Architecturally Integrated Multifunctional Solar-Thermal Façades

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Abstract This paper discusses relevant issue related to the architectural integration of active solar technologies (e.g. solar collectors) in the facades. In respect with the criteria which defines an optimal integration of solar technologies at the buildings level, the paper proposes a multifunctional solar facade concept that has the flexibility to be implemented in very different situations that can be met within the built environment. The results embed concepts of interest for architects, engineers and designers working on the implementation and integration of solar energy conversion systems in the built environment, towards sustainable communities.

Keywords Solar-thermal façades · Solar-thermal collector shape · Solar-thermal collector colour · Solar-thermal arrays

1 Introduction

A broad variety of solar technologies are still struggling to play the key role they deserve in the fossil fuel based energy reduction. One option recently more and more outlined is represented by the renewables' integration in the built environment, particularly of the solar energy conversion systems. Even though competitive technologies and innovative cost effective solutions raised on the market, this is not sufficient for increasing the spread of built integrated systems worldwide [1]. The most cited references in literature and the most recent developments are showing that multifunctionality is required for the building integrated solar facades, focusing on shape and aesthetics, on energy conversion efficiency and operation, correlated with multiple functionality as shadowing and insulation [2], and on modularity in obtaining innovative configurations; one emergent trend is related to the

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possibility/feasibility of sun tracking or reversed tracking (to avoid overheating or efficiency losses) [3, 4].

Both photovoltaics and solar-thermal flat plate collectors started to adapt to the aesthetics criteria required to increase the acceptance of solar building facades by developing coloured surfaces (reported at laboratory/pilot scale), but the flat rectangular traditional geometry of the solar energy convertors has to be carefully treated when it comes to the development of more appealing solar energy conversion systems [5]. This is particularly important, because the chromatic aspects are of average interest in terms of architectural quality as, the solar energy convertors are still considered as a technical component of the system [6–8]. Thus shape and colour could increase the acceptance of the solar facades.

The combined approach of novel shapes and novel colours is—to the best of our knowledge, not reported for flat plate solar-thermal collectors. Therefore, this paper fills the gap and describes the work developed for formulating a novel concept legotype that integrates new shapes and various colors of flat plate solar thermal collectors, aiming at increasing the social/architectural acceptance of renewables in the built environment towards Nearly Zero Energy Buildings. Further on, the energy efficiency can be controlled, by limited tracking; various tilt/tracking angles could be used for inverse tracking (decreasing the amount of solar radiation on the solar thermal flat plate collectors, thus avoiding overheating) [3]. The study is developed and the results are under implementation on an existing infrastructure that allows comparative monitoring and testing of the novel collectors and of the commercial ones.

2 Problem Formulation

As solar energy is available in its active or passive forms, the problem of integration is expected to provide a response to the energy needs of the building, in terms of thermal energy for domestic hot water (DHW) space heating and/or cooling, [9] and electric energy for lighting and powering the common appliances (Fig. 1).

Considering the architectural integration as a “form follows function” matter, the problem of solar technologies integration into the buildings it’s not to be approached only as a shape (aesthetic) issue but should simultaneously fulfil the functional demand. The building integration of current solar energy conversion systems is generally characterised by a low level of architectural quality. In the built environment, the photovoltaic technology usually has the advantage of the grid as a transport and “storage” system. This brings an added freedom related to mounting the conversion system at given distance from the consumer’s place. The concept developed for the next decade actually states that PV technologies should be concentrated in large facilities, in the outskirts of the communities or on degraded grounds. This is not possible/recommendable for solar-thermal systems, due to significant losses that may occur when the convertor is mounted far from the boiler/user [10]. Thus, large spread of solar-thermal collectors requires specific and novel

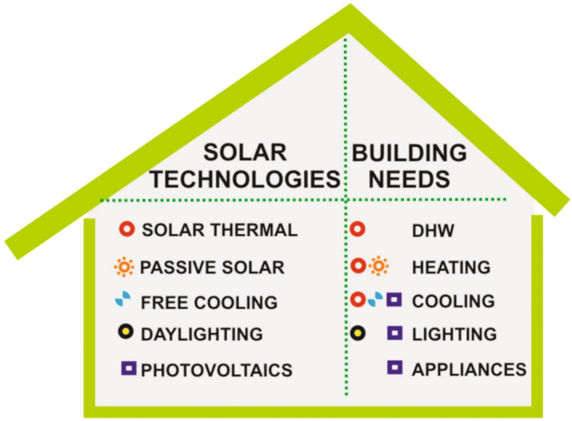

Fig. 1 Different energy needs covered by solar technologies

solutions for installing solar flat plate collectors on/near the building, for providing thermal energy, mainly for DHW and heating [11, 12]. Most often solar collectors are considered only as technical elements, being installed on the roof top, on flat or tilted surfaces. This type of installation, with low integration features, is less visible and makes the architectural impact minor. Unfortunately the solar thermal collectors are heavy structures that introduce a supplementary load on the roof structures. Even though the annual yield of the roof integrated systems is increased, the seasonal heat production and consumption variations may cause overheating and so the dimensioning of such systems becomes difficult and the durability can be affected.

Literature shows that for the mid-latitudes the installation of collectors on vertical surfaces is a viable option as it brings the advantages of an increased surface available for mounting and a better distribution of the heat production. The vertical implementation of solar collectors implies the integration in the facades which imposes a more elaborate approach when it comes to the design of the whole system as the facades represents the expression of the building [13]. The facades are mirror the functional structures of the interior and are influenced by proportion, size of openings (doors and windows), and material. The complexity of the facades design is imposed by the multitude of pre-requisites to be met: (1) functional (shading, insulation), aesthetic (proportion, rhythm of a structural matrix), constructive (respecting the principles of building construction), etc [14]. Thus, the quality of architectural integration of solar energy conversion systems has to be a controlled and coherent process, approaching simultaneously the functional, constructive, and aesthetic aspects (Fig. 2).

