COST Action TU1205 (BISTS)
Building Integration of Solar Thermal Systems

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Building Integrated Solar Thermal Systems

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ABSTRACT: With buildings accounting for 40% of primary energy requirements in EU and the implementation of the Energy Performance of Buildings Directive, developing effective energy alternatives for buildings is imperative. The increasing role for renewables implies that solar thermal systems (STS) will have a main role as they contribute directly to the heating and cooling of buildings and domestic hot water. Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures. These systems are typically mounted on building roofs with no attempt to incorporate them into the building envelope creating aesthetic challenges, space availability issues and envelope integrity problems. This paper aims to give a survey of possible solutions of STS integration on the building roofs and façades, applied so far. Through the presentation of the various examples, the advantages of integration are revealed.

Keywords: Solar energy, solar collectors, buildings, integration into facades.

1 INTRODUCTION

The Renewable Energy Framework Directive sets a 20% target for renewables by 2020. Buildings account for 40% of the total primary energy requirements in the EU (European Commission, 2005). Therefore, developing effective energy alternatives for buildings, used primarily for heating, cooling and the provision of hot water, is imperative. One way to reduce fossil fuel dependence is the use of renewable energy systems (RES) which are generally environmentally benign. In some countries, like Cyprus, RES and in particular solar water heating are used extensively. The benefits of such systems are well known but one area of concern has been their integration. Most solar components are mounted on building roofs and they are frequently seen as a foreign element on the building structure. Due to this fact alone and irrespective of the potential benefits, some architects object to this use of solar energy systems. It is therefore necessary to find ways to better integrate solar systems within the building envelope, which should be done in a way that blends into the aesthetic appearance and form of the building architecture in the most cost-effective way.

The Energy Performance of Buildings Directive (EPBD) requires that RES are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar thermal systems (STS) integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings, which is expected to rise dramatically in the coming years. This is further augmented by the recast of EPBD, which specifies that by the year 2020 the buildings in EU should be of nearly zero energy consumption. Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures, such as good thermal insulation, advanced glazing systems, etc. STS are expected to take a leading role in providing the thermal energy needs, as they can contribute directly to the building heating, cooling and domestic hot water requirements.

2 BUILDING INTEGRATION OF SOLAR THERMAL SYSTEMS

Among the renewable energy resources, solar energy is the most essential and prerequisite resource of sustainable energy because of its ubiquity, abundance, and sustainability. Solar thermal systems can supply thermal energy for space heating, cooling and the provision of hot water for the needs of a house/building. The advantages of building integration of STS are that more space is available on the building for the installation of the required area of the STS systems and that the traditional building component is replaced by the STS one, which increases the economic viability of the systems.

In the case that this concept is employed, coupled with aesthetic and architectural challenges of building integration, many practical issues need to be resolved; such as rainwater sealing and protection from overheating (avoiding increased cooling loads during summer). The extra thermal energy can also be used for the heating of the building in winter. As STS are latitude dependant, with respect to façade application and solar incidence angle effects, these needs to be considered as countries near the equator have high incidence angles (the sun is higher on the sky) but more energy is available compared to higher latitude countries.

The adoption of building integration of STS can fundamentally change the accepted solar installation methodologies that affect residential and commercial buildings throughout the world. Maybe the single most important benefit originating from this idea is the increased adoption of STS in buildings.

A solar energy system is considered to be building integrated, if for a building component this is a prerequisite for the integrity of the building's functionality. If the building integrated STS is dismounted, dismounting includes or affects the adjacent building component, which will have to be replaced partly or totally by a conventional/appropriate building element. This applies mostly to the case of structurally bonded modules but applies as well to other cases, like in the case of replacing with building integrated solar thermal system (BISTS) a wall-leaf in a double wall façade. Therefore, building integration must provide a combination of the following:

1. Mechanical rigidity and structural integrity.
2. Weather impact protection from rain, snow, wind and hail.
3. Energy economy, such as useful thermal energy, but also shading and thermal insulation.
4. Fire protection.
5. Noise protection.

The building integration of solar thermal systems can pose a number of problems that will need to be considered such as:

1. Amount of thermal energy collected and at what temperature range.
2. Resistance to wind-driven rain penetration.
3. If the underlying base layer is transparent, calculation of light and solar energy characteristics.
4. Calculation of thermal resistance and thermal transmittance characteristics of the construction (overall heat transfer coefficient).
5. Fire protection classification and fire protection from hot components in contact with flammable materials.
6. Noise attenuation.

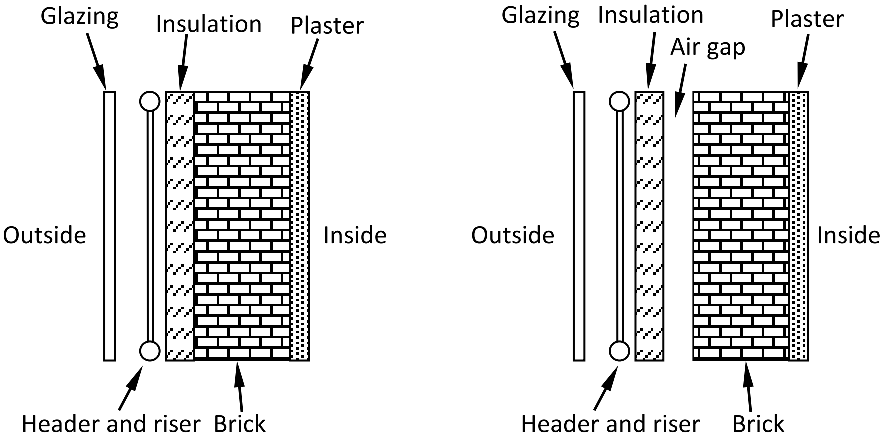
3 COLLECTOR SYSTEMS THAT CAN BE INTEGRATED

The solar collecting methodologies that can be applied in buildings are the simple thermo-siphonic units, forced circulation systems employing flat plate collectors, integrated collector storage units, evacuated tube collector systems and various low concentration compound parabolic units (Kalogirou, 2013). In some countries, such as Cyprus, renewable energy systems and in particular solar water heating are used extensively, with 93% of all domestic dwellings currently equipped with such a system (Maxoulis & Kalogirou, 2008).

The benefits of solar water heating systems are well known but one area of concern has been their integration. Most solar collecting components are mounted on building roofs with no attempt to incorporate them into the building envelope. In many instances, they are actually seen as a foreign element on the building roof. Many architects, irrespective of the potential benefits, object to this use of renewable energy systems due to this fact alone. The problem will be even more serious, when solar space heating and cooling systems are used, as they require much more solar collectors. It is therefore necessary to find ways to better integrate solar collectors within the building envelope and/or structures, which should be done in a way that blends into the aesthetic appearance and form of the building architecture in the most cost effective way.

As was seen above, various solar heating systems can be installed in buildings and each one of them has to be considered by itself when building integration is considered. Evacuated tube collectors can lead to serious rain penetration problems when integrated in buildings unless a special construction is done behind the collector to keep the rain out of the building structure.

Two solutions of building integrated flat-plate collectors are shown in Figure 1 as examples of this application. The collector consists of the usual parts found in stand-alone systems without the casing and the whole construction is set up in front of the brick of the normal brick-wall. The collector can be installed directly on the wall, as shown in Figure 1(a), or by leaving an air gap between the insulation and the brick, as shown in Figure 1(b), according to the prevailing conditions that exist in the area of installation and the necessity to avoid migration of moisture into the building. In both cases, good insulation is used to avoid transferring unwanted heat into the building, especially during the summer months. The same construction can be used for sloping roof applications in which case the brick is replaced by concrete slab.

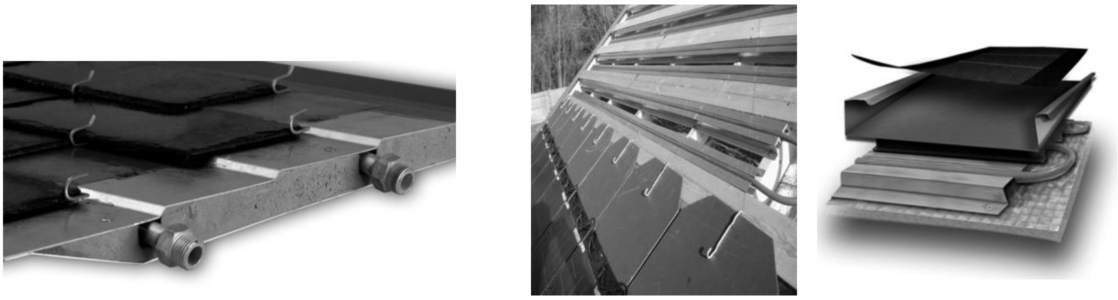


(a) STS adjacent to the brick

(b) STS with air gap

Figure 1 Two solutions of façade building integrated flat plate collectors.

In view of the EPBD, which requires also the extensive use of thermal insulation, the above solutions can be viewed, especially for retrofitting applications, as external insulation applied to the external wall surface, protected with glazing. So the only extra element required is the header and riser assembly, storage tank and piping (not shown) and glazing in order to convert the system into a thermal energy collection system. Of course, the ideas and systems to be used are not limited to the ones shown in Figure 1, but are extended to various other ones as shown subsequently. Additionally, many readymade products already appear on the market, like roof singles, façade coverings etc., all of which are also solar thermal collectors. Some typical examples are shown in Figure 2.



(a) Thermoslate

(b) Englert Solar Sandwich

Figure 2. Commercial BISTS components

4 BISTS CLASSIFICATIONS/SYSTEMS

Building Integrated Solar Thermal Systems (BISTS) have been classified across a range of operating characteristics, system features and mounting configurations. The main classification criteria of all STS are based on the method of transferring collected solar energy to the application (active or passive), the energy carrier (air, water, water-glycol, oil, etc.) and the final application for the energy collected (hot water and/or space heating, cooling, process heat or mixed applications).

Additionally for BISTS the architectural integration quality based on structural, functional and aesthetical variations have to be classified. The collector as a central element in the integration has to fulfill in some cases many more specifications than the ordinary “add-on” collectors.

The majority of BISTS can be classified as being either passive or active, e.g. in the first case using thermal buoyancy for fluid transport (natural convection or circulation) or no transport at all, and in the second case utilizing pumps or fans to circulate the thermal transfer fluid to a point of demand or storage (forced convection or circulation). A number of systems are however hybrids, operating in part through a combination of natural and forced transport methods. Many façade solar air heaters use thermal buoyancy to induce an air flow through the vertical cavities that can be further augmented with in-line fans (and heating) if necessary. The BISTS delivers thermal energy to the building but additionally other forms of energy may contribute to the buildings energy balance. For instance daylight comes through a transparent window or façade collector, or PV/T systems will also deliver electrical power which may be used directly by any auxiliary electrical services. Heated air or water can be stored or delivered directly to the point of use. Although the range of applications for thermal energy is extensive, all of the evaluated studies demonstrate that the energy is used to provide one or a combination of the following cases.

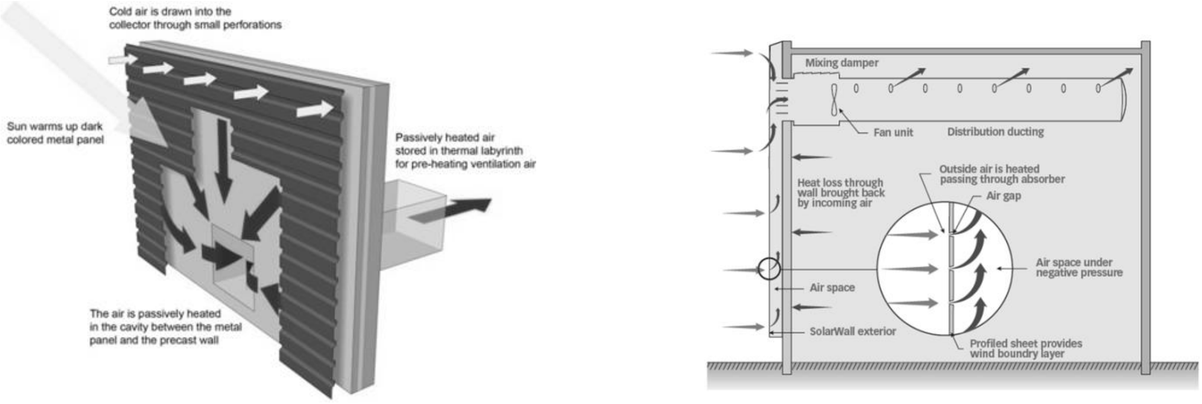
4.1 Space heating

Thermal energy produced by a BISTS may reduce the space heating load of a building by adding solar gains directly (e.g. by a passive window) or indirectly (e.g. by transferring heat from the collector via a storage to a heating element) into the building as shown in Figure 3.

Figure 3. An indirect solar-comb construction BISTS.

4.2 Air heating & ventilation

Thermal heat may be used also to preheat fresh air needed in the building. Air is heated di-rectly or indirectly (in a secondary circuit) and using forced flow or thermosiphonic action is used to provide space air heating and/or ventilation to the building as shown in Figure 4. In some instances, an auxiliary heating system is used to augment the heat input because of comfort reasons. This type of collector is called transpired air collector, shown in Figure 4(a). In this thousands of small holes are drilled on the building cladding, which is of dark colour. Air is drawn through these holes and by doing so it is heated and used directly in the space, as shown in Figure 4(b).

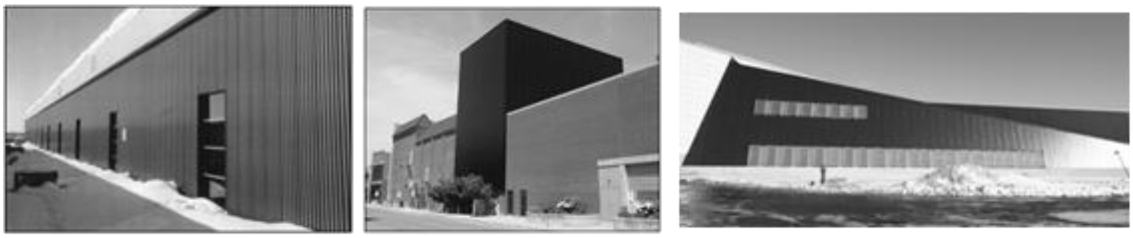


(a) Transpired collector

(b) Principle of operation

Figure 4. Transpired air collector.

This is one of the mostly used systems and is applied in a large number of buildings mainly in Canada and USA. Notably the first application, which is also the largest solar air heating system in the world, is the Canadair Facility in Bombardier, Montreal, renovated in 1991. The solar installation was integrated on the extensive renovations that were needed to improve the indoor air quality and the appearance of the aged buildings of the complex. This is shown in Figure 5 together with other buildings where this system is installed.



(a) Canadair facility

(b) Avon theatre, Canada

(c) Torondo airport, Canada

Figure 5. Applications of transpired air collector in various buildings.

A variation of this collector is the Kingspan façade solar air heater shown in Figure 6, where instead of small wholes air passage is used as shown in the figure. Here the air enters on one side of the passage, as shown, and is withdrawn on the other side.

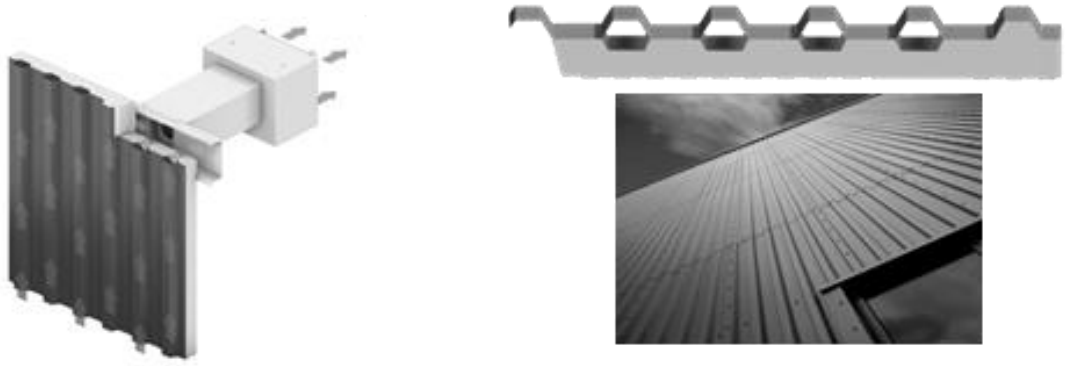


Figure 6. Solar air heating façade BISTS with auxiliary heating system.

4.3 Water heating

Covering hot water demand in the building is the most popular application. In the majority of water heating BISTS, a customized heat exchanger or integrated proprietary solar water heater is used to transfer collected heat to a (forced) heat transfer fluid circuit and on to an intermediate thermal store and/or directly to a DHW application. In most instances, an auxiliary heating system is used to augment the heat input. Two examples are shown in Figure 7.

(a) Roof integrated flat plate collectors

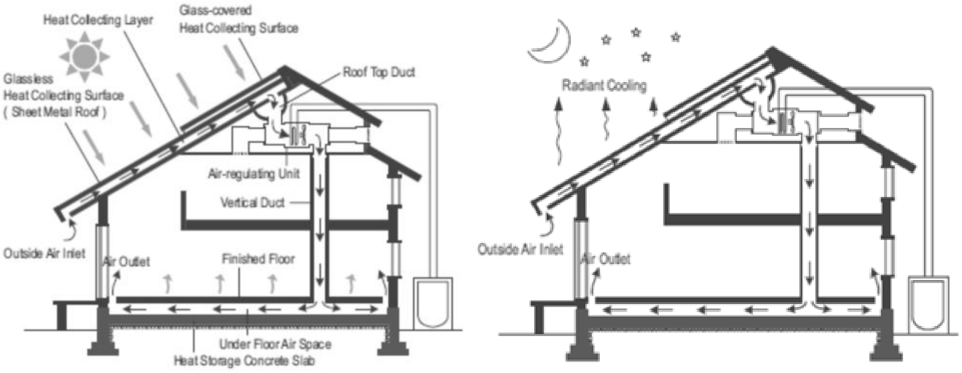
(b) Roof integrated integrated collector storage (ICS) unit

Figure 7. Roof integrated BISTS for Solar Water Heating.

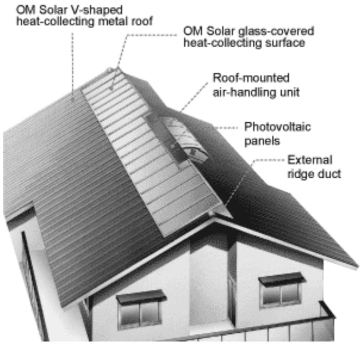
4.4 Cooling & ventilation

In cooling dominated climates, buildings most of the time have an excess of thermal energy, and there BISTS can also be a technology to extract heat from a building. There are a number of methods providing a cooling (and/or ventilation) effect to a building; shading vital building elements, desiccant linings and supplying heat directly to 'sorption' equipment. An interesting idea is using induced ventilation through a stack effect and reverse operation of solar collecting elements for night-time radiation cooling as illustrated in Figure 8 (OM, 2014).

During the solar heating mode, shown in Figure 8(a), fresh outdoor air enters a channel under the roof and flows upward. The air is heated on contact with the metal roof sheet, passing through an upper glazed section (to improve collection) whereupon the heated air enters roof top duct and is mechanically forced through the air-regulating unit. The temperature controlled air is directed down into the space to be heated via underfloor channels between the floor and the concrete slab before finally being diffused into the room through the floor diffusers. In summer cooling mode, shown in Figure 8(b), outdoor air is directed through the roof channels at night-time, thus sub-cooled using radiant cooling, and as with the heating mode, directed into the space to be cooled via the underfloor channels (OM, 2014). An actual domestic example of this system is shown in Figure 8(c).



(a) Heating mode (b) Cooling mode



(c) Actual application

Figure 8. Radiant cooling via a reversed BISTS (OM, 2014).

4.5 Other

The majority of BISTS documented are mounted on the façade or roofing structures, but a significant number can be classified as being ‘other’. This embraces a multitude of mounting options, from shading devices to balcony balustrades such as the ones shown in Figure 9.

Figure. 9. BISTS balustrade/railing feature.

An additional classification can relate to the mode of installation; new build, refurbishment or retrofit which is often related to the form of the design or components utilized be proprietary/pre-fabricated or customized. Further sub-section classification can be related to features such as optical enhancements or indirect benefits associated with the BISTS, such as weather-proofing, acoustic attenuation or thermal insulation.

The work presented in this paper gives a brief summary of the activities carried out during the first year of the COST Action TU1250. The subsequent activities of the Action include the development of new products/systems, some of which will be demonstrated with actual pilot units, the creation of new models to help in the design of such systems, and the suggestion of new testing techniques to evaluate the performance of such systems. These include the following five systems:

1. Integrated PV/T/storage – modular façade unit.
2. Concentrating transpired collector.
3. Glazing integrated day-lighting/thermal collector.
4. Vacuum tube collectors on vertical facades.
5. Total construction integration of solar thermal.

The last one is the system described in section 3 but the purpose is to find solutions on fixing the absorber plate in front of the insulation, solutions on fixing large glass covers in front and ways to integrated hot water storage on the building structure, if possible.

5 CONCLUSIONS

The Energy Performance of Buildings Directive (EPBD) requires that RES are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of PV and STS integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. This uptake in RES in buildings is expected to rise dramatically in the next few years. This is further augmented by a recast of the Directive, which specifies that the buildings in EU should be of nearly zero energy consumption (residential and commercial buildings by the year 2020 and public buildings by 2018). Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures, such as good insulation or advanced glazing systems. STS are expected to take a leading role in providing the electrical and thermal energy needs, as they can contribute directly to the building heating, cooling and domestic hot water requirements.

As can be seen from the solutions presented in this paper a number of ideas have been tried and others are just at the concept stage and generally more R&D effort is needed. It is believed that in the coming years more and more of these solutions/ideas will find their way in the market in view of the implementation of the directives imposed by the EU.

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Evaluation of the environmental profile of a building-integrated solar thermal collector, based on multiple life-cycle impact assessment methodologies

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ABSTRACT: The present article is based on the collaboration between the University of Lleida (Spain) and the University of Corsica (France). In the frame of this collaboration, the environmental profile of a patented building-integrated solar thermal collector is evaluated. The studied collector was developed and experimentally tested at the University of Corsica, within the concept ¨integration into gutters with no visual impact¨. For the environmental impact assessment, three configurations (the reference system and two alternative systems) are examined. Multiple life-cycle impact assessment methodologies (single-score/eco-point methodologies, embodied energy/embodied carbon) as well as multiple scenarios are adopted. Several environmental indicators are calculated and compared with data from the literature. By taking into account the full life-cycle of the systems, the results reveal that the configuration with collectors in parallel connection can considerably improve the energy performance and thus, the environmental profile of the reference system (collectors in series connection).

Keywords: Building-integrated solar thermal collector; Life-cycle analysis; Life-cycle impact assessment methodologies; Single-score/eco-point methodologies; Embodied energy and embodied carbon

1 INTRODUCTION

Building-Integrated (BI) solar systems offer several advantages compared to the Building-Added (BA) configurations. In the literature, there is a small number of experimental and/or numerical investigations about BI solar thermal systems (Notton et al, 2013; Motte et al., 2013a, b; Notton et al., 2014) since these configurations are a new tendency (even if some types of BI solar thermal systems exist several years ago).

Concerning studies which examine the environmental profile of the systems by means of Life Cycle Analysis (LCA), most of them are about BA solar thermal collectors for domestic hot water. Examples of LCA about BA active flat-plate collectors: 1) Kalogirou (2004): solar water heating and solar space/water heating systems (Nicosia, Cyprus); the energy for manufacture/installation was recouped in about 1.2 years while the payback time for the emissions ranged from few months to 9.5 years; 2) Carlsson et al. (2014): flat-plate, evacuated-tube and polymeric collectors; the polymeric collector showed the best environmental performance. There are also LCA about BA passive flat-plate collectors (Ardente et al. 2005; Kalogirou, 2009), integrated collector/storage solar water heaters (Battisti & Corrado, 2005) and passive solar walls (Bojíc et al., 2014). Nevertheless, there are very few LCA studies about BI active solar thermal systems (Lenz et al. 2012; Lamnatou et al. 2014). In the critical review of Lamnatou et al. (2015) the gaps in the literature regarding LCA of BI solar systems (with emphasis on BI solar thermal) are identified.

The literature review shows that most of the LCA studies about solar thermal systems for buildings are about embodied energy/CO_2 emissions of BA configurations. Therefore, more LCA studies about real BI solar thermal systems, especially with ¨eco-point/single-score¨ Life-Cycle Impact Assessment (LCIA) methodologies, are needed. The scope of the present investigation is to fill the above mentioned gaps by evaluating the environmental profile of a patented BI solar thermal collector by utilising multiple LCIA methodologies: Eco-indicator 99 (EI99), IMPACT 2002+, Embodied Energy (EE) and Embodied Carbon (EC). In this way, the present article, along with authors´ previous study (Lamnatou et al., 2014) offers a comprehensive environmental performance of the proposed BI active solar thermal system, based on multiple approaches and LCIA methodologies.

2 MATERIALS AND METHODS

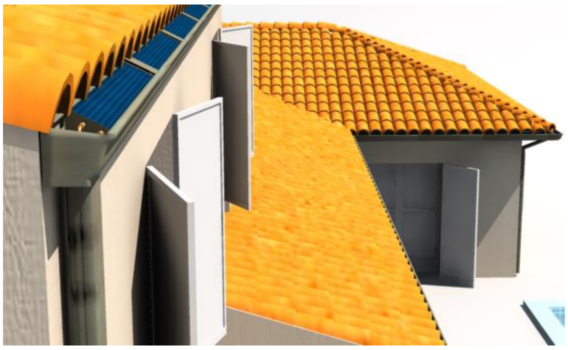
2.1 Phases, functional unit, system boundaries

Based on ISO 14040 (2006) and ISO 14044 (2006), the phases of: 1) goal and scope definition, 2) life-cycle inventory, 3) life-cycle impact assessment, 4) interpretation are adopted. The whole system (14 solar collectors; additional components: storage tank, pump, external tubes with their insulation, glycol) is the functional unit. The boundaries include the whole system in terms of: material manufacture (collectors and system additional components), manufacture of the collectors, system installation, use/maintenance, transportation and disposal.

2.2 Definition of the solar system

The BI solar thermal system which is evaluated (Fig. 1) was developed and tested at the University of Corsica, in France. It is based on a patented solar collector for water heating (Cristofari, 2006), integrated into building gutters (Fig. 1a). One installation contains several connected modules (one module is around 1 x 0.1 m^2). The components of one unit are presented in Figure 1b. In Tables 1 and 2, details about the studied configurations (Systems 1-3) are given. Systems 1 and 2 have been studied experimentally as well as numerically (Notton et al., 2013; Motte et al., 2013a, b; Notton et al., 2014) while System 3 has been studied only numerically (Motte, 2012) since absorbers of this size with tubes at the same level are not commercially available.

a)



b)

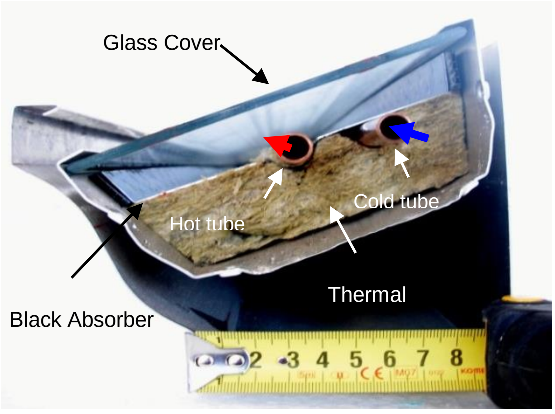


Figure 1. a) Solar gutter, b) Solar thermal module.

Table 1. Basic characteristics of the studied BI solar thermal systems (Systems 1-3).

System	Basic technical characteristics	Thermal energy production (kWh/year)	Electricity for pumping (kWh/year)	Electricity for auxiliary heating (kWh/year)
1 (Reference)	Collectors of series connection; Tubes at different levels	549.16	63.03	972.10
2	Collectors of parallel connection; Tubes at different levels	811.21	61.54	815.93
3	Collectors of series connection; Tubes at the same level	884.75	63.21	770.42

2.3 Assumptions

- The calculations refer to Systems 1-3 (Tables 1 and 2): 14 solar collectors (around 2 m^2 total solar absorber surface), one 100 l tank (for two persons).

- The impact due to the processes for collector manufacture is considered as 27% of the impact for the manufacture of collector materials (Kalogirou, 2009).

- The impact of system installation is assumed to be 3% of the total impact for the manufacture of collector/additional components (Kalogirou, 2009).

- Glycol is used as anti-freeze protection fluid (20% glycol in the glycol-water mixture).

- Use/operational phase includes: electricity for pumping/auxiliary heating; one replacement for glasses and storage tank; five replacements for glycol; general maintenance (= 10% of the material impact of the collectors: Nawaz & Tiwari, 2006).

- Transportation: truck (from factory gate to building; from building to disposal site); 50 km.

- Disposal: landfill for most of the materials; it includes: materials/components of all the collectors, system additional components, components which they are replaced over system lifetime; chemical landfill for the plastics; municipal waste incineration for glycol. For the EE and EC study, landfill is considered for all the materials (Lamnatou et al., 2014).

- Scenario ¨Recycling¨ concerns glass, aluminium, copper (for: collectors, system additional components, parts of the system that are replaced over system lifetime).

- ¨30-years system lifetime¨ is assumed (Source: Energy efficiency 2005-06).

- For the energy metrics, the output of the solar thermal system is converted into primary energy by adopting 1.085 $kWh_{primary\ energy}/kWh_{delivered\ energy}$ (conventional boiler (gas or oil); close to the value considered by Ardente et al., 2005).

2.4 Life Cycle Inventory

Life Cycle Inventory (LCI) (Table 2) is based on: 1) ecoinvent database for EI99 and IMPACT 2002+, 2) ICE (2011) and ALCORN (2003) databases for EE and EC. LCI includes the gutter in order to have a more complete picture of the materials, even if gutter could not be considered as part of the collector itself.

Table 2. Life Cycle Inventory (LCI) (the same for Systems 1-3).

Materials/components	Mass (kg)
<u>For one collector:</u>	
Black absorber (aluminium)	0.196
Cover (glass)	1.417
Tube 1 for cold water (copper)	0.253
Tube 2 for hot water (copper)	0.253
Thermal insulation (rockwool)	0.231
External casing (aluminium)	0.615
Two blades (polycarbonate (PC))	0.048
Polyester 1 (at the casing)	0.007
Gutter (aluminium)	0.728
Polyester 2 (at the gutter)	0.010
<u>Additional for the system:</u>	
Storage tank (stainless steel)	12.479
Storage tank (rockwool insulation)	4.081
Tubes (copper)	5.637
Tubes (polyurethane insulation)	1.804
Propylene glycol	1.400
Pump (stainless steel)	3.000

2.5 Life-cycle impact assessment methodologies

EI99 is an endpoint methodology and it includes three damage categories: human health, ecosystem quality and resources (PRé-Consultants, 2000). For the present LCA study, the hierarchic perspective (balance between short and long term time perspective: PRé-Consultants, 2000) is utilized. IMPACT 2002+ has a combined midpoint/damage approach and it includes four damage categories: human health, ecosystem quality, climate change, resources (Jolliet et al., 2003). EE is the amount of energy necessary to process (and supply to the construction site) a material. In the same way, the emission of energy-related pollutants such as CO_2 may be viewed over the life-cycle (e.g. of a product); thus, EC arises (Hammond & Jones, 2008).

For the EPBT, Eq. (1) (Lamnatou et al., 2014) is adopted:

$$EPBT = \frac{E_{in}}{E_{out.a} - E_{O\&M.a}} = \frac{E_{mat} + E_{inst} + E_{disp} + E_{transp}}{E_{out.a} - E_{O\&M.a}} \qquad (1)$$

(1)

where,

E_{in} = total input for system material/component manufacture, system installation, material disposal and transportation

$E_{out.a}$ = annual output of the solar system (converted into primary energy)

$E_{O\&M.a}$ = annual energy needs during the use phase of the system[*]

E_{mat} = total EE for material manufacture (materials of collectors/system additional components) and for collector manufacture

E_{inst} = energy needed for the installation of the system

E_{disp} = EE for material/component disposal at the end of their life

E_{trans} = EE regarding transportation of the materials/components from the factory gate to the building and from the building to the disposal site.

All the above mentioned *E* quantities refer to primary energy.

The equation of Greenhouse gas Payback Time (GPBT) (Eq. 2) is based on the carbon payback period of Marimuthu & Kirubakaran (2014):

$$GPBT = \frac{life-cycle\ CO_{2.eq}\ emissions}{annual\ avoided\ CO_{2.eq}\ emissions} \tag{2}$$

For the GPBT, the phases of material/collector manufacture, manufacture of the materials for the additional components, installation, transportation and disposal are considered as ¨life-cycle $CO_{2.eq}$ emissions¨ for Systems 1-3. Annual avoided $CO_{2.eq}$ emissions are calculated based on the annual output of each system and having as reference gas oil emissions (0.279 kg CO_2/kWh_{th}: DEFRA, 2012). The GPBT is also calculated with an alternative way (GPBT¨): for that case only the phase of material manufacture (for the collectors) is taken into account as ¨life-cycle $CO_{2.eq}$ emissions¨.

2.6 Sensitivity analysis, limitations

Multiple scenarios are adopted: 1) ¨No Recycling¨ vs. ¨Recycling¨; 2) France´s vs. Spain´s electricity mix. For the case of EE and EC, an additional scenario regarding databases, is also adopted: ICE vs. ALCORN database. The relatively high consumption of electricity during use/operational phase (Table 1) is a limitation of the proposed systems. For some cases building integration, apart from the considerable advantages that offers, is related with a reduction in system efficiency. For the present BI solar thermal system, the relatively small area of the gutter (Fig. 1) limits collector surface and thus, collector output decreases. Further research is currently being conducted at the University of Corsica in order to further develop the proposed systems. In the frame of this goal, alternative materials with low environmental impact could play an important role.

3 RESULTS AND DISCUSSION

3.1 Eco-indicator 99

In Figure 2, the full life-cycle[**] EI99 Pts (for all the impact categories) per kWh of produced thermal energy are presented and compared with conventional sources of heat. System 2 is selected since it has considerably better performance than System 1 (Table 1) and it can exist in practise. For the

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[*] For the energy-metric calculations, the energy inputs include electricity for pumping/auxiliary heating

[**] Material/collector manufacture; manufacture of the materials of the additional components; installation; use phase (pumping and auxiliary heating (based on France´s electricity mix), component replacement, general maintenance); transportation; disposal

comparison the results from the study of Adamczyk (2009) are used: small-scale boilers; conventional heat sources (Poland); generation of a defined thermal energy unit (excluding the impact of the boilers (manufacture, recycling)); functional unit: 1 kWh of thermal energy. From Figure 2 it can be observed that there is a considerable difference in the impact between solar System 2 and the conventional systems. More analytically, this difference ranges from around 0.005 to 0.038 Pts/kWh and it is higher for the comparison solar System 2 vs. electrical heating.

In Figure 3, the full life-cycle impact (EI99 Pts/kWh) regarding only ¨fossil fuels¨ impact category is illustrated. In the same way with Figure 2, Figure 3 refers to the comparison of solar System 2 with conventional boilers (Adamczyk, 2009). For that case the difference between solar System 2 and the conventional systems ranges from around 0.007 to 0.02 Pts/kWh and it is higher for the comparison of solar System 2 with electrical heating. Adamczyk (2009) noted that the high impact of electrical heating it is related with the use of hard coal in the electrical power plant.

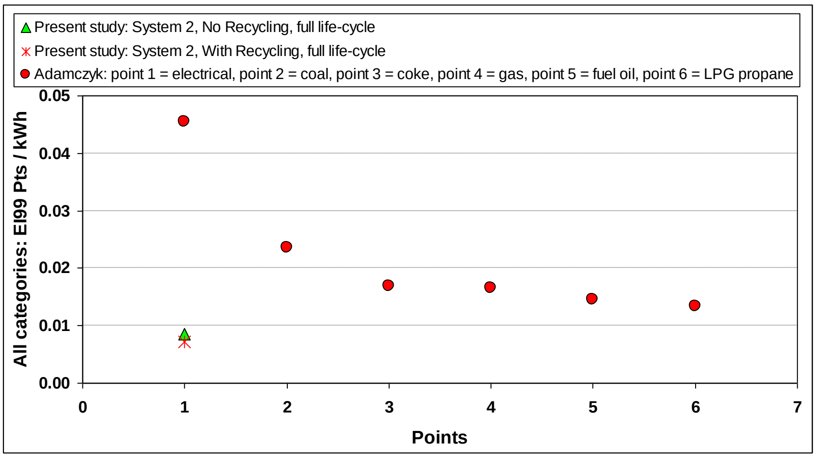

Figure 2. Full life-cycle impact (all the impact categories) EI99 Pts/kWh: System 2 vs. the boilers of Adamczyk (2009).

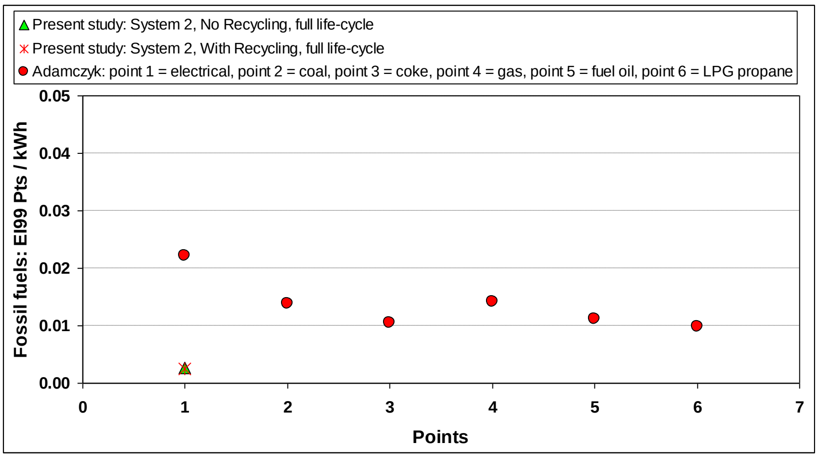

Figure 3. Full life-cycle impact (only for ¨fossil fuels¨) EI99 Pts/kWh: System 2 vs. the boilers of Adamczyk (2009).

3.2 IMPACT 2002+

The full life-cycle impact of System 2, based on IMPACT 2002+, is 0.000118 and 0.000111 Pts/kWh for scenario ¨No Recycling¨ and ¨Recycling¨, respectively.

The annual impact related with auxiliary heating is calculated based on two scenarios: France´s vs. Spain´s electricity mix. The results for France show an annual footprint of 0.095, 0.08 and 0.075 IMPACT 2002+ Pts for Systems 1, 2 and 3, respectively. For Spain these values are 0.186, 0.156 and 0.147 IMPACT 2002+ Pts for Systems 1, 2 and 3, respectively. Thus, there is a reduction of around 49% in the impact by using France´s instead of Spain´s electricity mix. At this point it should be noted that although France´s electricity has lower impact based on LCIA methodology IMPACT 2002+, the high penetration of nuclear energy in France´s electricity mix is associated with high Cumulative Energy Demand (CED) (total CED ≈ 12.04 MJ_{eq}/kWh), higher than Spain's electricity mix (total CED ≈ 10.93 MJ_{eq}/kWh) (Dones et al., 2007). It should be also mentioned that Corsica´s electricity mix is different from France´s electricity mix. In Corsica there is no nuclear energy while the greatest part of island basic needs for electricity is covered by Diesel power plants and light-fuel combustion turbines (Source: EDF). In the present investigation, France´s electricity is used because of the lack of detailed information about the environmental impact of Corsica´s electricity.

3.3 Embodied energy

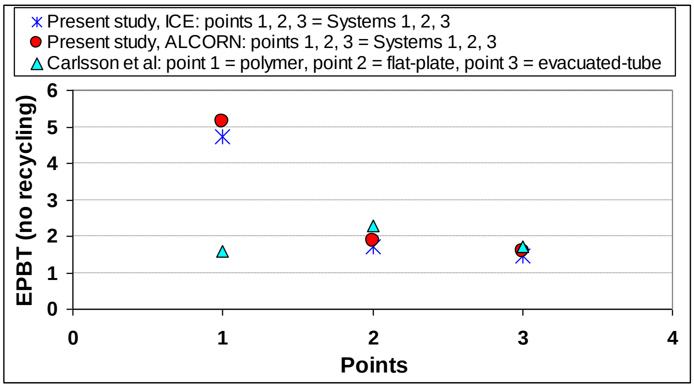

Figure 4. EPBT (years): Systems 1-3 (No Recycling; ICE vs. ALCORN) vs. the collectors of Carlsson et al. (2014).

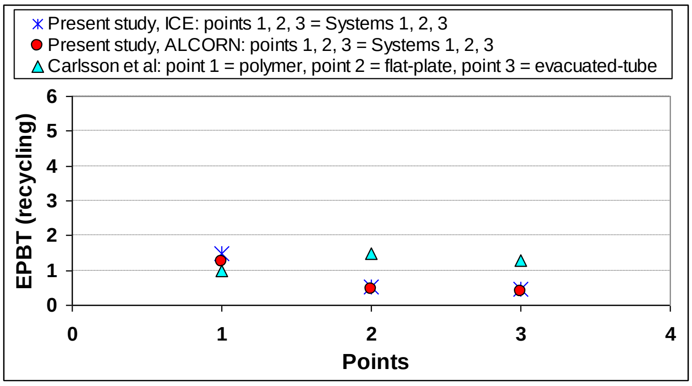

Figure 5. EPBT (years): Systems 1-3 (Recycling; ICE vs. ALCORN) vs. the collectors of Carlsson et al. (2014).

