Energy-active roof system – design, development and testing

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Abstract. The aim of the research is a development of a new energy effective roof system, fulfilling a function of a roof covering as well as solar active element, reducing energy performance of buildings. There were designed and tested energy active roof elements, consisted of glass-fibre-reinforced-concrete carrier with integrated photovoltaic and heat-exchange layer, which ensures cooling of photovoltaic elements as well as enables a transfer of excessive thermal energy into a storage tank for a later use. The effort of project solvers is to achieve entirely new economic efficient using solar energy by means of energy active roof covering. Current research and tests proved, that there is a possibility to create such a system using present materials and technological solutions. However, for the successful realization it is necessary to solve further technological aspects, namely mutual connection of the roof elements and prove load-bearing capacity and fire resistance of the designed system.

1. Introduction

Presented article briefly describes some of the phases of a research project focused on development and testing of a complete roof system that would serve as both cladding system and solar energy accumulator. The most appropriate materials for such purposes seem to be mutually connected thin-walled glass-fibre concrete (GFC) parts with integrated photovoltaic (PV) and heat-transfer (HT) layer. Such roof design would lower the energy demands of the building and fully substitute a standard roof system at the same time. Additionally, the excessive heat generated by PV cells would be transferred by liquid in a TC layer directly into a heat exchanger for further use in the building. Such cooling system would lead to higher energy yields of the PV cells and simultaneously prevent overheating inside the building. Mutual connection of the PV and HE systems must be solved so that an integrated roof cladding system is created. [1]

Thin-walled composites made from fine-grain cement-sand matrix reinforced by alkali-resistant glass fibres are currently used in numerous applications in building industry, mainly as architectural elements and facade panels. Their advantages are low weight and sufficient durability against mechanical stress and weather. These prerequisites led to the idea of this innovative design of roof tiles that produce both electricity and thermal energy. Solar energy will be transformed into electric and thermal energy thanks to an integrated system of photovoltaic cells and working fluid tubing on a glass-fibre carrier. The heat acquired will be stored via heat exchanger in a hot water storage tank. In comparison with typical photovoltaic panels, the roof cladding, the solar panels and the heat collectors are integrated in one complex functional unit.
A typical solar collector is composed of a tubular system that absorbs solar rays and transform them into thermal energy. The heat is prevented from discharging into the air and is transported by working fluid into the heat exchanger which serves also as a storage tank. Nowadays, commercially available solar collectors are products of an advanced development, however, high initial costs and susceptibility to damage during transport and assembly are still their major disadvantages. [1]

The subject of this project is design and development of solar-active roof tiles whose production and assembly would be cheaper while maintaining the same efficiency and life span as the standard solar panels. Rich experience of both participants were used for the development of the mixing GFRC formulas. DAKO Brno company deals with the production and installation of ventilated facades of fiberglass concrete and we also used the experience mainly from research projects dealing with the development of high-strength fiber-reinforced concrete [2, 3].

Suggested solution using glass-fibre carrier for installation of working fluid tubes and photovoltaic cells is an innovative approach that also fulfils a construction function as the resultant roof tiles can fully replace a typical roof cladding. [1]

2. Technical and material solution of the roof system
The aim of the project is to design and validate the whole new roof cladding system for sloped roofs of residential and industrial buildings, consisting of glass-fibre reinforced concrete roof tiles with integrated photovoltaic and heat-transfer layers.

2.1. Material composition
There were set mixing formulas for production of glass-fibre-reinforced-concrete (GFRC) carriers and subsequently tested their physico-mechanical parameters. At the same time, the most suitable types of photovoltaic panels were selected on the base of testing their energy efficiency and material characteristics.

The glass-fibre reinforced concrete (GFRC) element is made of fine-grain cement-sand matrix supplied with chemical admixtures, especially additives modifying texture or hydrofobization agents. The basic matrix is reinforced with spread glass-fibres and sprayed into moulds, sometimes spraying is combined with pouring (premix). The filler:binder:reinforcement ratio is determined by the physico-mechanical properties required, mainly flexural and impact strength values. The usual dose of binder is 7–65% (typically 50%), dose of filler is 10–70% (typically 50%) and dose of fibre 0.5–10% (typically 5%). The composition of the mixture guarantees stability of physico-mechanical properties for 30 years in common climate/weather conditions. Figure 1 shows an implementation example of a developed roof system.