Integration of solar-thermal systems represents the insertion a technical element (solar collector) in a new or existing exterior wall system. Different buildings, with different facades will therefore have specific and personalized demand for integrating the solar-thermal systems in the architectural concepts.

Lately, three different concepts were formulated on how solar energy conversion systems should be integrated into the buildings:

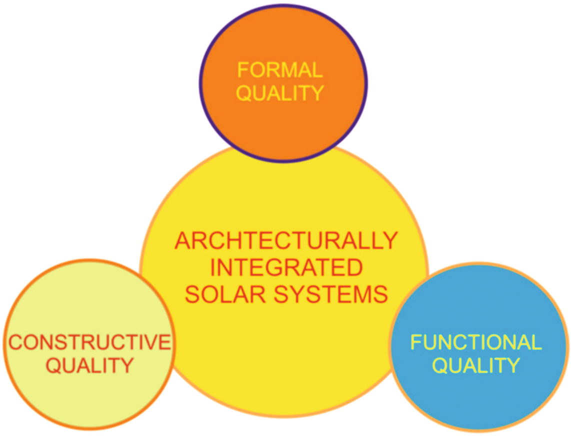

Fig. 2 Architectural integration quality

- *Hiding the components in the facade* [15];
- *Mounting the components on the facade, without drawing the attention*;
- *Outlining the solar components in the building design*.

Design aspects such as dimensions, proportions, the structure of the surface and colour have to be also considered in these strategies. Also the surfaces of roof and façade are essential as usually most of the roofing-materials and the materials used for facades show rough surfaces and warm colours while solar energy conversion systems are usually flat with shining faces made from metal and glass.

The energy demand in the building represents the key technical data that imposes the size of the systems that have to be installed. But, the optimal functional size has a significant impact on the building aspect and implicitly on the façade. This leads to a methodical approach focusing on the coherency of form, function and design. Previous studies highlight several guidelines [14, 16] that are to be considered for a qualitative architectural integrated solution:

- *Utilisation of the solar energy conversion system as a construction element* (facilitates the integration as the conversion system becomes a part of the building);
- *Optimal dimensioning and positioning of the conversion system* (in order to fulfil this goal, shape requirements, the conversion technology and energy production issues have to be simultaneously solved);
- *Balance of colors and textures;* for the selected solar technology this depends on the availability of a various range of colors and textures for the elements installed on visible surfaces; by considering the building as a whole entity, the “visible” elements (e.g. the solar-thermal collectors) need to comply with the aesthetic context of the building;
- *Sizing and shaping* considering the composition grid and stereotomy of the building.

The criteria imposed for a qualitative architectural integration are difficult to fulfil when using commercial collectors, therefore there is a need for novel, more "building oriented" solutions for solar thermal systems integrated in facades.

For state-of-the art collectors, development mainly focuses on sizing for optimisation of heat production, manufacturability, handling and installation [16]. Without compromising any of these features, the new generation of solar collectors/ facades must be developed as multifunctional structures, able to additionally meet several criteria:

- Broad range of implementation alternatives in various building/architectural functions: balconies, fences, roofs, curtain walls, brick walls, etc.;
- Modularity of the system, allowing to extend the collecting area;
- Flexibility in assembling, able to: (1) generate different geometries, particularly in the highly exposed places of the building, (2) allow various configuration connections (serial/parallel, unit-unit/grid piping) without major interventions in the building structure (mounting on adjacent light structure).
- Easy maintenance;
- Durability;

These criteria make possible the implementation of the novel solar-thermal facades in already existing or in new buildings.

To fulfil these criteria, novel concepts are required in the design of the solar-thermal collector in terms of: (1) shape and size, and (2) surface texture, finishing and colour [17]. Further on, integrated collectors into solar-thermal arrays represents another novel design concept that will be discussed.

3 Results and Discussions

3.1 The Solar Collector and the Array Units

Development of novel multifunctional solar thermal arrays/facades, able to have an optimal coverage degree of the available area, calls for a variety of shapes other than the regularly used rectangular geometry [13, 17].

In order to develop a multifunctional solar array/façade a requirements list was developed for the main unit (the collector):

- Type of collector: flat plate solar collector;
- Shape: different polygonal shapes;
- Colour: variety of colors for the absorber plate and/or for the glazing;
- Performance: efficiency meeting the market threshold;
- Durability: corrosion protected system;
- Manufacturing: using already existing technologies;
- System: common equipment for piping, pumping and storage;
- Mounting: easy coupling;
- Maintenance: accessible maintenance.

Considering the requirement list, the innovative multifunctional concept is based on colored flat solar-thermal collectors with various polygonal geometries as triangle, trapeze, and hexagon [17].

The modularity of the conversion unit (collector) imposes regular polygonal shapes (equilateral triangle, regular hexagon, isosceles trapeze) to get high flexibility in covering various facades.

Studies on the optimal size of the new collectors have to consider two different aspects: functionality and aesthetics.

Large dimensions collectors are efficient but aesthetically restrictive, as increasing size the coverage of medium and small facades becomes restricted. For the flexibility of the designs and configurations, the aesthetic aspect would impose small areas that allow a high degree of freedom in creating appealing structures of shapes and colours on the building facades, but the functional aspect imposes a minimum limit for small sizes considering the hydraulic balance of the assembly and the heat transfer capacity of the tubing [17]. Previous studies showed that polygonal geometries within a range of 700–1,200 mm are able to satisfy a good flexibility in filling different facades configurations (I. Visa et al., patent proposal no. A/00156/18.02.2013).