From Figure 4 and Figure 5 it can be observed that: 1) regarding the present findings, there is a good agreement between the results based on ICE and those based on ALCORN database; 2) concerning the comparison of the present results with those of Carlsson et al. (2014), in general, there is a good accordance; 3) System 1 for ¨No Recycling¨ has a high value of EPBT (as it was expected since this system has considerable lower performance in comparison with Systems 2 and 3: Table 1); 4) by adopting recycling there is a remarkable reduction in the EPBT values ranging from around 1 to 4 years and from 0.4 to 0.8 years, for the present study and for Carlsson et al. (2014), respectively; 5) the utilization of polymer as alternative material leads to an EPBT reduction ranging from 0.1 to 0.7 years (Carlsson et al., 2014).

It should be noted that Carlsson et al. (2014): 1) for the EPBT considered a solar heating system producing 17.6 GJ heat per year (Stockholm) while the surfaces of the studied BA solar thermal collectors were 15, 12.8 and 8.2 m^2 for the polymeric, flat-plate and evacuated-tube configuration, respectively; 2) for the scenario ¨Recycling¨, assumed metal recycling.

3.4 Embodied carbon

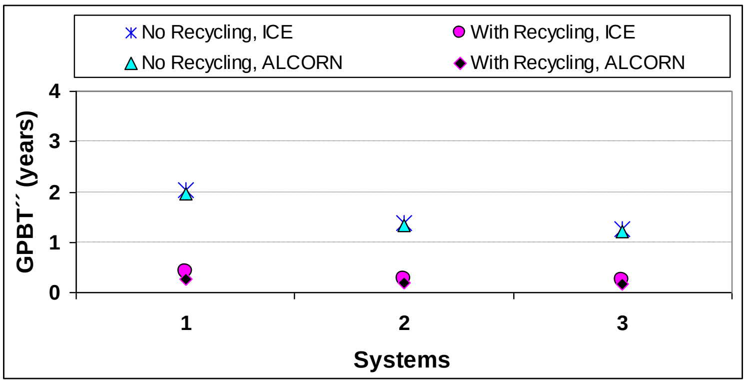

Figure 6. GPBT¨ (years): Systems 1-3. Scenarios: ¨Recycling¨ vs. ¨No Recycling¨; ICE vs. ALCORN.

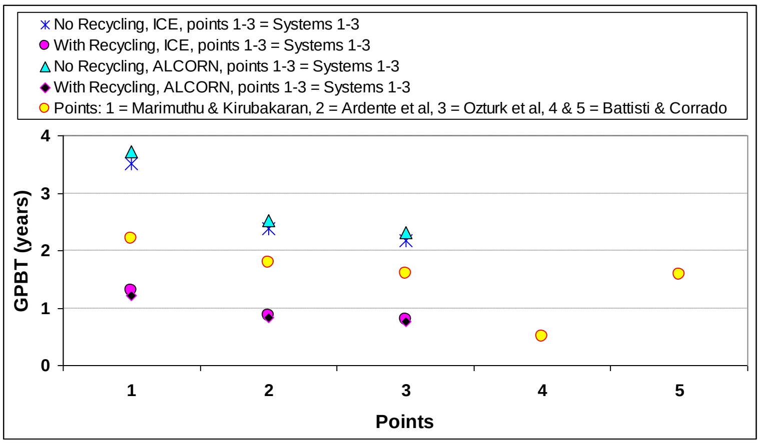

Figure 7. GPBT (years): Systems 1-3 (¨Recycling¨ vs. ¨No Recycling¨; ICE vs. ALCORN) vs. the collectors of Marimuthu & Kirubakaran (2014), Ardente et al. (2005), Ozturk et al. (2012), Battisti & Corrado (2005) (points 4 and 5 = configurations with electric and natural gas boiler, respectively).

By giving emphasis on the impact for the manufacture of collector materials, GPBT¨ is calculated based on the scenarios ¨No Recycling¨ vs. ¨Recycling¨ and ICE vs. ALCORN database. From Figure 6 it can be seen that GPBT¨ ranges from 1.22 to 2.03 years and from 0.17 to 0.41 years for the case ¨No Recycling¨ and ¨Recycling¨, respectively. Moreover, in Figure 6, a good agreement between the results based on ICE and those based on ALCORN can be observed.

Regarding Figure 7, it should be noted that the references included in this figure concern: flat-plate collector of capacity 100 l per day (Marimuthu & Kirubakaran, 2014), flat-plate collector with 180 l water tank (Ardente et al., 2005), flat-plate collector (Ozturk et al., 2012), integrated collector/storage system with 1.68 m^2 collector surface (Battisti & Corrado, 2005). All the above mentioned studies are about small-scale installations for domestic hot water and thereby, their impact can be compared with the impact of the proposed Systems 1-3.

From Figure 7, based on the findings of the present work, it can be observed that recycling leads to a GPBT reduction lying between 1.4 to 2.5 years while the results based on ICE are in accordance with those based on ALCORN database. Regarding the comparison of the present findings with the literature, the best agreement is between the GPBT of System 2 and System 3 (scenario ¨Recycling¨) and the GPBT of Battisti & Corrado (2005) (collector with electric boiler).

3.5 Conclusions

LCA of a BI active solar thermal system (three configurations) is performed. The LCIA methodologies EI99, IMPACT 2002+ along with embodied energy and embodied carbon, based on multiple scenarios and databases are adopted.

In terms of EI99, System 2 (collectors in parallel) for full life-cycle (all the impact categories) shows 0.0085 and 0.0072 Pts/kWh (for ¨No Recycling¨ and ¨Recycling¨, respectively): lower than the impact of conventional small-scale boilers from the literature.

Regarding IMPACT 2002+, the annual footprint for auxiliary heating has a reduction of around 49% if France´s electricity is used, instead of Spain´s electricity. Although France´s electricity has lower footprint based on IMPACT 2002+, the high penetration of nuclear energy leads to high CED (higher than Spain's electricity) (Dones et al., 2007).

Concerning EPBT: 1) for the present study, there is accordance between the results based on ICE and those based on ALCORN database; 2) in general, the present results show good agreement with those of Carlsson et al. (2014) (BA solar thermal collectors); 3) by recycling there is a remarkable EPBT reduction ranging from around 1 to 4 years (for the present study).

In regard to GPBT and based on the present investigation, recycling leads to a GPBT reduction lying between 1.4 to 2.5 years while the results based on ICE are in accordance with those based on ALCORN database. By examining the present findings vs. those of the literature, the best agreement is between the GPBT of System 2 and System 3 (scenario ¨Recycling¨) and the GPBT of and an integrated collector/storage configuration with electric boiler.

In general, the present results, based on all the LCIA methodologies used, demonstrate that the reference system (System 1) with small modifications such as parallel connection of the collectors (System 2) has significantly improved efficiency and thus, considerably improved environmental performance. A further reduction of the impact can be achieved by recycling.

Conclusively, the present article along with authors´ previous study (Lamnatou et al., 2014) provide a comprehensive investigation about the environmental profile of the proposed BI active solar thermal system, based on multiple approaches and LCIA methodologies.

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Investigation of Sun Protection Issues of Building Envelopes via Active Energy Production Systems

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ABSTRACT: This paper aims to examine whether specific building integrated solar systems (BISTS, BIPV), along with their basic operation can provide adequate sun protection when used as passive shading devices. The proposed research starts with the analysis of their geometry and philosophy of operation through a literature review, along with the presentation of case studies where these systems are integrated in buildings. Additionally, digital modeling is performed where each technology is examined separately as a passive shading device, as part of a building unit. This is then organized in various layouts, in order to analyze its environmental performance with regards to its passive characteristics and highlight its active energy production system. The ultimate aim is to present the advantages and disadvantages of different active systems when they operate as passive shading components.

Keywords: Active Solar Systems, Architectural Integration, BIPV, BISTS, Building Envelope, Sun Protection.

1 INTRODUCTION

Up until the 19th century, a lot of human energy needs were covered by renewable energy sources, which characterized the balanced coexistence of man and environment up to that point. With the advent of the industrial revolution this state of affairs was changed, and non-renewable fossil fuels began to be the driving force of industrialization, which basically shaped the sustainable environments discourse as we know it today. The first placements for environmental awareness and sustainable development, started appearing in the 1960s, coinciding with the implementation of the National Environmental Policy Act, in the USA. Conferences and international meetings that followed grappled with the issue, such as the report of the World Commission on Environment and Development of 1987 as well as the United Nations Conference on Environment and Development in 1992 (Mitchell, 2006). These environmental motions and expressions resulted a concentrated effort to reduce the heating needs of buildings, primarily with the implementation of mainly active systems, while passive methods were to follow later, in the mid 1970s (Tombazis, 1994).

Nowadays, the development of alternative energy sources for buildings is imperative, because buildings account for 40% of the primary energy needs in the EU, while there is now in place a legal obligation instituted by the Energy Performance of Buildings Directive, which gives an ever increasing role to efficient adoption of renewable energy sources, which means that solar thermal systems

(STS) and photovoltaics (PV) will contribute directly to heating and cooling loads, production of electricity and provision of hot water in buildings (Kalogirou, 2013).

The utilization of solar energy is one of the key pieces of the holistic view of the issue of environmental design, which is based on three key aspects: bioclimatic design, design of energy efficient structures and an ecological approach to design. The first two differ in their approach to the subject; the first examines passive issues, while the second examines energy / active issues. Taking into account the above, the full integration of such elements to the building envelope, gives, in many cases, a passive character to the environmental design concept for a structure, which may then play an important role to the passive behavior and energy saving performance of a building. The use of an active system (e.g. a PV) that is integrated in the building shell may have both active (e.g. electricity production) and passive role (e.g. sun shell). Specifically, the integration of photovoltaic elements on buildings may provide thermal protection and increased insulation against extensive insolation and noise. We also know that energy management techniques in buildings are divided into energy saving techniques, in passive and in active solar systems. However, in order to achieve high performances both in relation to a reduction in energy consumption, and also in relation to energy production, all three techniques must be used simultaneously. This means that buildings exploiting insolation to reduce their energy utilization requirements should be able to save energy by incorporating passive and active solar features (PVs and STSs) integrated in their facades and roofs (Hestnes, 1999). Therefore, the key to the success of the partnership of the above characteristics is the correct understanding of a holistic approach to the building design, which requires a concurrent joint design approach of active and passive systems.

2 STATE OF THE ART

2.1 Appraising related technologies

In the last years, the addressing of the prospect of increased environmental sustainability raises the need to reduce dependence on conventional energy sources. Consequently, many active systems were developed that use renewable sources for energy production. In this body of research, the effort is made to examine the possible application of some of these systems (PV and STS) in order to assign to them not only an active role, but also a passive role in buildings. In the first step, we must distinguish the systems that may be integrated into the building envelope and act as passive elements. Thus, through the research that has been carried out in the field of BIPVs, these systems are: BIPV foil products, BIPV tile products, BIPV module products and Solar cell glazing products (Jelle, Breivik, 2012). Furthermore, the corresponding BISTS systems include: Glazed Flat Plate Hydraulic Collectors, Unglazed Flat Plate Hydraulic Collectors, Unglazed Plastic Hydraulic Collectors, Unglazed Flat Plate Air Collectors, Vacuum Tube Hydraulic Collectors and Concentrating Hydraulic Collectors (Munari, Roecker, 2007).

In the context of a paper by Vassiliades C. et al., a comparative table between BIPV and BISTS applications in new and existing buildings, was created. One of the aims of that body of research was to investigate the PVs and STSs' technologies in current applications in terms of the transparency aspect of building facades, alongside the possibility of integrating a number of component assemblies that allow for increased insolation where required or reversely sun protection in the spaces shielded behind any such installation. Thus, the systems administer envelope transparency provide solar gains or sun protection while permitting visual access to the exterior, when used as components of the shell. According to this paper's research, these systems refer to PV Solar cell glazing and in the case of STSs they refer to Unglazed Flat Plate Hydraulic Collectors and Vacuum Tube Hydraulic Collectors (Vassiliades et al. 2014).

2.2 Vacuum Tube Hydraulic Collectors

A widely used system that may be relevant to this research is that of the Vacuum Tube Hydraulic Collectors which exhibit conventional configurations as indicated (Fig. 1). They consist of parallel transparent tubes, within which are other opaque tubes, wherein the fluid heated by solar insolation is circulating (Kalogirou, 2013a). These vary in circumference and length, but the main dimensions of a typical production system is 1,6 m length of tubing with a 5 cm diameter and separation between pipes.

Figure 1. Examples of the typology of Vacuum Tube Hydraulic Collectors [Available online from www.diytrade.com, www.zambia.africa-greenfields.com, www.alibaba.com (accessed November 2014)].

2.3 Unglazed Flat Plate Hydraulic Collectors

Another potential system utilization, is that of Unglazed Flat Plate Hydraulic Collectors (Fig. 2), part of the same technological category as that of the Vacuum Tube Hydraulic Collectors, although they are less powerful (Kalogirou, 2013a). Also, they are of metal construction, they are dark colored, and they are usually installed as plates or as free tubes (Fig. 2).

Figure 2. Typology of the Unglazed Flat Plate Hydraulic Collectors with visible pipes [Available online from www.bio-tecture.net (accessed July 2014)].

2.4 Solar cell glazing

The technology of Solar cell glazing (Fig. 3) refers to the integration of photovoltaic cells into conventional glass which allows for the use of different colored transparencies and beyond electricity production, it is also suitable for providing weather protection. The distance between the cells depends on the desired level of transparency and electricity production (Jelle, Breivik, 2012). The wide range of panels' sizes and cell arrays together with the characteristics of conventional glazing, gives many integration opportunities.

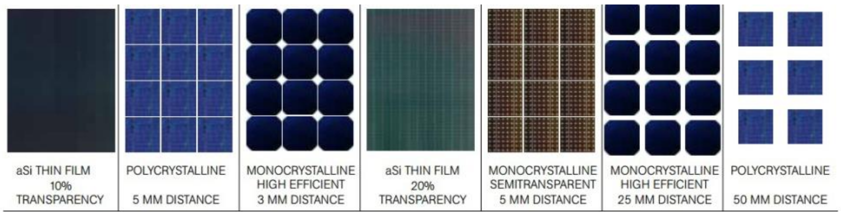


Figure 3. Analysis of the main typologies of Solar cell glazing (Sapa Building System).

2.5 Applications

There are a large number of examples in the application of PVs and STSs in buildings. However, in order for a PV to be considered building integrated (BIPV), it should form a functional part of the building's structure or it should be architecturally assembled on it (which is also directly applicable to building integrated solar thermal systems - BISTS) (Peng et al. 2011). In many cases, studying the contemporary building stock, one encounters the systems mentioned above in building applications that function as components of the shell, i.e. BIPV and BISTS, a sample of current applications in the field of integration of energy systems in buildings.

2.6 Garden Utopia

The case of the complex "Garden Utopia" features buildings in Dezhou, wherein 504 Vacuum Tube Hydraulic Collectors are placed horizontally in the form of a wave on their roofs, while vertical collector frames cover the facades (Fig. 4). The role of the system in this example is predominantly active (China: Utopia Garden Sets New Standard for Architectural Integration).

Figure 4. View of the building complex and of the system [Available online from www.solarthermalworld.org, www.renewableenergyworld.com (accessed November 2014)].

2.7 House on Durand

In this modern residence located in Beachwood Canyon in Hollywood, Unglazed Flat Plate Hydraulic Collectors were integrated into the building envelope (Fig. 5). The system placed in the southern facade and it functions both as shading device, and as a STS which produces hot water. The integration of this system in the House on Durand, is an example of how an active system can have passive features (BIST - Residential case study).

Figure 5. View of the house from which the integrated system appears [Available online from www.bio-tecture.net (accessed July 2014)].

2.8 California Academy of Sciences

In the field of Solar Cell Glazing, the application of such a system to the California Academy of Sciences by Renzo Piano is one of the most popular (Fig. 6). Simultaneous passive and active use of the system is achieved as the roof extends along the building perimeter glazing to provide sun and rain protection and to produce electricity through the 60,000 integrated PV cells which produce about 213,000 kWh of energy each year (California Academy of Sciences).

Figure 6. View of the Academy and the circumferential canopy with the photovoltaic cells [Available online from www.calacademy.org, www.dezeen.com (accessed November 2014)].

2.9 University of Ballarat

The integration of "aSi Thin Film" into the northern facade of Ballarat University (Fig. 7) consists the biggest BIPV facade in Australia. Double glazing ASI-glass by Schott Solar was used, which produces

7,3 MWh of energy per year. The impact of the inevitable production of shadows and the vertical placement was minimized by the use of amorphous silicon technology, which performs better in terms of partial shading (University of Ballarat, Victoria).

Figure 7. View of northern facade, consisted of photovoltaic glazing [Available online from www.mcildowiepartners.com.au (accessed November 2014)]

2.10 Observations

By examining the case studies, one can distinguish the potential of the systems in terms of adequate integration. When sun protection is required, the elements may form canopies or louvers (especially the BISTS). The examples showed that modules are limited to vertical frame systems which initially seem to encumber architectural flexibility, but the potential multitude of dimensions, may ultimately impart a morphological flexibility. PVs have a slight advantage in system maintenance, while they can be fully integrated and remain inconspicuous.

3 METHODOLOGY

The first step in the development of the experiment methodology is based on the knowledge that a passive solar system is defined as the total of building components, which allow the collection of solar energy during the winter and avoid it during the summer and by bearing in mind that one of the techniques for achieving it, is sun protection. This is achieved by various means such as the shading of facades and the applications of special coatings on a building glazing (Vrachopoulos, 2011). Based on the above, the passive features that could be replaced by active systems, to achieve sun protection and energy production simultaneously are divided to "Permanent external sunshades" (Vacuum Tube and Unglazed Flat Plate Hydraulic Collectors and Solar Cell Glazing) and "Glazing with special coatings" (Solar Cell Glazing).

For the examination of the behavior of each system in relation to the sun protection it provides, digital simulations were made utilizing Autodesk Ecotect Analysis software. In simulating living spaces, a fully insulated space was used, with external dimensions (LxWxH) 560 cm x 330 cm x 315 cm, whose long side was treated with conventional glazing (Fig. 8). The materials forming the designated area is Double Glazed Low E glass, with an aluminum frame of U-Value 2,41 W/m^{2}K, insulated brick walls with U-Value 0,58 W/m^{2}K, reinforced concrete floor and roof with U-Value of 0,50 W/m^{2}K and of 0,35 W/m^{2}K respectively. The high insulation values used, were in order to have the least possible loss of energy and a more predictable result when compared with the protection the above systems may provide to the single opening of the building. The aim was to analyze the correlation between insolation and shading, given that the above active components function as sunshades and help to reduce thermal and cooling loads inside the simulated space in the summer and winter respectively. Finally, the annual energy production of each system is examined in all configured layouts, which is compared with the energy consumption in each case, in order to be able to analyze both the passive and active characteristics of each layout.

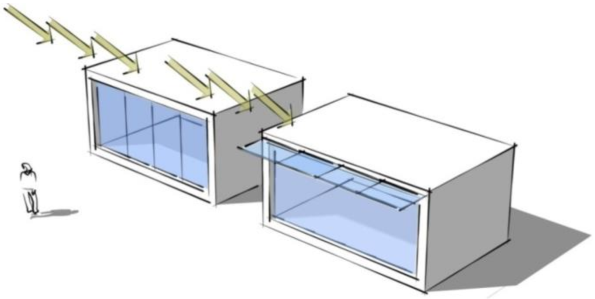


Figure 8. The methods of application of the different typologies, and the space being studied.

3.1 Typologies and Layouts of the Systems under investigation

Based on the analysis made above for each system, the most characteristic examples of typologies and geometries of the systems are selected. Through this choice the different geometries of the systems were highlighted, and in turn became the basic categories of active systems that were simulated. These are the "BISTS" (with the Vacuum Tube and the Unglazed Flat Plate Hydraulic Collectors) and the "BIPV" (with aSi Thin Film - Transparency 10%, Monocrystalline Semitransparent - Distance 5 mm and Polycrystalline - Distance 50 mm). The basic need for sun protection, especially in the Mediterranean climate, expose predominantly the southern surfaces of buildings during the midday hours and western surfaces during the evening hours of the summer season. So, the first step of the research for the extent of sun protection that each typology can provide, is the juxtaposition of the five systems acting as shading devices on different layouts, to highlight the ideal shading device. So, the simulated building and the systems are placed in 3 different layouts, based on the above observations. All the layouts are examined on an annual basis in order to determine the total annual heating and cooling loads of the building.

3.2 Assumptions

For the sake of clarity of the research process, some assumptions were made. For instance, the BISTS are presented in long lengths without the interference of the required header pipes. This was done to simplify the simulation, and does not alter the results, since the area covered by the specific piping is much smaller than the area of the opening (<2%). Also, in relation to the simulation of performance of each system, for which values had to be imported (type of liquid values of $F_R U_L$ and $F_R(\tau\alpha)$, etc.), the average values of modules currently in the market and relevant literature were selected.

4 SIMULATIONS

4.1 Thermal Analysis

The direction of the research shifted towards the determination of the optimal layout of the above systems, which can offer the perfect balance of passive and active behavior. The diagrams of "Thermal Analysis" are exported from the software, where the best combination of layout / system can be found. Specifically, the energy loads required to keep the interior of this prototype building unit at levels of thermal comfort, are calculated. After that, the total annual required heating and cooling loads, were noted. In this way a comparison was made of the contribution in terms of sun protection offered in a quantitative manner by each system in various configurations. The high thermal capabilities of the simulated building and the minimization of the heat loss from the building unit, make any variation in the energy consumption of each case a result of the differentiation of the typology and geometry of the shading system, hence the different systems. The definition in the software of a "Mixed Mode" air conditioning system, undertakes the cooling or heating the room depending on simulation parameters. The range of the thermostat of this system was adjusted between 18 and 26°C, in order to provide thermal comfort within the test area, throughout the year.

Thus, the software gives the energy needs of the space in Wh for each layout, in order to accomplish the above, and having these we can easily determine the most advantageous passive solution.

4.2 Layouts

In Layout A, the simulated building is placed facing south, while the solar panels replace the 1 m wide and 5,6 m^2 area horizontal canopy. The 5 selected systems are placed according to Figure 9. In the Layout B, the simulated building is also placed facing on the south, but this time the solar panels replace, or are placed in front of the large glazing of 15 m^2 area (Fig. 9). The Layout C is the same with B, except the simulated building is placed in west orientation. However the linear geometry systems (Unglazed Flat Plate and Vacuum Tube Hydraulic Collectors) are placed in front of the large glazing in a vertical piping layout in order to provide the greatest sun protection, since they are in a west orientation (Fig. 9).

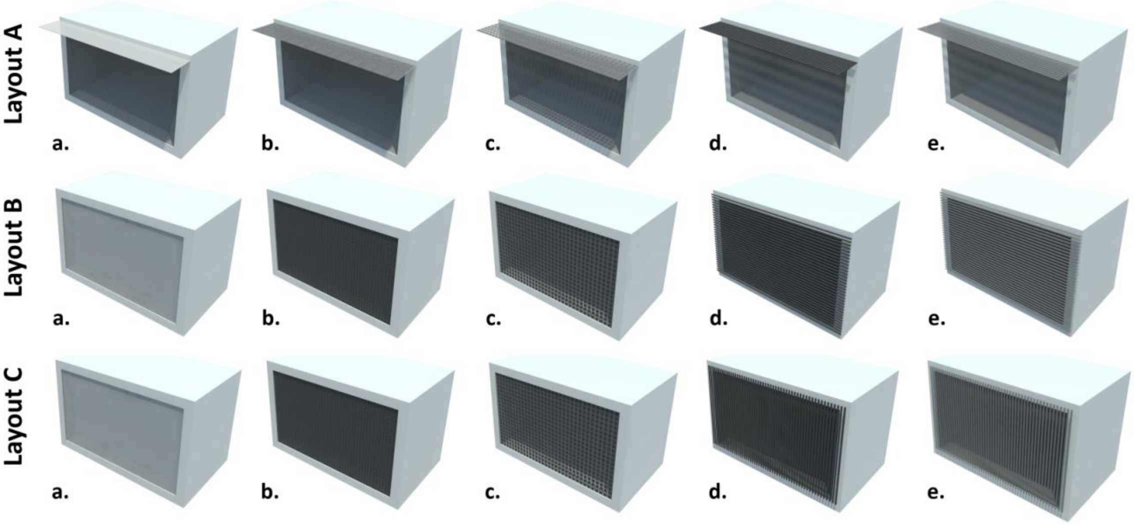


Figure 9. The five systems applied on the simulated building in the three Layouts: a. aSi Thin Film - Transparency 10%, b. Monocrystalline Semitransparent - Distance 5 mm, c. Polycrystalline - Distance 50 mm, d. Unglazed Flat Plate Hydraulic Collectors, e. Vacuum Tube Hydraulic Collectors. The differentiation of the orientation of the systems d and e in Layout C is evident.

4.3 Calculation of Systems' Production.

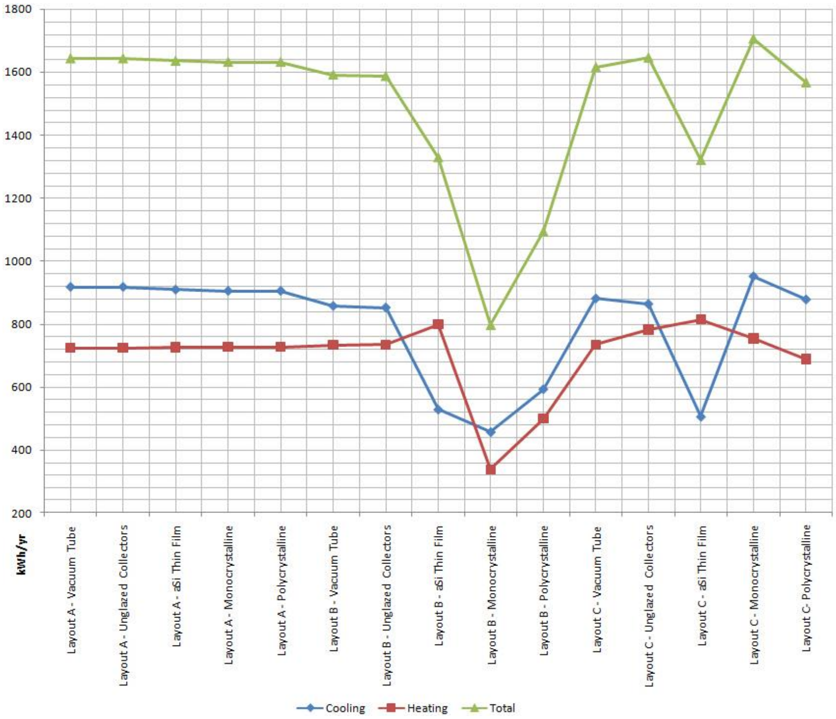
Given that the base of the research process lies on the use of an active system, beyond the analysis of its passive behavior, the definition of their energy contribution, plays a very important role to the research process. In the case of the PV, in order to calculate the potential generation of energy, the iSBEM CY was used, which is the user interface of the official free software Simplified Building Energy Model, which is designed and used for calculating the energy performance of buildings in Cyprus (Energy Performance of Buildings, 2014). The calculation of the energy production of STS is complicated and requires a lot of data in order to be accurate (piping dimensions, type of fluid, values of F_RU_L and $F_R(\tau\alpha)$ etc.). So for the objectives of the research, the characteristics of a particular commercial model was used, this of the "Apricus AP Evacuated Tube Solar Collector". In contrast to the above, the Unglazed Flat Plate Hydraulic Collectors are not as prevalent in the market, which makes their energy production calculation more difficult. Thus, in this case the calculations were made entirely by using data based on literature (Rosli et al. 2014). The realization of the simulations was done by using the Clean Energy Project Analysis Software Retscreen4 (RETScreen Software Package).

4.4 Primary Energy

In order to obtain reliable results from the research, the comparisons should be made with the same criteria. This lies on the difference between the active systems that are investigated, since the STS refer to kWh of thermal energy while the PV refers to kWh of electricity. Therefore for these values to be compared to the energy needs of the simulated building, they have to be converted into primary energy. The coefficients for the conversion is 1,1 for the thermal energy while 2,7 for electricity (Nearly Zero Energy Buildings (NZEB)).

5 RESULTS

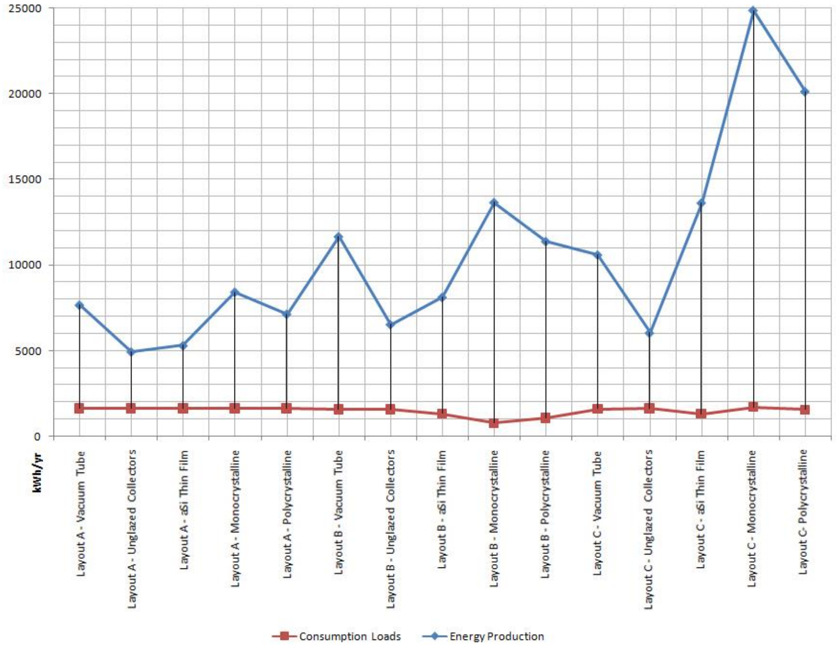
Initially, the total annual energy consumption of the simulated building unit is noted, which is divided into thermal loads, addressing the energy needed for the building in order to maintain indoor thermal comfort conditions during the winter and the cooling loads, needed in order to maintain indoor thermal comfort during the summer. These are presented for all the layouts and systems stated, in Graph 1.



Graph 1: Heating and Cooling loads.

Looking at Graph 1, we see a "stable performance" of the systems integrated in "Layout A", in relation to the simulated building's total energy consumption, which is around 1640 kWh / yr. Beyond that, there are significant variations in terms of energy consumption in the other layouts, with the Monocrystalline Semitransparent to have a very low energy consumption when they are placed under "Layout B", wherein the total energy consumption of the building unit is reduced to around 800 kWh / yr. The worst performance is observed when the same system is placed in "Layout C", in which the total consumption rises close to 1700 kWh / yr. A first observation is the fact that the combination of system - layout plays a significant role in the shaping of the outcome, rather than looking at the two separately.

However, the research also deals with active systems, wherein their relative positioning and area plays an important role in their performance. Thus, Graph 2 shows the overall annual primary energy production of each system, placed in each layout. This production is compared with the corresponding need for energy consumption, as described above. In this case it is observed that the energy production by the systems indicated has several variations and there is no "consistent" energy production in specific layouts. This is due to the difference in performance of each system in relation to the conversion of the solar insolation into heat or electricity. The system that offers the highest annual production of primary energy, is the Monocrystalline Semitransparent, when they are placed under the "Layout C", producing close to 25000 kWh/yr. This is probably due to the fact that in this orientation, solar incidence on the PVs is perpendicular for a long time of the day, which considerably improves their electricity production. In addition to quantifying energy production for each system, the purpose of Graph 2 is to visualize the relationship between energy production/consumption. It is observed that even in the lowest energy production cases the energy need of the building is much less. So we have a Positive Energy Building, through the integration and passive use of these systems.



Graph 2: Consumption / Energy Production.

To address the research question and indicate the most efficient combination of system / layout, both of the two important features of the research project must be taken into account, the combination of the passive and active behavior of the systems in various configurations. The combination of the two shows essentially the idealized configuration of passive and active system in a building unit. This is visualized in Graph 2, by the difference between the energy needs of the building unit and the corresponding energy production of each system. The greater this difference is, the more advantageous is the combination of each solution. It is observed that the biggest difference in energy production and consumption, is given by the Monocrystalline Semitransparent, when it is placed under "Layout C", and is close to the 21000 kWh / yr., and it is followed by the Polycrystalline also in "Layout C". This result shows that the western orientation combined with the vertical positioning and replacement of large glazing with Monocrystalline Semitransparent PVs, results in the best combination of passive and active performance by this integrated building system.

6 CONCLUSIONS

The wider aim of this research process is to highlight the most efficient way of integrating photovoltaic and solar thermal systems in a building unit, both from their active and passive side. Through the research process, the above results revealed that the combination of the ideal layout and the most efficient system for this layout, gives the best results. However, it is concluded that the combination of layout and system is more important than the system itself. For example, the use of Monocrystalline Semitransparent system in Layout C had the highest energy production, and also offered high sun protection, but it did not have the same performance on other Layouts. This also applies to Layout C, on which the aforementioned system performs adequately, while the other systems do not.

The observation that the most "conventional" typologies of passive sun protection did not perform as expected, led to the conclusion that even a slight declination in the geometrical layout of the systems from the conventional sun protection devices, has a significant impact on their ability to offer sufficient passive solar protection. Furthermore, it was observed that these "conventional" layouts are not offered in all cases for the use of integrated active systems, because in many cases these systems do not perform as expected. Subsequently, it was noted that photovoltaic systems have a significant advantage over solar thermal systems, regarding primary energy production and provision of solar protection. However, this does not mean that the STSs are inefficient, but it has to do with the need to compare similar systems. In fact, the choice between PV and STS is decided according to the need for a specific kind of energy (electric, thermal etc.) and geometry.

Finally, a general conclusion drawn across the whole project, is that integrating active devices in buildings with the dual character of solar protection / energy production is desirable, both for architectural / aesthetic reasons, given that they provide flexibility if design synthesis, while being economically feasible and efficient in terms of the production of electricity and / or heat.

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Towards the effective solar energy use in buildings in Lithuania

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ABSTRACT: The implementation of the Energy Performance of Building Directive (EPBD) in Lithuanian energy sector faces with a number of problems. One of the problems is the proper use of solar energy in Lithuania's climatic conditions. The solar collector installation projects are often criticized by the fact that the most of energy demand in building occurs during the periods when the solar energy radiation is low. However, the latest researches assume that the solar thermal technologies will be very soon one of the major renewable energy technologies for the low and medium temperature heat supply in buildings.

This paper represents the research which has been carried out in Lithuania concerning the use of solar collectors; which also analyzes the habits of Lithuanian consumer of hot water consumption at certain building types; which compares the energy consumption of different Lithuanian buildings depending on their class of energy performance. Obtained data are used in calculations of building energy performance.

This study is built on the objectives of contributing to the COST Action TU1205 "Building Integration of Solar Thermal Systems (BISTS)"

Keywords: solar thermal collectors, domestic hot water consumption, building energy performance classes.

1 INTRODUCTION

The building sector is responsible for more than 19% of the total of 38% of energy related to greenhouse gas emissions in Lithuania, which corresponds to the situation in other developed countries (Jaraminiene et al. 2012). The biggest part in environment pollution is formed by heating of buildings of 1960-1990 construction.

The Energy Performance of Building Directive became the EU policy instrument to improve the energy performance of building. The implementation of EPBD in Lithuania started in 2007. Directives of the European Union have set the new requirements of energy performance of buildings and use of renewable power sources which will have to be implemented from 2018 in newly erected public buildings, and from 2020 – in all newly erected buildings. If the existing housing was brought up to the current requirements in building regulations in Lithuania, 45% energy saving would be possible. The total amount of annual energy demand has to be covered by building integrated energy generation from renewable sources. Domestic hot water consumes nearly 20% of total energy consumption for an average family (Kishan et al. 2012). The energy demand in residential buildings can be decreased by reducing of domestic hot water consumption. Solar water heating systems are the most promising and most easily affordable energy available to homeowners. Long time scientific interest in exploring solar energy in Lithuania as energy source for heating and domestic hot water preparation was insignificant due to low and unstable solar irradiance and low energy costs. The situation began to change, when Lithuania became a member of the European Union and started to implement Directives of the European Parliament and European Council related with energy.

The majority of researches were carried out in energy policy area. Lithuanian researchers have made analysis in several aspects: renewable energy policy promotion and perspectives of usage renewable energy (Katinas et al. 2006), governmental policy and prospect in electricity production from renewables (Katinas et al. 2008), sustainable energy development – Lithuania's way to energy supply security and energetic independence (Katinas et al. 2014). This author has stated that the most attention should be taken in the energy production from renewable energy with special attention for local renewable energy resources and climatic conditions. Renewable energy promotion in Lithuania in compliance with the European Union strategy and policy was analyzed by Gaigalis (Gaigalis et al. 2014). The scientist stated that renewable energy and transport must have special financial support mechanism.

Lithuania receives 1,000 kWh/m^2 (total: 65 million kWh) of solar energy per year. But more than 80 percent of it is distributed during the 6 months from April to September. The solar thermal energy use is still not widely applied in Lithuania. According to the Ministry of Agriculture, in 2020, when other types of fuel become more expensive and new technologies developed, the prices of solar energy and of traditional generation of electric energy will become similar (Štreimikienė et al. 2014). However we have to pay special attention to the practices in Northern Countries.

In Europe the largest solar heating markets are present in the Southern and Central European Countries like Greece, Germany and Austria. The solar heating markets in the Northern European countries are not as good. In Denmark, Sweden, Norway and Latvia respectively 25%, 23%, 27% and 35% of the country's total annual energy consumption is used for heating of buildings, while the annual solar radiation to the horizontal surface of the Country is respectively 180, 1030, 1200 and 3130 times greater than the Country's total annual energy consumption (Furbo et al. 2014). It is evident that the use of solar heating systems is possible and has a big potential even in the Northern Countries. Although Greening (Greening et al. 2014) proposed that solar thermal collectors have slightly lower environmental impacts than other widely used domestic hot water preparation systems, their potential is hampered because they need a back-up heating system, typically a gas boiler. For this reason as well as due to a lack of suitable locations and poor efficiency, the potential of solar thermal systems to contribute to a more sustainable domestic energy supply in the UK is limited (Greening et al. 2014).

Calculation methodologies of renewable and non-renewable energy ratio used in building and determination of requirements for nZEB building were analyzed by (Tamasauskas et al. 2014). The energy demand for high (A, A+, A++) energy performance class building domestic hot water systems is almost three times higher than the energy demand for heating. The researcher statement was strengthen by one of Lithuania's city Elektrenai where consumption rates of domestic hot water in average relevant buildings has been higher to compare to values currently used for calculations from LST EN ISO 13790:2008 (Table 1).

Table 1. Comparison of domestic hot water consumption rates in Elektrenai city (Lithuania) average relevant buildings with the values currently used for calculations according to LST EN ISO 13790:2008.

Building category	According to LST EN ISO 13790:2008, kWh/m²	In Elektrėnai city, kWh/m²
Education buildings	10	28.6
Apartment buildings	20	19.2
Industrial buildings	10	24.9
Offices	10	18

This paper is built on the analysis of energy efficiency in buildings and case study of multi-story apartment residential houses in Lithuania by use of RES solutions and other innovative technologies, e.g.: innovative heating systems, individual regulation and metering, solar collectors.

2 ANALYSIS OF ENERGY EFFICIENCY IN MULTIAPPARTMENT BUILDINGS

The energy performance of a building is the total energy efficiency of a building, reflected in one or more numeric indicators taking into account insulation, installation characteristics, design and location, energy conversion in the building and other factors. Basic facts about Lithuanian housing stock:

- population <3,19 million;
- > 66 % of population lives in multi-apartment buildings built in 1961-1990;
- 97 % - private ownership, 3% - social housing.

The Construction technical regulation STR 2.01.09:2012 "Energy performance of buildings.

Energy performance certification" is intended for the implementation of the requirements of the new Directive 2010/31/EU, providing requirements for energy-efficient building envelopes, efficient energy use in buildings, and the use of renewable energy resources.

Lithuania has set the transitional requirements for newly constructed buildings in 2014, 2016, 2018, 2021 expressed by the energy efficiency classes of buildings (STR 2.01.09:2012).

New buildings or parts thereof must comply with the requirements of:

- till 1 January 2014 – for class C buildings;
- from 1 January 2014 – for class B buildings;
- from 1 January 2016 – for class A buildings;
- from 1 January 2018 – for class A+ buildings;
- from 1 January 2021 – for class A++ buildings.

The current analysis of energy efficiency of buildings according to the energy certification data shows that energy consumption in buildings is still very high. Energy costs in existing buildings (mostly D, E; F; G class buildings) are very high, so the renovation of these buildings (additional insulation, renewable energy sources) definitely has a very high potential for energy savings.

The major problem in the heating systems is inefficiency at the point of consumption – the annual average energy consumption for heating of Lithuanian building stock is 220 kWh/m², which is substantially higher than the average in Nordic Countries (128 kWh/m²) (National energy strategy 2010).

Lithuanian apartment houses by the amount of consumption of the heating energy (kWh/m² per month) are divided into 4 categories (Table 2).

Table 2. Energy consumption for heating in Lithuanian apartment housing (2011/2012 heating season) (Economic Activity Overview 2012).

