is of practical importance only for building structures which have a high storage capacity on the interior side in front of the ATP pipes, i.e. a suitable bulk density, thermal conductivity, and thermal capacity. Given the construction in the family house where the experimental measurements took place, the heating with ATP is considerably limited and economically inefficient. By wall cooling, it is practically possible to cover only the heat load through non-transparent constructions. For the use of ATP in the function of wall heating and cooling, it is recommended to design structures with suitable accumulation, e.g. reinforced concrete with a suitable thickness of thermal insulation from the exterior.
- Building structures that have a high thermal resistance in front of the ATP pipes are not suitable for the wall heating and wall cooling function. The system with ATP offered on the market, where the pipes are installed in a reinforced concrete structure, which is provided with thermal insulation on the interior and exterior side (ISOMAX system - self-supporting panels), cannot ensure year-round thermal comfort at normal temperature gradients of low-temperature heating and high-temperature cooling. At higher temperature gradients in the heating function, operation is inefficient from energy and economic viewpoints. With such constructions, it is necessary to design a heating system.
- Accumulation of heat in a common foundation slab is disadvantageous - it is advisable to consider the accumulation of heat in deep wells, or to apply large-capacity water tanks.
- In experimental measurements in the EB2020 experimental house in the heating period, the air temperature on the 2nd floor was often lower by more than 1 K compared to the air temperature on the ground floor. Underfloor heating on the ground floor and 1st floor are connected via one circulation pump. It is advisable to design two separate branches for each floor, just because there is ground heat storage under the ground floor.

- It is necessary to perform further measurements of heating operations with setting the attenuation of the indoor air temperature. It is advisable to perform measurements of operation only with underfloor heating, then only with active thermal protection and then in combined use with different temperatures. During experimental measurements in less than two heating seasons, it was not physically possible to perform further measurements, while the comfort of the inhabitants had to be taken into account.

VI. CONCLUSION

A combined building and energy system consisting of the use of solar energy by the energy roof, long-term heat accumulation in the ground storage, and active thermal protection was comprehensively evaluated on the basis of calculations and experimental measurements. This is probably the first object in Slovakia with such a system, where long-term measurements took place. To date, no independent (non-commercial) research is known from domestic or foreign sources with published output, based on long-term measurements of all components of this system from heat recovery, through accumulation to ATP supply. Outputs for the further development of the scientific field and for technical and social practice were defined.

Experimental measurements - energy roof measurements found real temperatures at the outlet of the energy roof and the heat that can be obtained. In the case of ground storage, the measured heat was stored and removed from the heat storage and the efficiency was evaluated. At the ATP, the parameters of operations at different temperatures in the ATP pipes were measured. Experimental measurements can serve as a basis for similar measurements, e.g. energy roofs with another upper part of the structure, ground heat accumulators under the foundation slab of the building, or ATP applications in other building structures, and also as support documentation for designers.

In the field of combined construction and energy systems, research and optimization of suitable solutions continues, which have been transformed into one European patent and three utility models [3, 4, 5, 6].

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