There were identified polygonal units as equilateral triangle Fig. 3a and isosceles trapeze that are able to satisfy the requirements above formulated; the triangular equilateral shape has a great flexibility in development of various patterns with

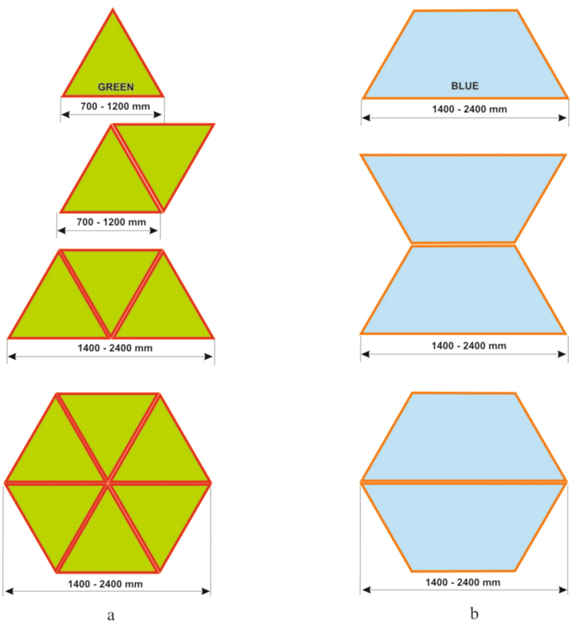

Fig. 3 Novel geometric configurations for solar thermal collectors and examples of derived geometries for **a** equilateral triangle basic unit and **b** isosceles trapeze

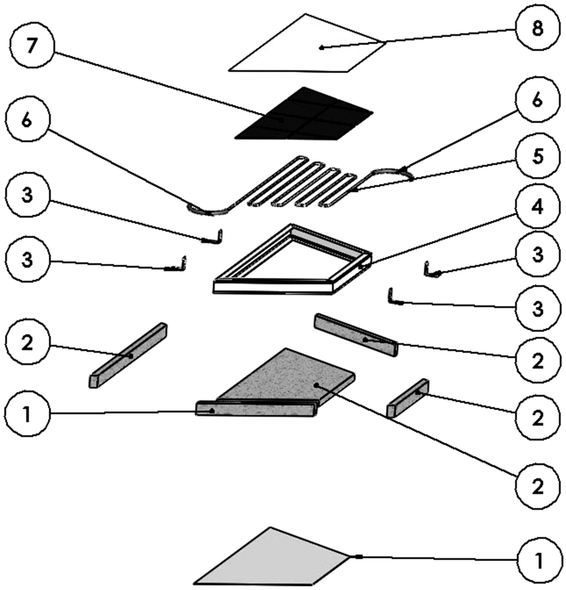

Fig. 4 The design of the collector (the trapeze configuration): *1* back aluminium plate, *2* basaltic foam insulation, *3* aluminium flanges, *4* aluminium frame, *5* copper tube serpentine, *6* rubber quick connections, *7* absorber plate, *8* glazing

direct applications for small and medium facades, with various openings and volumetric structures. The requirements for cost effective larger arrays are better met by the isosceles trapeze unit which facilitates an easier connection and mounting. Both solutions may be used in combined structures and can also include rectangular collectors.

These novel shapes impose new solutions for the internal tubing; this has to be designed to provide a maximum collection of heat from the absorber plate. In the design of the internal piping one has also to consider the interconnectivity between the collector units, to form an array with a given configuration.

The structure of the novel type of the solar thermal collector is mounted inside an aluminum frame profile, giving the triangular or trapeze (element 4 Fig. 4.) shape and is backwards closed with a 1.2 mm sheet of aluminum plate (element 1 Fig. 4). A copper tube serpentine Ø10 × 1 mm (element 5 Fig. 4) is integrated within the frame, on a 50 mm thick basaltic foam insulation (elements 2 Fig. 4). The absorber plate (element 7 Fig. 4) is an aluminum or copper thin plate covered with the selective absorber coating and is attached on the tube by using tin welding. A single or double glazing layer (element 8 Fig. 4) ensures the enclosing of the collector being attached with a silicon gasket on the frame. Flexible rubber quick connections (element 6 Fig. 4) provide the high flexibility degree of mounting while aluminum flanges 3 mm thick (element 3 Fig. 4) support the entire collector assembly on the mounting structure attached to the façade.

Considering the previous investigations on the optimum ratio between the collector's shape and area (*I. Visa et al., Patent proposal no. A/00156/18.02.2013*), several possibilities were explored. The obvious possibilities for the inlet/outlet

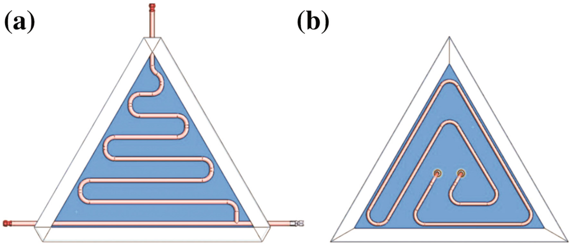

Fig. 5 The design of internal tubes for the triangular unit: **a** traditional design; **b** novel design

tubes in a triangulated geometry were identified on the corners, Fig. 5a, or in the center, Fig. 5b. These solutions are considered for a further step of implementation and testing in order to determine basic units able to provide the optimal solution in terms of flexibility, functionality and aesthetic.