![Figure 1. Energy-active roof panels – implementation example.](image_url)
2.2. Shape and system solution

The technical details of the manufacture procedure of the proposed GFC panels with integrated PV and HT layer were solved in this phase of research. The HT layer has been designed to ensure efficient transfer of thermal energy from the PV module to a carrier liquid medium with sufficiently low hydraulic resistance, so that individual GFC elements can be serially chained according to the required parameters.

Therefore, it was necessary to design and verify the main key details of the HT layer in order to ensure the optimal transfer of thermal energy. After evaluating the results, a type of structural element in the form of a scalloped flexible steel tube with a diameter of 11.7 mm and a wall thickness of 0.26 mm was selected, with respect to the properties and thermal conductivity of the GFC panel in which the HT layer is intercalated.

![Figure 2. Possible layout of developed HT layer.](image)

In relation to optimal HT layer efficiency, the placement of the HT layer structural elements was designed and verified by measuring of the resulting roof system elements. The measurement was also supplemented with results from the software module calculation performed on the VUT FEKT in Brno. The results of the measurements showed the optimum distribution of the HT structural element pipes at a distance of 50–75 mm from each other. One example of possible layout of developed HT layer is shown in figure 2.

During designing of production technology of GFC elements, limiting values of production and assembly technology were taken into account. An important factor influencing the final measures of the element (together with photovoltaic (PV) and heat-transfer (HT) layers, is its weight. Given that the complete roof system must be composed of several different sizes of elements, smaller elements are designed individually. Elements intended to complete the functional composition are atypical, with neither the PV nor the HT layer.

Overall, two variants of the constructional-technical solution of the system, which differ in the manner of anchoring, were verified. The first variant, which is expected to be for new buildings, is anchored as a larger roof element by means of anchors attached through the roof batten to the rafters. The second variant, designed mainly for reconstructions, is anchored similarly, but only on additionally installed vertical roof battens.
Both variants of the constructional-technical solution of the system also differ in their technical parameters, i.e., different volt-amp characteristics and different heat recovery properties from the HT layer. However, the performance per 1 m² is similar for both variants.

2.3. Solution of electrical interconnection of individual PV roof elements

In our measuring kits, we used only 1 + 1 PV modules to compare current data. The panels tested had a $U_{oc}$ voltage of $12 < U_{oc} < 20$ V. This voltage is low for further commercial use, it will be necessary to connect these modules into strings series in a real installation, to get higher voltage as well as higher power of the whole assembly for further processing. In terms of electrical connection of the final modules, we will be limited only by the maximum voltage given by the manufacturer of the PV layer (1000 V) and by the voltage required for the operation of the next link in the energy processing chain - inverters. However, it is necessary to assess the individual strings with a heat transfer layer in terms of the limitations associated with the maximum liquid flow rate through the heat transfer layer of the individual PV modules.

For further utilization of produced DC energy, it is possible to consider:
- off grid systems
- modern hybrid systems with HV accumulator
- hybrid systems with low voltage accumulators
- on-grid connection
- on-grid connection in combination with optimizers and inverter

On-grid connection with optimizers and inverter is best suited for our purpose, see Figure 3. With this type of connection we can combine not only modules with different performance, but also modules with and without heat exchange layer and without loss of performance. Optimizer manufacturer software will allow the designer to lay out roof panels for a specific application. The designer will be able to select the inverter and the optimizer and connect them. In the next step, the software will calculate the parameters of installation and future production. This eliminates the possibility of errors or poor design choices. After successful completion of the design, the project can be turned into monitoring and the whole system can be monitored via the corporate cloud. The entire system can therefore be perfectly supervised and evaluated.

![Figure 3. On-grid connection in combination with optimizers and inverter.](image-url)
It is possible to use another system, but it is always necessary to carefully check the individual parameters during the design, especially the minimum DC voltage of the inverter.