Apartments	Energy consumption for heating, kWh/m²	Occupied part of building stock in Lithuania
Sustainable, new construction	9	4,6% 32'000 apartments (0.09 mln residents)
New construction (low or medium heat consumption)	19	17,3% 121'000 apartments (0.36 mln residents)
Existing old apartments, not renovated (high heat consumption)	27	55,7% 390'000 apartments (1.17 mln residents)
Existing old apartments, poor insulation (very high heat consumption)	40	22,4% 157'000 apartments (0.47 mln residents)

The thermal energy consumed in a house is measured by heat meter that show how much the house uses the thermal energy for heating. This amount of consumed energy is divided by the total floor heated area of the building this way acquiring the amount of used thermal energy for heating for 1m² per month.

According to the database (Table 3), the maximum quantities of certificated buildings have EP class G (54 %). It is because all currently non renovated typical existing old block houses (1960-1990) are automatically classified as class G. This is a trend observed in all EU countries where in some cases buildings from the 1960s are worse than buildings constructed in the years before that (Europe's buildings under the microscope 2011).

Table 3. The number of certificated buildings in Lithuania (2007-2014 year).

Energy performance class	Certificated buildings, unit	Percent of issued certificates, %
A, A+, A++	32	0.04
B	6854	8.79
C	10504	13.46
D	6333	8.12
E	7547	9.67
F	3932	5.04
G	42813	54.09
Total:	78015	100

The energy consumption for heating varies according to the energy performance class: the buildings with EP of class A, the energy consumption for heating takes 45,8 percent of the total energy consumption while the energy consumption for heating of buildings with EP of class C takes 87 percent of total energy consumption of building stock (Table 4).

Table 4. The ratio between the total and heating energy consumption of certificated buildings in Lithuania (2007-2014 year).

Energy performance class	Total energy consumption, $kWh/m^2/year$	Energy consumption for heating,		Heating energy from total, %
		$kWh/m^2/year$	$kWh/m^2/DD$*	
A, A+, A++	47,6	21,8	5,708	45,8
B	126,6	100	26,185	79,0
C	208,3	181,3	47,473	87,0

*DD – degree days (3819 at 18°C base temperature)

Renovation of residential buildings is an urgent problem in Lithuania. This need for renovation provides an opportunity to apply the solar energy strategies.

3 CASE STUDY OF RENOVATED HOUSE IN LITHUANIA

Solar systems are not a novel product in Lithuanian market. Significant amount of installations appeared over the last few years. However from this amount there are almost no BISTS (Building Integrated Solar Thermal Systems) installations. This tendency is strongly influenced by two factors. The first - Government policy, which promote a bigger compensation and buying of electric energy prices produced by building integrated solar photovoltaic systems (National Commission for Energy Control and Prices), but at the same it does not provide the clear definitions of house integrated systems. The second – belief in society (a strong conviction between sellers, designers, builders and owners) that solar systems are only the engineering elements with no architectural, aesthetic relation with building and its surrounding.

Three main building service systems - hot water, space heating and electricity for lighting and appliances are used in typical apartment house in Lithuania.

In our case study house in order to achieve more energy savings, it has been retrofitted and solar energy hot water system was installed. The views of Solar thermal system are presented in Figures 1, 2 and 3.

Figure 1. The view of house with the solar thermal system.

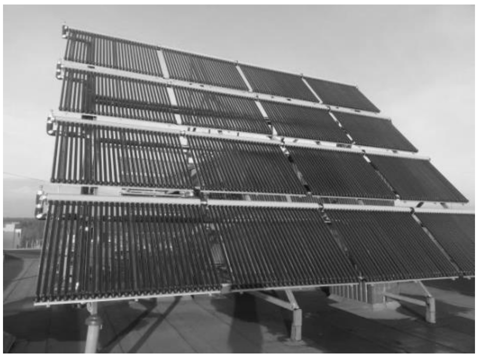


Figure 2. The solar thermal collectors.

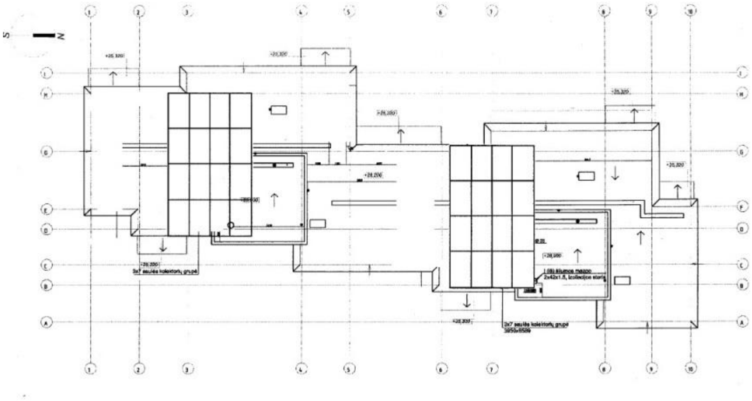
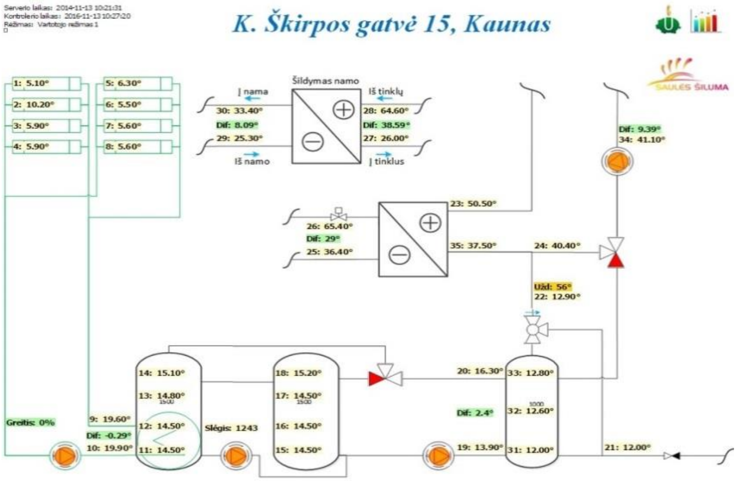


Figure 3. Roof plan of the house with the solar thermal system.

Main parameters of the building and the solar thermal system: house' year of construction - 1978 (retrofitted in 2013); 9 storied, 54 apartments; total floor area - 2178 m^2; installation year of Solar thermal system - 11/2013; capacity of installed Solar thermal collector's - 69.824 kW;
Collectors' total area - 155.55 m^2; collectors' orientation - South; tilt angle - 45°.



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Kontrolerio laikas: 2016-11-13 10:27:20
Režimas: Vartotojo režimas 1

K. Škirpos gatvė 15, Kaunas

Figure 4. The domestic hot water solar heating system is controlled and monitored through the internet.

3.1 Solar domestic hot water heating system

In this case study the solar thermal collectors are used only for heating of domestic hot water. The system was installed on the roof of a building and it consists of evacuated tubular solar thermal collectors, 3 units of storage tanks located in a basement and water preheat system in a boiler room. According to hygienic requirements in huge solar energy in systems domestic hot water have to be heated by fresh-flowing water heating principle without collecting it into tanks. In our case study house for storage of solar energy two 1500 liter tanks are used (one storage tank consist of 2 heat exchangers, total area 5, 9 m^2, another tank - without heat exchanger). Preheating of primary cold water is carried out in 1000 liters preparation tank of water mixing capacity. The case of lack of energy from Solar system domestic hot water is heated to desired temperature from the district heating network. The system is designed for periodical raise of temperature in domestic hot water heating system for the hygienic antibacterial disinfection of pipelines. The capacity of collector's solar energy power absorber is around 1000 W/m^2. The pipelines are thermally insulated. The outside located pipelines are additionally isolated by the UV protective cover. The whole process is controlled by central controller with flow and temperature measuring sensors. Process could be controlled and monitored through the internet access.

3.2 System exploitation analysis

The amount of energy used for domestic hot water heating from the district heating network during sun dominating months (May-September) is presented in (Figure 5).

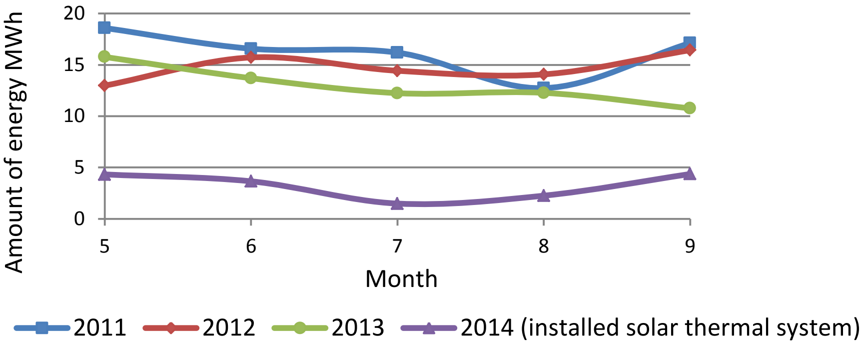

Figure 5. Amounts of energy used for domestic hot water heating from the district heating network during sun dominating months

This data show that solar thermal system during these months could reduce amounts of energy from 3 to 4 times depending on a month. It should also be taken into account that energy used for domestic hot water preparation is used for heating of water and hot water circulation. Analysis of these components amounts in Kaunas city apartment buildings (Table 5) has revealed that depending on the energy performance class of a building energy use for circulation varied from 50% to 150% compared to energy use for heating of hot water. Consequently the more energy efficient building the lower demand of energy for circulation, but circulation still takes a significant portion of energy consumption in a building. According this data hot water circulation coils in bathrooms were replaced into electric heaters during reconstruction, in order to optimize domestic hot water heating system and minimize the energy need for hot water.

During non-sun dominating months (November-April) amounts of energy consumed in case study house and other buildings remained almost stable. Small fluctuation could be assigned to user's behavior. Significant changes in case study house occurred only in April, when solar radiation increased.

Table 5. Average energy consumption for domestic hot water (DHW) preparation and domestic hot water circulation in different energy performance class apartment houses in Kaunas city (Lithuania) (2007-2014 year)

Group of building due to energy consumption	Very low energy apartments (new construction, high quality houses)		Low and medium energy apartments (new construction, heat-efficient houses)		High energy apartments (old buildings with poor thermal insulation)		Very high energy apartments (old buildings with very poor thermal insulation)	
Energy class	C		D		E		F/G	
Average energy consumption MWh	DHW	DHW circulation	DHW	DHW circulation	DHW	DHW circulation	DHW	DHW circulation
2007	7,62	5,71	7,45	9,23	7,80	11,18	5,55	1,14
2008	8,42	5,21	7,29	9,22	8,20	11,25	6,33	1,14
2009	8,95	4,81	7,90	10,00	7,63	11,29	7,38	1,21
2010	9,16	5,42	8,31	10,41	7,20	11,27	6,88	1,87
2011	9,6	4,54	7,95	9,93	7,11	11,48	6,19	2,88
2012	9,60	4,95	8,45	8,65	7,20	10,56	6,22	8,49
2013	9,17	4,67	7,97	9,07	7,14	11,01	5,73	8,54
2014	8,96	4,51	7,69	9,09	7,53	11,19	6,11	8,55

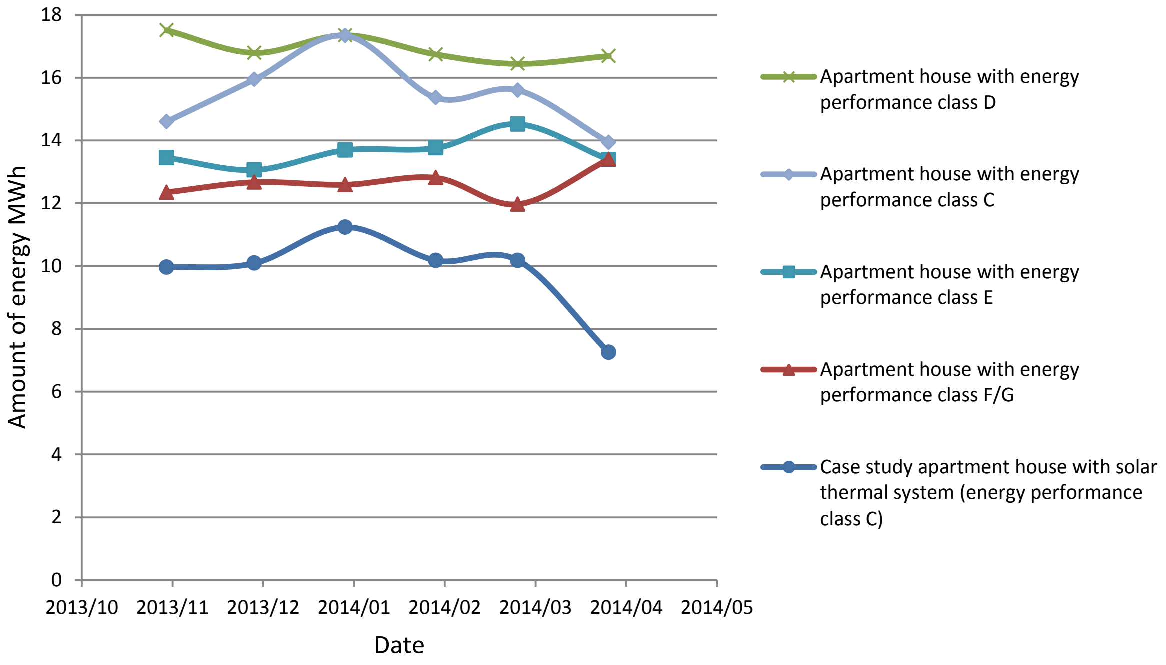

Figure 6. Amounts of energy used for domestic hot water preparation and domestic hot water circulation in different energy class apartment houses from district heating during non-sun dominating months.

4 CONCLUSIONS

Renovation of residential buildings is an urgent problem in Lithuania and many other new EU member states. This need for renovation provides an opportunity to apply solar energy strategies.

Energy certification increases the understanding of energy consumption and allows us to compare buildings, motivating the builders to increase the energy efficiency in buildings.

The reduction of energy consumption of domestic hot water heating systems is a considerably difficult task. It is clear that the largest energy saving potential is related with the older building stock due to the highest heating energy consumption. The use of solar thermal collectors is expected to reduce the net energy demand for domestic hot water up to 10 - 32 kWh/m^2 of occupied floor area per year. For the case study example the 7% of solar collector's system area from the total floor area of a house is the optimal ratio in Lithuanian climatic conditions. It is a need to elaborate the general procedure to select, install and monitor the solar water heating systems concerning the availability of solar radiation and local geographical conditions. The currently existing standard apartment house retrofitting and modernization guidance projects should be fulfilled by BISTS recommendations.

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Consideration of Certain Health Issues Related to Solar Hot Water Systems

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ABSTRACT: In the process of design and development of building integrated solar hot water systems (SHWS), in addition to functional, technical and aesthetic, aspect of health have to be taken into consideration. The subject of this paper is the impact that makes water on the surface of metal pipes and heater-heat exchanger and effects on potable water quality and human health. Corroded areas are places where metal ions pass into the water, resulting in a continuous increase in the amount of metal ions in water which can compromise human health. Changes can occur in all human organs including the oral cavity. In order to remain healthy consumers, it is necessary to examine the causes and consequences of increased amount of metal ions in potable water. The methodological approach includes consideration of the problem of corrosion of heater-heat exchanger, discussion of the impact of metal ions on human health and observation of the prevention measures. The aim is to point out the existing problems and ways to overcome them through the process of designing and constructing the SHWS.

Keywords: SHWS, heat exchanger, human health, drinking water quality, metal ions.

1 INTRODUCTION

The building sector, which accounts for ca. 40% of total final energy consumption in Europe, provides good opportunities for energy savings (Bloem & Atanasiu, 2006). Energy consumption in buildings is mainly for heating, cooling and for the provision of hot water. Appropriate building design, implementation of renewable energy sources and rational use of energy in buildings, can reduce energy use in buildings, consumption of pollutant energy sources and thereby reduce CO_2 emissions (Krstic-Furundzic & Kosoric, 2009). Solar thermal collectors (STC) have a significant role in reducing energy consumption in buildings and thus reducing environmental pollution. It is well known that the hot water consumption in buildings is significant. For this reason, there is an increasing number of integration of solar hot water collectors (SHWC) in the building envelope and scientific publications indicate that depending on the design variants of integration (orientation, inclination, type and color of SHWC) savings can vary from 30% to 50 or 60% (Golic et al., 2011, Krstic-Furundzic et al., 2012). Development of the SHWS is on the rise, but besides technical and functional improvements, it is important to improve the system in terms of security, including the prevention of ill-effects on human health.

Solar systems for water heating in addition to its energy efficiency must be harmless to human health. This paper is referred to the materials used for production of heaters-heat exchangers that are immersed in lumen of the boiler. Since these heaters are made of materials that are used for water pipes construction, the review of the scientific papers that discuss the behavior of the tube for drinking water distribution is conducted, especially as these experiences are based on decades of testing the impact of water on the surface of the pipe. Drinking water quality affects human health. In addition to the natural characteristics of water, which are related to the location and source, the composition of the water is significantly affected by pipes material, the degree of corrosion of the internal surface of the metal pipe and the flow rate of water through the pipe.

In the paper the methodological approach includes:

- consideration of the problem of corrosion of heater-heat exchanger;
- discussion of the impact of metal ions on human health;
- observation of the prevention measures.

2 CONSIDERATION OF BEHAVIOR OF METAL TUBES OF HEATERS-HEAT EXCHANGERS IN CONTACT WITH TAP WATER

This chapter is devoted to the problem of corrosion of heater-heat exchanger.

Metal tubes of heater, i.e. heat exchanger in case of solar hot water systems (SHWS) are immersed in water and make chemical reactions. Because of these reactions, metal ions transfer from surface of the tube into the water. The surface of the tube has protective film. The protective film on the surface of the tube is made of metal oxides. There are conditions when the film is weakened. Weakened place is called pitting corrosion and it is a common type of corrosion that occurs in situations where tubes have direct contact with tap water (Figs 1, 2). The first stage of pitting corrosion is the moment when metal oxides are demolished and free metal ions run into the water, causing problems like blue water and metal taste. Also, there are limited values of metal ions in tap water which are strictly defined by the relevant standards.

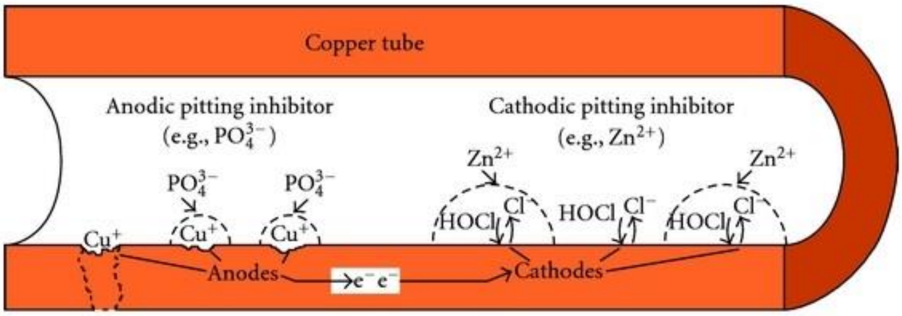

Figure 1. The mechanism of pitting corrosion of copper http://www.hindawi.com/journals/ijc/2012/857823/fig1/

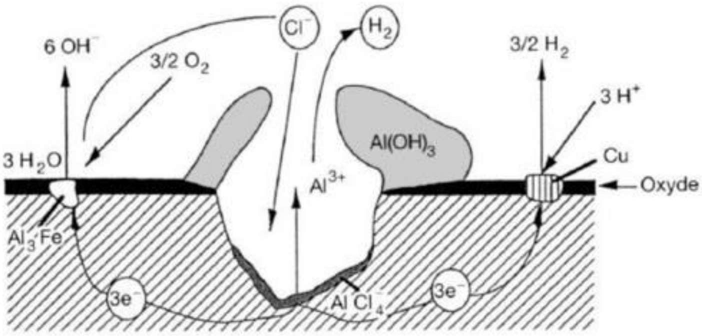

Figure 2. The mechanism of pitting corrosion of aluminium (Vargel C., 2004)

Characteristics of water quality (pH, electric conductivity, elements in water), movements of the water and procedures of making alloys for tubes are circumstances that are affecting the appearance of pitting corrosion on tubes. The resistance to corrosion is better in running water than in stagnant water, so the rate of pitting corrosion is higher in stagnant water. The reason is that the running water removes corrosion products and local excess of hydrogen and hydroxide ions (Vargel, 2004; Szklarska-Smialowska, 1998; Ambat, 2006).

Most common metals used for heaters-heat exchangers are copper and aluminum, so in tap water can be expected ions of these metals. According to some standards there are limited concentrations of these ions.

A revised Public Health Goal (PHG) of 300 parts per billion (ppb) has been developed for copper in drinking water, based on a re-review of the scientific literature since the original PHG, developed in 1997 (PHG, 2008). Results from a number of studies from Europe, Canada and the USA indicate that copper levels in drinking-water can range from ≤0.005 to >30 mg/litre, with the primary source most often being the corrosion of interior copper plumbing (US EPA, 1991; Health Canada, 1992; IPCS, 1998; US NRC, 2000). Copper piping used for water distribution can add 0.1mg/day to intakes in hard water areas but 10x this amount in acid and soft water conditions (Ralph & Arthur 2000). The current EU standard is 2 mg/l for the maximum concentration of copper in drinking water (EU Directive, 98/83). Concentrations that are greater than these values may cause toxic effects on the body, i.e. acute and chronic poisoning or illness.

One possible application for aluminium in tap water is aluminium in water pipes. In this application the aluminium content in the water is a critical parameter due to regulations; the limit is set for practical reasons, not for health considerations (Gustafsson, 2011).

A health-based value derived from the JECFA (Joint FAO/WHO Expert Committee on Food Additives) and PTWI (Provisional Tolerable Weekly Intake) would be 0.9 mg/l (rounded value), based on an allocation of 20% of the PTWI to drinking-water and assuming a 60 kg adult drinking 2 litres of water per day; however, practicable levels based on optimization of the coagulation process in drinking-water plants using aluminium-based coagulants are 0.1 mg/l or less in large water treatment facilities and 0.2 mg/l or less in small facilities; in view of the importance of optimizing coagulation to prevent microbial contamination and the need to minimize deposition of aluminium floc in distribution systems, it is important to ensure that average residuals do not exceed these values (WHO, 2004b).

3 DISCUSSION OF THE IMPACT OF METAL IONS ON HUMAN HEALTH

Domestic hot water can be obtained from the boiler with electrical or gas heaters or from a SHWS. Based on the previous considerations it can be concluded that the above-mentioned metals, which are commonly used for creation of heaters-heat exchangers, are subject to corrosion. Water is constantly stored in the boiler, and during the heating of the water usually no or minimal water flow is present. After a certain time, corrosion appears on the surface of the metal heater-heat exchanger immersed in the lumen of the boiler. This occurs in both cases, when the water is heated by electric heaters, as well as when the water is indirectly heated via a heat exchanger in case of SHWS. Corrosion as a chemical process that occurs on metal surfaces, leads to a reduction in the thickness of the metal surface, which results in leakage in a certain time. Corroded areas are also the places where metal ions pass into the water, resulting in a continuous increase in the amount of metal ions in water. Flow rate of water affects the speed at which metal ions pass into the water. Therefore, the water may contain a significant concentration of metal ions and metal salts, which is higher than the allowed maximum value defined in the respective standards. The increase of amounts of metal ions and metal salts in potable water can compromise human health. The longer the period of time of entry of increased amounts of metal ions and metal salts into the body, the greater damages of organs are caused.

3.1 Impact of high concentration of cooper ions in tap water on human health

Increased levels of copper in the water can lead to violations of human health. Changes can affect different organs with plenty of specific and nonspecific symptoms (Fig. 3). Copper ions are normally present in the human body and participate in the normal functioning of the body. Higher concentrations of copper than allowed lead to an imbalance in the body.

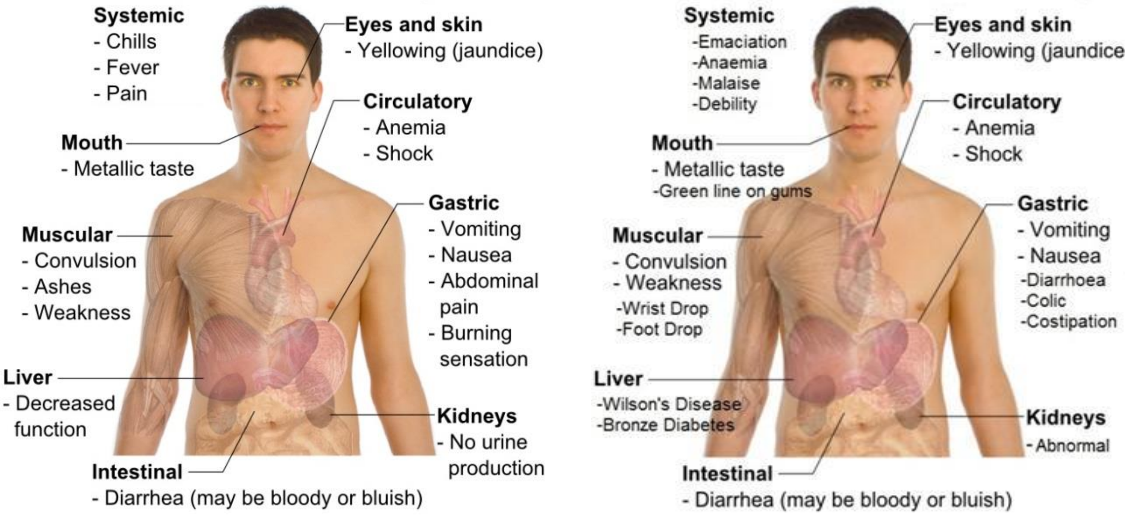

Figure 3. Main symptoms of acute (left) and chronic (right) copper poisoning (Ashish et al. 2013)

Acute exposure of higher concentration of copper ions can cause symptoms typical of food poisoning like headache, nausea, vomiting, diarrhoea (WHO 2004a). Among outbreaks with quantitative data, the lowest copper concentrations associated with effects were about 4mg/litre or higher (WHO, 2004a).

Also, European Commission gives reports on the acute toxicity of the human body caused by copper (EC, 2003): acute symptoms include salivation, epigastric pain, nausea, vomiting and diarrhoea (Olivares & Uauy 1996). Copper ions have an irritant effect on mucosal membranes and daily intakes ranging from 2 to 32mg in drinking water have been reported to cause symptoms of general gastric irritation (US EPA, 1987).

In the oral cavity can be also seen changes that are caused by long term exposure to increased concentrations of copper in drinking water like oral submucous fibrosis. Oral submucous fibrosis is chronic disease affecting the oral cavity; numerous scientific studies show that there are changes in the oral cavity due to the increased concentration of copper in the body (Gupta et al., 1987).

It is not realistic that large amounts of copper can be entered via the drinking water, since the change of water color and the taste (metal taste) are easily noticeable and indicate that the water should not be used.

3.2 Impact of high concentration of aluminium ions in tap water on human health

There is little indication that aluminium is acutely toxic by oral exposure despite its widespread occurrence in foods, drinking water and many antacid preparations (WHO, 1997).

Certain studies have shown that short-term exposure to high concentrations of aluminum in drinking water can cause a variety of health problems-acute toxicity. Report, made by Clayton, explains that in 1988 a population of about 20,000 individuals in Camelford, England, was exposed for at least 5 days to unknown but increased levels of aluminium accidentally distributed to the population from a water supply facility using aluminium sulfate for water treatment; symptoms including nausea, vomiting, diarrhoea, mouth ulcers, skin ulcers, skin rashes and arthritic pain were noted. It was concluded that the symptoms were mostly mild and short-lived; no lasting effects on health could be attributed to the known exposures from aluminium in the drinking water (Clayton, 1989).

A number of studies were carried out to determine if aluminium could cause dementia as a consequence of environmental exposure over long periods (long-term exposure). Aluminium was identified, along with other elements, in the amyloid plaques that are one of the diagnostic lesions in the brain for Alzheimer disease, a common form of senile and pre-senile dementia (WHO, 2010). A study by Rondeau found that high aluminum levels in drinking water (≥0.1mg/l) were associated with an elevated risk of dementia and Alzheimer's disease (Rondeau et al., 2000). Numerous epidemiological studies have been carried out to try to determine the validity of this hypothesis. These have been reviewed in detail by several authorities, including JECFA (FAO/WHO, 2007; WHO, 2007), the United Kingdom Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT, 2005), the United States Agency for Toxic Substances and Disease Registry (ATSDR, 2008) and Environment Canada & Health Canada (2010).

The conclusion of the recent JECFA (Joint FAO/WHO Expert Committee on Food Additives) evaluation (FAO/WHO, 2007) was that "some of the epidemiology studies suggest the possibility of an association of Alzheimer disease with aluminium in water, but other studies do not confirm this association…. All studies lack information on ingestion of aluminium from food and how concentrations of aluminium in food affect the association between aluminium in water and Alzheimer disease." There are suggestions that some genetic variants may absorb more aluminium than others, but there is a need for more analytical research to determine whether aluminium from various sources has a significant causal association with Alzheimer disease and other neurodegenerative diseases (WHO, 2010).

4 CONCLUSIONS

Nowadays solar hot water system is desirable component of building. Water heaters are subject to corrosion. In order to remain healthy consumers, it is necessary to examine the causes and consequences of increased amount of metal ions in potable water. In this sense, this problem should be taken into consideration when designing systems for water heating, including SHWS, in fact when choosing materials and technical solutions in order negative effects to be avoided.

The resistance to corrosion is better in running water than in stagnant water, so the rate of pitting corrosion is higher in stagnant water. In the boiler water stagnates, which reduces resistance to corrosion.

This paper point out the existing problems and in order to overcome them through the process of designing and constructing the SHWS following conclusions can be listed:

- it is important to use the heaters manufactured in a factory with a certificate for the function of heating drinking water; production at the factory gives controlled quality of materials and products;
- it is necessary that the heater is made of a continuous piece of tubing in order to avoid connecting tubes inside the boiler because the joints quickly corrode;
- connection between the heater and water pipes should be outside the boiler;
- heater does not need to have a strong angulation of tubes; places of extreme angulations are poorly resistant to corrosive processes.

Heat exchanger and heater are tubes through which the fluid flows. This fluid can be water, but recently fluid with antifreeze agents is used. The reason for the transition from water to fluid with antifreeze agents are large fluctuations in temperature during the day and night in winter period. These oscillations can be observed during the winter months, especially in northern countries. If pots appear in the tube of heater-heat exchanger, as a result of corrosion, leakage occurs and in drinking water can be found antifreeze compounds that can significantly impair the health of users. So, in spite of high concentrations of metal ions and metal salts, the presence of other compounds that exceed the lumen of the heater into the lumen of the boiler can be expected in some cases, which can have an impact on human health.

Periodically water sampling and its analysis in certified laboratories is a way for early detection of contaminated water. Results can be used for monitoring the state of the heater as the component of solar hot water system.

ACKNOWLEDGMENTS

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Economic aspect of solar thermal collectors' integration into facade of multifamily housing

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ABSTRACT: The subject of this research is the Life cycle costs analysis of the building in order to evaluate the economic efficiency and cost-effectiveness of investments in various variants of application of active solar systems in aim to achieve the reduction of energy consumption and environmental pollution.

Different variants of solar thermal collector's application to the existing prefabricated residential building in the settlement Konjarnik in Belgrade, Serbia, are considered from the economic point of view. Cost-effectiveness and feasibility of various scenarios of energy optimization achieved by application of solar thermal collectors into the building envelope are evaluated on the basis of final energy consumption (within the EU-ISO standards).

The methodological approach involves the analysis of the costs of energy consumption for water heating, financial analysis of costs and savings over the life cycle of the existing building in case of solar thermal collectors' application to the building envelope as well as a comparative analysis of achieved results. Criteria for the economic analysis include the amount of investment, energy costs and life cycle costs of the building. According to the adopted criteria, the most suitable models are selected. This methodological approach is generally applicable in the analysis of investments in improvement of building energy performances, while possible technical solutions and the resulting economic benefits must be carefully considered.

Keywords: solar thermal collectors, investment projects, life cycle costs analyses, life cycle savings, greenhouse gases emissions.

1 INTRODUCTION

New energy-efficient buildings represent a small percentage in relation to the total building stock. Until the seventies, in Belgrade, buildings were designed without consideration of energy demands and consumption (Krstic-Furundzic & Djukic, 2009). According to the data collected by Serbia's Statistical Office, about 55 percent of the total of 583,908 existing housing units in Belgrade was built in this period (Krstic-Furundzic & Bogdanov, 2010). This figure reveals that Belgrade's building stock has a significant number of buildings whose energy performance has to be improved. It should not be disregarded because significant energy savings and reduction of fossil fuels consumption can be achieved.

In the paper, solutions for reducing energy consumption for water heating in existing housing are examined from economic point of view.

The methodological approach includes the analysis of the costs of energy consumption for water heating, financial analysis of costs and savings over the life cycle of the existing building in case of solar thermal collectors' application to the building envelope as well as a comparative analysis of achieved results. Criteria for the economic analysis include the amount of investment, energy costs and life cycle costs of the building. According to the adopted criteria, the most suitable models are selected. This approach could generally be applicable for building refurbishment, but generalization of technical solutions and possible benefits have to be carefully individually considered.

2 METHODOLOGY

During 1950's to 1970's, lot of suburban settlements had been built in Belgrade. The residential buildings in settlement Konjarnik, as the model on which different design variants and possibilities for improvements of energy performances by application of solar thermal collector systems are analysed and discussed from the aspect of energy benefits in a few papers by authors Krstic-Furundzic & Kosoric (2009a; b). Those scenarios are analysed from economic point of view in this paper.

Figure 1. Location of Konjarnik on the map of city of Belgrade.

Figure 2. Typical building with attic annex.

The analysis in the paper is hypothetical and it aims to show economic benefits of solar thermal collector system application on residential buildings in Belgrade climate. Methodological access includes description of the model for economic analysis, evaluation of economic efficiency, LCC analysis of variants of solar thermal collectors' application and comparative analysis of achieved results.

2.1 Description of the model for economic analysis

Settlement Konjarnik begins 4 km south-east of downtown Belgrade and stretches itself over 2 km (Fig. 1). It is selected for the analysis as settlement consisted mainly of typical buildings (Fig. 2) built in 1960's and 1970's. The settlement is characterized by large rectangular shaped residential buildings with typical south-north orientation, more exactly deviation of 10˚ to southwest is present (Fig. 3).

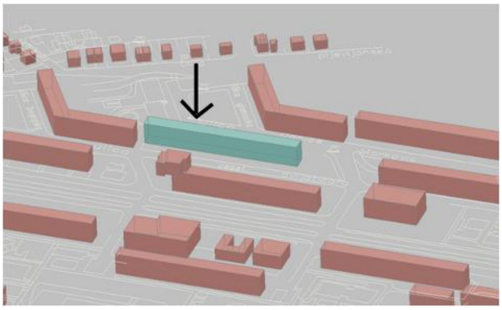

Figure 3. Buildings disposition in Konjarnik settlement

The selected multifamily housing, the 8-storey building, has rectangular and compact form and consists of 5 lamellas. It is located in a semi-closed block, on the south oriented hillside. The neighbouring buildings are sufficiently far to prevent overshading. One of the central lamellas, with four one-side oriented flats, is chosen for the analysis. As shown in Figure 2, facades oriented south and north consist rows of windows and parapets, which represent 70% and loggias, which represent 30% of facade surfaces (Krstic-Furundzic & Kosoric, 2009a). Existing refurbishment strategies applying on these residential buildings are transformations of flat roofs into slopping roofs by attic annex, which was action organized by municipality and glazing of loggias, which was illegal action usually realized by tenants (Krstic-Furundzic, 2010).

As the buildings in the analyzed settlement consisted number of lamellas, and as in the analysis of possibilities for solar thermal collectors application on south-west oriented facade and roof surfaces was selected central lamella (Krstic-Furundzic & Kosoric 2009a, b), in the paper evaluation of economic efficiency and feasibility were done for the same lamella. Authors of design variants calculated thermal energy for water heating (20-50˚C) according to number of apartments and occupants inside one lamella altogether which presents 251 kWh per day, i.e. 91,618.3 kWh per year for one lamella and the existing water heating system fully based on electricity was substituted with the new system – solar thermal collectors (AKS Doma –manufacturer), with the auxiliary system powered by electricity (Krstic-Furundzic & Kosoric 2009a, b). Solar thermal collectors with liquid working medium had been proposed. According to Polysun 4 Version 4.3.0.1., which was used for the analyses of energy contribution of solar thermal collectors, Belgrade is the city with global irradiance of 1341.8 kWh/m^2, and 2123.25 sunny hours per year (Krstic-Furundzic & Kosoric, 2009a; b).

Modern architectural concepts, which are based on rational energy consumption of buildings and the use of solar energy as a renewable energy source, give the new and significant role to the roofs (Krstic-Furundzic, 2006) and facades that become multifunctional structures. By application of solar thermal collectors, multifunctional roofs and facades could be created.

Four variants of position of solar thermal collectors on building envelope, designed by Krstic-Furundzic & Kosoric (2009a; b), are taken into consideration in the analysis of economic efficiency and cost-effectiveness of investments (Fig. 4).

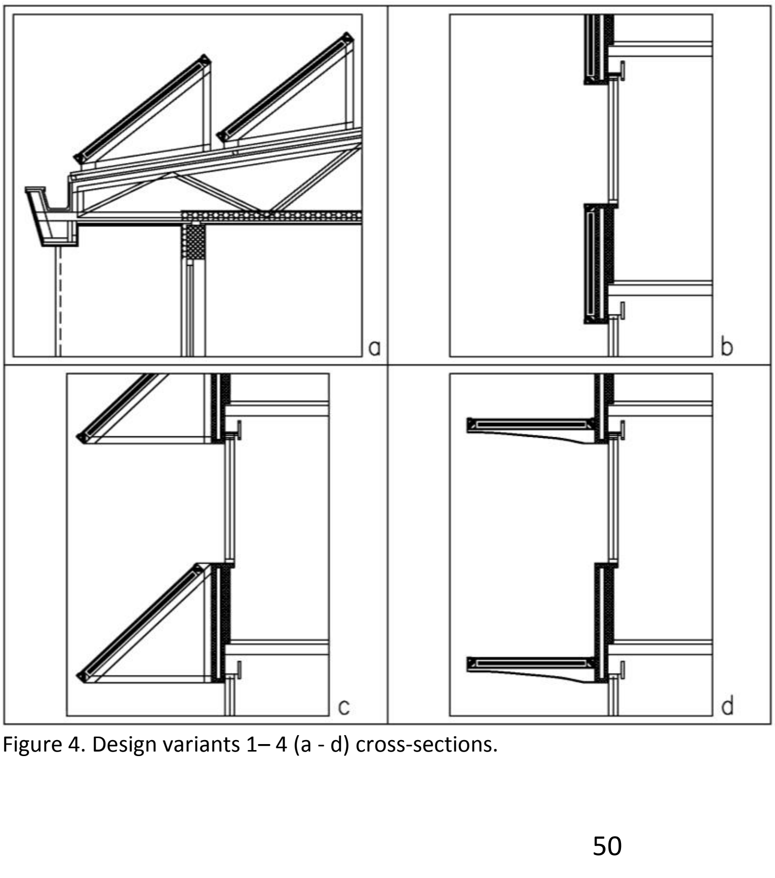

Figure 4. Design variants 1– 4 (a - d) cross-sections.

Variants of position of solar thermal collectors on building envelope are: 1) variant - solar panels mounted on the roof and tilted at 40˚, area of 100 m^2 (Fig. 4a); 2) variant - solar panels integrated in parapets (vertical position-90˚), area of 90 m^2 (Fig. 4b); 3) variant - solar panels integrated in parapets and tilted at 45˚, area of 120 m^2 (Fig. 4c); and 4) variant - solar panels integrated as sun shadings (horizontal position-0˚), area of 55 m^2 (Fig. 4d); which is described in detail in Krstic-Furundzic, & Kosoric (2009a; b).

2.2 Evaluation of economic efficiency

The goal of this LCC analysis is to evaluate economic efficiency and feasibility of different scenarios of solar thermal collectors' application into the envelope of existing multifamily housing in Belgrade and their impact on the environment.

The economic assessment includes LCC analysis of four scenarios that evaluates feasibility of solar thermal collectors' integration in the building facade and roof in order to reduce electricity demands from public electrical distribution network. Economic efficiency of accomplished energy optimization of presented variants is assessed according to final energy consumption (Krstic-Furundzic et al., 2013).

LCC analysis are carried out by Net Present Value methodology, which implies present value of investment plus discounting of all future costs to present value, and is suitable for comparative assessment of several different scenarios (different energy improvements of the same building). The LCC analysis which deals with application of solar thermal collectors for water heating is carried out as cost analysis through whole lifecycle of analysed components (WLC – Whole Life Cycle) (König et al., 2010). In addition to life cycle costs, this analysis includes also monetary benefits from electric energy feed-in tariff related to exploitation of solar energy.

Selected tool for LCC analysis in this study is BLCC (Building Life Cycle Cost) software, version 5.3-12 (EERE, 2012). BLCC software was developed by United State Department of Energy and it is used for calculation of buildings life-cycle energy savings. The LCC calculations are based on the FEMP (Federal Energy Management Program) discount rates and energy price escalation rates which are updated and published every year on April 1. With certain modifications, this software was used in several investment analyses in Serbia which required feasibility study for different models of optimization of facade, building structure, lighting and heating system (Plavsic & Grujic, 2005).