The corner inlet/outlet allows left or right mounting depending on the array design by closing one of the fittings while the other one is used for the water circuit. The design allows serial or parallel connection of multiple triangular collectors. For the serial connection the number of collectors is limited but considering the reduced size of the unit preliminary estimations show that is higher than in the case of the serially connected regular collectors. Various geometries of the tube design are available considering that sizing calculations. The preliminary optimization of heat transfer developed by using "the wing method" led to an optimal distance of 60–90 mm between the tubes if the tube diameter is Ø10 mm with a thickness of 1 mm.

The center inlet/outlet supports a hidden mounting of the coupling system if flexible tubes with fast fitting are used for the interconnection of the collector. The tubing scheme also allows serial or parallel connection in between the collectors or to a central pipeline of the building.

For the isosceles trapeze units, the geometry of internal tubing may have a wide variety of solutions. One conceptual solution follows the classic serpentine with two inlet/outlet connection (Fig. 6). As a novel collector has to be approached also from the technology aspects an optimized serpentine in two stages is proposed in Fig. 7, combining 2 regularly used serpentines having two different sizes for the straight lines of the tubes. This reduces the production costs of the inner tubing by 9 %.

By assembling the basic units on the opaque areas of the buildings/facades (preferably South, acceptable SE or SW), the novel solar thermal collectors may provide a wide range of solutions for building rehabilitation or for efficiency increasing of the building.

Having a large spectrum of implementation the design imposes adaptability to parallel and serial interconnection (i.e Fig. 8). Flexible tubes and fast fittings are able to provide the modularity of the system while the installation on the facades is recommended on light frames/structures to support the array.

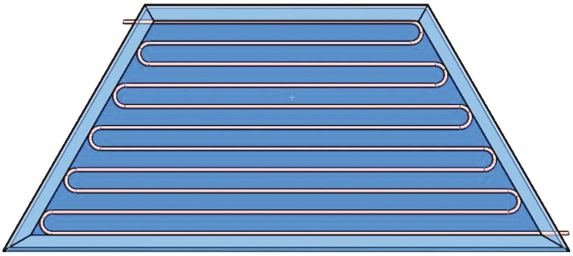

Fig. 6 The design of internal tubes for the isosceles trapeze unit

Fig. 7 Technologically optimized design of internal tubes for the isosceles trapeze unit

Such approach ensures the protection of the façade, hiding the adjacent water circuit, ensuring an additional insulation. Tracking is possible for limited angles for the entire array or for specific strings within the configuration. This may provide an increase in energy gain (direct tracking) or allows to avoid overheating during the warm seasons, by back-tracking.

Another aspect that contributes to increasing the acceptance and architectural integration is represented by the possibility to provide a variety of coloring options. As already mentioned, aesthetics imposes various colours of the absorber plate, while preserving the threshold spectral selectivity, S, accepted for quality commercial collectors (S = 9). So far there were obtained red absorbers plates, with shades varying from bright to dark red, with the composition $Al/Al_2O_3/Fe_2O_3/Au/TiO_2$ (S = 9, 7), [18, 19]. Colour can be obtained also through the glazing, by covering the solar glass with multiple layers having various porosity of TiO_2 [6], TiO_2/Fe_2O_3 or TiO_2/Co_2O_3.

The modularity of the geometrical structure allows the possibility to deliver array units readily made. Several variants of array units are proposed for the triangular collector unit (Fig. 9), for the trapeze based array unit (Fig. 10) and for the hexagonal based array unit (Fig. 11).

The main advantage of the modular array units is the wide range of possibilities to develop aesthetical and architectural complex facades. These units already equipped and connected may be lego-like configured in combined structures in order to respond to the customers and architects requirements. By combining