3. Experimental works

3.1. Measurement of GFC panels with integrated PV and HT layers
The aim of the measurement was to verify the heat transfer efficiency from the integrated PV layer to the HT layer in the GFC panel. The measurement was carried out at 3 measuring stations with regard to the environment, exposure and diversity of used roof elements. Two sites were selected in the urban agglomeration (approx. 200 above sea level) and one measurement in an environment with a higher altitude of approx. 500 above sea level.

The measurements showed slightly different values, which were caused by different meteorological conditions. For the evaluation we considered only the period from April to the end of September. The same pair of roof elements connected individually was used for the measurements, with the one test specimen without active TS layer and one test specimen with integrated active TS layer. The whole measuring system can be safely used in the seasons just from April to September. After this period, the heat obtained has a lower nominal temperature and is therefore unsuitable for direct storage. There is also a risk of frost damage to the measuring system. It can be stated that the roof elements continue to generate a temperature difference of 1.5 to 2.5°C during sunny days. This predetermines the system utilization, for example, as the primary heat source for the heat pump, in the case the antifreeze heat transfer medium will be used.

The measurements showed that the roof elements with active heat transfer layer had about 8% higher performance due to heat removal. Moreover, the thermal energy generated was directly proportional to the electrical energy obtained. The daily yield was in the range 1,100 to 2,000 J.

3.2. Methodological procedure for energy efficiency measuring
The energy efficiency of the developed roof elements was measured in terms of proportion. Two nearly identical PV modules, in terms of dimensions and performance, were compared. This was achieved by laboratory measuring of the I/V characteristics of PV modules on the PASAN Sun Sim3C tester. The selected PV modules were applied to the manufactured GFC panels with and without integrated HT layer and also another measurement was made to see whether the PV layer was damaged during application.

As shown in the graphs in figures 4 and 5, we were able to select pairs with very similar I/V characteristics and with a power difference $P_{mpp}$<0.5W at its operating point.
Figure 4. I/V characteristic of PV module without active HT layer.

Figure 5. I/V characteristic of PV module with active HT layer.

The basic measurement took place over time and the electrical power of the PV panel and the heat extracted from the HT layer were monitored in dependence on the incident sun radiation. The realized measurements showed that the change in power depending on the incident radiation was
rapid, whereas the value of the removed heat changed slowly due to the accumulation ability of the GFC elements.

![Image of GFC elements with and without active TS layer](image1)

**Figure 6.** Temperatures of GFC elements without active TS layer (left) and with active TS layer (right).

![Image of GFC elements with and without active TS layer](image2)

**Figure 7.** Temperatures of GFC elements without active TS layer (left) and with active TS layer (right).

Figures 6 and 7 show the UV diagnostics of developed roof elements. The pictures on the left shows roof elements with the deactivated HT layer and both modules were without the active PV layer. The pictures on the right show panels with a clearly visible active heat exchange layer, which has a significantly lower temperature due to flowing liquid (bright spiral on purple background).

An important aspect of quality control of active roof modules is the functionality of the PV layer. It is necessary to check whether there was any damage during production or installation, or in time due to external climatic influences. Such damage can be detected by a diagnostic electroluminescence method.
Figure 8 shows the possible damage to PV modules displayed by the electroluminescence method. Such damage can occur during winter season when water is used as the heat transfer medium in the HT layer. Cracks are visible in the figure and the pipeline that deformed the PV layer due to frost is clearly visible. Despite this considerable damage, the PV layer generated power only about 25% lower than before damage.

The actual methodology of energy efficiency evaluation is based on the conclusion of the applied comparative measurement method, where we used the possibility of measuring the parameters of PV modules and their energy outputs without the need to use information about spectrum and intensity of illumination. The principle of the method is to compare the achieved electrical powers of the measured PV layers of GFC panels with the active and inactive HT layers.

### 3.3. Calculation of obtained heat from active HT layer

In the actual measurement, periodically obtained heat from the active heat exchange layer was monitored in relation to the flow rate of the heat transfer medium through the heat exchange layer. The difference between input and output temperatures was also monitored. These data were entered into the calorimetric equation and the obtained heat was then calculated.