Evaluation criteria of the analyses results are divided into two groups (Plavsic, 2004):

1. Evaluation criteria for financial efficiency of each scenario include:
- Net Present Value (NPV);
- Adjusted Internal Rate of Return (AIRR);
- Simple Payback Period (in years).
2. Evaluation criteria for external effects include:
- protection and conservation of the environment;
- sustainability of energy resources.

Final efficiency assessment of the design and its scenarios (using computer software BLCC) is expressed in two areas:

- assessment of financial and market efficiency of the design, which determinates feasibility of the investment under real market conditions, measured by accumulation;
- assessment of social and economic efficiency of the design which evaluate the effects on social and economic development of the country.

Design scenarios are ranked by each criterion in final stage of the analysis. BLCC software provides choices such as:

1. design scenario which is most favourable in terms of lowest LCC.
2. design scenario with shortest Simple Payback Period.
3. design scenario with lowest emission of greenhouse gases.

With the assumption that lowest LCC and shortest SPP are of equivalent importance, final selection of the best scenario would be the one that best meets both criteria.

2.3 Criteria for efficiency evaluation

Criteria for efficiency evaluation include economic efficiency criteria and external effects.

Economic efficiency criteria involve:
Adjusted Internal Rate of Return (AIRR) - represents the discount rate which is investment value reduced to zero. This data indicates optimal ratio of income (savings) and expenses (costs) during economic life cycle of building.

Net Present Value (NPV) - is the sum of income during building life cycle which is reduced to its value of the first year of its life cycle (present value). Net Present Value presents an absolute indicator of profitability of the design taking into account the time preferences and, using discounting technique, it reduces all future design effects to their present value. For practical reasons, the initial investment period of building economic life cycle (beginning of investment study) is taken as base time for calculation of NPV. Discounting is performed according to previously established discount rate (usually the individual discount rate that makes the weighted arithmetic mean of real interest rates on funding sources). The discount rates of 10-12% are traditionally used by The World Bank for all funded projects. However, as the entire calculation in this study was done in euro currency, the average interest rate in Western Europe was taken into account. In this case, NPV is calculated for savings - as a specific design profit.

Simple Payback Period (SPP) - refers to necessary time (in years) for return of initial investment. Invested funds are returned in the year when the cumulative net effects of economic life cycle become positive. The aim is to reduce a simple payback period (value SPP), in order to be as short as possible. The acceptable payback time of the initial investment is considered to be before the end of last year of economic life cycle. Data such as initial investment, annual costs and balance saving during life cycle of the design are used to calculate SPP. Building Life Cycle Cost (BLCC) software operates with simple payback period, which is simple ratio of initial investment increased for all annual costs and savings (as the equivalent of income in one year).

External effects involve:
Different social and economic effects which do not need to be quantified. For improvement of energy efficiency these effects are of great social benefits such as conservation of the environment and non-renewable resources, influence on technical progress, quality of life of the population, increase of consumer surplus, etc.

2.4 LCC analysis of variants of solar thermal collectors‘ application

Comparative LCC analysis of the existing building model and different variants of solar thermal collectors’ integration in the building roof or facade takes into account: (a) capital costs, (b) energy costs - costs of electric energy consumption for water heating (electric boilers) from public network, (c) energy costs/incomes - feed-in tariff for renewable energy sources and (d) operating, maintenance and repair (OM&R) costs of installed solar system.

In this study, feasibility of investment in solar thermal collectors system, which would substitute certain percentage of production of hot water in the building, is estimated according to consumption of final electrical energy (from renewable and non-renewable sources).

2.5 Investment

A capital investment is considered as onetime cost in the first year of the economic life cycle of the project.

In the analysis of solar thermal collectors’ integration into the building facade and roof, the value of complete installed system for each scenario is based on average value per 1m^2 of solar collector panel. According to manufacturer, the average price of solar collector system for hot water is 700€ per 1m^2 of solar panel. For four scenarios of solar thermal collectors’ integration, total initial capital investments are shown in Tables 1 and 2.

2.5.1 Energy costs

Analysis of energy efficiency of solar collectors’ integration assumes that there is constant electrical energy consumption for water heating within observed part of residential building. Four selected scenarios, with different solar collectors’ positions, result in different capacity for production of electrical energy from renewable sources, and thus different consumption of electrical energy from public electricity network. In the analysis, public network electrical energy price was adopted according to current price list approved by "EPS - Elektroprivreda Srbije" in December 1, 2012, for consumers within the blue zone (351-1600 kWh per month), which represents zone of average household electricity consumption per month. This price is average price for households with two phase measurement of electricity consumption (1/3 of day – lower tariff). The price of 0.06 €/kWh was established as an input for electrical energy costs calculation. The price of 0.23 €/kWh was adopted for electricity from renewable sources (according to feed-in tariff of EPS and Regulation on Incentives for the production of electricity by using renewable energy sources and combined production of electricity and thermal energy).

3 RESULTS OF LIFE CYCLE COST ANALYSIS

Life cycle period for scenarios of solar collectors’ integration in LCC analysis is 15 years. According to manufacturer, life cycle of proposed system for hot water is 20 to 25 years, while full capacity of the system is reduced by 20% after 15 years of use. Since energy efficiency analysis was carried out for system`s full capacity, period of full system capacity was adopted in this LCC analysis.

Majority of investments that have an impact on energy savings and environment conservation are long term investments and usually have very high capital costs. Since this investment analysis is limited to 15 years (period of full capacity of the system) and the system capacity cannot be determined precisely after this period, all future costs are discounted to present value using a real discount rate of 3.5%, so that the costs in very far future have as less as possible influence on analysis results.

Life cycle cost analysis is performed for each design variant of solar thermal collector’ integration in the building envelope. Using BLCC software, the Net Present Value (NPV) is determined for each scenario, and the scenario that gives the best results during the life cycle was chosen. All future costs are discounted to present value using a discount rate of 3.5%.

Basic assumption is that inflation has a neutral effect on building life cycle if price relations (parity of prices) do not change in life cycle or if impact of inflation is identical on both income and costs of the building.

Results of LCC analysis, LC savings and greenhouse gases emissions for variants of solar collectors’ integration are shown in Table 1, 2 and 3.

3.1 LCC Analysis results – application of solar thermal collectors

From the LCC analysis of variants of solar thermal collectors’ integration, the following conclusions can be listed:

- Results of LCC analysis (Table 1) show that Variant 1, scenario with thermal collectors positioned on the roof in the area of $100m^2$, is the most favourable variant, because it has the highest incomes from investment in renewable energy sources. Variant 3 also has incomes, but, although the area of solar collectors is bigger in comparison to Variant 1, energy production capacity is reduced as solar collectors are placed on the parapets of the facade. Also, Variant 3 has higher initial investments, so the overall incomes are smaller than in Variant 1.

Table 1. Results of LCC analyses of the four variants (design variants of integration of solar thermal collectors) compared to Reference model (Model of the existing building).

	Annual Costs			Present Value Costs			
Scenario	Annual Electricity Costs (base-year) (public) (€)	Annual Electricity Costs (base-year) (solar collect.) (€)	Annual OM&R* Costs (€)	Total Initial Capital Costs (€)	Discounted Total OM&R* Costs (€)	Discounted Total Energy Costs (€)	LCC (€)
Reference model	5,499.00					63,321.00	63,321.00
Variant 1	2,541.00	-11,332.00	100.00	70,000.00	1,152.00	-101,264.00	-30,112.00
Variant 2	3,570.00	-7,386.00	100.00	63,000.00	1,152.00	-43,959.00	20,193.00
Variant 3	2,653.00	-10,904.00	100.00	84,000.00	1,152.00	-95,051.00	-9,899.00
Variant 4	4,209.00	-4,939.00	100.00	38,500.00	1,152.00	-8,418.00	31,234.00

* Operating, Maintenance, and Repair

- Results of the analysis of LC savings (Table 2) also show that Variant 1 has better financial advantages compared to other variants. First of all, Simple Payback Period (SPP) is the shortest (8.05 years), Savings to Investment Ratio (SIR) is most favourable, as well as Adjusted Internal Rate of Return (AIRR). Shortest Simple Payback Period (SPP) shows that this variant has the highest savings.
- Variant 2 and Variant 4 certainly have positive influence on environment and reduction of energy consumption from non-renewable sources. But, from the investment standpoint, these variants are considered unacceptable, since the Simple Payback Period exceeds LC period of solar thermal collectors (15 years of full system capacity). Variant 2, with SPP of 16.95 years, might be acceptable if we take into account the fact that the real life cycle of solar collectors system is longer than 15 years.
- Variant 1, which has the highest savings in electrical energy consumption from public network, also has the lowest greenhouse gases emission (Table 3).
- From the aspect of LCC analysis the most favourable is Variant 1.
- Combination of Variant 1 and Variant 3 (solar collectors on the roof and facade) would certainly give much better results in the evaluation of the economic efficiency of investment in renewable energy.

Table 2. Results of Life cycle savings analysis of four scenarios (design variants of integration of solar thermal collectors)

	Annual Energy Consumption			Electrical energy Savings (+) or Cost (−)		Non−Energy Savings or Cost (−)						
Scenario	Electricity Consumption (public) (kWh)	Electricity Consumption (solar collec.) (kWh)	Total Investment (€)	Annual Electricity Savings (€)	Discounted Electricity Savings (€)	Annual OM&R* Costs (€)	Discounted OM&R* Costs (€)	First year savings (€)	Simple Payback Period (SPP) (year)	Adjusted Internal Rate of Return (AIRR) (%)	Total Discounted Operational Savings (€)	Savings to Investment Ratio (SIR)
Variant 1	-42,348.80	49,269.50	70,000.00	8,791.00	101,264.00	-100.00	-1,152.00	8,691.00	8.05	6.00	100,112.00	1.43
Variant 2	-59,503.50	32,114.80	63,000.00	3,816.00	43,959.00	-100.00	-1,152.00	3,716.00	16.95	0.87	42,807.00	0.68
Variant 3	-44,208.80	47,409.50	84,000.00	8,252.00	95,051.00	-100.00	-1,152.00	8,152.00	10.30	4.27	93,899.00	1.12
Variant 4	-70,142.80	21,475.50	38,500.00	731.00	8,418.00	-100.00	-1,152.00	631.00	61.03	-7.39	7,266.00	0.19

* Operating, Maintenance, and Repair

Table 3. Analysis of greenhouse gases emissions of four scenarios (design variants of integration of solar thermal collectors)

	Reference Model		Variant 1		Variant 2		Variant 3		Variant 4	
	Annual emissions (kg)	Life-Cycle emissions (kg)	Annual emissions (kg)	Life-Cycle emissions (kg)	Annual emissions (kg)	Life-Cycle emissions (kg)	Annual emissions (kg)	Life-Cycle emissions (kg)	Annual emissions (kg)	Life-Cycle emissions (kg)
CO_2	59,910.57	898,371.49	27,692.51	415,254.97	38,910.22	583,466.92	28,908.79	433,493.37	45,867.42	687,791.54
SO_2	301.89	4,526.86	139.54	2,092.45	196.07	2,940.07	145.67	2,184.36	231.12	3,465.76
NOx	89.41	1,340.74	41.33	619.73	58.07	870.77	43.14	646.95	68.45	1026.47

4 CONCLUSION

Investments in energy production from renewable sources always have a positive effect on the economy (reducing energy consumption costs) and the ecology of a country (reducing greenhouse gases emissions). Life cycle costs analyses for different variants of integration of solar thermal collectors for water heating show that feasibility of investments in renewable energy sources is based on price difference between standard and feed-in tariff of electricity per kWh.

In this analysis, feasibility of investment in solar thermal collectors system is economically efficient only for scenarios where renewable energy sources meet energy needs in the percentage of about 50% or more. Therefore, whether a system for production of energy from renewable sources results in incomes or costs in life cycle depends on the policy of the country and values (prices) of feed-in tariff for energy from renewable sources. It is certain that all investments in renewable energy have positive impact on preservation of healthy environment, but their cost effectiveness depends on the goals and policies of economic and energy development.

In surrounding countries of Serbia and EU countries, the values of electricity feed-in tariff per kWh are twice or three times higher than in Serbia (although the price of electricity from public network is significantly higher). Political aspect of feed-in tariff values in Serbia is based on Directive on the promotion of the use of energy from renewable sources (RES Directive 2009/28/EC, 2009) according to which Serbia, as signatory of the Agreement of Energy Community, will be obliged to provide at least 20% of energy consumption from renewable sources. This percentage, which is already reached in Serbia through the production of electricity from hydro-power plants, amounts to about 24% (MERZ, 2012). As long as the target level does not increase above current production of electricity from renewable sources will not be changes in Serbia government’s efforts to support investments in other renewable energy sources.

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The energy requirements by the ventilation system in housing: A review of the Polish legislation and standards

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ABSTRACT: The main purpose of that paper is to present the state of the Polish legislation concerning a ventilation system in housing, and to compare the result of the last amendment of the methodology for determining the energy performance of the building.

In well-insulated buildings the main part of the energy used is generated by the ventilation system heat demand, and because of that it should be properly established. This is very important especially in the ventilated naturally buildings, which are still popular in Poland. Unfortunately most of these houses have no measurements of the number of air changes per hour, so the energy demand is referenced to the design conditions.

In order to show evolution of the law regulation some examples of the calculations for different buildings are described. Finally, the consequences of the changes in legislation will be summarised.

Keywords: natural ventilation systems, regulations, energy conservation, energy efficiency

1 INTRODUCTION

Outdoor air is supplied to rooms in residential buildings to provide adequate amount of oxygen. At the same time, contaminants (not only gases, such as water vapour and carbon dioxide, but also odours and excess heat) are removed from the residential space.

A ventilation system that is most common in multi-family buildings in Poland is the natural ventilation system. Its operation depends mainly on the difference between the indoor and outdoor air temperatures, the air tightness of a building, effects of wind, and the way in which the building is used. In many cases limiting the flow of outdoor air leads to exposing rooms to excess moisture. As a result of reducing operating costs and 'energy conservation', mould develops even in recently erected residential buildings.

Considering Poland's climatic conditions, to provide indoor thermal comfort for a large part of the year (about 8 months) the supply air temperature has to be increased. However, as building constructions or rooms (e.g. attics) of low thermal capacity are used, cooling rooms in summer season is increasingly essential.

The paper presents some aspects of energy assessment regarding residential buildings with the natural ventilation system.

2 LEGAL AND DESIGN REQUIREMENTS

2.1 Legal requirements

The main legal instrument regarding the building industry in Poland is the Building Code ([1]). It is the Building Code that provides for the obligation of the proper energy performance of a building and rationalizing energy use, among basic requirements which building structures should meet.

Detailed technical requirements are included in repeatedly amended Regulation of the Minister of Infrastructure dated 12 April 2002 on technical specifications for buildings and their location ([2]). Another important legal instrument is the Regulation on the methodology of calculating energy performance of a building and a dwelling or part of a building being a self-contained technical unit, and on preparing templates of their energy performance certificates; the Regulation was adopted for the first time in 2008 ([4]), and was largely amended in 2013 ([5]).

Due to clearly improved thermal insulation of an envelope (Table 1), the heating power and the heat required to warm up the ventilation air have become considerable quantities in energy calculations. As it is shown later in the paper, this contribution can amount to about 50%. Thus, in order to perform a reliable energy performance assessment it is crucial to determine a representative ventilation air flow rate and meteorological data relevant to a given location.

Table 1. Changes in the required thermal insulation of selected external partitions

Type of external partition	Maximum allowable overall heat-transfer coefficient, W $m^{-2}K^{-1}$				
	PN-82/ B-02020 *) [1]	PN-91/ B-02020 [2]	OJ 2002 no 75 item 690 **) [3]	OJ 2013 item 926 (until 31 Dec. 2017) [4]	OJ 2013 item 926 (after 1 Feb. 2021) [5]
External partition	0.75	0.55	0.3 1) or 0.5 1)	0.25	0.20
Deck roof	0.45	0.30	0.3 1) 2)	0.20	0.15
Ceiling over an unheated cellar	1.00	0.60	0.6 1) 2)	0.25	0.25
Ceiling under an unheated attic	0.40	0.30	0.3 1) 2)	0.20	0.15
Windows	2.60	2.60	2.6 3) or 2.0 3)	1.3	0.9
External door	2.50	3.00	2.6 2)	1.7	1.3

*) In the standard PN-82/B-02020 additional requirements regarding the average coefficient k_B for a building were introduced.

**) In the Regulation, maximum values of overall heat-transfer coefficients are provided according to the type of building, divided by production, public utility, single-family, multi-family and collective dwelling buildings. In the case of the latter, the value of E is crucial, indicating the design demand for final energy (heat) for heating the building during the heating season, expressed by the amount of energy per 1 m^3 of the heated part of the building per year.

1) For a single-family building.

1) For multi-family and collective dwelling buildings.

3) For multi-family and collective dwelling buildings, depending on the climatic zone.

2.2 Design power of heating equipment

To calculate the heating power demand for the purpose of selecting heating equipment, the design temperature difference and the required ventilation air flow rate must be determined. The design indoor air temperature depends on the building's purpose. Its value can be taken from the Regulation [2], standard PN-EN 12831:2006 [10], standard PN-B-03421:1978 [6], or separate regulations. The value of 20°C is assumed for rooms, kitchens, and anterooms, and 24°C for bathrooms. The design outdoor air temperature is set out for five climatic zones, into which Poland was divided (Table 2).

Table 2. Design outdoor air temperature [10]

Climatic zone	I	II	III	IV	V
Design temperature, °C	-16	-18	-20	-22	-24
Sample cities	Gdańsk, Koszalin, Szczecin	Kalisz, Poznań, Wrocław	Kraków, Łódź, Warszawa	Olsztyn, Białystok	Suwałki, Zakopane

In residential buildings with a natural ventilation system the air flow rate as required for hygienic reasons is usually taken from the standard PN-B-03430:1983/Az3:2000 (Table. 3, [7]), although the recommendations in the Technical Report PKN-CEN/TR 14788:2012 [12] allow to perform calculations considering building-specific conditions.

Table 3. Design ventilation air flow rate [7]

Room type and equipment	Design ventilation air flow rate, $m^3 h^{-1}$
Kitchen with a window and gas cooker	70
Kitchen with a window and electric oven in a flat for not more than 3 persons	30
Kitchen with a window and electric oven in a flat for more than 3 persons	50
Bathroom with or without lavatory	50
Separate lavatory	30
Auxiliary room without windows (e.g., dressing room)	15
Residential room on the floor higher than the ground floor in a single-family building or in a two-storey apartment.	30

2.3 Energy performance assessment of residential buildings

The calculations of heat demand for heating and ventilation purposes are performed according to the Regulation [5] by applying the method of monthly balances, and in principle as per PN-EN ISO 13790:2009 [11]. A simplified hourly method 5R1C is also allowed ([11]). In the previous revision of the Regulation ([4]) simulation-based methods were not allowed.

Meteorological data required to assess the energy performance are provided on websites of a relevant ministry, currently being the Ministry of Infrastructure and Development ([14]).

Indoor air temperature in each assessed zone is determined as weighted mean as per the usable area.

The ventilation air flow rate (V_{ve}) in buildings with a natural ventilation system depends on the flow rate of the air needed for hygienic reasons (V_0) and on the uncontrollable flow rate of infiltration air (V_{inf}); thus, the ventilation transfer coefficient, which describes the effect of the ventilation system on heating needs, is:

$$H_{ve} = 1200 \cdot (V_0 + V_{inf}), \text{ W K}^{-1}.$$

The basic ventilation air flow rate (V_0) is now determined by considering the usable area, type of room, type of installation, heating mode, and ventilation system. Air flow rates with respect to the usable area are listed in Table 4 ([5]).

Table 4. Specific basic air flow rate [5]

Description	Specific basic air flow rate, $m^3 s^{-1} m^{-2}$
Residential rooms in multi-family buildings	0.32×10^{-3}
Staircases in multi-family buildings built before 1990 without vestibule	0.43×10^{-3}
Staircases in multi-family buildings built before 1990 with vestibule	0.22×10^{-3}
Staircases in other multi-family buildings without a vestibule	0.22×10^{-3}
Staircases in other multi-family buildings with a vestibule	0.07×10^{-3}
Single-family buildings	0.31×10^{-3}

The infiltration air flow rate if no building air tightness test was performed equals:

$$V_{inf} = n \cdot V/3600, \mathrm{m^3\ s^{-1}},$$

where: n – number of air changes due to air infiltration through leaks in an envelope under operating conditions: n = 0.2 – buildings erected after 1995 and those with upgraded windows and balcony doors, h^{-1}; n = 0.3 – other buildings, h^{-1}, V – volume of the heated space, m^3.

In the previously applicable 2008 Regulation [4], the basic air flow rate was determined according to PN-B-03430:1983/Az3:2000 [9], and the infiltration air flow rate was 20% of the heated cubic capacity per one hour.

The air change rate (Table 5) should be determined based on building air tightness tests (so-called n_{50}), and under this condition it is justified to assume specific values. For most buildings, however, the value of n_{50} is not known. According to [13] the true air change rate in residential buildings can be in the range of 0.1 h^{-1} to 40.0 h^{-1}.

Table 5. Suggested air change rate in residential rooms [5]

Type of building with the room	Air change rate $[h^{-1}]$
Passive residential buildings	0.6
Buildings with low energy demand for heating	1.5 (1.0)
Buildings with a gravitational system (new)	4.0
Buildings with a gravitational system	from 7.0

2.4 Energy effectiveness requirements

The Regulation [3] set out limits to the non-renewable primary energy demand for heating, ventilation and domestic hot water (DHW) supply (Table 6).

Table 6. Maximum demand for non-renewable primary energy in residential buildings (EP_{max}, kWh m^{-2} $year^{-1}$([3])

Type of building	EP_{max}, kWh m^{-2} $year^{-1}$		
	After 1 Jan. 2014	After 1 Jan. 2017	After 1 Jan. 2021
Single-family building	120	95	70
Multi-family building	105	85	65
Collective dwelling building	95	85	75

3 THE EFFECT OF VENTILATION ON THE ENERGY PERFORMANCE ASSESSMENT

A series of calculations was performed to evaluate how ventilation affects the energy performance assessment. The selected location was Warsaw, the capital of Poland. Single-family buildings without air cooling systems were analysed. Components of thermal balance and energy performance were determined by applying the method of monthly balances. The calculations were performed for variants, i.e. by assuming variable thermal insulation of the envelope according to the 1991, 2002, and 2014 requirements. Dynamic properties of buildings were considered as an internal heat capacity ([11]). The main source of heat was assumed to be a combination gas boiler.

The energy performance assessments were compared as per the 2008 ([4]) and the 2014 ([5]) Regulations. Buildings inhabited by four or five persons were considered. Temperature-controlled spaces of 100 m^2 (1 floor) and 200 m^2 (two storeys) were selected. Variants of the calculations are shown in Table. 7, and their results in Tables 8 and 9.

4 SUMMARY AND CONCLUSIONS

According to the recent Regulation on energy performance [5] the ventilation air flow rate in buildings depends only on the surface area (the basic air flow rate) and cubic capacity (the infiltration air flow rate) of the temperature-controlled space. Hence, designing buildings with more rooms that require removing air (kitchens, bathrooms, lavatories, auxiliary rooms) has no effect on the energy performance.

Improving the envelope's thermal insulation increases the contribution of the energy demand for heating the ventilation air to the total thermal balance.

As for buildings with very good insulation of external partitions, the effect of the heat needed to warm up the ventilation air can significantly contribute to heat losses (according to the calculations up to about 50%).

A considerable improvement of the primary energy demand for heating, ventilation and DHW supply (EP) can be achieved by replacing a conventional fuel (e.g., gas) with biofuel. The improvement is significant, even with lower efficiency of the biofuel-based heat source; it stems from the fact that the coefficient of non-renewal primary energy supply for producing and transferring energy media is 1.10 for gas, 0.50 for biogas, and 0.20 for biomass.

The 2014 revision of the Regulation on the methodology of determining the energy performance ([5]) considerably changed the way in which it is determined, which is why energy performance according to the 2008 Regulation ([4]) cannot be directly compared with those obtained according to the 2014 Regulation ([5]).

Final energy demand (EK) according to [5] is higher because the energy demand for supplying auxiliary equipment is included. According to the 2008 Regulation ([4]), the energy for supplying auxiliary equipment was included only in the primary energy demand for heating, ventilation and DHW supply.

In the case of buildings with smaller temperature-controlled space (100 m2), the energy performance of each of the single-family buildings with a gravitational ventilation system under consideration according to the 2014 Regulation is clearly more favourable in terms of the primary energy demand for heating, ventilation and DHW supply than that assessed as per the 2008 Regulation. On the other hand, however, in the case of buildings with larger area but with smaller number of users, the more favourable assessment will be that obtained using the algorithm provided for in the earlier revision of the Regulation ([4]).

A building with very good thermal insulation of external partitions but with a standard heating and DHW system does not meet the currently applicable legal requirements (according to [3]).

Table 7. Considered variants of calculations

Item	Thermal protection standard	Internal heat capacity	Number of storeys	Surface area of the heated space
[-]	[-]	[-]	[number]	[m²]
1	1991	very light	1	100
2	1991	very light	2	200
3	1991	light	1	100
4	1991	light	2	200
5	1991	average	1	100
6	1991	average	2	200
7	1991	heavy	1	100
8	1991	heavy	2	200
9	1991	very heavy	1	100
10	1991	very heavy	2	200
11	2002	very light	1	100
12	2002	very light	2	200
13	2002	light	1	100
14	2002	light	2	200
15	2002	average	1	100
16	2002	average	2	200
17	2002	heavy	1	100
18	2002	heavy	2	200
19	2002	very heavy	1	100
20	2002	very heavy	2	200
21	2014	very light	1	100
22	2014	very light	2	200
23	2014	light	1	100
24	2014	light	2	200
25	2014	average	1	100
26	2014	average	2	200
27	2014	heavy	1	100
28	2014	heavy	2	200
29	2014	very heavy	1	100
30	2014	very heavy	2	200
31	2021	very light	1	100
32	2021	very light	2	200
33	2021	light	1	100
34	2021	light	2	200
35	2021	average	1	100
36	2021	average	2	200
37	2021	heavy	1	100
38	2021	heavy	2	200
39	2021	very heavy	1	100
40	2021	very heavy	2	200

Table 8. Energy performance meeting the requirements introduced in 2008 ([4])

Item	EU	EK	EP	Contribution of ventilation to heat losses
[-]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[%]
1	261.6	397	445.1	25.0
2	182.6	265.2	300	21.7
3	260.8	395.9	443.8	25.0
4	181.9	264.3	299	21.7
5	259.7	394.4	442.1	25.0
6	181.1	263.3	297.8	21.7
7	258.6	393	440.5	25.0
8	180.4	262.4	296.7	21.7
9	257.9	392.1	439.5	25.0
10	180.0	261.9	296.2	21.7
11	218.9	341.8	384.3	29.3
12	143.8	215.2	244.8	26.7
13	218.1	340.8	383.1	29.3
14	143.2	214.4	243.9	26.7
15	217.1	339.5	381.6	29.3
16	142.5	213.6	242.9	26.7
17	216.2	338.4	380.3	29.3
18	142.0	212.9	242.1	26.7
19	215.7	337.7	379.5	29.3
20	141.7	212.6	241.7	26.7
21	140.2	240.5	272.3	42.7
22	91.2	147.5	170	38.6
23	139.5	239.5	271.3	42.7
24	90.7	146.8	169.2	38.6
25	138.7	238.5	270.1	42.7
26	90.2	146.1	168.3	38.6
27	138.1	237.7	269.2	42.7
28	89.8	145.6	167.7	38.6
29	137.7	237.3	268.7	42.7
30	89.7	145.4	167.5	38.6
31	122.1	217.1	246.6	47.8
32	76.8	128.8	149.3	44.1
33	121.4	216.2	245.6	47.8
34	76.2	128.1	148.5	44.1
35	120.6	215.2	244.4	47.8
36	75.8	127.5	147.7	44.1
37	120.0	214.5	243.5	47.8
38	75.4	127.1	147.1	44.1
39	119.8	214.1	243	47.8
40	75.3	127	146.9	44.1

Table 9. Energy performance meeting the requirements introduced in 2014 ([5])

Item	EU (2014)	EK	EP	Contribution of ventilation to heat losses
[-]	[kWh/m²]	[kWh/m²]	[kWh/m²]	[%]
1	227.6	407.7	451.7	22.6
2	176.82	333.1	369.7	28.1
3	226.15	405.6	449.4	22.6
4	175.44	331.1	367.5	28.1
5	224.31	402.9	446.4	22.6
6	173.8	328.7	364.8	28.1
7	222.54	400.3	443.5	22.6
8	172.34	326.6	362.5	28.1
9	221.52	398.8	441.9	22.6
10	171.56	325.4	361.2	28.1
11	177.35	333.9	370.5	23.8
12	130.65	265.3	295.1	30.7
13	175.86	331.7	368.1	23.8
14	129.19	263.2	292.8	30.7
15	174.03	329	365.2	23.8
16	127.55	260.8	290.1	30.7
17	172.35	326.6	362.5	23.8
18	126.18	258.8	287.9	30.7
19	171.47	325.3	361.1	23.8
20	125.54	257.8	286.9	30.7
21	101.5	222.5	248.1	35.9
22	79.65	190.5	212.8	43.3
23	99.72	219.9	245.2	35.9
24	78.06	188.1	210.2	43.3
25	97.75	217	242	35.9
26	76.24	185.5	207.3	43.3
27	96.02	214.5	239.2	35.9
28	74.86	183.4	205	43.3
29	95.13	213.2	237.8	35.9
30	74.22	182.5	204	43.3
31	83.82	196.6	219.5	40.8
32	65.46	169.6	189.9	49.0
33	81.99	193.9	216.5	40.8
34	63.85	167.3	187.2	49.0
35	80.03	191	213.4	40.8
36	62.2	164.8	184.6	49.0
37	78.5	188.8	210.9	40.8
38	61	163.1	182.6	49.0
39	77.77	187.7	209.7	40.8
40	60.46	162.3	181.8	49.0

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Experimental evaluation of a Hybrid Photovoltaic/Solar Thermal (HyPV/T) Façade Module

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ABSTRACT: The Energy Performance of Buildings Directive and Renewable Energy Framework Directive require that Renewable Energy Systems (RES) are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar systems integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. By integrating these systems into the building elements (walls, roofs, etc.) not only means replacing a conventional building material (and associated costs), but also aesthetically integrating it into the building design leads to improved architectural integration.

A modular Hybrid Photovoltaic/Solar Thermal (HyPV/T) Façade technology that utilizes Integrated Collector Storage (ICS) solar technology, providing cost effective solar PV and thermal energy collection for direct use in the building, whilst providing significant thermal insulation has been developed and evaluated experimentally at Ulster University. The HyPV/T system, based upon a patented ICS solar thermal diode concept and shaped into a flat modular profile incorporating PV cells/module can provide space heating, domestic water heating and power generation. The complete system is designed to be compatible with traditional façade structures and fenestration framing arrangements, facilitating direct integration into new and retrofit building applications.

The experimental thermal performance of a prototype HyPV/T unit has been determined under constant indoor solar simulated conditions. The thermal and electrical performances of various modified HyPV/T designs have been investigated and the thermal collection efficiencies, ‘diodicity’ and heat loss performance are presented. The ability for a single product to offer multiple functionality in a unique modular design and being the first to use ICS technology, presents a huge commercial opportunity. The HyPV/T whilst offering a more cost effective solar investment will

combine performance and quality and be fit for purpose, robust, visually appealing and exceptionally easy to install. These characteristics are expected in all premium solar collector-related products.

Keywords: Building integration, modular, hybrid, PV/T, façade, Integrated Collector Storage (ICS), thermal diode.

1 INTRODUCTION

The Energy Performance of Buildings Directive and Renewable Energy Framework Directive requires that Renewable Energy Systems (RES) are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar systems integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. By integrating these systems (Building Integrated Photovoltaic (BIPV) and Building Integrated Solar Thermal Systems (BISTS)) into the building elements (walls, roofs, etc.) not only means replacing a conventional building material (and associated costs), but also aesthetically integrating it into the building design leads to improved architectural integration.

Traditionally, solar thermal systems compete for suitable roof or façade areas with photovoltaics. Combining photovoltaics with solar thermal collectors give rise to PV Thermal (PVT) collector solutions which can offer an alternative option as they deliver solar thermal heat at levels similar to conventional solar thermal collectors and generate electricity similar to standard PV modules. Careful design is necessary as thermal applications often require higher operational temperatures, whereas the PV module efficiency drops with increasing temperature. Some examples of optimized collector solutions are in development [Dupeyrat et al., 2011a; Dupeyrat et al., 2011b].

Building Integrated Photovoltaic Thermal (BIPVT) systems are a further enhancement of the building integrated solar family. They still offer material displacement of traditional building components (totally or partially) but produce a greater cross-functional role. A publication by IEA Task 41 [Wall et al., 2012] gives a complex approach about integration solutions of PV(T) as a different building envelope component (tilted roof, flat roof, skylight, façade cladding, façade glazing, external device). One interesting area that to date have received minimal interest concerns the development of building integrated PV combined with integral solar thermal storage concepts.

Integrated Collector Storage Solar Water Heaters (ICSSWH) are simple, low cost solar devices. The development of these systems is detailed in Smyth et al. [2006]. They suffer however significant ambient heat loss, especially at night-time and during non-collection periods [Tripanagnostopoulos & Yianoulis, 1992]. Several studies have been carried out focusing on the improvement of the thermal performance of ICSSWH systems, primarily during night operation. Previous ICSSWH designs have attempted to improve thermal energy storage during non-collection periods by; (i) reducing heat loss from the aperture [Baer, 1975; Bishop, 1983; Schmidt et al., 1988 and Schmidt & Goetzberger, 1990], (ii) reducing convective heat transfer in the collector cavity from the store to the aperture [Tripanagnostopoulos & Yianoulis, 1992] or (iii) reducing heat transfer from the store surface [Stickney & Nagy, 1980; Burton & Zweig, 1981; Bainbridge, 1981]. Recent studies to reduce night-time thermal losses include the use of two stores Tripanagnostopoulos & Souliotis [2003]. The use of low pressure and Phase Change Materials (PCM), such as water, within an ICS unit was first suggested by De Beijer [1998]. The evaporator is the collector absorbing surface and the condenser is the surface of the inner storage vessel. The working principle exploits the latent heat transfer characteristics of liquid to gas phase change whilst reducing heat loss during non-collection periods. The work presented in this paper details the experimental characterisation of a pre-heat ICSSWH that utilises the novel thermal diode operation presented by De Beijer [1998].

This paper presents a modular Hybrid Photovoltaic/Solar Thermal (HyPV/T) Façade technology that utilizes Integrated Collector Storage (ICS) solar technology, providing cost effective solar PV and thermal energy collection for direct use in the building, whilst providing significant thermal insulation. The HyPV/T system, based upon a patented ICS solar thermal diode concept and shaped into a flat modular profile incorporating PV cells/module can provide space heating, domestic water heating and power generation. The complete system is designed to be compatible with traditional façade structures and fenestration framing arrangements, facilitating direct integration into new and retrofit building applications.

2 THE HYBRID PHOTOVOLTAIC/SOLAR THERMAL (HYPV/T) FAÇADE MODULE

The conceptual Hybrid Photovoltaic/Solar Thermal (HyPV/T) Façade technology was designed and developed by the team at Ulster University. Using a multiple vessel design, a cavity is created between an outer absorbing vessel and an inner storage vessel. This volume is partially evacuated to a very low pressure and contains a small amount of PCM heat transfer fluid. Just like a thermal diode, the design promotes solar collection but reduces thermal losses. During collection periods, solar radiation incident is on the outer absorbing surface causes the Heat Transfer Fluid (HTF) to evaporate at low temperature thus producing a vapour. The vapour condenses on contact with colder inner vessel surface and the collected thermal energy is transferred to water store through latent heat exchange. Condensed HTF runs down the inner vessel to a reservoir at base of cavity to continue the cycle. During non-collection periods no evaporation takes place and due to the very low pressure environment in the cavity, heat loss is reduced from the store.

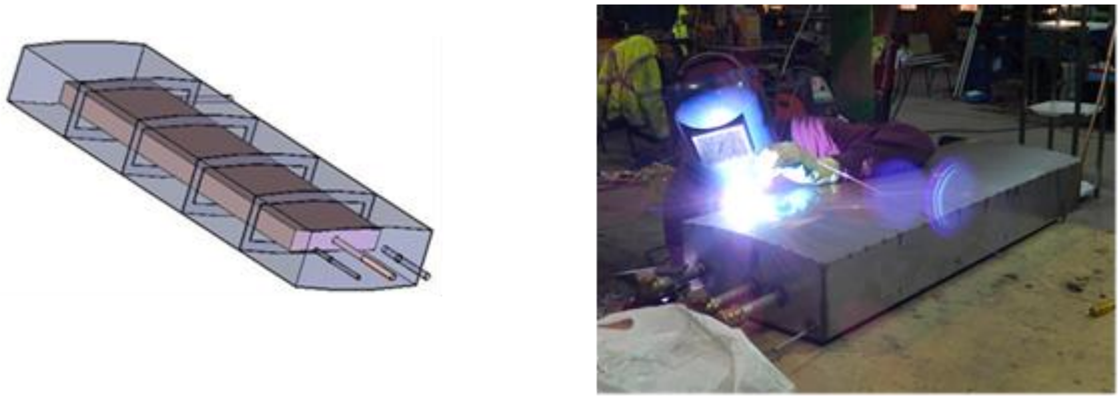

Figure 1: Detail of the small scale laboratory prototype HyPV/T unit and its final welding and assembly

The technology builds upon research conducted by Smyth et al. [2003]. Two flattened structural vessels (outer absorbing vessel and inner storage vessel) are arranged to create a cavity between the walls of respective vessels. Installed on a building façade, the unit will provide significant thermal insulation, whilst producing useful amounts of hot water and electricity. A small scale V1 prototype design was developed and engineering drawing prepared. The drawings were supplied to fabrication specialists and the prototype HyPVT unit completed to specification. Figure 1 details the unit's fabrication. The basic unit was made from an external stainless steel outer vessel supported by an internal exo-skeleton of 4 structural ribs. The inner (thermal storage) vessel was a simple rectangular unit with a volume of 11.2 litres, giving a volume to collection ratio of 31 litres per m^2. A value of 30 litres per m^2 is deemed suitable for ICS type solar water heaters by much of the published literature [Tripanagnostopoulos & Yianoulis, 1992].

3 DESCRIPTION OF THE EXPERIMENTAL FACILITY

On completion of the V1 HyPVT assembly, the partial size prototype was experimentally evaluated over sustained collection and cool-down periods at the solar simulator facility at Ulster University. Table 1 describes the range of tests conducted on the V1 unit to indicate performance enhancements and Figure 2 shows one of the unit variations under test.

Table 1: Range of indoor experimental tests conducted on the HyPVT V1

Test	description	volume	pressure	duration
V1 11/02	no cover no vacuum no PV no pump	11.2 litre and 0 litre HTF	-0.00bar	1 day collection and 1 day cool down period
V1 12/02	no cover no vacuum no PV	11.2 litre and 0.5 litre HTF	-0.00bar	1 day collection and 1 day cool down period
V1 09/03	no cover no PV	11.2 litre and 0.5 litre HTF	-0.400bar	1 day collection and 1 day cool down period
V1 13/03	no cover	11.2 litre and 0.5 litre HTF	-0.400bar	1 day collection and 1 day cool down period
V1 18/03	no cover no PV	11.2 litre and 0.5 litre HTF	-0.800bar	1 day collection and 1 day cool down period
V1 20/03	no cover no PV	11.2 litre and 0.5 litre HTF	-0.950bar	1 day collection and 1 day cool down period
V1 24/03	no PV	11.2 litre and 0.5 litre HTF	-0.950bar	1 day collection and 1 day cool down period

Figure 2: Prototype HyPVT unit (V1 09/03 without PV panels) ready for testing

The performance of the HyPVT unit was experimentally determined at the indoor solar simulator testing facility at Ulster University (schematically represented in Figure 3). The simulator lamp array consists of high power 35 metal halide lamps arranged in 7 rows of 5 lamps each. Each lamp is equipped with a rotation symmetrical paraboloidal reflector to provide a light beam of high collimation. In order to achieve uniform distribution of light intensity on the test area, a lens is inserted in each lamp to widen the illumination of light. The combination of reflector-characteristics, lens and lamps ensures a realistic simulation of the beam path, spectrum and uniformity. The solar simulator control panel maintained the constant level light intensity automatically on the collector surface via a pyranometer mounted at the centre of the test plane.

T-type copper-constantan thermocouples, which had an error of ± 0.5°C between 0 and 70°C, were used to measure the water storage temperatures within the HyPVT versions, various surface temperatures and ambient air temperature. Water storage temperatures were measured at 5 locations to record the variation of water temperature within the inner store. All sensors were connected to a stand-alone Delta-T data logger unit to record all measured variables. The logger data were transferred to a PC via a data transmission cable for storage. The HyPVT unit versions were mounted vertically in front of the state-of-the-art solar simulator. All tests were conducted under a constant 700 W/m^2 (± 30 Wm^2) solar simulated radiation.