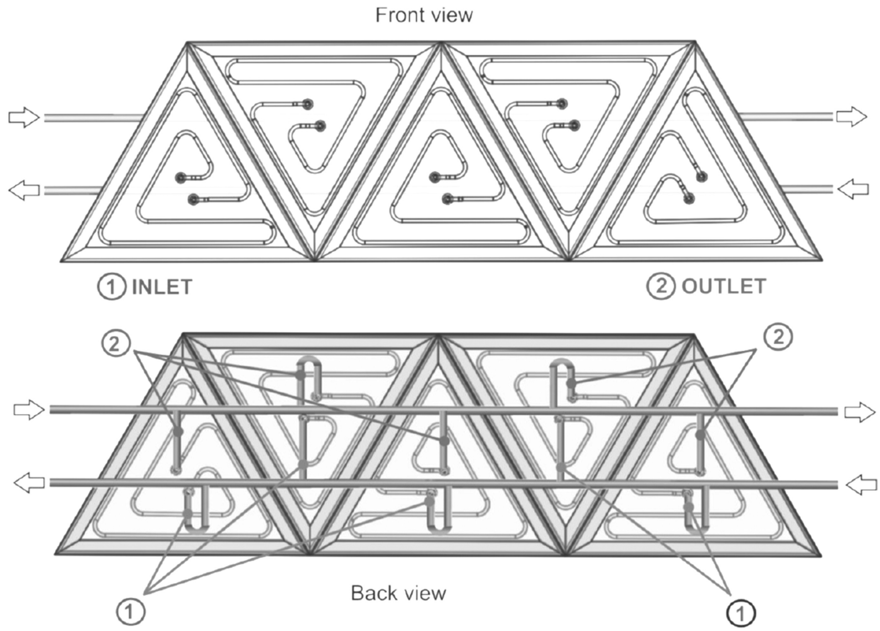

Fig. 8 Example of serially connected triangular solar collectors units

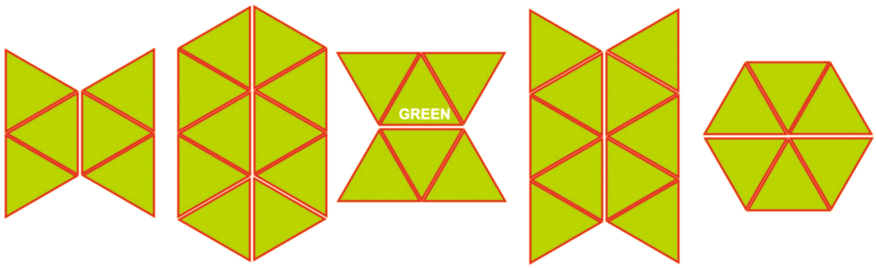

Fig. 9 Various configurations of triangle based array units

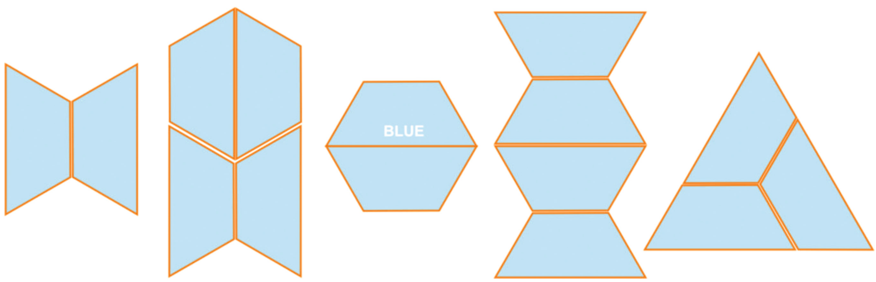

Fig. 10 Various configurations of trapeze based array units

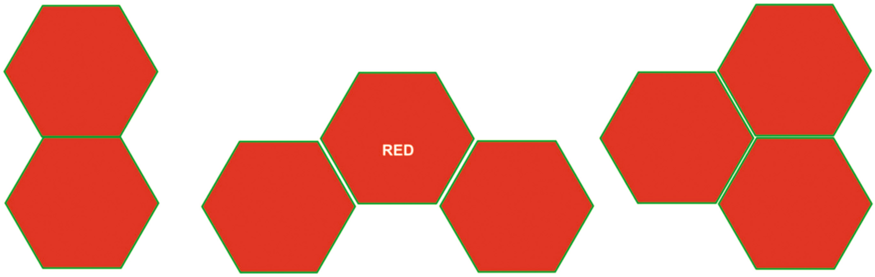

Fig. 11 Various configurations of hexagonal based array units

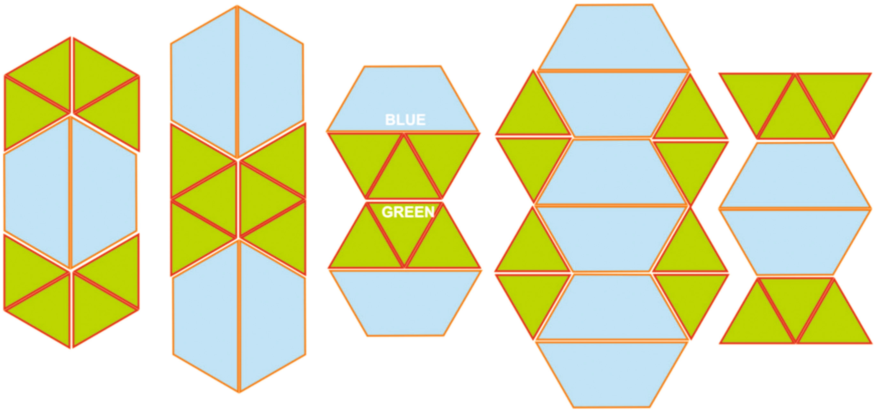

Fig. 12 Combinations between triangle and trapeze based array units

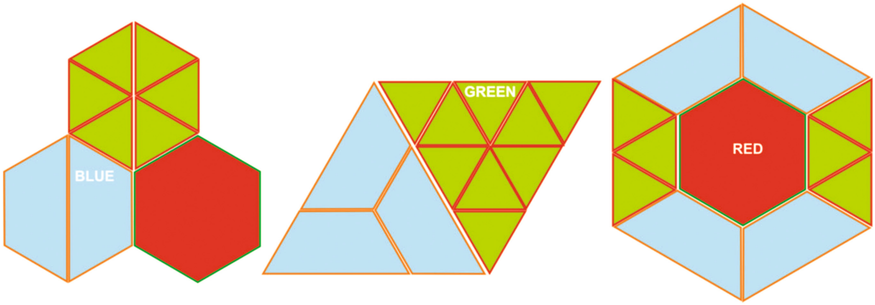

Fig. 13 Combinations between triangle, trapeze and hexagonal based array units

different array units of different geometries and/or colors, spectacular effects to improve the appearance of the buildings may be obtained. A series o combined solutions of array units are provided in the Figs. 12 and 13.

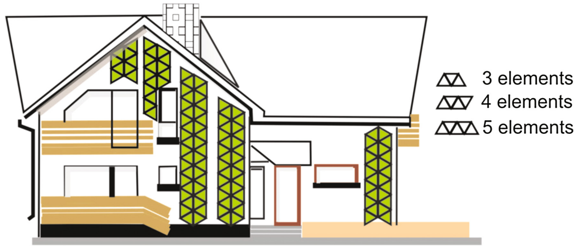

Fig. 14 Vertically disposed array units with triangular elements on the façade of a residential house

This array units, associating solar-thermal collectors give a certain flexibility in dimensioning and designing reliable circuits for the heating agent and for the hydraulic balance of the thermal system.