The calculation of the obtained heat from the activated heat exchange layer of the GFC panel with the PV layer is based on the Calorimetric equation $Q = m \times c \times (\vartheta_2 - \vartheta_1)$, where:

- $Q =$ obtained heat [J],
- $m =$ weight [kg × m$^{-3}$],
- $c =$ specific heat of water [J × K$^{-1}$ × kg$^{-1}$ ],
- $\vartheta_2 =$ liquid output temperature [°C],
- $\vartheta_1 =$ liquid input temperature [°C].

Then, from the above relationship, we apply the measured units to the simplified relationship. The input temperature of the GFC panel $\vartheta_1$ [°C], the output temperature of the GFC panel $\vartheta_2$ [°C], the average flow rate $V$ [liters × sec$^{-1}$] and the specific gravity of water $m = 991$ [kg × m$^{-3}$] are measured. The heat obtained is calculated as follows:

$$Q = V \times (991 \times 10^{-3}) \times 4.185 \times (\vartheta_2 - \vartheta_1) \Rightarrow$$
$$Q = V \times 4,147.3 \times (\vartheta_2 - \vartheta_1) \text{ [J]}$$
3.4. Static assessment of the system, measurement of wind resistance

The described stage summarizes the most important findings, results of measurement and evaluation of resistance tests, ie. the load-bearing capacity and serviceability of the developed roof elements under wind loads. The assessment of PV roof elements in terms of resistance to wind was carried out in cooperation with VUT FAST university.

The subject of the load tests were concrete roof panels with a photovoltaic layer with dimensions $a \times b = 1,050 \times 845$ mm and the thickness of the load-bearing, ie concrete part of the panel structure (without photovoltaic layer) $d = 20$ mm. The aim of the load tests was to verify the load-bearing capacity of the panels in order to determine the recommendations for the ultimate load from the effects of suction or wind pressure based on the test results.

In case of loading of the roof element by wind suction, the safe recommended design value of the surface uniform load was equal to $p_d = 3.75$ kN/m$^2$, based on the performed tests. In the case of a roof element loaded with effects simulating wind pressure, the safe recommended design value of the surface uniform load was equal to $p_d = 3.80$ kN/m$^2$. Performing of the test is shown in figure 9.

![Figure 9. Wind load test of developed roof element.](image)

A complete static calculation was also performed during this stage. The assessment was performed according to ČSN EN 1991-1-3, for the roofs of buildings for the Czech Republic snow areas, class I to VII. The results showed that the construction of the developed roof element is suitable for I. and II. limit state in terms of static assessment.

4. Conclusions

The effort of project solvers is to achieve entirely new economic efficient using solar energy by means of energy active roof covering. Current research and tests proved, that there is a possibility to create such a system using present materials and technological solutions.

Numerous laboratory testing tasks were accomplished at the beginning of the project to design and verify suitability of chosen materials for active roof cladding system production. During the process, the technological solution of individual tile structure was developed, including profiled GFC element with integrated HT layer bearing a system of PV cells, joint together by carefully chosen silicon putty, which effectively joints and seals the whole structure. All the components needed for manufacturing
the roof tiles were purchased. In laboratory conditions, different GFC recipes were tested to find the most suitable composition.

Research works in 2017, which are not mentioned in this paper, included testing of the individual parts of the roof system, their connection and composition, mostly from a long-term point of view. Testing criteria were technological, physical-mechanical, hydrophobic and visual. Strength characteristics of the profiled GFC elements, adhesion of the PV layer to the GFC element, water-resistance and climate influence (temperature fluctuation, UV radiation, etc.) of the whole roof cladding system were tested. Electric parameters and temperature coefficient were measured.

In following years 2018–2019, technical realization of the whole system was made, where we mainly focused on achieving the highest functionality – durability, effectivity and energetic efficiency. Static and fire-resistance evaluation of the system was also conducted. Interconnection of individual tiles was designed and electric and heat-transfer efficiency was studied and calculated. Some examples are shown in the text above.

The authors’ efforts aim was to develop a completely new system of economically effective use of solar energy. Electric energy acquired will be used immediately, while acquired thermal energy can be stored for future use. The developed system can be installed on both civil and commercial buildings. The results achieved during this project will be protected by copyright and commercialized both in domestic market and abroad until 2022.

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