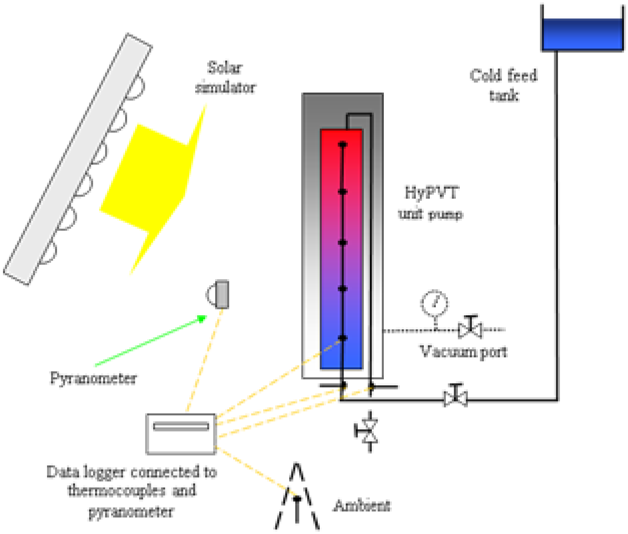

Figure 3: Schematic of the test set-up

4 EXPERIMENTAL (THERMAL) RESULTS AND ANALYSIS FOR THE V1 PROTOTYPE HYPVT UNIT

Each HyPVT unit variation was subjected to the same test procedure. Each unit was evaluated and normalised prior to the start of the test (sensors tested, temperatures normalised to ambient and pressures set). The unit was shielded from the solar simulator to allow for lamp warm up. Once the test (proper) was initiated, the logger was started and the unit exposed to the simulated solar radiation. After a 10 minute period, the HyPVT pump was activated and the 'collection' period carried out for a 4 hour duration. At the end of this 4 hour period, the lamps were switched off and the unit left to cool-down for a period no less than 14 hours in duration.

The experimental results from the study are presented in the form of the thermal collection and retention capabilities within each design variation. The recorded temperatures within the vessel were used to calculate mean temperatures in the entire volume and using Equation 1 the amount of thermal energy collected and retained was determined.

$$Q_{col} = mc_p\left(T_{end} - T_{start}\right) \tag{1}$$

The thermal heat loss from the system during the cooldown period was determined by:

$$Q_{loss} = mc_p\left(T_{initial} - T_{final}\right) \tag{2}$$

The thermal collection and heat retention efficiencies are determined by Equations 3 and 4:

$$\eta_{col} = \frac{mc_P\left(T_{end} - T_{start}\right)}{I_{ave}A_{ap}\Delta t} \tag{3}$$

$$\eta_{ret} = \frac{mc_p\left(T_{final} - T_{amb}\right)}{mc_p\left(T_{initial} - T_{amb}\right)} \tag{4}$$

Figures 4 and 5 graphically represent the measured and normalised temperatures from the various tests conducted and Table 2 shows the collection and heat retention efficiencies determined from the thermal performance and associated variables measured from the various tests conducted.

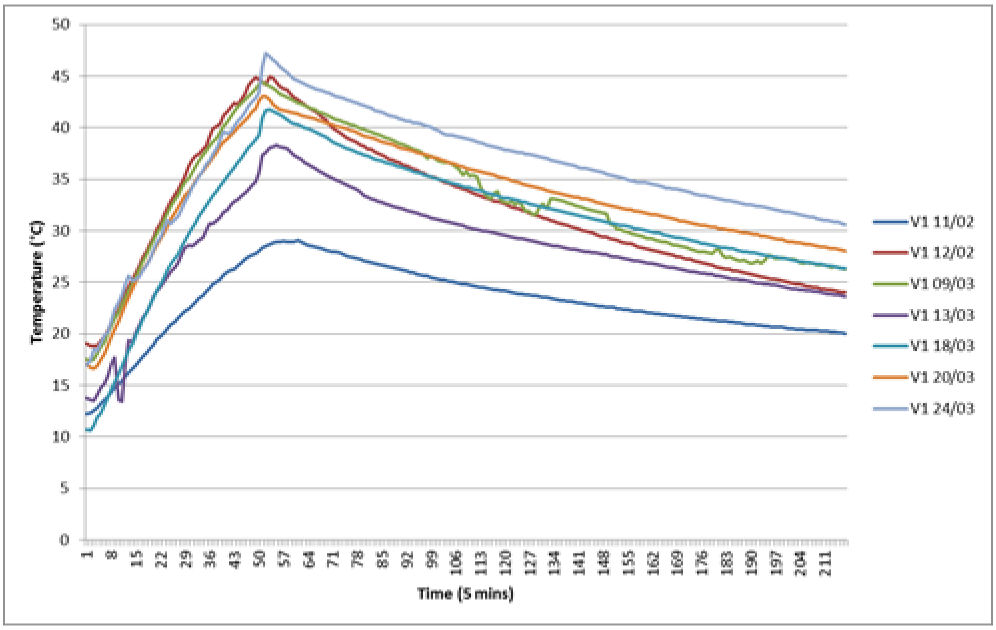

Figure 4: Average storage temperature profiles for all tests over the collecting and cool-down periods

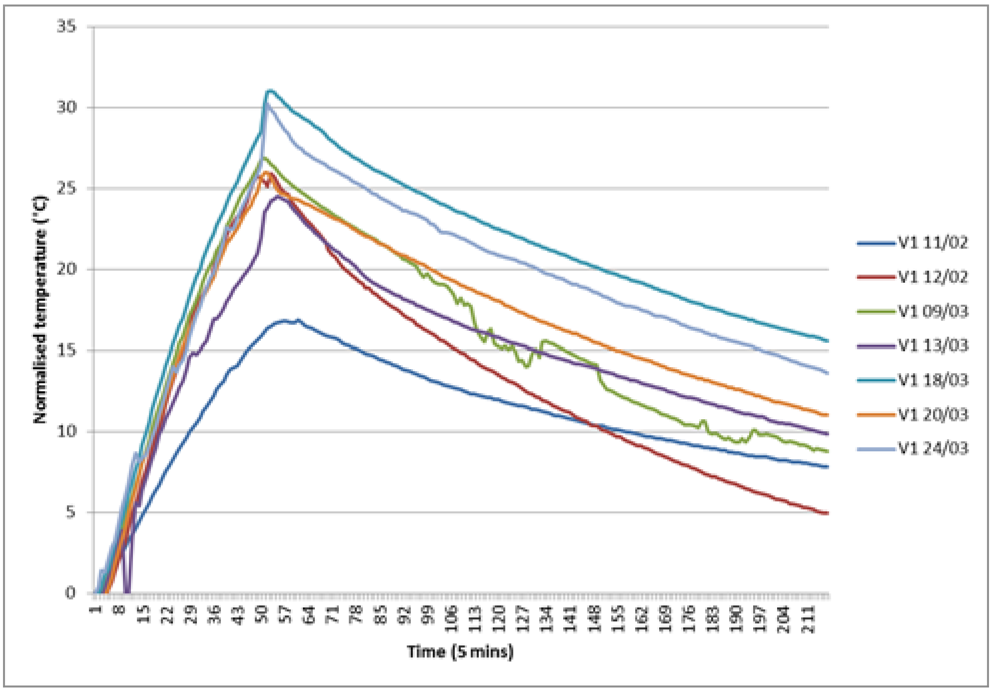

Figure 5: Normalised average storage temperature profiles for all tests over the collecting and cool-down periods

Table 2: Test results from indoor experimental tests conducted on the HyPVT V

Test	description	Input (kJ)	Output (kJ)	Collection eff (4 hrs)	Retention eff (14 hrs)
V1 11/02	no cover no vacuum no PV no pump	3516.31	786.13	**0.223**	**0.314**
V1 12/02	no cover no vacuum no PV	3416.26	1211.97	**0.355**	**0.286**
V1 09/03	no cover no PV	3559.33	1258.04	**0.353**	**0.379**
V1 13/03	no cover	3628.8	1146.71	**0.316**	**0.364**
V1 18/03	no cover no PV	3677.01	1452.61	**0.395**	**0.417**
V1 20/03	no cover no PV	3623.62	1215.34	**0.335**	**0.452**
V1 24/03	no PV	3727.30	1414.69	**0.380**	**0.491**

5 DISCUSSION

It is clear that no transparent cover, vacuum and pump operation results in the lowest collection performance (22.3%) and a low heat retention value. The addition of the pump improves the collection efficiency to 33.5%, although a slight drop in heat retention due to the HTF is now observed. Reducing the chamber pressure by 400mb (V1 09/03) has no impact on collection performance but increase the heat retention efficiency to 37.9%. V1 13/03 is the previous test condition with the PV panels added. It can be seen that the thermal collection efficiency without the PV is 35.3% and 31.6 % with the PV. This is a 4% overall drop in the thermal collection performance but is made up by the additional production of electricity. There is minimal difference in heat retention performance. This seems to indicate that mounting PVs with conductive paste to the external collecting surface is a beneficial development resulting in an electrical gain but only a small drop on the thermal performance.

Tests V1 18/03, V1 20/03 and V1 24/03 all operated at pressures greater than or equal -800mb. The importance of the vacuum and external transparent cover is related in the observed performances. In all cases the collection and heat retention efficiencies are greater than the previous tests with a maximum collection efficiency of 39.5% and heat retention efficiency of 49.1% being attained. These values are based on the initial prototype and indicate that (based on the author's past experience) can be significantly improved upon so that thermal collection efficiencies of 60% and heat retention efficiencies of 75% are very achievable.

6 CONCLUSIONS

The experimental evaluation of the small scale (V1) prototype HyPVT unit indicate that the concept is sound and is applicable for larger scale implementation and further research and development. Importantly the proposed flattened design is structurally sound under proposed operating conditions and was able maintain the 'flat' absorbing surface at -950mb. The design is flexible enough to be extended to the larger proposed 1m x 1m modular units to be evaluated in further experimental evaluation. The drop in the thermal performance due to the introduction of the PV module was deemed acceptable as a 4% overall drop in the thermal collection performance can be made up by the additional production of electricity, indicating the selected conductive paste and PV module to absorber surface contact is appropriate. The testing demonstrated that a maximum collection efficiency of 39.5% and heat retention efficiency of 49.1% is possible, but as these values are based on the initial prototype, the author's experiences indicate that thermal collection efficiencies of 60% and heat retention efficiencies of 75% are very achievable.

A modular building integrated HyPVT ICS collector has been experimentally evaluated. Whilst the technology is in the early stages of development, the unique modular design being the first to use ICS technology, presents a huge commercial opportunity. If the development in unit performance can achieve the expected values, the HyPV/T concept in time should offer a more cost effective solar investment combining performance and quality.

ACKNOWLEDGEMENTS

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NOMENCLATURE

$\mathbf{A_{ap}}$	aperture area (m^2)
$\mathbf{c_p}$	specific heat capacity of water (J/kg°C)
$\mathbf{I_{ave}}$	incident solar radiation (W/m^2)

M	mass of water (kg)
$\mathbf{Q_{col}}$	thermal energy collected (J)
$\mathbf{Q_{loss}}$	thermal energy loss (J)
T	temperature (°C)
$\mathbf{\Delta t}$	time of test interval (s)
η_{col}	collection efficiency
η_{ret}	retention efficiency

Subscripts

amb	average ambient temperature
end	average water temperature at end of heating period
final	average final water temperature at end of cooling period
initial	average initial water temperature at start of cooling period
start	average water temperature at start of heating period

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Operational and aesthetical aspects of solar energy systems for building integration

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ABSTRACT: Building integrated solar energy systems should be harmonized with the building architecture, reducing building heating, cooling and electricity demand. Innovative solar energy devices that have been designed and developed at the University of Patras are briefly described and aspects regarding operation and aesthetics for their building integration are presented. These systems are ICS solar water heaters, solar collectors with colored absorbers, CPC type collectors, PV/T collectors that produce efficiently electricity and heat and low concentration solar energy systems with booster flat reflectors and CPC or Fresnel lens concentrators, that increase energy output and can achieve solar control of building atria. The presented solar energy systems aim to cost effective architectural solutions for buildings, by replacing the conventional energy sources and contributing to CO_2 reduction.

Keywords: building integration, solar thermal systems, CPC collectors, hybrid PV/T collectors

1 INTRODUCTION

Towards adapting energy demand in the next years, solar energy systems start to fill the energy gap in the buildings, together with other renewable energy sources (biomass and geothermal) and new concepts are introduced regarding energy economy. In this frame, the energy targets of EC for 2020 and 2030 are critical requirements to the achievement of energy saving and CO_2 reduction. The changing in the energy mix that is planning for the next decade, aims to the preparation for the exit from the “kingdom” of hydrocarbons and to the entrance to the new “landscape” of renewables. This transition is not easy and several difficulties should be overcome. Energy saving should be of first priority for the achievement of global energy targets, as it contributes to lower consumption level and the built sector is the first one that should contribute, with most important the introduction of the nearly Zero Energy Building concept from 2020. The external surface of buildings constitutes the surface area for an effective, multifunctional building “skin”. Towards the design of such buildings, alternative “skin” designs are suggested regarding effective integration of solar thermal collectors, photovoltaics and hybrid photovoltaic/thermal collectors. These systems can provide heat and electricity, combined with geothermal heat pumps, biomass boilers and also with small wind turbines, if it is efficient and of practical use, to adapt energy building needs. In addition, the suitable design of building balconies and atrium spaces with the integration of curved reflectors and Fresnel lenses, could provide solar control to the buildings.

Buildings can be designed according to bioclimatic architecture, using new heat-insulating materials and special effective glazing (smart windows), which reduce effectively thermal losses during the winter and the energy consumption for cooling during summer. The installation of devices and active solar energy units is related with their cost increase and their harmonization with the architecture of the buildings and the environment. In Physics Department at the University of Patras several solar energy devices with innovative design have been developed and prototypes have been studied, which can be aesthetically integrated on buildings. New types of ICS solar systems, alternative devices to the thermosiphonic solar water heaters, flat solar collectors with colored absorber, to avoid the black monotony of the facades and the roofs of buildings and new designs of stationary booster reflectors and CPC solar collectors, suitable for medium temperature applications, have been investigated. The light and the temperature of atria can be controlled by using linear Fresnel lenses combined with multifunctional absorbers. In addition, photovoltaic/thermal (PV/T) solar systems that convert the incoming solar radiation into electricity and heat have been extensively sytudied as alternative to plain photovoltaics. A brief description of these systems and aspects for their aesthetic integration are included in this work.

2 SOLAR THERMAL COLLECTORS

2.1 Integrated Collector Storage (ICS) solar water heaters

Integrated Collector Storage Systems (ICS) systems are less applied solar water heaters, although they are cheaper and of better view than thermosiphonic systems. The heating of 100-200 l of water by solar energy is usually achieved, using flat plate (or vacuum tube) thermosiphonic units (FPTU) and integrated collector storage systems (ICS). ICS systems are simpler solar devices compared with the FPTU ones (Fig. 1), but their small ability in preserving the water tank temperature during the night has set limitations to their expanded application. Water heating by ICS devices is inexpensive and efficient and they represent an alternative solution for building integration. For the heating of bigger quantities of water, a group of ICS collectors (multi-ICS system) combined with a water tank placed inside the building and a system of forced water circulation, are used (Fig. 1, right). Improved types of ICS devices came up as a result of laboratory research. The developed devices are based on the combination of horizontal cylindrical tanks and stationary symmetric or asymmetric CPC reflectors by which increase of water temperature and reduced thermal losses are achieved. The developed devices are based on the productive combination of horizontal cylindrical tanks and stationary symmetric or asymmetric CPC reflectors by which efficient increase of water temperature and reduced thermal losses are achieved (Tripanagnostopoulos et al., 2002a; Souliotis and Tripanagnostopoulos, 2008).

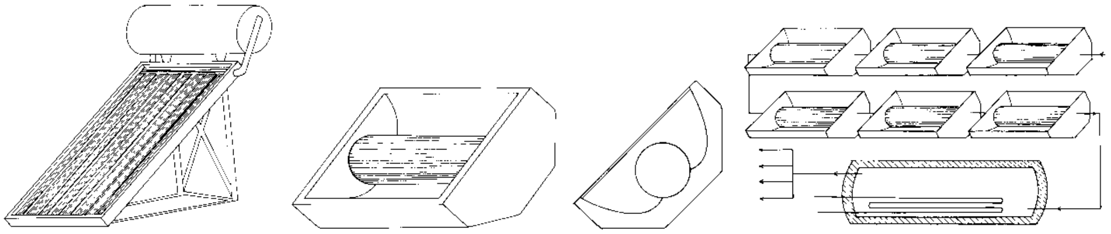

Fig. 1 FPTU and ICS solar water heaters and multi-ICS system

2.2 Solar collectors with colored absorber

The issue of aesthetic integration of solar collectors in building architecture and the environment is important and constitutes a reason for the limited application of these devices in the built environment. In an extended use of solar energy, the majority of the exterior surfaces of buildings will be covered with absorbing surfaces of solar collectors and their color (the monotony of black color) is a basic factor that has to be taken under consideration, especially in the case of traditional communities. Another option to typical solar collectors with black absorber is to use a colored absorber aiming to adapt solar systems with building architecture, regarding the appearance in the color (Tripanagnostopoulos et al, 2000a, Kalogirou et al 2005) and changing the monotony of black view of the roofs by these solar collectors. Instead of black color, collectors with different colors as of blue, red-brown, green etc. can be applied and although their absorption ability is a little lower (20%), their use offers an interesting colorful aspect to the exterior of buildings. Colored solar absorbers can contribute in the expansion of solar energy systems utilization and sensitize or even motivate architectures to include these systems in their designs. The lower efficiency of collectors with colored absorbers (Fig. 2, left) requires an increase of about 20% of the needed collector area for the same amount of thermal output that corresponds to black collectors. The additional cost from the extended aperture surface area is balanced by the improvement of the aesthetic view. These collectors can have selective or non-selective colored absorber and also spectral selective glazing. The solar collectors could be used to several buildings (Fig. 2 and Fig. 3) regarding their particular architecture. To overcome the lower thermal output due to the reduced absorptance, flat booster reflectors can be used between the parallel rows of the collectors on building roof. By this installation, higher thermal output or higher fluid output temperatures can be achieved.

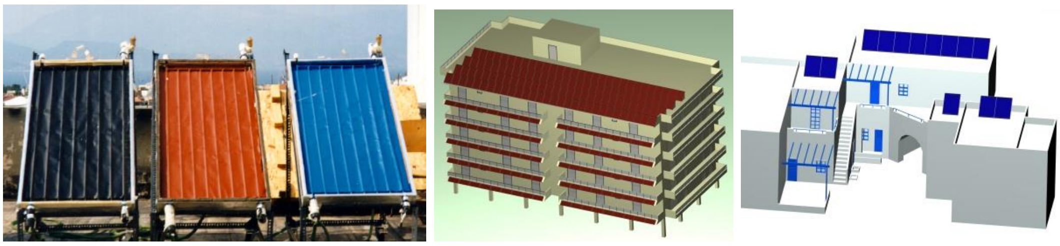

Fig. 2 Tested colored collectors and application examples on a building roofs

Fig. 3 Colored collectors on a building façade, balconies and roofs

2.3 Use of booster reflectors

Buildings that are placed in low latitude locations usually have horizontal roofs where the installation of solar collectors and photovoltaics, is easy. The installation of solar devices on the rooftops of buildings differs from the installation on the inclined roofs or the facades of buildings because, even if we can succeed better energy orientation (south), the sun height difference between seasons determines their placement in a certain distance to avoid shading (Tripanagnostopoulos and Souliotis 2005). In the installation on horizontal roofs, the placement of flat reflectors between the series of collectors has been studied (Tripanagnostopoulos et al., 2000a). These reflectors can utilize the solar radiation that falls into the gaps between collector rows. In these cases, the reflectors are stationary and their contribution depends on the position of the sun, which means that in the winter, this contribution is smaller than that of the other seasons.

The effect of flat booster reflectors to performance improvement of solar thermal collectors has been extensively studied. The results showed that the reflector contributes to a considerable increase of thermal output from spring to fall (about 25%) and satisfactory during winter (about 10%), for system operation in low water input temperatures. It is remarkable that the effect of booster reflectors is significant for system operation in higher temperatures, presenting an increase of 50%-100%. The additional cost of the booster reflectors is about 20% and is overcome by the higher thermal energy output (40% annually), resulting to a reduction of system payback time and making these systems more attractive for application.

In Fig. 4 the coupling of collector with reflector is shown, including the incoming and the reflecting solar rays, the slope β of the collector, and λ of the reflector and the angle γ between collector and reflector are shown. In addition, the collector width L, the reflector width R and the distance D between the parallel collector rows are included.

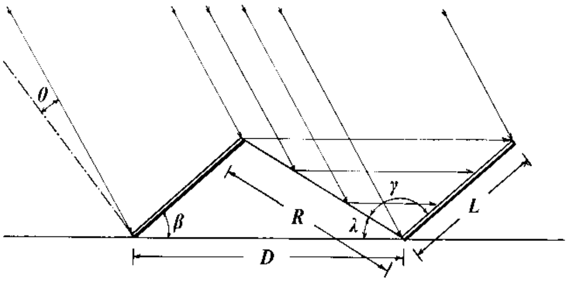

Fig. 4 Installation geometry of the collectors with the stationary booster reflectors

Fig 5 gives an idea about the building integration of solar thermal collectors combined with booster reflectors, where the interior building space can be additionally illuminated by the solar radiation that is transmitted directly through the window or after reflection.

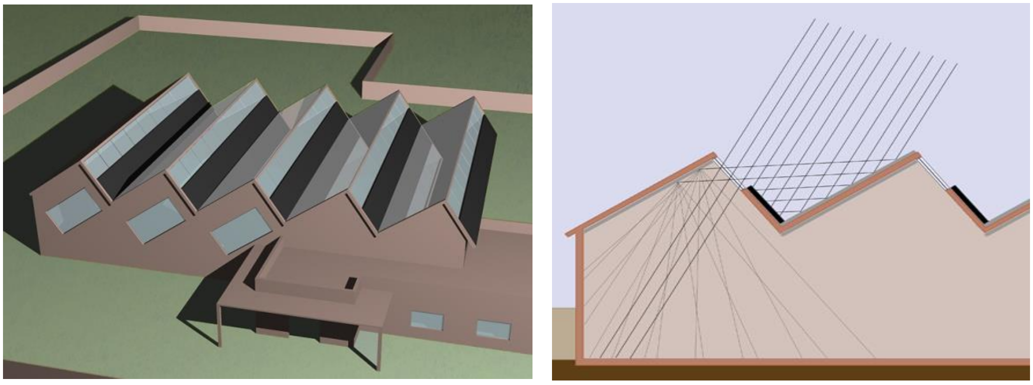

Fig. 5 Examples of building integration of booster reflectors with solar energy systems

3. HYBRID PHOTOVOLTAIC/THERMAL SOLAR COLLECTORS

3.1 Basic aspects for hybrid PV/T collectors

Photovoltaic (PV) convert a small percentage of solar radiation into electricity, 5%-18% depending on the type of PV, with the greater percentage converted into heat. The solar radiation increases the temperature of PV modules, resulting in a drop of their electrical efficiency, but their installation on horizontal roofs of buildings permits their natural cooling. In the facades and inclined roofs, cooling of PV rear surface is under research, which will also have positive result in protecting building overheating during summer. Hybrid PV/T systems can be applied mainly in buildings for the production of electricity and heat and are suitable for PV applications under high values of solar radiation and ambient temperature. In these devices, water or air (Fig. 6) is circulated in thermal contact with the PV, exchanging heat. When air is used, the contact with PV panels is direct, while in the case of use of fluids, the contact is made through a heat exchanger (Tripanagnostopoulos et al., 2002b; Kalogirou et al., 2006).

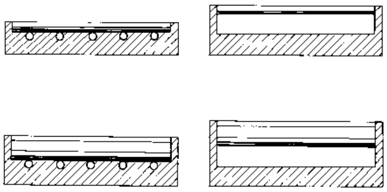

Fig. 6 PV/T water and air collectors without and with extra transparent cover.

To develop hybrid PV/T systems, experimental models have been constructed, using water or air as the heat removal fluid (Tripanagnostopoulos et al., 2000b; Tripanagnostopoulos et al., 2005; 2006). Hybrid PV/T using air can be applied for space heating of building during winter and for cooling during summer by the creation of strong upward air stream. Water hybrid PV/T can be used for the pre-heating of water, since the temperature of water in the water supply network is no more than 20° C, even during summer months. Hybrid PV/T systems are appropriate for installation in buildings with thermal and electricity needs, like houses, apartment buildings, hotels, hospitals, athletic centers and industries. They can be placed on the facades, inclined or horizontal roofs of buildings - instead of separate PV panels and solar thermal collectors - in a more practical utilization of the existing surfaces.

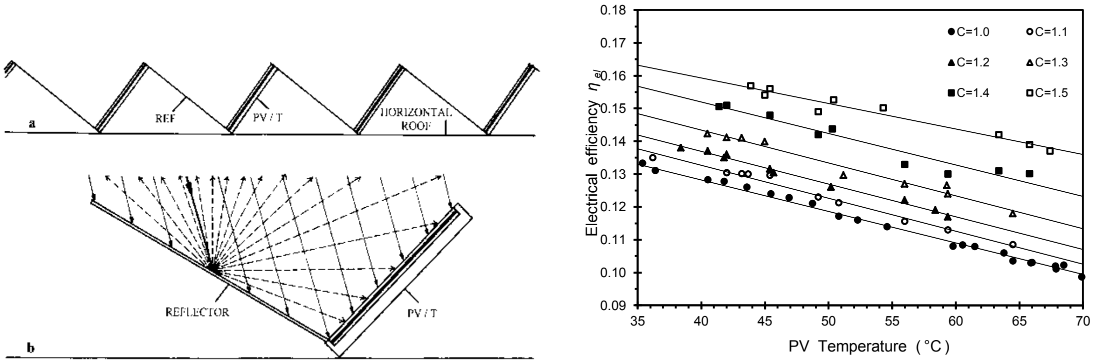

Fig. 7 PV/T systems with booster diffuse reflectors: Building roof system installation, indication of diffuse reflected solar rays to a PV/T+REF system and electrical performance

Considering PV/T solar systems installed on horizontal building roof, the parallel rows keep a distance from one to the other in order to avoid PV module shading. The investigated stationary flat diffuse reflectors (Fig. 7) can be placed between the PV modules from the higher part of the one row of them to the lower part of the next row. This installation increases solar input on PVs almost all year, resulting to PV/T system electrical and thermal output increase. The diffuse reflectors differ from the specular reflectors, as they avoid the illumination differences on module surface and the reduction of the electrical efficiency, because they provide an almost uniform distribution of reflected solar radiation on PV module surface. Diffuse reflectors can be effectively applied in the residential and the industrial sector, overcoming some limitations of PV/T systems, as the low operating temperature of the thermal unit of typical PV/T collectors and also the reduction of electricity if an additional glazing is used. In case of domestic use systems the booster reflectors can be of diffuse or specular type, depending on the installation flexibility for orientation adjustments to the sun and also application requirements. The diffuse reflectors can operate without (or few) adjustments, but with lower additional solar input to the PV modules, while the specular reflectors need more adjustments but their contribution to solar input increase is higher. From the results obtained, we observe an important increase of about 25% in thermal and electric energy output due to use of diffuse booster reflectors. Fig. 8 gives an image of roof integration of PVs or PV/T collectors with booster diffuse reflectors (Tripanagnostopoulos, 2008) and Fig. 9 the integration of PV/T collectors on Cycladic buildings, using effectively the white painted roofs as diffuse reflectors (Tripanagnostopoulos et al., 2009).

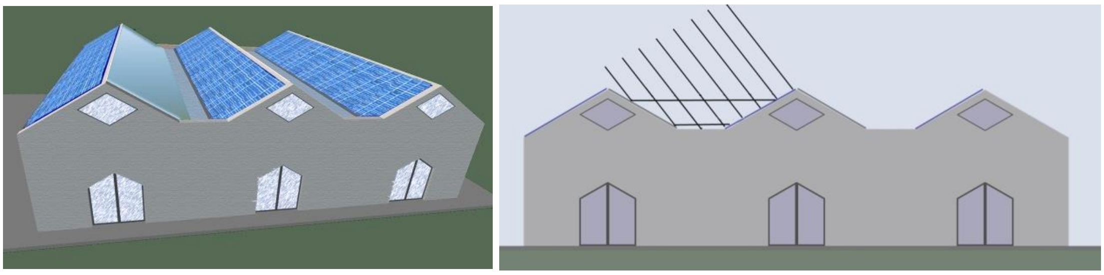

Fig. 8 Building integration of PVs or PV/T collectors with booster diffuse reflectors

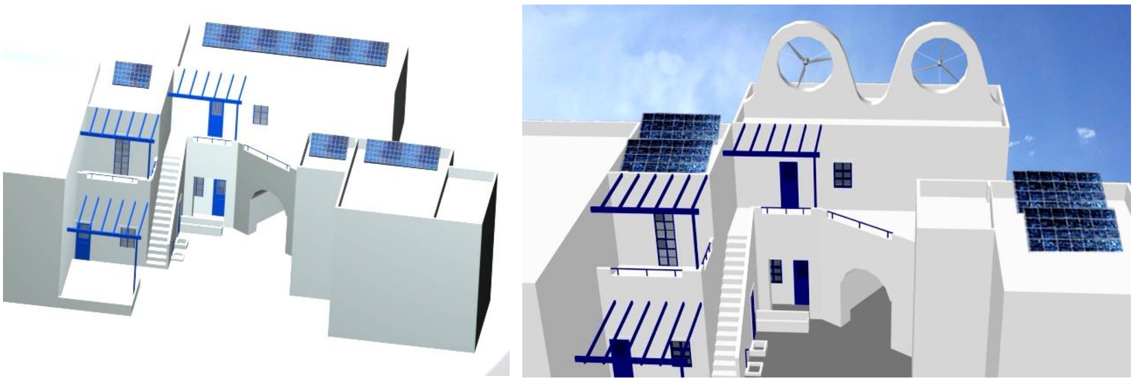

Fig. 9 Building integration of PVs or PV/T collectors on the roofs of Cycladic buildings

3.2 The PVT/DUAL system concept

The PVT/WATER collectors can effectively operate all seasons, mainly for application at locations in low latitudes where favorable weather conditions regarding the efficient operation of the thermal collectors usually exist, or marginally in medium latitudes to avoid freezing. On the other hand, the PVT/AIR collectors can effectively operate mainly at locations of medium and high latitudes without freezing problems, but for low latitude applications the summer period with the high ambient temperatures PV cooling by the circulating air is less effective. In addition, the hot air is not useful to the buildings during summer, except if the system is used to enhance natural ventilation by the solar chimney effect, but in this case the heated air is usually rejected to the ambient. A combination of both heat extraction modes in one device is interesting and could possibly overcome the limitations of the two PV/T type collectors. Based on this principle, a new type of PV/T collector with dual heat extraction operation (PVT/DUAL) either to heat water or to heat air (Fig. 10) depending on the weather conditions and building needs, was investigated (Tripanagnostopoulos, 2007). The water heat extraction could operate mainly during periods of higher ambient temperatures, as water from mains is not usually over 20 ^{o}C and the air heat extraction is applied, mainly for low ambient temperature. It should be taken care to drain the water from the pipes when ambient air drops under zero and to operate the system only with air circulation (except if anti-freezing liquid is used). Under mild weather conditions it is possible to operate both heat extraction modes, if it is considered useful for the application.

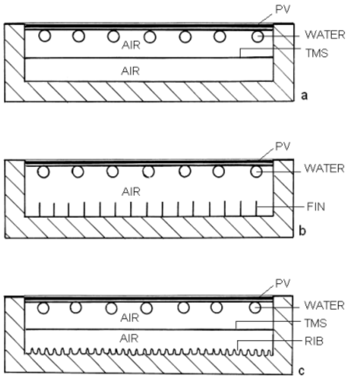

Fig. 10 Cross section of the studied PVT/DUAL solar systems

4. LOW CONCENTRATION SOLAR ENERGY SYSTEMS

4.1 Solar energy systems with CPC reflectors

These systems consist of stationary CPC reflectors and absorbers or combined tracking absorbers and fixed flat secondary absorbers. The symmetric CPC collector (Fig. 11) includes a flat bifacial absorber, where two absorber strips can track the converged solar radiation on each absorber side and absorb the concentrated solar radiation. The other two designs of Fig. 11 are the asymmetric CPC systems. In these systems, the parabola axis is directed to the higher altitude of sun (summer solstice, Fig. 11b) and alternatively to the lower sun altitude (winter solstice, Fig. 11c). Experiments have been performed and a mean concentration ratio of about 6 was obtained. Depending on concentrator geometry, absorber shape and incidence angle of solar radiation, areas on the receiver can have no incident solar flux, while other areas can receive multiple flux intensities. Optical simulations and experimental measurements have shown that areas on the absorber plane can have incident solar fluxes with intensities several times higher than that of the incident solar radiation on the aperture of the concentrator. By placing an evacuated tubular collector with selectively coated thermal absorber at the areas of high intensity, solar flux formed at these locations achieve collector high system operating efficiencies in the medium temperature range and the measured stagnation temperature was at the level of 400 ^{o}C (Tripanagnostopoulos and Yianoulis, 1996; Tripanagnostopoulos et al., 2000b; Tripanagnostopoulos, 2008).

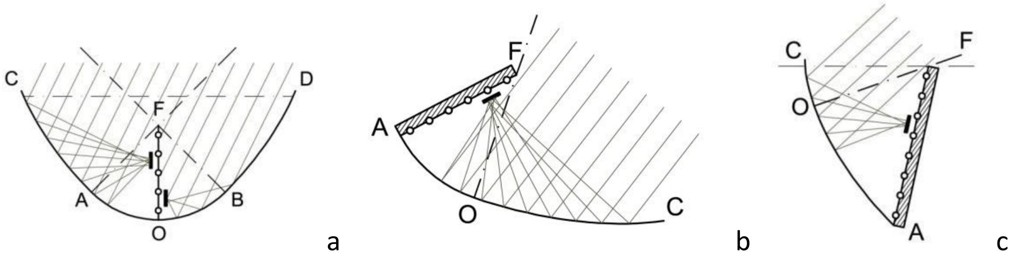

Fig. 11 Symmetric (a) and asymmetric CPC reflectors with orientation to summer (b) and winter (c) solstice

Considering the static concentrator geometry, the incidence angle and the size of the tracking absorber, a part of the collected solar radiation may not converge on the tracking absorber. It can however be captured along with the diffuse solar radiation by the secondary thermal absorber, which is adapted to system geometry. This low density solar radiation can heat a fluid at lower temperatures, for preheating or for other applications. In these systems high concentration ratios can be achieved on evacuated tube absorber, including some optical losses at the reflector and glass absorber tube. With this novel approach, efficient system operation with working fluid temperature range up to 250°C, can be performed.

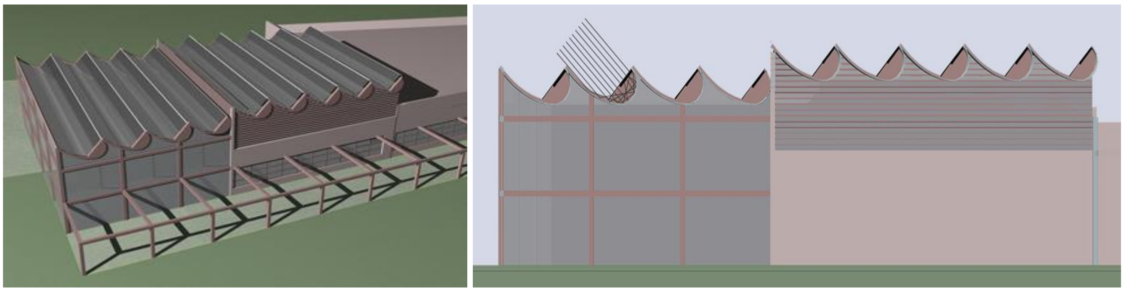

Fig. 12 Building integrated CPC collectors

In Figures 12 to 14 there are presented some designs of building integrated CPC type collectors. In Fig. 12 the building roof has been properly formed to adapt the figure of CPC collectors, which can effectively operate in intermediate temperatures (Tripanagnostopoulos and Yianoulis, 1996; Tripanagnostopoulos et al., 2000b; Tripanagnostopoulos, 2008). In case of flat roof installation (Fig. 13), the asymmetric CPC collectors with tracking receivers are suitable, achieving higher temperatures, while in Fig. 14 the reflector is now the façade of the building, with the tracking absorber on the opposite building.

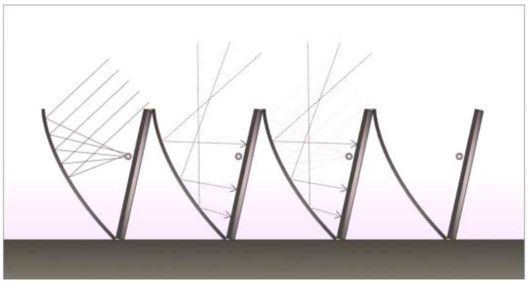

Fig. 13 Suggested installation of asymmetric CPC reflectors on building horizontal roof

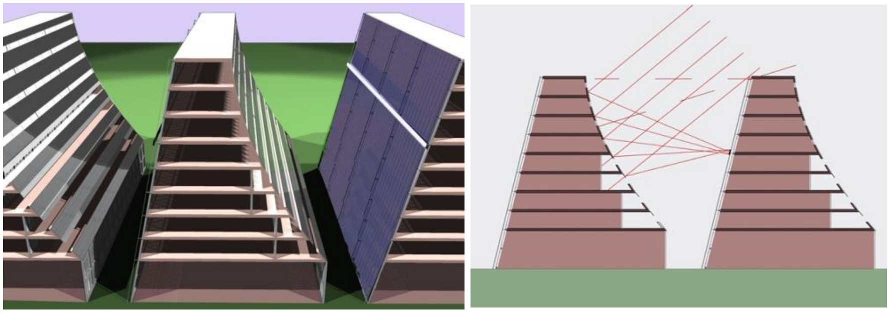

Fig. 14 Building integration of CPC reflectors, with tracking absorber on opposite building

4.2 Fresnel lenses for solar control of building atria

Fresnel lenses are optical devices for solar radiation concentration, which are used in several solar energy systems as the thermal collectors and photovoltaics because of their attractive features. Their advantages are the lower volume, weight and cost, compared to the thick ordinary lenses. Several types of Fresnel lenses have been investigated, consisting of linear or circular grooves. Fresnel lenses of 2D type (linear geometry lenses) are more practical than 3D type lenses (circular geometry lenses), as they can have East-West lens axis orientation and therefore they need less adjustments per year for system orientation to the sun. Optical losses in a Fresnel lens are high and are mainly due to reflection at the interfaces, to diffraction from close groove spacing, to absorption in the lens material, to chromatic aberration and also to slope errors. These losses result to lower optical performance of Fresnel lens and also to create non-uniform illumination at the focal plane. In a linear Fresnel lens concentrator an absorber can be used to track the high intensity solar flux areas, which are formed at system's focal plane of the static Fresnel lens (Tripanagnostopoulos et al., 2006). The absorber can be a vacuum tube, a thermal absorber or a PV/T receiver unit (Fig.12, left). This system can operate in two modes: as a solar energy conversion system, providing electricity, heat, or electricity and heat (Fig.12, left) or as a solar control system for a building atrium with energy conversion in case of solar radiation excess. Based on the concentrator design and tracking absorber method at low intensity solar radiation periods, the absorber(s) can be out of focus to allow sunlight to enter the building's interior space and maintain acceptable illumination level.

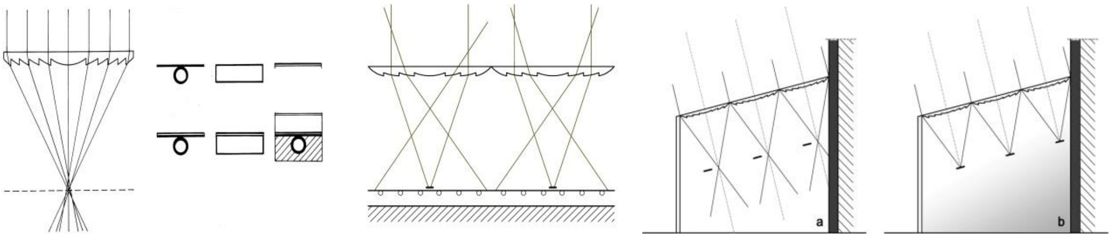

Fig. 15 Fresnel lens system design for energy conversion (left) and building solar control (right)

In the case where the solar gain of the interior building space is excessive, the absorber(s) can be placed on focus to capture the major part of the incoming solar radiation and reduce light entering the building. In Fig.15 the active role of absorbers to solar control of the interior space is illustrated (Fig. 15a absorbers out of focus, 15b on focus and in Fig. 16). A similar operation can be obtained in case of using the Fresnel lens system as transparent cover of a sunspace attached to building south wall (Fig. 15 right). In this way, a greater conversion rate of the incoming solar radiation can be achieved and a supplementary heating for the building can be performed, resulting in a reduction of system payback period. The application of Fresnel lenses to buildings has a special interest to low latitude countries with many sunny days during year, as the transparently covered interior spaces are overheated very often and a high amount of electricity is needed to drive the air-conditioning system in order to reduce the temperature.