While these configurations outline the capability of the collector units to adapt to a large variety of combinations between shapes and color, the functionality of the array unit it's yet to be discussed, considering sizing and connections between the collector units within the array. This significantly depends on the type of the building and the available surfaces for implementing the solar-thermal façade. The geometrical modularity makes the units suitable for residential homes, public buildings, blocks of flats, offices, etc. Avoiding monotony, is possible as the collector/array units allow to cover a given area in different combinations or mountings, forming different structures.

To identify the optimal array units requires a closer study on the typology of certain types of facades. For residential houses an example is presented in Fig. 14; starting from the triangular basic collector unit and considering the stereotomy of the south façade, different configurations were developed on the same areas available on the façade.

Using only the triangular collector unit, several unit arrays were developed that can be vertically or horizontally mounted on the same available areas of the facade. The development of the array units becomes very useful when avoiding the problems of wrong mounting. For the same available area the vertical and horizontal disposure of the triangular based arrays allows an approximately equivalent degree of coverage but the connections and hydraulic circuit of the façade is completely different. The vertical configuration has the disadvantage of pressure losses on the collecting water columns which would involve higher energy consumption for pumps circulation while the horizontal disposure is allowing a parallel connection between the rows (Fig. 15).

The triangular units can evolve in a multitude of configurations, diversely disposed on the same available areas of the façade, but they have the disadvantage of a large numbers of units necessary to cover the façade.

Considering the cost involved because of the large number of units, configurations based on trapeze units and trapeze based array units were proposed for horizontal and vertical mounting as shown in Figs. 16 and 17. Similarly to the case

Fig. 15 Horizontally disposed array units with triangular elements on the façade of a residential house

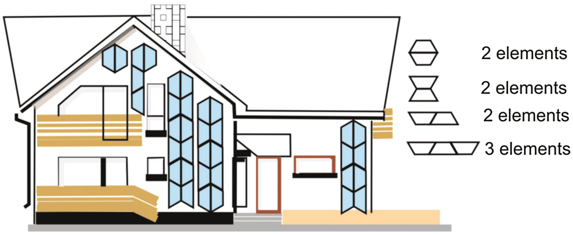

Fig. 16 Vertically disposed array units with trapeze elements on the façade of a residential house

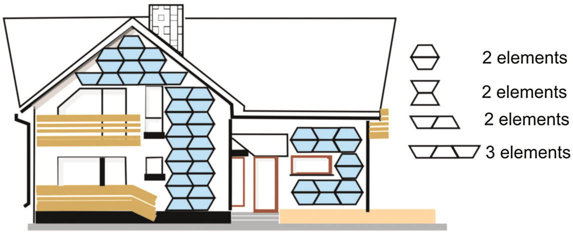

Fig. 17 Horizontally disposed array units with trapeze elements on the façade of a residential house

of the triangle based array units, the horizontal disposure of the trapeze based array units support a better functional solution.

The disadvantage of the horizontal mounting consists in a lower aesthetical quality of the façade than in the case of vertical ones. As the block of flats are not even nowadays architecturally and structurally different of the old ones which need rehabilitation, several facades proposals developed from array units are presented in Figs. 18 and 19.

These configurations prove the utility and the flexibility and support the development of a personalized signature within the community.

Fig. 18 Horizontally and vertically disposed triangular array units on the façade of a block of flats

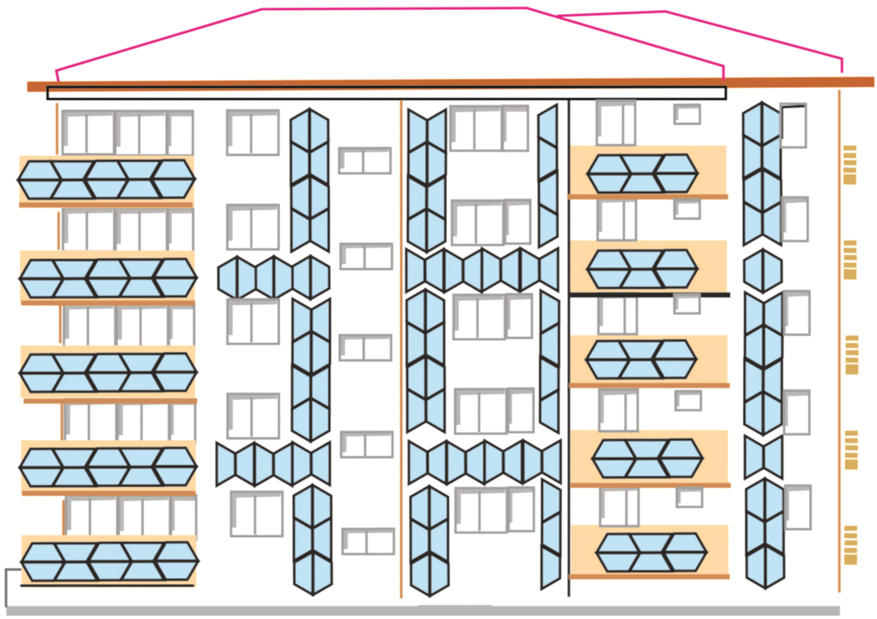

Fig. 19 Horizontally and vertically disposed triangular array units on the façade of a block of flats

3.2 Multifunctional Solar-Thermal Facades

The implementation of solar thermal systems integrated in the building facades may significantly contribute to the acceptance of the implemented renewable solar conversion systems by improving the aspects of the block of flats built in the last three decades of the 20th century which, were characterized by monotonous parallelepipedic grey concrete structures.