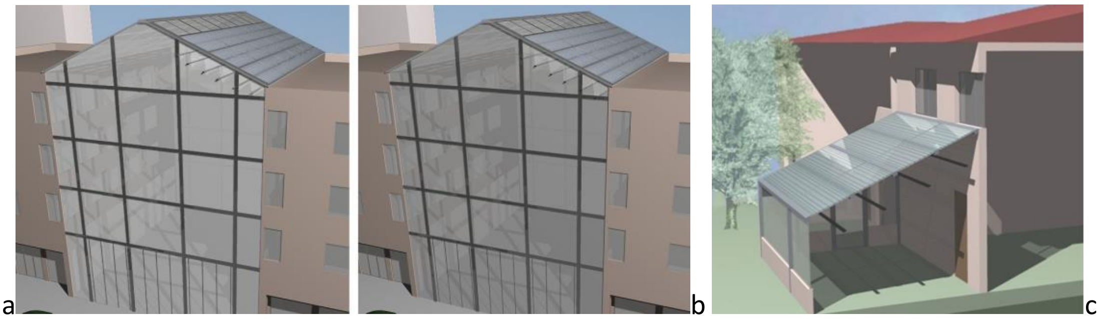

Fig. 16 Example of Fresnel lens integration on building atrium (a, b) and sunspace (c)

5. CONCLUSIONS

Aspects and perspectives for building integration of solar energy systems that have been investigated at the University of Patras are presented. Studies on building integration of these systems have been performed, aiming to make practically feasible and aesthetically accepted the effective combination of architecture with solar energy systems. Among the investigated solar energy systems, ICS solar water heaters, solar collectors with colored absorbers and static concentrating devices, as of booster reflectors, CPC reflectors and Fresnel lenses are suggested in this paper aiming to provide new solutions for building integration.

Static concentrator configurations are effective solutions for building integration, as they can be of considerable size with greater structural strength and thus minimized stability problems, thereby larger concentrator sizes can be accommodated. These systems can be installed in parallel format, requiring no extra space between the collectors and are of flexible operation depending on the solar and climatic conditions, as well as the application energy requirements. Apart of heat and electricity Fresnel lenses can adapt solar control of building atria.

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Validation of developed codes, thermal and optical, for building-integrated solar thermal systems

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ABSTRACT: The present study has been conducted in the frame of the COST Action TU1205 and presents an overview on the validation of developed codes, thermal and optical, within the field of Building-Integrated Solar Thermal (BIST) systems. The results reveal that there are specific requirements for BIST modelling. Regarding validation methodologies, on-site validation has been conducted for several types of systems (active façades, etc). On the other hand, indoor solar simulators facilitate solar research in cold climates while test cells offer an intermediate between a real building and an experiment in the laboratory.

Keywords: validation of codes; building-integrated solar thermal systems

1 INTRODUCTION

Building-Integrated Solar Thermal (BIST) systems, and in general BI solar systems, provide multiple advantages (higher aesthetic value, etc) in comparison with the configurations which are added (and not integrated) on the building (Kalogirou, 2013) known as Building-Added (BA) systems. In the literature, there are only few studies about BIST systems regarding for example façade-integration (Maurer and Kuhn, 2012; Maurer et al., 2013) and gutter-integration (Motte et al., 2013; Notton et al, 2014). Since building integration is a crucial factor in the spreading of solar thermal systems (Munari Probst and Roecker, 2007), further investigation in the field of BIST is needed. Certainly, the experimental works are important for testing a system; however, modelling can be utilized to predict a system performance, saving time and cost. Thus, further modelling investigations along with BIST experimental testing are necessary. The present study provides useful information about the developed BIST codes, thermal and optical models available in the literature. Emphasis is given on the codes which have been built and validated, identifying critical aspects such as the requirements of BIST simulation and validation methodologies.

2 SPECIFIC REQUIREMENTS OF BIST MODELLING AND SIMULATION

Athienitis and O'Brien studied issues related with modelling and design of net-zero energy solar buildings and integration of dynamic building envelope systems. Aspects such as modelling of complex perimeter zones with advanced envelopes and daylighting, integration of active and passive systems and comfort were presented. The challenge in fenestration design is related with solar gain control vs. daylight utilisation. The solar gains should be taken into account in the design and control of high-performance buildings in an integrated manner. A key challenge is balancing the need for daylight throughout the year, passive solar gains in the heating season and need to limit excessive solar gains during cooling season. Moreover, there is a need for prediction of weather and building model for model predictive control. The impact of motorized blinds and light dimming should also be taken into account. Another issue is related with indoor environmental quality and it includes parameters such as thermal comfort, air quality, acoustic and visual comfort.

In the study of Chen et al. (2012), thermal network models for different collectors were developed by means of MATLAB for steady state and transient analyses. The simulation results were validated with experimental data under a solar simulator with a prototype combining components such as Unglazed Transpired Collector (UTC), transpired glazing and Photovoltaic/Thermal (PVT) collectors on structural insulated panel wall.

In general, BIST elements have a variable *g* value or solar heat gain coefficient (Maurer and Kuhn, 2013). This means that heating and cooling demand depends on irradiance and operation of the collector. Standard collector models consider only the ambient temperature. For BIST elements, the temperature of the interior should be also considered. The performance of a BIST collector can be higher than in BA systems due to the decreased back losses. Models which include the energetic coupling between absorber and building interior can provide accurate predictions.

3 VALIDATION METHODOLOGIES

3.1 On-site validation

Ji et al. (2011a; 2011b) studied a dual-function solar collector. The developed numerical model was validated based on experimental data. Other examples of studies which include model validation by means of experimental data are those of: Diarce et al. (2014) regarding a Computational Fluid Dynamics (CFD) model for an active façade; Chan and Tzempelikos (2012) concerning a method for assessing the integrated energy performance of passive and active multi-section façade systems; Pappas and Zhai (2008) about an integrated and iterative modelling process for analysing the thermal performance of Double-Skin Façade (DSF) cavities; Rundle et al. (2011) about validation of CFD simulations for atria geometries; Li et al. (2014) for BIPVT with UTCs (CFD); Sohel et al. (2014) for BIPVT.

3.2 Test cells

Test cells represent an intermediate between a real building and an experiment conducted in the laboratory. Test cells also have an important advantage: the initial and particularly important boundary conditions can be controlled to a much higher degree than in real buildings while still maintaining dimensions and thermophysical properties very close to those found in rooms of real buildings (Loutzenhiser et al., 2006). An empirical validation of modelling solar gains through a glazing unit by using building energy simulation programs was presented by Loutzenhiser et al. (2006). Moreover, Strachan (1993) presented a work about model validation by using the PASSYS test cells. PASSYS project was a European action by ten countries in the field of passive solar architecture.

3.3 Laboratory

In the field of laboratory testing are included tests by means of indoor solar simulators, facilitating solar research in cold climates (Source: University of Minnesota). Chen et al. (2012) conducted a study about modelling of passive solar potential and innovative façade-integrated solar systems. The simulation results were validated with experimental data under a solar simulator with a prototype. Regarding BI concentrating PV, Baig et al. (2015) performed an optical, thermal and electrical analysis of a dielectric-based BI concentrating PV. The solar spectrum of a Class AAA solar simulator was utilized. Furthermore, a novel PV module with isolated cells was designed, fabricated and experimentally characterised with/without Compound Parabolic Concentrator (CPC), by utilising a solar simulator, by Paul et al. (2013).

At this point it should be noted that it is important to have well-defined heat-transfer coefficients and temperatures at the front and back of the BIST component during laboratory measurements. For instance, Maurer (2012) measured a BIST collector in a solar-simulator test facility with adjustable temperatures of the interior and exterior and standard heat transfer coefficients. A detailed physical BIST model was built based on optical measurements and CFD simulations (Maurer et al., 2012). Finally, the detailed model was calibrated to the results of the laboratory measurements.

4 VALIDATED MODELS FOR DIFFERENT INTEGRATED SOLAR THERMAL COLLECTORS

4.1 Building-added systems: modelling/simulation and validation

In this section, studies from the field of BA systems are mentioned because they could be adapted for BI applications. The studies of Oliva et al. (1991), Plantier et al. (2003), Cadafalch (2009) and Molero Villar et al. (2009) concern detailed physical models for solar thermal collectors which in principle could be coupled to a building. Furthermore, Luo et al. (2014) developed a model for a nanofluid solar collector based on direct-absorption-collection concepts, by solving the radiative transfer equations of particulate media and combining conduction and convection heat transfer equations. The simulation results were in accordance with the experimental data.

4.2 Building-integrated systems: modelling/simulation and validation

4.2.1. Opaque systems

A dual-function solar collector system can provide passive space heating in cold winter and water heating in warm seasons. This type of system has higher annual utilization ratio than a conventional system designed for passive space heating. A coupled numerical model was developed by Ji et al. (2011a) for such a configuration (Hefei, China). By means of experimental validation, the numerical model was proved to be able to give accurate predictions. Ji et al. (2011b) also conducted another study related with the above mentioned system. They developed two dynamic numerical models based on the finite-difference method for two different operating modes of the testing system. Experimental data were used to validate the two models.

Yang and Athienitis (2012; 2014) developed a numerical control-volume method to simulate an open-loop air-based BIPVT system with a single inlet. The simulated results were validated with indoor-test data. The tests were conducted by means of a solar simulator. Chen et al. (2010) also investigated a BIPVT system. Li and Karava (2014) presented an energy modelling and performance analysis of BIPVT systems with corrugated UTCs. Assoa and Ménézo (2014) studied a roof-integrated PVT air collector. Corbin and Zhai (2010) used a CFD model to simulate the effect of active heat recovery on cell efficiency and the performance of a BIPVT system. The simulated results were verified with experimental data. In Fig. 1(a) the experimental test collector is illustrated and in Fig. 1(b) the PV temperature contours are presented (Source: Corbin and Zhai, 2010).

a)

b)

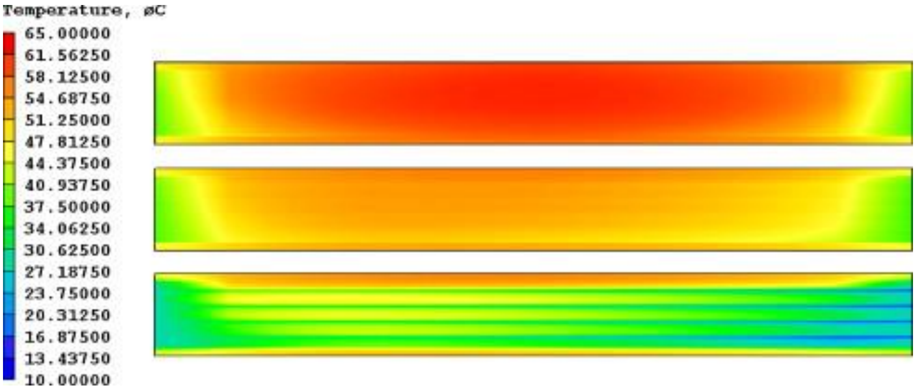

Figure 1. a) Experimental test collector and b) PV temperature contours for natural convection (top), heat recovery (middle), thermal absorber temperature contour (bottom) at 1000 W/m^2 and 10^{o}C inlet temperature (Source: Corbin and Zhai, 2010).

Other studies are those of: 1) Li et al. (2014) (simulation of BIPVT systems with UTCs), 2) Buker et al. (2014) (BIPVT system), 3) Li et al. (2015a) (TRNSYS simulations about a balcony wall type solar water heater system), 4) Agrawal and Tiwari (2011) (a simulation model, by using MATLAB, for a glazed hybrid micro-channel solar cell thermal tile), 5) Diarce et al. (2014) (CFD modelling for a ventilated active façade), 6) Motte et al. (2013) (gutter-integrated solar collector for water heating), 7) Anderson et al. (2010) (about the effect of colour on the thermal performance of BI solar collectors), 8) Sarachitti et al. (2011) (roof-integrated solar concrete collector), 9) Albanese et al. (2012) (heat-pipe assisted solar wall).

4.2.2. Transparent systems

4.2.2.1. Several BIST configurations

Maurer et al. (2013) investigated the performance (in terms of heating and cooling) of a high-rise building incorporating façade-integrated Transparent Solar Thermal Collectors (TSTCs). It should be noted that two new TRNSYS types were developed to simulate the performance of the TSTC system as well as the passive solar gains of a glazing with venetian blinds. The simulation examined the overall performance including heating, ventilation and air conditioning of the building with façade-integrated TSTC system. Further investigation was also conducted in order to study the possibility for primary energy savings by utilizing building mass as an additional thermal storage.

A new methodology was developed based on a ¨black box¨ model for the modelling of solar gains through complex façades (Kuhn et al., 2011). The advantage of this new methodology is that it only uses measurable quantities of the transparent or translucent part of the façade as a whole. The method was designed for complex façades such as façades with prismatic layers, light re-directing surfaces and in general, for façade properties with complex angular dependence, façades with non-airtight layers, non-flat surfaces and other complex configurations. The method was implemented in ESP-r and TRNSYS (Maurer, 2012) and was also validated. In addition, this method could also be implemented in other detailed simulation programs such as DOE-2, EnergyPlus or TAS thermal analysis software (Kuhn et al., 2011).

Maurer and Kuhn (2012) investigated the effect of variable *g* value of transparent façade collectors. A new TRNSYS Type 871 was developed and the model was successfully validated and used to calculate the primary energy savings. The developed model can also be used to simulate new BIST elements. A detailed model like Type 871 offers an accurate prediction of the collector gain, the heating and cooling load of the building and even the indoor surface temperatures to allow detailed calculations of the thermal comfort, including an optical simulation and a thermal network. Furthermore, the BlackBox Type 861 provides unprecedented accuracy in modelling glazing with blinds in TRNSYS.

Chan and Tzempelikos (2012) developed a method for assessing the integrated energy performance of passive and active multi-section façade systems combined with lighting and thermal controls of perimeter building zones by using open source language. A thermal network approach was utilized to predict indoor thermal environmental conditions and annual energy consumption of perimeter zones equipped with combinations of passive and active facade systems.

Maurer et al. (2012) conducted a study which included measurements and corresponding modelling of transparent solar thermal façades. Angle-dependent spectrally resolved optical measurements of the different collector layers were used for an optical simulation to determine the angle-dependent absorptance of each layer and the angle-dependent transmittance of the whole collector. Perez et al. (1993) sky model with Tregenza (1987) sky patches were used for accurate treatment of the diffuse radiation. The thermal network was first modelled by CFD and then it was calibrated by calorimetric measurements. The resulting detailed physical model offers multiple benefits such as predictions of the advantages, easy collector optimization and the possibility of quantifying the uncertainties of the simulation. The method to determine these uncertainties was presented.

Other studies are those of: 1) Glória Gomes et al. (2014) (numerical/experimental study of solar and visible optical properties of glazing systems with venetian blinds), 2) Li et al. (2015b) (a novel solar thermal curtain wall was investigated), 3) Palmero-Marrero and Oliveira (2006) (a numerical model was developed to investigate the thermal performance of a solar collector integrated into the external louvres of buildings), 4) Joudi and Farhan (2014) (about a solar air heater for heating an innovative greenhouse: the proposed greenhouse combined a traditional greenhouse with a system of solar air heaters on the roof (as one structure)).

4.2.2.2. Double-Skin Façade (DSF)

Transparent BIST category also includes multi-skin façades, for example DSF configurations. A multi-skin façade is a type of façade which includes different layers. Between these layers air can move. The multi-skin façades can be used to provide heat for the building. In the following paragraphs, studies about DSF modelling are presented.

Joe et al. (2014) analyzed a multi-story DSF (Korea). Parametric and optimization studies on the DSF design were performed based on a validated model. Algorithm GenOpt was adopted for the optimization of the system. A binary version of the Particle Swarm Optimization (PSO) algorithm was utilized.

An integrated and iterative modelling process for analyzing the thermal performance of DSF cavities with buoyancy-driven airflow by utilizing a building energy simulation program (BESP) along with a CFD package was presented by Pappas and Zhai (2008). A typical DSF cavity model was established and simulated while the model and the modelling process were calibrated and validated against experimental data.

Moon et al. (2014) developed an Artificial Neural Network (ANN)-based temperature control method for energy efficient indoor thermal environment in buildings with double-skin envelope systems. For the validation, field measurements were performed in an actual double-skinned building (Ansan, South Korea).

Moreover, von Grabe (2002) developed a simulation method in order to investigate the temperature behaviour of double façades. The model accuracy was tested by utilizing experimental data. The model accuracy was improved by modifying flow resistance for multiple geometries.

Additional studies are those of: 1) Park et al. (2004) (regarding a lumped simulation model which was calibrated for DSF systems with controlled rotating louvers and ventilation openings), 2) Balocco and Colombari (2006) (about a non-dimensional analysis for mechanically-ventilated double-glazed façade energy performance), 3) Jiru and Haghighat (2008) (concerning a ventilated DSF system based on a zonal approach), 4) Blanco et al. (2014) (regarding DSF), 5) Saelens et al. (2008) (about multiple-skin façades).

4.3 Issues about the insulation of the systems

In terms of the building integration of solar collectors, it is important to ensure that the building envelope is of high insulation quality. When a solar collector is to be mounted on an existing building, it is important that the installation to be performed quickly and safely, but correctly (Gajbert, 2008).

Fieber et al. (2003) developed a multi-functional wall element: a PVT on the inside of an anti-reflective insulation window with concentrating mobile reflector screens makes the system fully integrated into the building, even its interior. The proposed solar window provides electricity and warm water, passive space heating and daylighting. Moreover, the reflector screens act as sunshades and added internal insulation for the window.

There is also another study about the optimisation of reflector and module geometries for stationary, low-concentrating, façade-integrated PVs (Gajbert et al., 2007). The studied collector included a PVT absorber, parabolic aluminium reflectors, PV string modules and expanded polystyrene insulation. Due to the insulation material attached to the back of the reflector sheet metal, the façade element can serve as an integrated part of building envelope.

Matuska and Sourek (2006) studied façade-integrated solar thermal collectors for water heating in an existing building stock (Czech Republic). The thermal behaviour of the façade collectors was compared with standard roof-located collectors in solar domestic hot water systems. The application of façade solar collectors affects indoor comfort of the building (in a reasonable range). Building behaviour was not strongly affected by the façade collectors when sufficient insulation layers were used.

Nowzari and Atikol (2009) performed TRNSYS simulation for a building integrated with a Trombe wall (Larnaca, Cyprus). A vented Trombe wall was used for the south façade of the ground floor and a direct gain window of area 6.5 m^2 was placed on the south façade of the first floor. It was verified that the presence of a 5 cm-thick extruded polystyrene thermal insulation improved building thermal comfort by about 17%.

Dowson et al. (2012) studied a polymer air collector with aerogel using a steady state model. The collector efficiency improved due to the replacement of the conventional glass covers with lightweight polycarbonate panels filled with aerogel insulation.

Hauer et al. (2012) extended an existing BA solar thermal collector model in order to couple it with a building within TRNSYS simulation environment. They used another way for this coupling than that of Maurer (2012). Hauer et al. (2013) compared the building integration with and without a gap between the collector and the building insulation. Instead of analysing air flow in the gap by CFD or measurements, they assumed very small, intermediate and very high air flows in the gap and they discussed the results.

5 CONCLUSIONS

This study presents an overview on the validation of developed codes, thermal and optical, within the field of BIST systems. Specific requirements for BIST modelling and simulation are highlighted. Representative studies from the literature are presented according to the validation methodologies: on-site validation, test cells and laboratory. In addition, literature references for validated models are cited separately into two main categories: building-added and building-integrated systems. Within the building-integrated configurations the systems are presented divided into two groups: opaque and transparent systems. Additional issues regarding system insulation are also presented in order to provide a more complete picture of the studied issues.

The results reveal that there are some specific requirements such as solar gain control, daylight utilisation and indoor environment quality which should be taken into account in the frame of a model for a BIST system.

Regarding validation methodologies, on-site validation has been conducted for several types of systems (active façades, multi-section façades, etc). On the other hand, indoor solar simulators facilitate solar research in cold climates and in the literature there are studies about laboratory validation for multiple configurations (concentrating BIPV, façade-integrated solar systems, PV with CPC, etc). Moreover, test cells provide an intermediate solution between a real building and an experiment in the laboratory and have been also adopted for some studies.

The literature concerning the validated models for BIST reveals that there are studies for opaque as well as for transparent systems. Within the field of transparent BIST several configurations have been modelled: façade-integrated collectors for high-rise buildings, complex façades, glazings with venetian blinds, curtain walls, double-skin façades, etc. Finally, it should be noted that there are few studies in the field of BIST in the agricultural sector and thus, it would be interesting the investigation of systems such as innovative greenhouses with BIST systems.

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BISTS technologies for NZEBs: a case study for a non-residential building in Mediterranean climate

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ABSTRACT: In this paper the feasibility of several new technologies for energy efficiency in buildings is investigated by means of a novel in-house developed Building Energy Performance Simulation (BEPS) code (DETECt) written in Matlab. In particular, two different Building Integrated Solar Thermal Systems (BISTSs) are analysed: high vacuum solar thermal collectors (for obtaining high temperature working fluids) and PV/T panels, also combined to Phase Change Materials (PCM). In order to assess the energy and economic performance of such BISTSs, a suitable case study was developed. It concerns a Net Zero Energy Buildings (NZEB) to be built up in Naples (South-Italy). Numerical results show that interesting energy and economic savings can be achieved. Results can be useful for stakeholders working on non-residential NZEBs in temperate climates.

Keywords: BIPV/T, BIST, NZEB.

1 INTRODUCTION

Buildings energy efficiency targets have led the research interest toward new energy saving strategies to be integrated into the design, construction, and operation of new and retrofitted existing buildings. Particularly for sizing and optimising purposes (especially for NZEBs), advanced energy analysis tools should be adopted to analyse the potential effects of crucial design and operating variables on the building energy performances (Todorović 2012). In this regard, commercial or in-house developed BEPS codes have been recently enhanced and developed, mainly for research purposes. Their aim is to produce NZEBs computer based analyses necessary to analyse: i) new or not yet commercialised materials and technologies; ii) novel operating strategies. In particular, several simulation models have been developed with the aim to study the effectiveness of innovative building integrated technologies and configurations, including the adoption of Phase Change Materials (PCMs) and building solar systems, e.g. PhotoVoltaic (PV) and PhotoVoltaic/Thermal (PV/T) plants (Athienitis et al., 2012; Soares et al., 2013; Tripanagnostopoulos, 2014; Yang & Athienitis, 2014). The available literature shows a lack of knowledge regarding the overall building energy performance achievable through the integration of such technologies (Ho et al., 2012). Recently, few tools for the energy performance simulation of buildings equipped with PV panels and PCMs wallboards were developed (Bigot et al., 2013; Guichard et al., 2014). Nevertheless, the development of reliable models and tools for the building integration design of PCMs in BIPV and solar thermal systems is highly encouraged (Ho et al., 2012).

The presented paper is focused on the above described framework. In particular, aim of this work is also to follow the above mentioned literature recommendation to: i) properly simulate the integration of BIPV and BIPV/T modules into the building envelope; ii) develop models and tools for the PCMs-BIPV system design and energy performance analysis. For this aim, several new tools were added to a previously developed dynamic simulation code (called DETECt 2.2 (Buonomano et al., 2013; Buonomano & Palombo, 2014)), validated by following the BESTEST procedure (Buonomano & Palombo, 2014). The obtained reliable simulation tool allows to dynamically predict the buildings thermal behaviour and to assess the benefits of different and advanced building envelope techniques, solar gain controls and daylighting solutions in case of different weather locations, envelope materials, building shapes, orientations and geometries.

In particular, in order to take into account the mutual energy interaction between the PV system and indoor building spaces, a specific tool for the dynamic energy performance analysis of BIPV and BIPV/T systems was developed. This feature allows the calculation of the variation of the heating and cooling demand due to the building architectural integration of such systems. The tool also enables the simulation of BIPV systems coupled to PCM sub layers. In addition to the above mentioned features, in case of BIPV/T systems, the recovered or exhausted heat, obtained by air or water utilised for cooling the PV panels, and the electricity efficiency and power production are dynamically assessed. Note that in the developed model the capacitance of such devices is always taken into account in the heat transfer calculation. The simulation model allows the analysis of solar thermal systems integrated into the building roof and/or façades, as well as in parts of them. It is worth noting that often (e.g. in commercial tools), BIPV and BIPV/T systems cannot be simulated as integrated in only a portion of the simulated surface. Concerning the simulation of the thermal behaviour of PCMs, the tool enables the building integration of such materials in the opaque envelope (e.g walls and roofs, where PCM is embedded in matrixes of traditional building construction materials) and in the transparent one (e.g. in windows glazing systems, where PCM is encapsulated in the gap of double or triple glazing systems). Through such tool, it is possible to assess the optimal position of the adopted PCM layer among those of the investigated building elements (e.g. massive structure and thermal insulation layers).

The additional novelties of the developed BEPS tool, included in this work, regard the modelling of: i) multi-zone buildings; ii) attached sunspaces (for the exploitation of solar greenhouse effect); iii) smart daylighting (shading of windows and artificial lights can be modulated for optimizing the building heating and cooling demands, without missing the indoor visual comfort). It is also worth noting that, through the developed simulation tool, parametric, multi-criteria and/or multi-objective analyses can be carried out from energy, economic and environmental points of view. Such analyses are performed through a one-click simulation run and the automatic comparison of the simulations results (Buonomano & Palombo, 2014). This is achieved through a built-in functionality which enables to quickly and easily generate multiple building models, avoiding the annoying and troublesome process of manually creating a building model (e.g. different shape and orientation, envelope features, occupant and operation profiles, etc.) for each investigated scenario or retrofit.

In order to show the potentiality of the presented tool, a suitable case study, referred to a new non-residential NZEB, was developed. The building, to be located in Naples (Southern Italy), is purposely conceived for Mediterranean temperate climates. In particular, a multi-zone NZEB, with different innovative building integrated energy saving techniques (PCM, sunspace, smart daylighting, etc.), is taken into account. Electricity is produced through a BIPV (or BIPV/T) system, while heat is obtained by suitable integrated solar collectors. A suitable parametric analysis is carried out to identify the optimal set of design and operating parameters that minimize the building heating and cooling energy consumptions. A comparison between BIPV and BIPV/T in terms of heating saving and extra-cooling demands and electricity efficiency is performed. Details about the simulation results and the economic convenience of all the considered energy saving techniques are provided, with special attention to the adopted BISTS. According to the authors' knowledge this is the first design and energy analysis focused on a non-residential NZEB conceived for Mediterranean climates.

2 CASE STUDY

The developed case study is referred to a non-residential NZEB to be located in Naples (Southern Italy, 40°20'N - 14°15'E), which features a Mediterranean temperate climate with dry hot summers (CDD = 185 Kd) and mild winters (HDD = 1163 Kd). During winter, outdoor air temperatures are not excessively low (design and average outdoor temperature: 2 and 10°C, respectively), while quite high outdoor air temperatures and humidity occur in several summer days (design temperature and humidity: 32°C and 60%). The building project initiative stems from the action ED6 of the Sustainable Energy Action Plan (SEAP, Covenant of Majors of the European Community, August 3rd 2012) and from an explicit Resolution (n. 517 on April 21st 2011) of the Municipality of Naples. The building will be built up on three floors, two of them above the ground level. It will host offices (at the ground floor) and conference and exposition spaces (at the first floor). Some equipment rooms and stories will be located at the basement.

2.1 Building shape and envelope features

In order to obtain suitable criteria for passive heating and cooling techniques, the building, shown in Figure 1, is conceived with a rectangular shape (15.0 × 24.5 m, East-West oriented longitudinal axis) and it is subdivided in ten different thermal zones. The S/V ratio is 0.38. In the initial design (before the optimization procedure), the adopted U values for all the opaque building elements and windows were considered equal to the maximum ones allowed by the present Italian regulation concerning the energy efficiency in public buildings (Table 1). For minimizing the winter heat loss and the summer solar radiation loads, no windows are designed on the eastern, northern and western façades. The building window to wall surface area ratio is quite low (about 15%), while it becomes very high (about 70%) when referred to the southern façade only (because of the wide windows conceived also for maximizing the winter solar heat gain). The initial glass type (before the optimization procedure) for sunspace exterior windows was 1 while 3 for the other building windows, Table 2.

Table 1. Opaque building envelope (before the optimization procedure)

Building opaque element	Weight Ms [kg/m^2]	Transmittance U [W/m^{2}K]	Layers from outside to inside	Thickness d [mm]
Vertical walls	242	0.35	Exterior plasterboard	30
			Thermal insulation	50
			Semi-hollow bricks	300
			Interior plasterboard	20
Tilted roof	233	0.33	PV panels /solar collectors	45
			Thermal insulation	80
			Concrete slab	230
			Interior plasterboard	20

Table 2. Windows glasses

Glazing type	Gap	Thermal transm. U [W/m^{2}K]	Solar heat gain coeff. g [%]	Solar transm. τ_{sol} [%]	Visible transm. τ_{vis} [%]	Emissivity ε [-]
1 6/13/6	Air	2.7	0.70	0.61	0.78	0.84
2 6/13/6	Argon	2.5	0.70	0.60	0.78	0.84
3 6/13/6 (low-ε)	Argon	1.6	0.58	0.51	0.75	0.10
4 6/8/6 (low-ε)	Krypton	1.3	0.54	0.47	0.74	0.10
5 6/13/6/13/6	Air	1.7	0.61	0.48	0.71	0.84
6 6/8/6/8/6 (low-ε)	Krypton	0.9	0.46	0.29	0.63	0.10

Note that all the investigated windows are equipped by metallic frames with a suitable thermal cut

The first floor terrace windows are equipped by external horizontal variable tilt solar shadings, while horizontal overhangs are modelled on the top of the roof windows. At the southern side of the ground floor, a sunspace is designed to maximize the winter passive heating. During the summer season such space becomes (by completely opening the external sliding windows) a shaded open porch. Note that, due to such building metamorphosis, the simulated thermal zones become nine and the S/V ratio decreases to 0.36. The porch ceiling width and height are designed to avoid the indoor space superheating, enhancing the system energy efficiency.

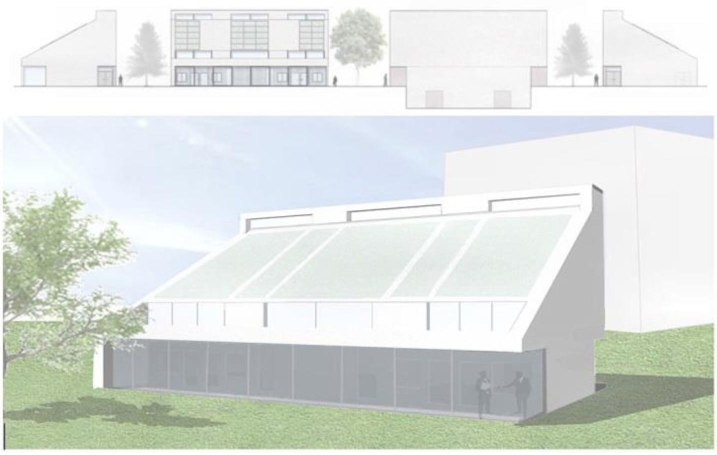


Figure 1. NZEB prototype in Naples (South-Italy)

2.2 Operating conditions

All the simulation assumptions are reported in Table 3. A 50% efficiency air-to-air sensible heat exchanger is taken into account for the energy recovery of the building exhausted air. The assumed air infiltration rate is equal to 0.4 vol/h (even during the night hours). Simulations are carried out by using the IWEC hourly weather data (air dry bulb temperature and humidity, solar radiation, etc.) of Naples. The simulation starts at January 1st and ends at December 31st. The HVAC system is activated (from 9:00 to 18:00) in winter from November 15th to March 31st and in summer from June 1st to September 30th (in August it is switched off). The modelled indoor air set-point temperature for the heating season is 20°C (sensible heating only). The summer set-points for temperature and humidity are 26°C and 60% (sensible cooling and dehumidification).

Table 3. Simulation assumptions

Building space	Hours	Days per week	People [p/m^2] ([W/p])	Lighting [W/m^2] winter	Lighting [W/m^2] summer	Mach. [W/m^2]	Outdoor air flow rate [l/s·p]
Office	9 ÷ 12	5 (Mon. to Fri.)	0.12 (130)	Modulated from 0 to 10 (at least 500 lux on office desk level)		9	11
	13 ÷ 14		0.03 (130)				
	15 ÷ 17		0.10 (130)				
Expo	9 ÷ 11	3 (Mon., Wed., Fri.)	0.28 (140)	Modulated from 0 to 8 (at least 400 lux at 1.5 m height from floor)		-	6
	12 ÷ 13		0.35 (140)				
	14 ÷ 15		0.15 (140)				
	16 ÷ 17		0.25 (140)				
Conference	9 ÷ 12	1 (Fri.)	0.6 (100)	Modulated from 0 to 6 (at least 200 lux on office desk level)		5	5.5
	13 ÷ 14		0.1 (100)				
	15 ÷ 17		0.4 (100)				

2.3 BISTS technologies

Note that the building roof has a slope of 30° and is equipped by BISTSs. In particular, 70% of this area (135 m2) is covered by BIPV or BIPV/T panels (each module is 1694 x 998 mm, mono-crystalline cells 156 × 156 mm, nominal efficiency of 0.147, for a total peak power of 16.5 kW). The remaining 30% of the roof area (58 m^2) is equipped by innovative building integrated flat-plate evacuated solar thermal collectors (500 W/m^2 at 180°C and 650 W/m^2 at 130°C, total peak power of 37 kW). Each module is 1690 x 690 mm.

2.3.1 BIPV and BIPV/T systems

Both BIPV and BIPV/T technologies were analysed by dynamically assessing their passive effect on the thermal building behaviour. In particular, for the BIPV/T system, in summer the exhausted collected air flows in a rectangular channel underlying and integrated to the PV panels, Figure 2 (left). The system is utilised as a ventilated roof by an average outdoor air flow rate of 0.5 kg/s; such air stream collects the heat produced by the solar radiation incident on the PV panel, decreasing the building cooling load. Therefore, during the cooling season the dampers at the top of the BIPV/T air channel are set to partially driven away the solar radiation load through the exhausted air (the exhausting of the indoor air could be also obtained). On the contrary, during winter the dampers of the air channel are suitably closed, resulting in an air gap between PV panels and the other roof layers, Figure 2 (right).

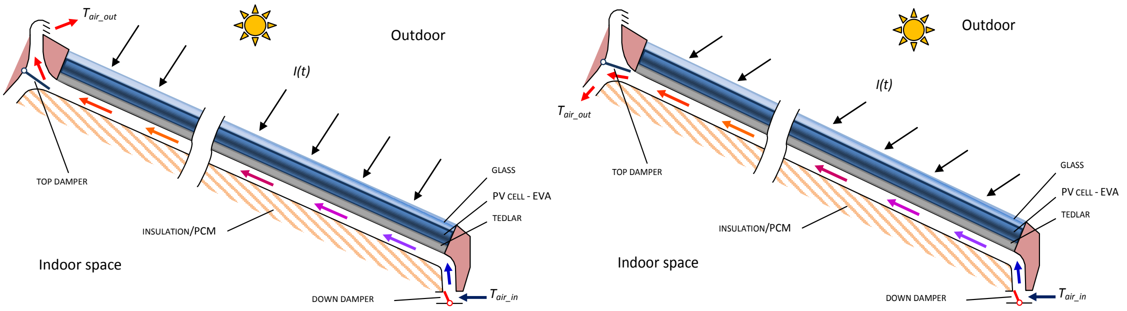


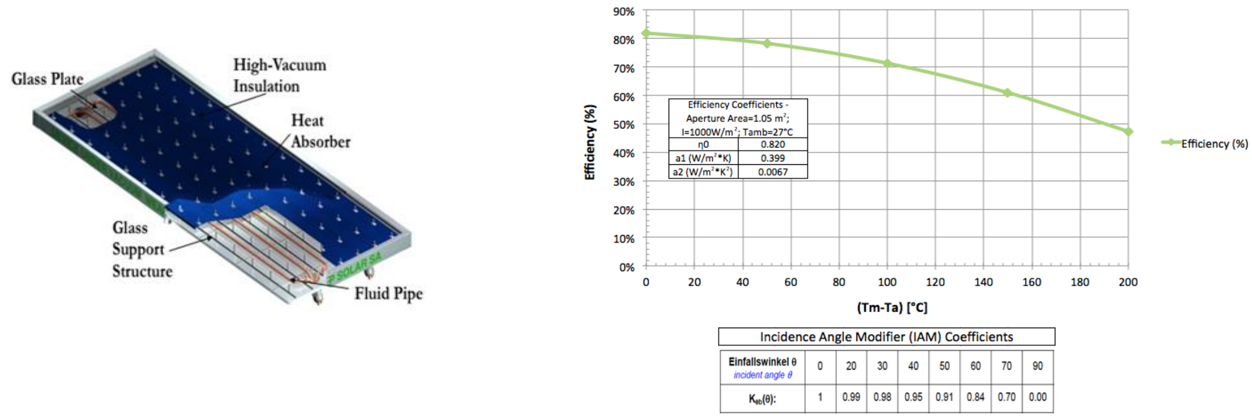
Figure 2. BIPV/T system: summer (left), middle seasons (right)

The BIPV/T active thermal behaviour can be also taken into account. In particular, during the middle seasons free heating of the indoor space can be obtained through the thermal energy released by the PV panels and recovered by indoor (recirculation) and/or outdoor collected air, Figure 2 (right).

Here, the ventilation target is achieved by a hybrid system: natural convection (obtained by stack effect due to the tilted roof) and by mechanical ventilation system (if necessary as a function of the ventilation demand). Note that, during spring and autumn the heat obtained by such BIPV/T system could be enough for the occupants thermal comfort requirements. Note that by comparing the BIPV/T system to the BIPV one, an increase of the summer electricity efficiency of the PV panels is achieved through to the cells cooling effect due to the underlying air flow. Note that for enhancing the system energy performance such devices are suitably coupled to PCM panels too.

2.3.2 Building integrated solar thermal collector system

The building integrated solar thermal collectors were analysed by dynamically assessing their passive and active effects on the energy building behaviour. The active-mode regards the space solar heating and cooling obtained by the produced hot water. The system can be also considered as passive since it decreases the winter heating load (by the high efficient thermal insulation obtained by the deep vacuum (10-9 mbar) into the flat plate solar collector, Figure 3). Also for this BISTS, the effect on the analysed NZEB depends on the occurring season. In winter the thermal energy released by the thermal panels is suitably exploited for space heating (supporting the building HVAC system) and for domestic hot water production. In summer, the solar collector outlet hot fluid (up to 250°C) is suitably exploited for space cooling (supporting the building HVAC system through a double stage absorption chiller).



Efficiency Coefficients - Aperture Area=1.05 m²; I=1000W/m²; Tamb=27°C	
η0	0.820
a1 (W/m²*K)	0.399
a2 (W/m²*K²)	0.0067

Incidence Angle Modifier (IAM) Coefficients

Einfallswinkel θ *incident angle θ*	0	20	30	40	50	60	70	90
$K_{\theta b}(\theta)$:	1	0.99	0.98	0.95	0.91	0.84	0.70	0.00

Figure 3. High vacuum, high temperature solar collectors (*TVP Solar, HT-Power panels v. 4.0*)

3 RESULTS AND DISCUSSION

The following NZEB design and operating parameters were optimized through a suitable parametric analysis for maximizing the Primary Energy Saving (PES) starting from an initial NZEB system configuration (CASE 0). The parametric analysis is obtained through the simulation code (DETECt 2.2) by means of the built-in functionality which allows the automatic comparison of different building choices or scenarios, by a single simulation run. For all the investigated parameters (e.g. related to the building shape, envelope and operating features), the selected ranges and steps, shown in Table 4, are set only once at the beginning of the simulation procedure. In Table 4 the results of such investigation are also reported.

- <u>Parameters referred to the opaque building envelope</u>: i) thermal insulation thickness in the perimeter walls *($InsTh_{wall}$)* and roof *($InsTh_{roof}$)*; ii) thermal insulation position in the perimeter walls *($InsPs_{wall}$)* and roof *($InsPs_{roof}$)*; iii) weight of the perimeter walls *(Wgh_{wall})* and roof *(Wgh_{roof})*; iv) PCM thickness in the perimeter walls *($PcmTh_{wall}$)* and roof *($PcmTh_{roof}$)*; v) PCM position in the perimeter walls *($PcmPs_{wall}$)* and roof *($PcmPS_{roof}$)*, as shown in
- Table 5. Note that PCM layer effect on both the heating and cooling demands depends on the ma-

terial activation (as a function of the charging and discharging cycle). Such phenomenon is governed by the PCM melting temperature range and peak. In this analysis, the PCM features were selected for the cooling season requirements. This choice is due to the higher building cooling demands vs. the heating ones. Therefore, the selected melting temperature ranges between 19 and 28°C, while the peak melting temperature is 26°C. The effect of the adoption of 3 cm of a PCM layer produces: a significant reduction of the temperature across the wall; a very small fluctuation of the internal surface temperature that always approaches 26°C during the day. The convenience to suitably locate the PCM depends on the higher building thermal solicitation between the internal and the external one.

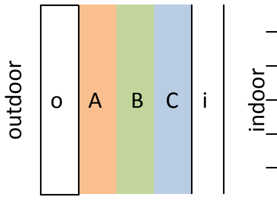
- Parameters referred to the transparent building envelope: i) glazing type of the sunspace exterior windows (Typ_{gl1}); ii) glazing type of the remaining NZEB windows (Typ_{gl2}); iii) window to wall surface area ratio ($W/W_{\%}$).
- Parameters referred to the sunspace: i) sunspace width (Wd_{sg}); ii) solar absorption coefficients of the floor (FAb_{sg}) and wall separating the sunspace and the adjacent offices (SWAb_{sg}); thickness of the wall between the sunspace and the offices (SWTh_{sg}). Note that reducing Wdsg a solar gain growth is obtained for the increased incident solar radiation on the wall separating the sunspace and the adjacent offices, while in summer, when the sunspace becomes an open porch, the lower the width the higher the cooling demand.
- Night free cooling ventilation: (NFC_{ac}, volume air changes per hour). Obviously, for higher NFC_{ac} the heavier the external walls, the higher the PES.

In the following, CASE OPT is referred to a NZEB configuration in which all the above mentioned parameters are taken into account as optimized (Table 4).

Table 4. Results of the parametric analysis

Variable	Range	Step	Starting value (CASE 0)	Optimal value (CASE OPT)
InsTh_{wall} [mm]	40-90	10	50	90 (wall: $U_{OPT} = 0.23$ W/m^{2}K)
InsPs_{wall} [-]	Table 5	1	configuration 1	configurations 4 (offices) and 8 (elsewhere)
Wgh_{wall} [kg/m^3]	800-1300	250	800	1050
PcmTh_{wall} [mm]	10-30	10	0	30
PcmPs_{wall} [-]	Table 5	1	-	configurations 4 (offices) and 8 (elsewhere)
InsTh_{roof} [mm]	60-110	10	80	110 (roof: $U_{OPT} = 0.23$ W/m^{2}K)
InsPs_{roof} [-]	Table 5	1	configuration 1	configuration 2
Wgh_{roof} [kg/m^3]	800-1300	250	1050	1300
PcmTh_{roof} [mm]	10-30	10	0	30
PcmPs_{roof} [-]	Table 5	1	-	configuration 2
$W/W_{\%}$ [%]	30-70	20	70	70
Typ_{gl1} [-]	Table 2	1	glazing type 1	glazing type 3
Typ_{gl2} [-]	Table 2	1	glazing type 3	glazing type 3 (East office, conference room) glazing type 6 (elsewhere)
Wd_{sg} [m]	1-5	1	4	3
SWAbs_{sg} [-]	0.3-0.6	0.15	0.6	0.6
FAbs_{sg} [-]	0.3-0.6	0.15	0.6	0.45
SWTh_{sg} [mm]	0.15-0.30	0.05	0.25	0.30
NFC_{ac} [vol/h]	1-3	0.5	0.5	3

Table 5. Investigated combinations of the external walls and roof layers

Building element	Config.	Layers
	1	A = Thermal insulation; B = Hollow brick / concrete slab
	2	A = PCM; B =Thermal insulation; C = Hollow brick / concrete slab
	3	A = Thermal insulation; B =PCM; C = Hollow brick / concrete slab
	4	A = Thermal insulation; B = Hollow brick / concrete slab; C = PCM
	5	A = Hollow brick / concrete slab; B = Thermal insulation
	6	A = PCM; B = Hollow brick / concrete slab; C = Thermal insulation
	7	A = Hollow brick / concrete slab; B = PCM; C = Thermal insulation
	8	A = Hollow brick / concrete slab; B = Thermal insulation; C = PCM

Note that o corresponds to walls exterior plasterboards and roof covers, while i corresponds to walls and roof interior plasterboards

Special attention is paid to the discussion of the BISTS analysis. The yearly production of electricity through BIPV or BIPV/T systems, as well as of the heat obtained by the building integrated solar thermal collectors, is reported in Table 6. An increase of more than 8% of the electricity production is observed by shifting from the BIPV system to the BIPV/T one coupled to an underlying PCM layer. Note that the primary energy (Ep) is calculated by taking into account a reference system (electric heat pump / chiller), whose nominal COPs are 3 and 2.5 for heating and cooling season, respectively. The simulated performance enhancement of the BIPV collectors obtained by coupling them to PCM panels is reported for a spring sample day in Figure 4.

Table 6. Electricity and heat production

CASE	BIPV		BIPV/T		Solar thermal	
	E_{el} [MWh/y]	E_p [kWh/m^{3}y]	E_{el} [MWh/y]	E_p [kWh/m^{3}y]	E_t [MWh/y]	E_p [kWh/m^{3}y]
0	18.5	18.0	19.2	18.7	29.5	10.1
OPT	19.3	18.8	20.0	19.4		

- Here, the hourly time histories of the PV cell temperature and electric efficiency with and without PCM are shown. In Figure 5 the analysis of BISTSs influence on the heating and cooling primary demands, E_p, is shown for several NZEB roof configurations:

- BIPV (135 m^2) and BISTS (58 m^2), CASE 0;
- BIPV/T (135 m^2) and BISTS (58 m^2), CASE OPT;
- BISTS (58 m^2). The rest of the roof is covered by traditional tiles;
- All the roof is covered by traditional tiles.

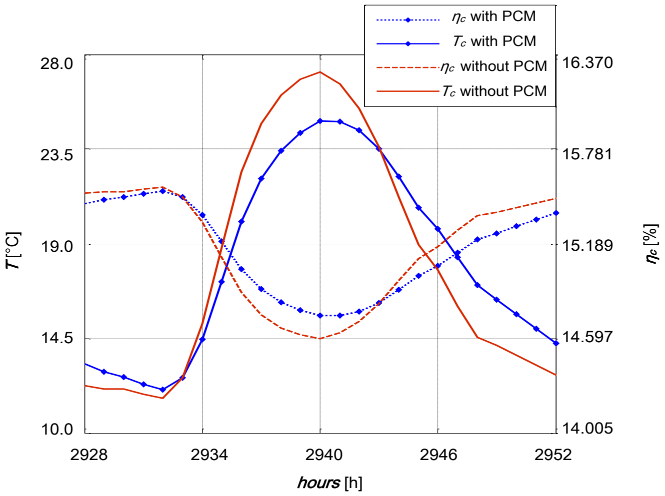


Figure 4. May 3rd: average temperature and efficiency of the PV cell with and without PCM

The adoption of both PV and solar thermal collectors implies a reduction of the heating demands with an increase of the cooling one. As an example, by comparing the CASE OPT referred to BIPV/T+BIST configuration vs. CASE OPT without solar technologies, a 18.6% reduction of the heating demand and a 8.4% increase of the cooling one are obtained. These different effects almost counterbalance each other. For the previous example, a negligible reduction of the overall E_p is detected (2.2%), Figure 5. The energy needs for the building lighting and equipment (included HVAC system ones) are reported in Table 7.

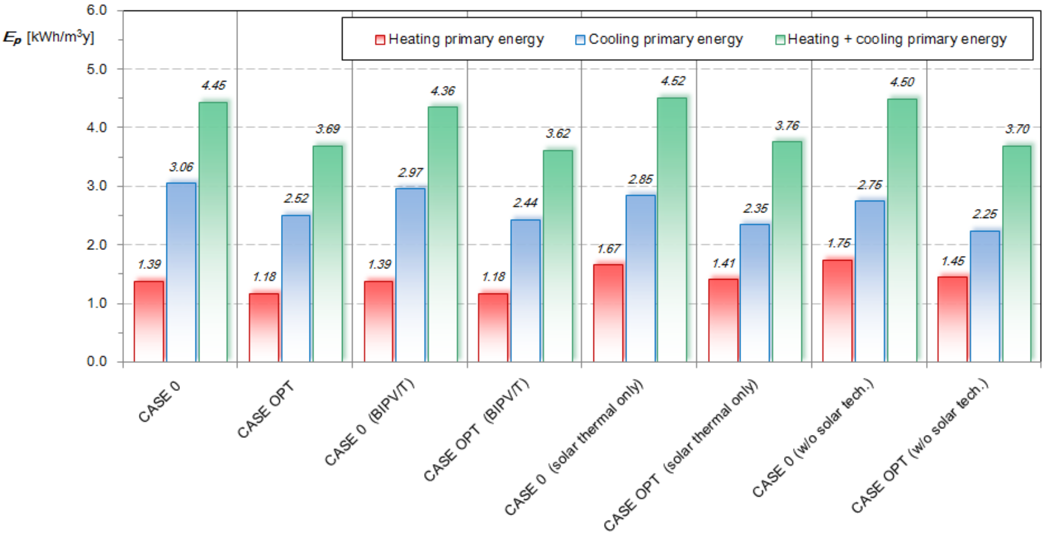


Figure 5. Primary energy demand as a function of the implemented solar technologies

Note that, for all the investigated cases the PES achieved by the electricity production of the PV collectors resulted much higher than the primary energy demand due to heating, cooling, lighting and equipment. The extra-production of electricity and thermal energy is considered to be sold to the national grid (at 0.08 €/kWh following the present Italian rule) and to be supplied to a close non-residential building, respectively. In particular, for CASE OPT (with BIPV/T and PCM) the extra-production of electricity is 13.8 MWh/y. Since the design of the initial NZEB configuration (CASE 0) follows all the requirements provided by the Italian rule for the buildings energy efficiency, the resulting economic analysis is referred to all the extra-costs of CASE OPT (including BIPV/T and BISTS plants).

Table 7. Electricity demand for lighting and equipment

	Lighting		Equipment		Ventilation	
CASE	E_{el} [MWh/y]	E_p [kWh/m^{3}y]	E_{el} [MWh/y]	E_p [kWh/m^{3}y]	E_{el} [MWh/y]	E_p [kWh/m^{3}y]
0	2.1	2.0	3.1	3.0	1.3	1.3
OPT	1.8	1.7				

The results of this analysis are reported in Figure 6. Here, the weight of each investigated measure on the building energy performance, varying as a function of the investigated parameters ranges, is also shown. In this figure it is clearly noticeable that the extra-costs of the considered energy saving solutions are very low. The only exception is the one referred to the PCM implementation, equal to 46.6 k€. The total extra-cost for all the accounted enhancements reaches 48.2 k€, but without PCM it decreases to 1.6 k€. In the same figure, the yearly economic savings obtained for each CASE OPT investigated parameter are also reported. Here, it is clearly shown that the high PCM extra-costs are not counterbalanced by correspondent economic savings (about 20 €/year). Notice that, an economic saving of about 64 €/year is obtained by adopting all the considered CASE OPT solutions except the PCM one (not shown in figure). By such results a Simple Bay Back (SPB) analysis can be easily carried out. For calculating the SPB, the variation of heating and cooling demands of the final CASE OPT (with BIPV/T and without PCM) vs. CASE 0 (in terms of electricity demand) is equal to 0.510 MWh/y while the one due to the lighting demand is about 0.580 MWh/y. For the SPB assessment, the net extra-production of electricity (PV electricity production minus overall electricity demand) obtained through BIPV/T vs. BIPV (without PCM) is 1.44 MWh/y. As a result, the SPB period obtained for the final CASE OPT vs. CASE 0 is of about 14 years without national funding for energy saving. Presently, such incentives are essential for the PCM adoption, otherwise the related SPB results unfeasible (a reduction of PCM costs for production and installation is expected in the next future).

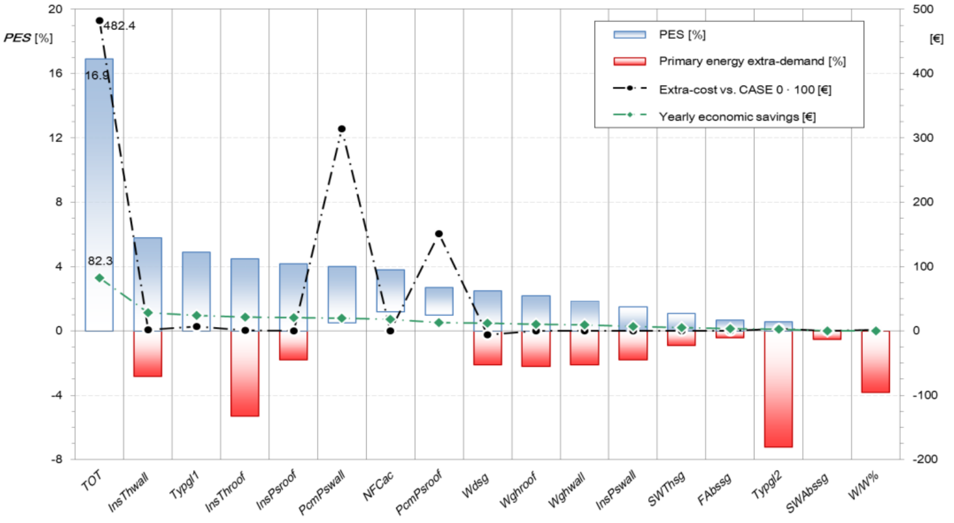


Figure 6. *PES*, extra costs and economic savings of the considered energy efficiency solutions

4 CONCLUSIONS

In this paper a new in house developed simulation model (DETECt 2.2) for the dynamic energy performance analysis of multi-zone buildings was utilised for assessing the behaviour of several innovative energy saving techniques for buildings including BIPV/T (also coupled to PCM) and BISTS. Such tool was adopted for the energy design and performance analysis of a non-residential NZEB to be built up in Mediterranean climates (Naples, South-Italy). To the author's knowledge this is the first attempt in such operating conditions. A sensitivity analysis related to the design and operating parameters with a heavy impact on the overall building energy performance was carried out. All the obtained results can be useful for stakeholders working on non-residential NZEBs in temperate climates. The following innovative findings can be highlighted. The adoption of PCM wallboards in opaque elements reduces the building energy demand. In particular, the minimum energy requirement is obtained by applying PCM panels as interior layers in the perimeter walls (vs. massive and insulation ones) and as exterior layer into the roof. By coupling PCM to the roof BIPV (BIPV/T) panels, a 4.2% (8.1%) increase of PV electricity production is obtained. Currently, the initial cost of such materials, for both building walls and roof applications, is still excessively high for achieving acceptable payback periods. The results of the comparison analysis among the investigated building roof configurations recommend the adoption of a BIPV/T system instead of BIPV one. In addition to the higher electricity production, the better performance vs. a BIPV system is due to lower extra-cooling demands. In any case, the electricity production of such systems counterbalances the lower yearly HVAC energy demand obtained by traditional medium reflectance roofs. Very low energy demands are achieved for the optimal modelled NZEB configuration: 0.9 and 1.5 kWh/m^{3}y for heating and cooling, respectively. In particular, by optimising all the considered parameters a primary energy saving of 16.9% (13.3% without PCM) is obtained.

ACKNOLEDGMENTS

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Experimental performance of a Fresnel-transmission PVT concentrator for building-façade integration

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ABSTRACT: A building-façade integrated concentrating photovoltaic-thermal system has been designed, constructed and experimentally characterised. Comparative performances with a non-concentration reference unit have been conducted to analyse the differential outputs. The concentrating system consists of double-side reflective strips which concentrate the incident beam towards a static photovoltaic-thermal receiver. The reflectors are placed vertically at the façade and track the sun by rotating axially. The concentrating reflector outperforms the reference one in both, thermal and electrical power. The thermal output of the concentration module almost doubles the reference one and the electrical power registered is more than 4.5 times in the case of the concentrating configuration.

Keywords: Building integration; Photovoltaic-Thermal collectors; Concentrating photovoltaics

1 INTRODUCTION

Building-Integrated Concentrating Photovoltaics (BICPV) present characteristics that could qualify them as an attractive configuration to be incorporated in buildings. The reduction of cell area can lead to more cost-efficient systems from both, economical and environmental aspect (Menoufi et al., 2013). The concentrating element plays a dual function by balancing the light which passes into the interior space and the light that converges onto the PVs. Several configurations of BIPV systems can be found in the literature: for installing at the roof or at the façade (Chemisana, 2011; Aste et al., 2015; Baig et al., 2014a; 2014b; 2015; Chemisana et al., 2013a; Chen et al., 2012; Mallick & Eames, 2007; Sarmah & Mallick, 2015; Zacharopoulos et al., 2000). Most of them are designed to be static with low concentration ratios, but others increase the concentration ratio by incorporating a solar tracking system. Medium-concentration technologies (10-100 suns) present some possible advantages with respect to low- and high-concentration devices. From one side, the concentration is higher than in static artefacts and this means a reduction in cells quantity with its consequent repercussion on cost. From the other side, medium concentration systems allow for single-axis tracking which simplifies the mechanics and the control associated (Chemisana & Ibáñez, 2010; Chemisana & Rosell, 2011; Chemisana et al., 2009; 2013b). When increasing the concentration ratio, the percentage which is not converted into electricity becomes much higher in absolute terms. This could cause PV overheating. A strategy to profit the removal heat which negatively influences system performance is to use a hybrid Photovoltaic-Thermal (PVT) receptor. PVT module controls PV temperature while simultaneously produces thermal energy. Hybrid collectors integrated onto the building could be an interesting option as both energies, thermal and electrical, could be directly used (Cristofari et al., 2009; Kalogirou, S.A. & Tripanagnostopoulos, 2006; Buonomano et al., 2013; Lamnatou et al., 2015a; Lamnatou et al., 2015b). In the frame of the present work, a medium-concentration system for façade building-integration has been constructed and experimentally characterised. The prototype consists of a Fresnel-reflector concentrator which delivers solar irradiance onto a PVT module.

2 SYSTEM DESCRIPTION

2.1 Optical system

The optical analysis of the present system is described in Chemisana & Rosell (2011). The most important parameters and characteristics involved in the optical design are briefly illustrated in fig. 1a and 1b. Fig. 1a shows the parameters used in system design, for a configuration of 21 reflectors. Parameter f represents the focal length, the distance of the centre of rotation of the i^{th} reflector from the origin O is defined to be x_i and the angle subtended at the centre of the receiver by the reflector and the origin is α_i. The relation between them is that $\alpha_i = \mathrm{atan}(x_i / f)$. ϑ_s is the angle of incidence of the solar radiation and the inclination of reflectors is defined as β_i. Both angles are related by $\beta_i = 0.5(\vartheta_s - \alpha_i)$ and the variation of β_i with respect to ϑ_s is 0.5 ($\partial\beta_i / \partial\vartheta_s = 0.5$). This means that once the initial position of the reflectors has been established, the relative movement required to achieve sun tracking is the same for all reflectors. This permits the use of a single linear driver, representing an important mechanical advantage. The receiver remains static while sun tracking is performed by the reflectors rotating simultaneously.

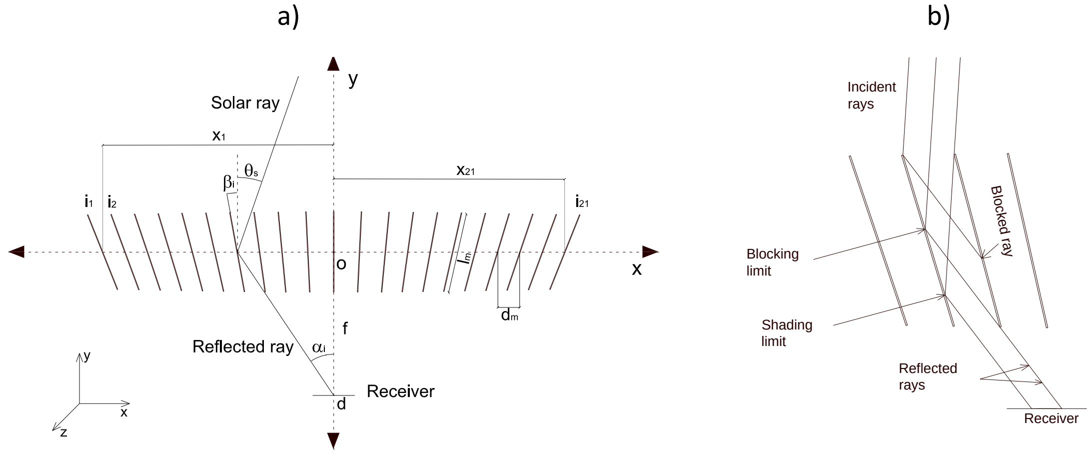

Figure 1. a) Schematic showing parameters used in the mathematical model; b) shading and blocking effects.

Two phenomena are crucial in terms of system efficiency: blocking and shading. The positions of the upper and lower limits of the shaded and blocked rays are represented in figure 1b. The rays that fall on the mirror to the left of the shading limit are shaded and those that fall to the right of the blocking limit are blocked; therefore, decrease the optical efficiency. These limits have been calculated by using a ray tracing algorithm. Once the algorithm converged for a selected set of parameters, an optimisation procedure for maximising the optical efficiency and the flux uniformity on the receiver, in a range of angles of incidence [-45º, 45º], was applied to obtain the best option for each studied configuration. In the present investigation, 11 strips of double-side reflective material of 160 mm wide by 2000 mm long have been assembled. The thickness of each reflector is 4 mm. The numerical aperture (NA) of the system is 0.5, with an entrance pupil of 800 mm by 2000 mm.

2.2 Photovoltaic-thermal module

The PVT module consists of 13 series connected crystalline silicon cells optimized for concentrating systems operating in a range from 10 to 20 suns (Fig. 2). The size of each cell is 3.5 cm by 4.8 cm. The cells (NaREC®) are attached to a water active heat dissipater with a special adhesive tape with high heat-transfer conductivity that is also resistant to extreme temperatures and is an excellent electrical insulator (Chomerics Thermattach T404). The hybrid absorber is enclosed in an aluminium case with U cross-section made of copper; the encapsulation of the collector is finished fixing one top glass cover of 77.5 mm wide by 600 mm long by 4 mm thick. From these dimensions it can be arranged the geometrical concentration ratio (quotient between the concentrator aperture area and receiver area), which takes a value of 16.67x with respect to the cell width and 10.32x with respect to the PVT module gross width.

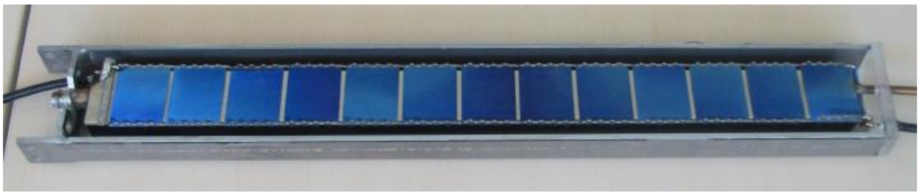

Figure 2. PVT module fabricated before the top glass fixing.

2.3 Mechanical structure

The 11 reflectors are fixed and placed vertically in a metallic framing structure. The inferior and superior profiles are drilled and prepared to hold the reflectors and at the same time to allow them rotating. The metallic frame constitutes the South façade of a testing-unit made of 4 cm wood white panes which was built to house all the sensors and instruments for the experimental campaign and to achieve a more controlled testing conditions by minimising the wind effect, the ground temperature influence, albedo, etc.

In order to transform the rotational movement required to track the sun by the mirrors into a linear one, each reflector was attached mechanically onto a steel plate designed to have one point at the rotation centre of the reflector and another located with the corresponding angle for the specific reflector strip. In this manner, all reflectors are driven with the same actuator through the connecting rods fabricated (Figure 3).

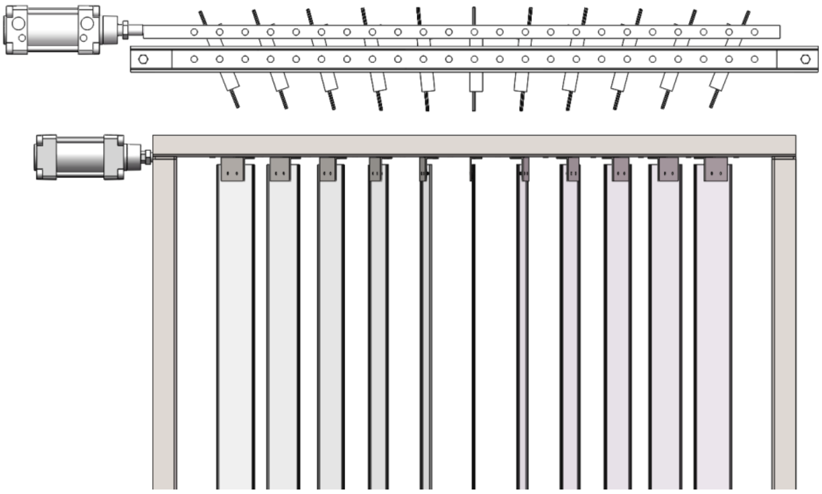

Figure 3. Detail of the mechanical system for tracking. Top and frontal view of the concentrating system.

As explained in 2.1, the angular rotation of the reflectors is equal in all of them, and at the same time is the half than the angular movement of the Sun. To transfer this relation a very simple reduction gear (1:2) is used (see Fig. 4). The tracking control is conducted by means of 2 photo resistances and a shading plate connected to an electronic circuit which in function of the current delivered from the resistors transfers a pulse to the actuator. In figure 4, a picture of the built prototype shows the tracking and control system. On the left it can be seen the control box, the driver with a limit switch sensor. The light sensor which tracks the sun through the photo resistances can be seen on the right of the image.

Figure 4. Detail of the implemented tracking system.

In this configuration, reflector strips rotate with respect to its vertical axis. It keeps track of the solar azimuth in its daily path. Its incorporation as an architectural element could replace a constructive element such as a vertical lattice arrangement. Receivers can be placed at the façade or in any location in order to facilitate the interconnection of different facilities.

3 EXPERIMENTAL TESTING SET-UP

The experiments were carried out at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain). Fig. 5 shows the experimental installation during one of the tests. In the photograph, two modules, the reference and the concentrated one, can be seen. This configuration was adopted in order to perform differential assessment, taking as reference the module without concentrator. Also it can be observed the hydraulic circuit of both modules connected to the water tank. In Figure 6, a schematic of the monitoring system is depicted.

Figure 5. Experimental set-up during operation.

Differential performances were monitored according to the diagram which is shown in Fig. 6. The electrical parameters were measured by using two switching relay circuits to alternate short circuit an open circuit conditions every 30s. The short circuit currents were monitored through a Fluke i30s amperimetric clamp (accuracy ± 1 % of reading ± 2 mA) connected to a data acquisition (DAQ) system (datalogger Campbell CR3000). Open circuit potential and relays were also collected and controlled respectively through the DAQ system. The thermal behavior of the systems was characterized by recording the inlet and outlet temperatures of the PVT modules by means of T-type thermocouples (accuracy ± 0.5ºC). In addition, a Kipp & Zonen CMP11 pyranometer (daily uncertainty < 2%) was positioned vertically at the wall at the same height than the modules. All the sensors were connected to the datalogger. The different input variables were measured every 1 s and their mean values were recorded every 5 s. For data processing and graphical representations, 30-second averaging was performed (in agreement with the switching time of relays).

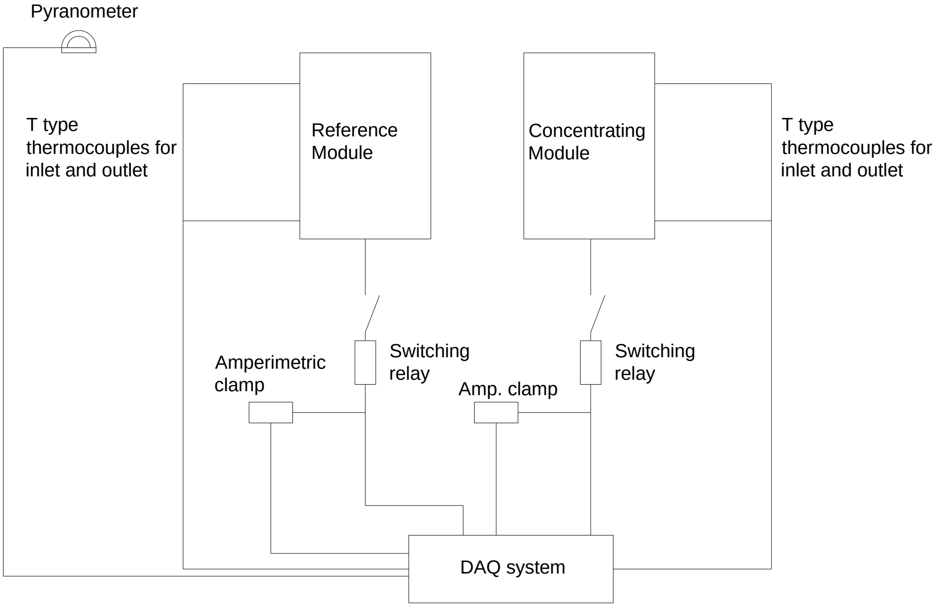

Figure 6. Schematic of the monitoring system.

4 RESULTS

4.1 Optical efficiency

The optical efficiency was calculated from the electrical parameters measured. Since the short circuit current is proportional to the solar irradiance on the cell, the optical efficiency (η_o) can be determined by dividing the short circuit current of the concentrating module by the geometrical concentration (C_g) and the short circuit current of reference module:

$$\eta_o = \frac{I_{sc,CPV}}{C_g \, I_{sc,PVref}} \tag{1}$$

For one day with quite stable solar irradiance, the optical efficiency throughout the day achieves the pattern shown in Fig. 7:

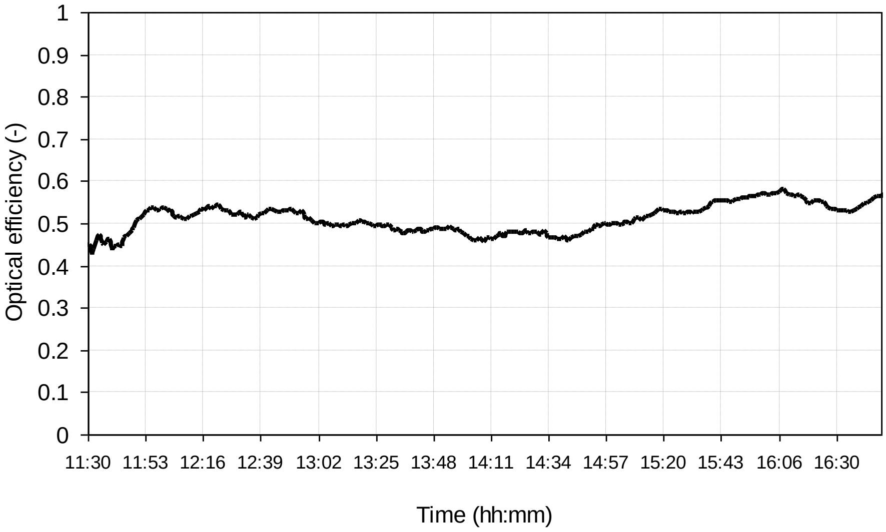

Figure 7. Daily temporal evolution of the concentrator optical efficiency. Date: 26/9/2014.

The mean optical efficiency achieved is 0.51. This value agrees very well with the equivalent calculated through simulation in (Chemisana & Rosell, 2011), which was referred as Base System (BS) configuration. In this previous research, the authors found a daily efficiency average value of 51.87 % for a range of angles of solar incidence from -45º to 45 (6-hour time period). It should be noted that the present efficiency is calculated for a 5-hour time period, which corresponds to the interval (-37.5º- 37.5º). For this narrower range of angles the simulated optical efficiency takes a value of 57.95%. The 7% difference observed from the experimental value to the simulated one is attributed to two factors: (1) a few tracking mismatch caused by the pulses delivered to the driver which, as it can be observed in Figs. 7 & 8, do not follow the sun continuously; (2) 90% average reflectance was considered in the simulation whilst the average reflectance of the reflector used was measured to be slightly lower (87%).

4.2 Electrical and thermal performance

The electrical performance of the system was characterized, as explained in section 3, by measuring the short circuit and open voltage conditions, as both are two key parameters to determine the effect of the solar concentration from the irradiance and temperature points of view. In figure 8, the short circuit current and the open circuit potential for both, the CPV and reference system, are represented jointly with the solar irradiance.

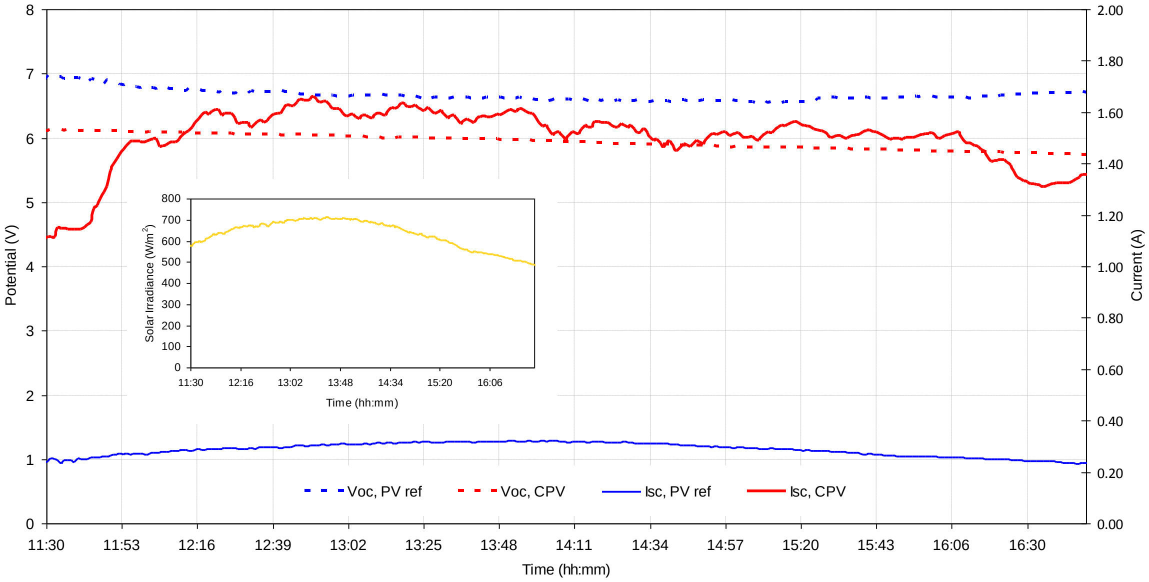

Figure 8. Irradiance, V_{oc} and I_{sc} profiles for the reference and the concentrating modules. Date: 26/9/2014.

The short circuit current of the reference module presents exactly the same profile than the irradiance curve, as expected. However, due to the action of the reflectors, apart that the current increases proportionally with the concentrated light, the CPV module experiments local variations because the reflectors control actuates by pulses, thereby the solar tracking suffers small mismatches. The open circuit potential, by contrast, reflects that the CPV module operates always worse than the reference module with a 10% difference in average. This fact is predictable since the concentrated irradiance that is not converted into electricity must be evacuated as heat, and as both modules are cooled with the same flow rate (3 l/h), the temperature of the CPV module is always higher. In Figure 9, this effect is illustrated. The inlet temperature for both modules was the same as the water tank from were the pump distributed the inflows was the same. The outlet flows were connected also to the tank in a closed-loop circuit. The temperatures average relative difference between the CPV and the reference modules is 11.3%.

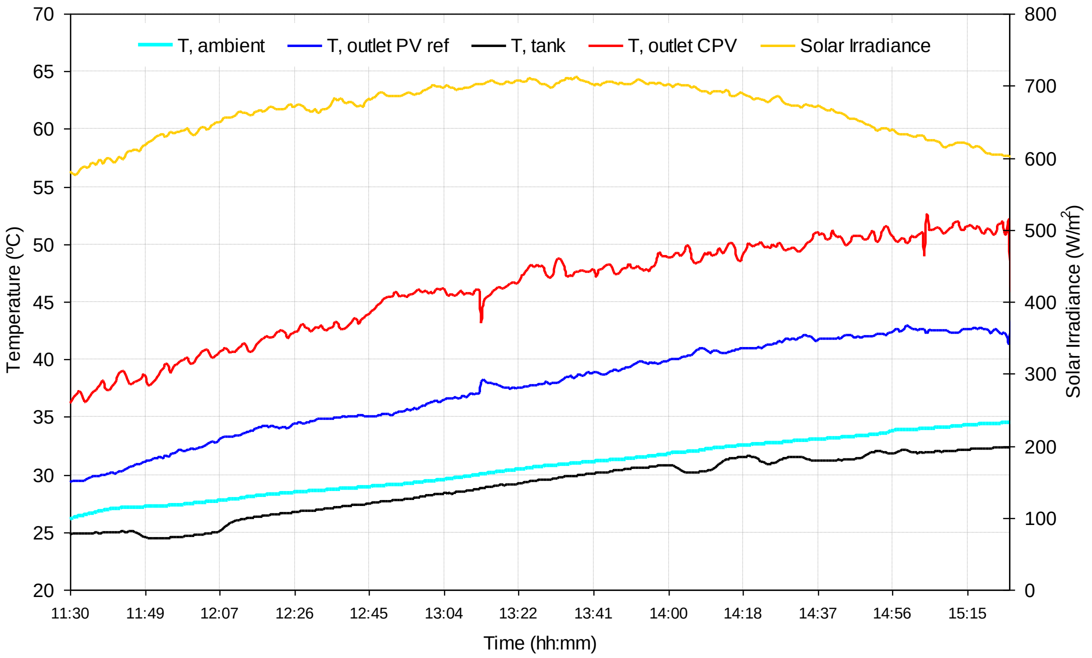

Figure 9. Temperature profiles for the reference and concentrating modules. Date: 26/9/2014

The short circuit current in the concentrating system is, in average, 5.3 times the one from the reference module and the open circuit potential is 1.1 times higher in the reference configuration. Therefore, considering the fill factor to be constant, it can be concluded that the maximum electrical power of the concentrating device takes a value of around 4.8 times more than in the case of the reference one.

The thermal power output differentia performance can be easily deducted from the outlet temperatures of the two systems, as the flow rate, the fluid and the inlet temperatures are the same. The concentrator outperforms the reference systems producing 1.9 times thermal energy.

5 CONCLUSIONS

A building façade-integrated concentrating photovoltaic-thermal system has been constructed and experimentally characterised outdoors. Every component, including concentrator, hybrid module, mechanical system and electronics, has been designed and fabricated. The concentrator behaves achieving an average optical efficiency slightly above 51%, which is in agreement with the simulated results. The concentrating PVT system outperforms the conventional reference PVT module in both, electrical and thermal energy production. The thermal output of the concentration module almost doubles the reference one and the electrical power registered is more than 4.5 times in the case of the concentrating configuration. The tracking system and system performance was analysed also under variable irradiance conditions to determine its sensitivity to these conditions. The tracking response was adequate as no significant decrease in the electrical power was observed due to possible tracking mismatches. From the above commented results it can be concluded that the concentrating system presented offers advantages in energy generation which qualifies it as an attractive solution for building-integrated applications.

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Flexible Thin-film Photovoltaic Technologies in Building Integration

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ABSTRACT: New PV technologies that may advance new innovations, which may be developed into building integrated photovoltaics, might be found in flexible thin film solar cells. The use of flexible substrates offers new possibilities for the application of solar cells for building integration. Flexible cells are very thin and lightweight, which makes them also more flexible in use than rigid cells. One of the most important advantages of flexible solar cells is the potential to reduce production costs. Development of photovoltaic thin film modules ensures a satisfying flexibility of the surface, and the possibility to design appropriate shapes. In a past few years producers offered various products and new ways to integrate lightweight, flexible solar modules into buildings to achieve cost-effective and high-performance solar power.

Keywords: photovoltaics, flexible solar cells, building integrated photovoltaic

1 INTRODUCTION

Photovoltaic (PV) is one of the most prominent renewable energy technologies, characterized by a world-wide abundant available fuel source – the sun. Solar photovoltaic technologies are an attractive option for clean and renewable electricity generation – it is the direct conversion of sunlight into electricity. Photovoltaic devices are rugged and simple in design requiring very little maintenance. Solar energy using contributes to more efficient use of the countries own potentials in generating electrical and thermal energy, reduction of the greenhouse emission, reduction of importing and use of the fossil fuels, development of the local industry and new job openings (Pavlovic, 2013). PV systems are still an expensive option for producing electricity compared to other energy sources, but many countries support this technology.

Starting from 1990 industry of photovoltaic conversion of solar irradiation shows constant annual economical growth of over 20%, and from 1997 over 33% annually. In 2000 total installed capacities worldwide have surpassed 1000 MW, and in developing countries have overreached more than million house-holds which are using electrical energy generated by means of the photovoltaic systems. It is predicted that PV will deliver about 345 GW by 2020 and 1081 GW by 2030 (Ingmar, 2011). Over the last five years, the global PV industry has grown more than 40 % each year, (Radulovic, 2014). Overgrowing number of companies and organizations is taking active part in the promotion, development and the production of photovoltaic devices and systems.

Solar cells developed rapidly in the 1950s owing to space programs and used on satellites (crystalline Si, or c-Si, solar cells with efficiency of 6–10%). The energy crisis of the 1970s greatly stimulated research and development for PV. Research on semi-conductors (III–V and II–VI) based solar cells were studied since 1960 and at that time, new technology for poly-crystalline Si (pc-Si) and thin-film solar cell have been establish in order to lower the material cost and energy input but increase the production capacity (Razykov, 2011).

Silicon is still a leading technology in making solar cell because of its high efficiency. But many researchers, due to its high cost, are trying to find new technology to reduce the material costs for production of solar cells and thin film technology can be seen as a suitable substitution. However, the efficiency of solar cells based on this technology is still low, and researchers are intensively making an effort to enhance the efficiency (Razykov, 2011). Commercial PV materials commonly used for PV systems, besides silicium (Si), include solar cells of cadmium-telluride (CdTe), coper-indium-diselenide (CIS) and solar cells made of other thin layer materials.

Flexible modules are light-weight and suitable for applications where weight is important, and they offer a much faster payback than products based on conventional photovoltaics (Kessler, 2004). It is expected that they will play a very important role in the world PV market in the near future. In this paper the advantages and perspective of the flexible thin film photovoltaic technology for building integration are pointed out.

2 FLEXIBLE SOLAR CELLS

Very important perspective of thin film PV technology is flexible modules with strategic space and military use, integration in roofs and buildings facades, etc. The ultimate advantage of thin-film technology is roll-to-roll manufacturing to produce monolithically interconnected solar modules leading to low time for energy payback because of high-throughput processing and to low cost of the overall system (Kessler, 2004).

2.1 A-Si flexible modules

Flexible a-Si solar cells are likely to be very popular and in demand for applications in the low to medium range of power, since they can be made in different shades (even semi-transparent), shapes, and sizes. Digital photograph of a-Si cell device deposited on patterned Al substrate is shown at Figure 1, (Xiaoa, 2015).