The aspect improvement may contribute to the rehabilitation of these edifices not only from aesthetical perspective but also considering the reduction of the thermal energy losses, providing insulation on the concrete walls *and* domestic hot water for the residents. As the Romanian architectural environment has a large distribution of such structures in the urban areas, a preliminary design study was developed considering the geometrical features of a wide range of blocks and conceptual designs were proposed as solutions for implementation, Fig. 20:

The studies developed within the EST IN URBA project proved a high versatility of the modular solar thermal arrays. The geometry and the variety of colours allow installation on residential buildings or public edifices, on the facades or on the roof tops, improving the appearance of the building as shown in Fig. 21.

One of the project outcomes involves the implementation of a modular solar thermal façade within the R&D Institute of the Transilvania University in Brasov. The institute consist in eleven low energy buildings with three floors. As the buildings aims to the Zero Energy Building status they integrate different solutions for energy mixes. These mixes will include solar thermal systems to meet the domestic hot water need, while the excess of thermal energy may be used for cooling [20]. Thus, solutions for façade integration of solar-thermal arrays were proposed, Fig. 22.

The implementation of these innovative solutions are subject to further calculation, to identify the optimal configuration able to provide domestic hot water yield and a low energy consumption for the forced circulation. The calculation will be validated on a pilot installation in the Institute, allowing testing and optimizing the

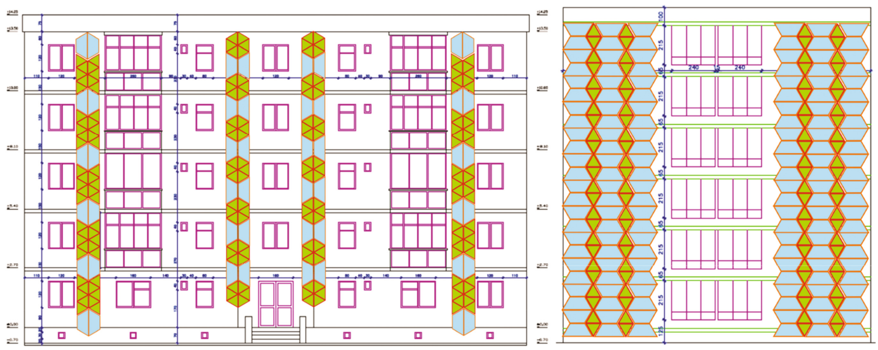

Fig. 20 Solar thermal facades obtained by combining unit arrays of triangular and trapeze STC

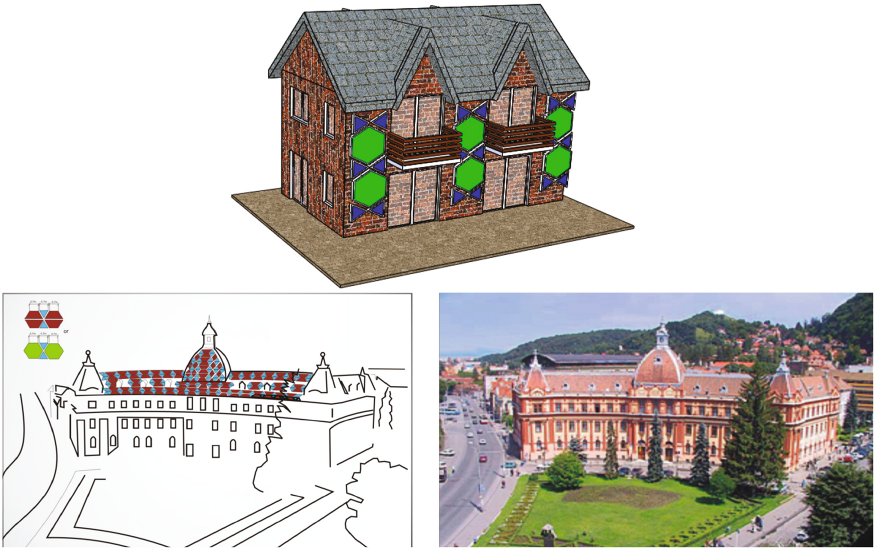

Fig. 21 Solar thermal arrays on community buildings

collector/array units. This is under development on the façade of a parallelepiped structure and will be equipped with all the necessary features for outdoor testing (sensors, piping, mounting structure, boilers, storage etc.). This testing facility is designed for simultaneously testing: (1) one trapeze collector with red absorber plate; (2) one trapeze collector with black absorber plate; one commercial flat plate solar thermal collector and one commercial vacuum tube collector, the last allowing benchmarking the novel collectors. Each collector is connected to an individual storage tank by individual pumping group and solar controller for the automation of each solar circuit. Two Identical commercial collectors are installed at an optimized tilt angle on the rooftop.

The monitoring testing system of the facility consists of: thermal probes to the inlet/outlet of each collector, storage tank and energy meters installed on each solar circuit.

The testing rig has the following components:

1. Red absorber plate ($S > 9$)
2. Black absorber plate ($S > 13$)

B. Reference: commercial ST collectors

3. Flat plate ST—vertical
4. Flat plate ST tilted (30°)
5. Vacuum tube ST—vertical
6. Vacuum tube ST tilted (30°)

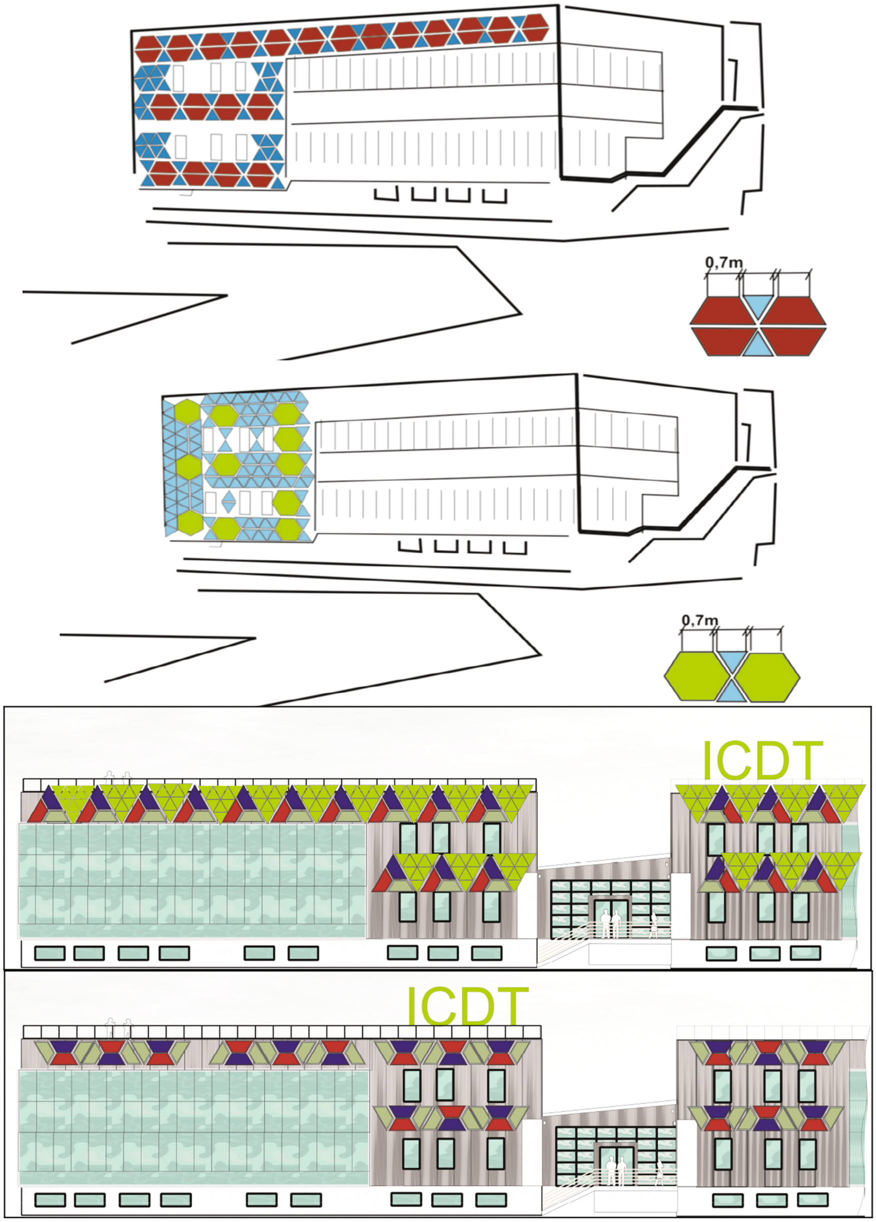

Fig. 22 Solar-thermal façades on a laboratory building of the R&D Institute of the Transilvania University of Brasov, Romania—conceptual design solutions

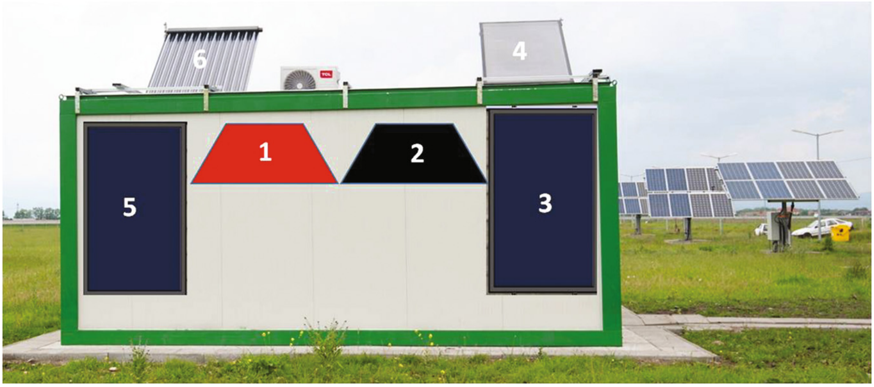

Fig. 23 The concept of the testing facility for the novel shaped solar thermal collectors

The outdoor parameters (ambient temperature, relative humidity, wind speed and direction, solar radiation) are monitored by a Delta T weather station and a Solys 2 Sun Tracker available on site. The testing facility is presented in Fig. 23.

The outdoor testing rig will allow characterizing the novel collectors, outlining the differences brought by shape, colour and mounting. After optimizing the prototype, a 10 m^2 façade is designed to be installed in the Institute.

4 Conclusions

Novel active multifunctional solar thermal systems impose the development of efficient convertors with increased architectural acceptance. The novel concept of solar thermal collectors units and solar thermal units arrays based on triangular, trapeze and/or hexagonal geometry represents a possible response to this need.

The paper presents solutions also for the internal structure of the collector: case, insulation, pipes, inter-connecting solutions. These solutions ensure large heat coverage and allow serial and parallel connections in various positions and assemblies.

Additionally, novel coloured absorber plates and/or glazing will increase the aesthetic component and can impose the solar-thermal facades as the representative features describing a community.

The novel type of solar collector and array units in different geometrical configurations or colour combinations will be tested on the outdoor testing rig available in the Institute.

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