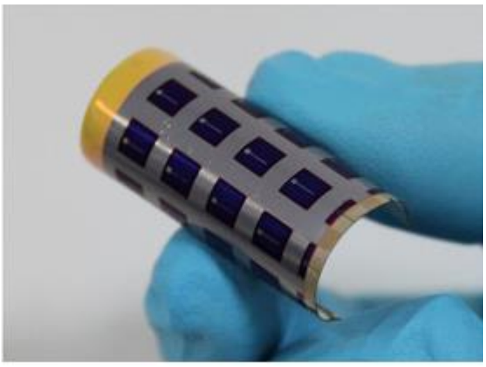

Figure 1. *Flexible a-Si solar module - photograph of a-Si cell device deposited on patterned Al substrate.*

Commercial solar cell devices based on hydrogenated amorphous silicon rapidly surpassed 10% efficiency, but suffered from light-induced degradation that leads to a reduction of the solar cell efficiency. The best initial efficiencies of 13.7 % and 9.8 % were achieved on triple-junction cells and modules, respectively. However, stabilized efficiencies are still low, around 6–7% for the best commercial modules. Nevertheless, at present, about 8–10% of the worldwide PV production uses a-Si technology (Razykov, 2011).

The world's leading companies in a-Si TFPV manufacturing are undergoing rapid expansion from an annual production capacity of about 30 MW to 300 MW by 2010, to apply this technology as widely as possible and drive the expansion of its market share by applying its products to free-land applications and building-integrated photovoltaics (Pagliaro, 2008).

2.2 Flexible CdTe cells

Also, CdTe is one of the leading candidates for the solar cells due to its optimum band gap and the variety of film preparation methods. It is achieved the lab efficiency on plastic foil of 11.4% (single-junction cell), and on metal foil 8% (single-junction cell) (Razykov, 2011).

These devices allow building integration in structures, which cannot take the additional load of heavy and rigid glass laminated solar modules. The flexible solar modules can be laminated to building elements such as flat roof membranes, tiles or metallic covers without adding weight and thus, the installation costs can be reduced significantly (Zhu , 2012).

2.3 Flexible CIGS cells

A large number of activities on highly efficient, stable, and flexible thin-film modules based on CIGS has recently drawn much interest for flexible solar cells on metal and plastic foils. Apart from the expected high efficiency and long-term stability for terrestrial applications, flexible CIGS has excellent potential for space application because of their tolerance to space radiation, being 2–4 times superior to conventional Si and GaAs cells. Flexible CIGS cells can be grown on polymide and on a variety of metals, e.g., stainless steel, Mo, and Ti (Kessler, 2004).

The flexible prototype mini-module developed on polymer foil is shown in Figure 2 (Zhu, 2012). These devices allow building integration in structures, which cannot take the additional load of heavy and rigid glass, laminated solar modules.

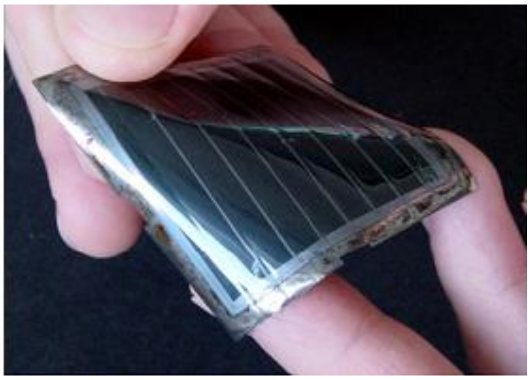

Figure 2. *Flexible CIGS solar module - photograph of flexible CdTe solar modules.*

Scientists at EMPA, the Swiss Federal Laboratories for Materials Science and Technology, have developed thin film solar cells on flexible polymer foils, based on CIGS with a new record efficiency of 20.4% for converting sunlight into electricity. The technology is currently awaiting scale-up for industrial applications (EMPA, 2015).

Flexible CIGS solar cells have the ability to both realize their potential as the most efficient thin film technology and to dominate the building-integrated photovoltaics (BIPV) market in the future (Jelle, 2012a).

3 ADVANTAGES OF FLEXIBLE SOLAR CELLS FOR BUILDING INTEGRATION

The Building integrated Photovoltaics (BIPV) market, which got increased political support during the last years is still one of the big hopes for TF technologies. In this context, these modules have many advantages compared to c-Si ones: strongly reduced weight for the application to the building stock, see through property, adjustable optical transmittance, excellent building appearance, potential capability for applying flexible substrates, and less sensitivity to the degradation of light intensity and increasing temperature of the module (Radulovic, 2014).

Also, compared to traditional Si-based photovoltaics, flexible PV technologies offer a unique versatility that architects and engineers will harness to renew the facades of existing buildings, as well as in the construction of new buildings and in the development of power-generating products. Flexible solar cells provide building component manufacturers with thin and lightweight PV foils that allows integration with building materials of various architectural shapes, thus combining PVs and architecture, and also cost-effective PV integration (Pagliaro, 2008). Flexible solar PV devices offer a convenient alternative energy source for indoor and outdoor applications. Besides being flexible and thus easily integrated with elements of various shapes and sizes for the design of innovative energy-generating products, these unbreakable flexible modules are light-weight and suitable for applications where weight is important, while they offer a much faster payback than products based on conventional PVs (Pagliaro, 2008).

There are some new material tehnologies, like organic PV (OPV) and dye-sensitized solar cells (DSC or DSSC), which are also applicable for building integration module (Radulovic, 2014). Since organic PV (OPV) relies on carbon based semiconductors, low cost high volume manufacturing of flexible solar modules without any raw-material concern appears feasible. In combination with the feature that devices can be fabricated in a number of colors and levels of transparency, this makes DSSC an attractive applicant for BIPV applications. Fortunately, cell efficiencies are stagnant at about 11% since more than 15 years and further optimization of any main component of DSSC devices is not likely to yield significant efficiency improvements. In Table 1 overview of different flexible solar cell technologies is given (Razykov, 2011).

Table 1. Overview of different flexible solar cell technologies.

	CIGS	CdTe	Amorphous silicon	Organic and titanium oxide
Lab efficiency on plastic foil	14.1% (single-junction cell)	11.4% (singlejunction cell)	8%*–12%* (multi-junction cell)	5–8%
Lab efficiency on metal foil	20.4% (single-junction cell)	8% (single-junction cell)	14.6% /13%* (multi-junction cell)	
Industrial efficiency (typical values)	6–11% (On steel foil, not yet available on plastic foil)	Not yet demonstrated	4–8% * (available on plastic and metal foils	Not yet demonstrated
Stability under light	Material stable	Material stable	Degrades	Stability not proven

*Initial values measured before light-induced degradation of solar cells.

In perspective, new photovoltaic thin film will be the only technology suitable to satisfy the requirements of the most advanced architectural theories, and also the development of new photovoltaic thin film modules will be able to match not only traditional architectures, but also the most innovative tendencies that favour envelopes characterized by free morphologies.

4 FLEXIBLE THIN FILM BIPV PRODUCTS

The BIPV foil products are lightweight and flexible, which is ideal for easy installation and the weight constraints most roofs have (Jelle, 2012b). They provide some specific features, which the rigid, conventional ones do not. Products from this group use newer and innovative materials platforms (such as thin-film and organic PV) and can be used in a variety of different applications, mainly flat and curved roofs.

Many of the flexible modules are designed to avoid conventional framework of rigid panels and can be adhesively bonded to roofing materials. They brings along many advantages like light weight, avoidance of heavy wind loads (because they do not allow wind beneath them) and avoidance of rack mounting system since they can be directly glued to the roofing material. Thanks to the above mentioned features, the mounting procedure of the panels on roofs as well as other building structures is different (easier) than the conventional, rigid ones (Montoro, 2013).

There are a number of manufacturers of flexible thin film PV products. The major technologies families are thin film amorphous silicon and thin film CIGS. In most cases the flexible product comes encapsulated and only has to be attached to the existing flat or curved roof. In few cases the PV manufacturer supplies a non-encapsulated functional PV laminate on a metal or plastic carrier foil. The manufacturer of the roofing product encapsulates the product in the building element (flexible or non-flexible) or applies encapsulation on the complete roof (Sinapis, 2013).

4.1 Flexible thin-film laminates - Centrosolar

So that solar plants can also be fitted to arched roofs, Centrosolar Italia is now offering flexible thin-film laminates alongside the frame-mounted standard modules, so that they can be optimally matched to the more complex curved roof shape. The flexible modules used, embedded in plastic, are particularly durable and light. They are therefore suitable for solar plants on lightweight-construction halls of the type commonly encountered in agriculture or industry (Centrosolar Group, 2015). The first Centrosolar Italia reference projects for such systems have already been connected to the grid (Figure 3).

Figure 3. *Centrosolar - Thin-film solar plant on the arched roof of a waste sorting station in Monte Crocetta, near Vicenza (40 kWp), constructed in collaboration with Rewatt, Vicenza.*

4.2 Flexible a-Si laminates - Alwitra

A system of technically and technologically integrated product groups, which have proven themselves in practice, for multifunctional roofing solutions including all flashings, capping and roof penetration details, which ensures permanent and reliable resistance to all impacts and loads on the roof sealing and serves for direct conversion of solar energy into electric power. The system ensures reliable and quick laying, application and installation by the roofer and the electrician. It provides maximum freedom of design for new build and refurbishment works and is extraordinary durable and economical.

Figure 4 represents the solution of flexible laminate (triple junction a-Si) installing on the rooftops, in Germany. The size of building blocks is 2848mm x 394mm (Alwitra Group, 2015).

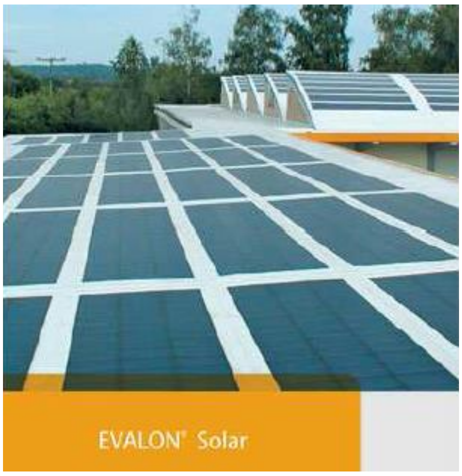

Figure 4. *Alwitra – Roof with flexible a-Si laminate*

4.3 Flexible CIGS laminates – Global Solar

Global Solar's high efficiency CIGS solar modules are designed for rooftops (Figure 5). The flexible module fits all roof shapes, is lightweight, and requires no roof perforations or mounting hardware.

Figure 5. *Global Solar – Roof with flexible CIGS laminate*

The Global Solar produces three types of flexible laminates. PowerFLEX® modules with 12.6 % efficiency (Figure 6), deliver the highest efficiency among flexible modules (Global Solar, 2015). It is also lightweight and can be applied directly to multiple surfaces without penetrations, and creates no additional wind load maintaining the integrity and aesthetics. The module has a large format (5.75 m x 0.5 m) and a high power density (300 W), enabling it to outperform other flexible solar solutions, including 50 percent more energy and power than the current amorphous silicon standard.

Figure 6. *Global Solar – PowerFLEX flexible CIGS module*

4.4 Flexible CIGS laminates – Ascent Solar

Ascent Solar's flexible, lightweight CIGS modules allow for seamless integration of solar power into a limitless number of applications without the restrictions of conventional glass panels. Ascent's high-efficiency modules provide the transformational ability to generate power anywhere, anytime. Ascent Solar WaveSol™ Light provides a new way to integrate lightweight, flexible CIGS solar modules into building materials to achieve cost-effective, high-performance solar power – Figure 7. WaveSol™ Light modules deliver the highest power density available on thin-film plastic substrates. WaveSol™ Light modules laminate onto roofing, shading and building surfaces to decrease energy costs and provide a clean, renewable source of energy (Ascent Solar, 2015).

Figure 7. *Ascent Solar – WaweSol flexible CIGS module*

4.5 Flexible thin-film laminates – Xunlight

Xunlight's offers a line of lightweight and mechanically flexible photovoltaic modules. The products are specifically designed for rooftop installations (Figure 8). These products all use the bandgap-tuned triple-junction thin-film silicon solar cells, manufactured by Xunlight at its Toledo, Ohio, USA factory. Xunlight also welcomes enquiries for custom sized product. Their flexible manufacturing process can allow to offer custom product at relative low minimum volumes. Xunlight's certified modules can be utilized for either on-grid or off-grid applications and they come backed by 25 year power-output warranty. Solar modules are produced using the company's innovative and patented manufacturing process and are designed to deliver high energy efficiency at a low cost for years to come.

Xunlight currently offers four widths of products, the XR (for TPO and EPDM membrane roofs), XRS (for 24" standing seam roofs), XRU (for 16" standing seam roofs) and XRN series (for 12" standing seam roofs) (Xunlight, 2015).

Figure 8. *Xunlight flexible module*

5 CONCLUSION

The present study has shown that there is great perspective for development flexible thin-film building integrated photovoltaic products. There is a progress in production of devices based on flexible thin-film technology, which are commercially available and present on market today. These products may have a great range of application due to the flexibility of the material and low cost. One of the main tasks of researchers is to develop products that can achieve a higher efficiency with better materials and better solutions. Advances in the development of PV materials will lead to advances for the BIPV systems.

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Experimental Evaluation of a Concentrating PV/Thermal Glazing Façade Technology

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Abstract: The Renewable Energy Framework Directive sets a target of 20% for renewables by 2020. Buildings account for 40% of the total primary energy requirements in the EU and are responsible for 30% of the generated greenhouse gas emissions. Therefore, developing effective solar energy technologies which can be integrated into buildings and provide heat, electricity and/or reduce energy needs, is vital to achieving the set targets. While a range of technologies are available at the moment for building integration most of them are simply super-imposed on the building structure rather than becoming an essential part of it. This does not allow for the full advantages of building integration to materialise as it does not reduce costs by replacing conventional building materials and components.

A Concentrating PV/Thermal Glazing (CoPVTG) façade technology that combines glazing based solar concentrating elements, coupled with PV/Thermal absorbers has been developed and experimentally evaluated at the Centre for Sustainable Technologies of the University of Ulster. As a modular multifunctional building component based on conventional double glazing, the CoPVTG is designed to be compatible with traditional façade structures and fenestration framing arrangements, facilitating direct integration into new and retrofit building applications. It can provide solar generated electricity and air heating through the PV/T absorbers while insulating the building thermally. The glazing based concentrating elements are designed to allow the sunlight to enter the building and provide natural daylight when required while redirecting it onto the PV/T absorbers to generate electricity/heat when solar gains need to be minimised to reduce cooling demands.

A CoPVTG prototype unit has been fabricated using opti-white glass sheets. The concentrating elements have been cut onto the surface of one of the glass sheets and the PV/T absorbers have been attached using opti-clear silicon. The experimental performance of the prototype has been investigated under a solar simulator. Generation of electricity and heated air has been determined for two directions of the incident solar radiation. The CoPVTG is an innovative multi-functional building component that can contribute to the electrical and thermal building needs while reducing its heating and cooling loads.

Keywords: Building integration, PV/Thermal glazing, concentrating BIPV, dielectric concentrators, façade, daylight control, air collector, total internal reflection, BISTS.

1 INTRODUCTION

Energy use in buildings represents 40% of the total primary energy used in the EU. The Energy Performance of Buildings Directive (EPBD) requires Member States to set minimum energy performance requirements for buildings, taking into account the positive contribution of renewable energy sources. Developing building integrated renewable energy technologies that offer effective energy alternatives is vital.

Many modern buildings (commercial and domestic) incorporate large glazed areas following architectural expression, providing improved daylighting and wellbeing for their occupants. However conventional fenestration systems have poor insulating properties (compared to traditional constructional elements) resulting in excessive heat loss during cold conditions and increased cooling loads during warmer, sunnier conditions. Integrating advanced glazing with renewable energy generation technologies whilst controlling daylight penetration can create comfortable building internal spaces while ensuring lower energy bills and associated carbon emissions.

Air present in the cavity of double glazing units allows convective and conductive heat transfer between the inside and the outside glass panes which, in buildings with large glazed areas, cause significant heat loss or heat gain in cold and warm climates respectively. Incorporating inert gases such as argon in the sealed cavity improves the thermal performance of insulating glazing systems. Double glazing products currently in the market which incorporate these features can achieve thermal transmittance U-values of approximately 1.1 $Wm^{-2}K^{-1}$. Further improvements in thermal insulation can be achieved using 3 to 4 panes of glass however the units become very heavy and bulky requiring expensive framing systems and have reduced light transmission. Research and development on advanced glazing systems has focused on further improving the thermal insulation by removing the air from within the cavity to create a vacuum. The thin evacuated cavity (typically 0.2 mm wide) minimises conductive and convective heat transfer. Evacuated glazing systems have significant potential in reducing heat loss from buildings (Griffiths et al., 1998). An innovative low-temperature (<200 ºC) edge-sealing technique using indium metal was developed and subsequently patented (Eames et al., 2000). Laboratory evacuated glazing prototypes were produced and experimentally characterised under controlled conditions. The results demonstrated that U-values as low as 0.6 $Wm^{-2}K^{-1}$ can be achieved (Papaefthimiou et al., 2000). Recent work has focused on the development of triple vacuum glazing and the refinement of the edge-sealing technique (Fang et al., 2010).

Transparent concentrating lens for PV façade building integration have been developed to enable increased electricity generation per unit area of PV material compared to conventional PV panels (Zacharopoulos et al., 2000). Prototype transparent concentrating PV lens were fabricated and experimentally characterised. The results demonstrated that by using the concentrating lens, almost double the amount of electricity per unit of PV material can be generated compared to conventional PV panels (Mallick and Eames, 2007). Daylighting control is possible by tailoring the concentrating lens design to allow incident solar radiation to enter the building at different times during the day. By combining the concentrating lens with a flat glass pane into a double glazing unit and evacuating the cavity, convective heat losses can be eliminated (Zacharopoulos et al., 2011).

Using photovoltaics with solar thermal elements produces a PV Thermal (PVT) solution than can deliver solar thermal heat at levels similar to conventional solar thermal collectors and generate electricity similar to standard PV modules. However a balance needs to be achieved between thermal and electrical energy generation as thermal applications often require higher operational temperatures, whereas the PV module efficiency drops with increasing temperature. Some examples of optimized collector solutions are in development (Dupeyrat et al., 2011a; Dupeyrat et al., 2011b).

This paper presents a Concentrating PV/Thermal Glazing (CoPVTG) façade technology that combines glazing based solar concentrating elements coupled with PV/Thermal absorbers. As a modular multifunctional building component based on conventional double glazing, the CoPVTG is designed to be compatible with traditional façade structures and fenestration framing arrangements, facilitating direct integration into new and retrofit building applications. It can provide solar generated electricity and heated air through the PV/T absorbers while insulating the building thermally. The glazing based concentrating elements are designed to allow the sunlight to enter the building and provide natural daylight when required while redirecting it onto the PV/T absorbers to generate electricity/heat when solar gains need to be minimised to reduce cooling demands.

2 THE COPVTG TECHNOLOGY

The technology consists of a double glazing panel where the outside pane of glass is shaped into a series of concentrating lens. A thin layer of photovoltaic cells is placed at the focus of the concentrating lens to act as PV/T absorber. The inner pane of glass is a conventional flat pane. Forced air flow between the two glass panes can be used to remove waste heat from the back of the PV and use for space heating or pre-heating purposes. To increase the thermal insulation properties of the technology a third (optional) flat glass pane can be used in front of the concentrating lens pane and the resulting cavity can be filled up with inert gases such as argon or evacuated to eliminate convective heat loss (Figure 1).

Depending on the design of the concentrating lens, a part of the incident solar radiation can reach the PV/T absorbers generating electricity and waste heat while the rest can travel through the unit to provide daylight to the building interior. Using total internal reflection (TIR), the lens design can produce a seasonal effect with more light allowed into the building at low incidence angles (i.e. in the winter months) and less light at high incidence angles (i.e., in the summer). Figure 2 demonstrates how by using TIR different amounts of light can be collected onto the PV/T absorbers or transmitted through the glazing unit depending on the incident angle of the solar radiation.

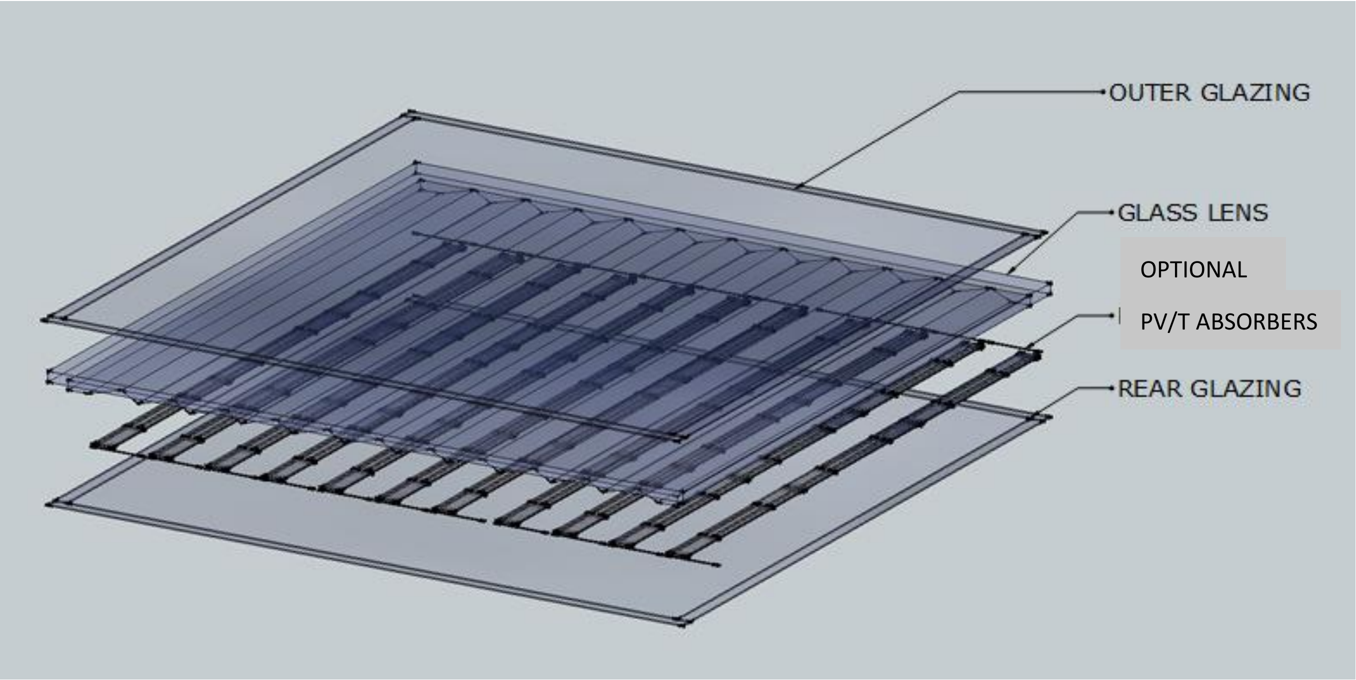


Figure 1. The CoPVTG technology combining concentrating glass lens with PV/T absorber elements.

For a 30^{o} incidence angle the PV cells receive the beam radiation light which is directly incident on them. The remaining radiation is refracted through the lens and transmitted to the back of the unit. At a 55^{o} incidence angle all beam solar radiation is reflected onto the PV/T absorbers by TIR at the back of the glass lens. The few rays missing the absorber at the bottom of the unit are due to edge-effects related to the size of the concentrating glass pane. Depending on the design of the concentrating lens there is a critical incidence angle that switches "on" or "off" the TIR of the solar radiation at the back of the glass lens. Glass lens that can control daylight transmission to the rear of the unit (i.e. into the building) for a specified range of incidence angles of solar radiation can be designed for a given building and geographic location.

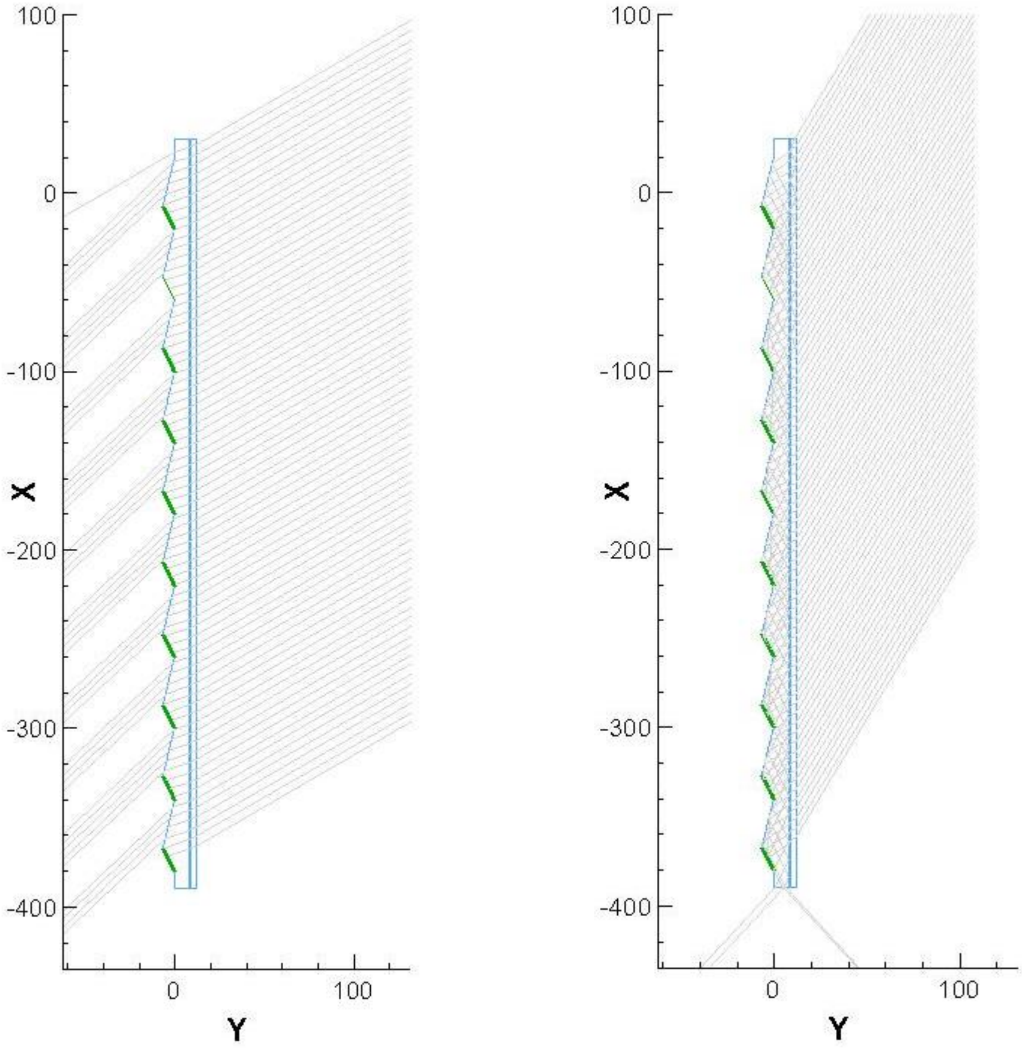


Figure 2. Ray trace diagrams demonstrating the control of light transmittance through the CoPVTG by TIR at the concentrating lens. Light incident at 30o (left) and 55o (right) from the perpendicular to the surface of the glazing.

3 FABRICATION OF THE COPVTG PROTOTYPE

A prototype 500mm x 500 mm CoPVTG unit was fabricated using an outer 15 mm (max) thickness concentrating lens pane and an inner 4 mm thickness flat glass pane (Figure 3). The concentrating lens were designed to totally internally reflect to their focus all light incident above a 40° angle from the perpendicular to the surface of the glazing. Both glass panes were opti-white for optimum solar transmission. A 25 mm cavity was formed between two glass panes using appropriate size spacers which accommodated the air inlet and outlets at the bottom and top of the cavity respectively (Figure 3a). 33 multi-crystalline PV cells configured as 11 strips of 3 cells each were bonded at the focus of the concentrating lens using opti-clear silicon resin. Green coloured cells were used (C-Cell range by LOF Solar) to achieve better aesthetics (Figure 4). A PVC window frame was used to mount the fabricated CoPVTG unit (Figure 3a). The frame had a slot cut out along its top and bottom to allow the air to flow through the unit. The air was supplied by flow and return header ducts with slots cut identical to that of the window frame allowing a clear passage of air. The fabricated CoPVTG inserted into the PVC window frame is illustrated in Figure 4b.

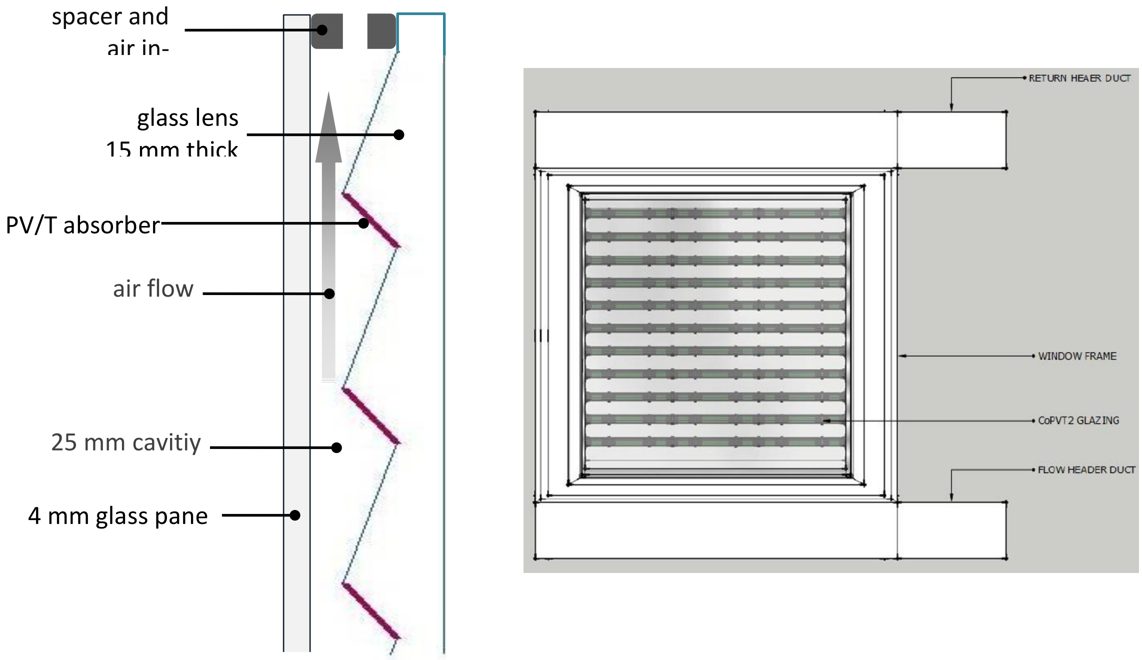


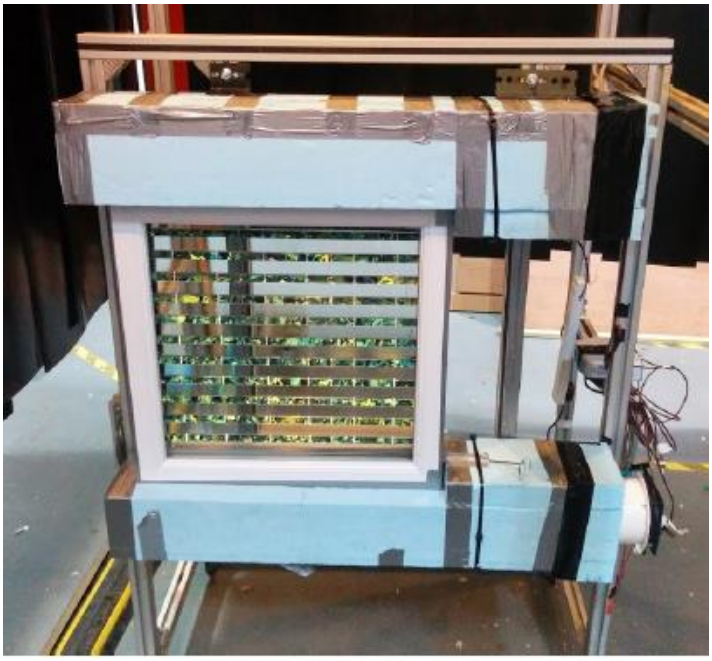
Figure 3. a) Cross section of the fabricated CoPVTG prototype and b) schematic of the prototype unit inserted into a PVC window frame (right). (a) (b)

Both header and return flow ducts were covered with polystyrene insulation to minimise heat loss. A DC fan was used to produce and control an air flow through the CoPVTG glazing cavity using a power supply. K-type thermocouples were placed inside the glazing cavity to monitor PV cell and concentrating glass temperatures. Further thermocouples were placed inside the header and return ducts to monitor air inlet and outer temperatures.

4 EXPERIMENTAL SET UP AND METHODOLOGY

The thermal and electrical performance of the fabricated CoPVTG prototype was evaluated under the CST solar simulator (Zacharopoulos et al., 2009). The experimental set up is shown in Figure 4. The simulator lamp array consists of high power 35 metal halide lamps arranged in 7 rows of 5 lamps each. Each lamp is equipped with a rotation symmetrical paraboloidal reflector to provide a light beam of high collimation. In order to achieve uniform distribution of light intensity on the test area, a lens is inserted in each lamp to widen the illumination of light. The combination of reflector-characteristics, lens and lamps ensures a realistic simulation of the beam path, spectrum and uniformity. The lamp array is mounted on a frame which allows simulation of different incidence angles for the illumination on the test target plane. The solar simulator control panel was used to maintain the constant level light intensity on the test target surface via a pyranometer mounted at the centre of the test target plane.

The performance of the prototype was evaluated for 30° and 55° incidence angles of illumination chosen to allow the light to transmit through the lens and to focus the incident light by TIR onto the PVT absorber respectively. For both incidence angles the intensity of the illumination on the horizontal plane was set at 760 W/m^2 to simulate an average solar radiation intensity of a day with good weather conditions. Due to the different incidence angles the resulting intensities measured on the surface of the window were 654 W/m^2 (at 30° incidence angle) and 458 W/m^2 (at 55° incidence angle). For each incidence angle the air flow velocity was set to 2.93 m/sec and measurements were taken at set intervals until inlet and outlet temperatures were stabilised and the system reached equilibrium. Concurrently with the thermal measurements, the electrical output of the 10 of the PV cells of the prototype connected in series was measured using a DayStar 1000 IV- curve tracer. A Testo 405-V1 hot-wire manometer was used to monitor the air flow velocity.



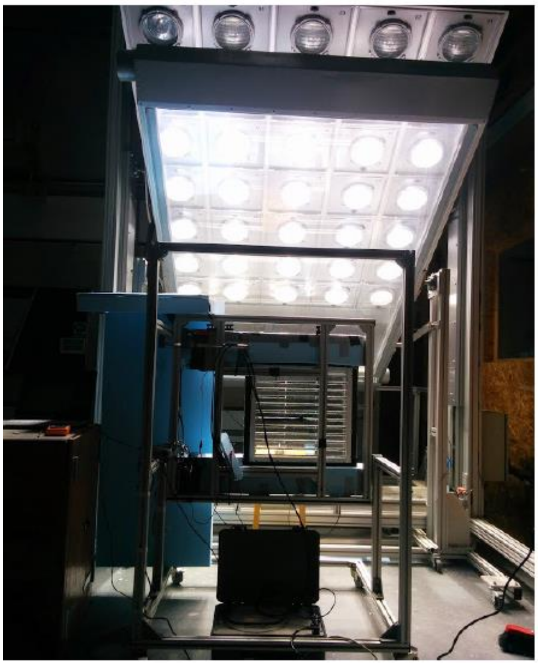


Figure 4. Font view of the experimental CoPVTG prototype (left) and rear view (right) placed under the solar simulator

5 THERMAL AND ELECTRICAL PERFORMANCE EXPERIMENTAL ANALYSIS

A temperature rise of 4.8 °C was measured between inlet and outlet when the illumination was incident at 30° and had an intensity of 654 W/m^2. The corresponding rise with illumination incident at 55° was comparable (4.5 °C) although the intensity of the illumination was only 458 W/m^2. Similar

PV and glass lens temperatures were measured for the two incidence angles. PV operating temperatures were between 29.4 and 30.3 °C. In both cases glass lens temperatures were measured slightly higher, at 31.5 and 30.3°C for the 30° and 55° incidence angles respectively. The comparable measured temperatures for the two incidence angles with a 196 W/m^2 difference between illumination intensity levels can be attributed to the TIR as illustrated in Figure 2. The increased amount of light incident onto the PV/T absorber for the 55° incidence angle results in higher amounts of waste heat generated which in turn produces similar temperatures compared to the 30° incidence angle. Table 1 summarises the temperatures measurements for the two incidence angles.

The instantaneous thermal power output from the prototype was calculated as:

$$\mathrm{Q} = m\mathrm{c}_{\mathrm{p}}\left(\mathrm{T}_{\mathrm{out}} - \mathrm{T}_{\mathrm{in}}\right) \qquad (1)$$

The thermal efficiency can then be calculated:

$$\eta_{\mathrm{thermal}} = \frac{\mathrm{Q}}{\mathrm{AI}_{\mathrm{in}}} \qquad (2)$$

Using the electrical power output from the IV curve tracer, the electrical efficiency was calculated:

$$\eta_{\mathrm{electrical}} = \frac{\mathrm{E}}{\mathrm{AI}_{\mathrm{in}}} \qquad (3)$$

The thermal power output in the form of heated air from the prototype is 85.0 W and 79.7 W for the 30° and 55° incidence angles respectively (table 2). The measured electrical power output reached 7.0 W for the 30° incidence angle and 6.0 W for the 55° incidence angle. It is evident that the TIR that occurs when the illumination is incident at a 55° angle results increases thermal and electrical efficiencies compared to the 30° incidence angle. Electrical efficiency increases by 1% (from 4.7% to 5.7%) and thermal efficiency by 17.6% (56.7% to 75.4%). The overall efficiency of the prototype for generating thermal and electrical power was measured at 56.7% and 75.4% for the 30° and the 55° incidence angles respectively. The energy losses for both incidence angles are due to light reflected on the glass aperture of the prototype, light that is transmitted through it and thermal losses through the glazing surfaces.

Table 1. Temperatures achieved by the CoPVTG prototype for the 30° and 55° incidence angles of illumination

Incidence angle (^{o})	Temperatures (^{o}C)					Intensity of illumination (W/m^2)
	PV	Glass lens	Ambient	Inlet	Outlet	
30	30	31.5	25.6	24.8	29.6	654
55	29.4	30.3	25.6	24.4	28.9	458

Table 2. Thermal and electrical power produced by the CoPVTG prototype for the 30° and 55° incidence angles of illumination

Incidence angle (°)	Power (W)			Efficiency			Intensity of illumination (W/m^2)
	Thermal	Electrical	Total	Thermal	Electrical	Total	
30	85.0	7.0	92.0	52.0%	4.7%	56.7%	654
55	79.7	6.0	85.7	69.6%	5.7%	75.4%	458

The effect of the average inlet-outlet temperature on the electrical power output of the prototype was evaluated for the two examined incidence angles of illumination. The results presented in Figure 5 show that a greater reduction in the electrical power output is expected for the 30° incidence angle due to the higher PV temperature resulting from the higher intensity of illumination.

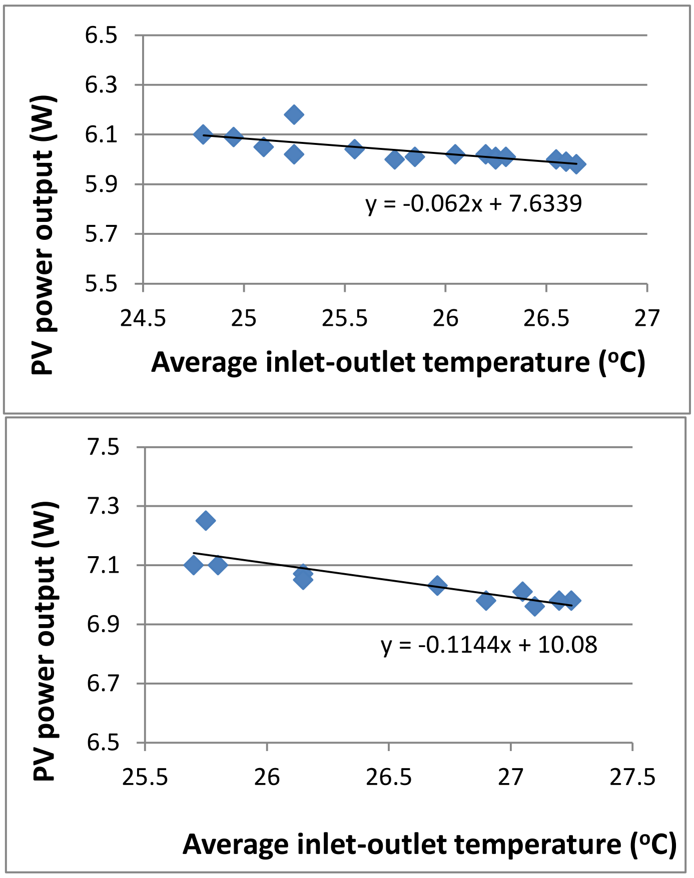


Figure 5. The effect of the average inlet-outlet air temperature on the electrical power output of the CoPVTG prototype.

A stagnation tests was also carried out to investigate the maximum temperature that can be reached by the prototype. A 6.7 °C rise above the ambient temperature was recorded at a 654 W/m^2 intensity of illumination incident on the aperture of the unit. Assuming a constant heat loss coefficient for the prototype a maximum 10.2 °C rise above ambient temperature can be predicted under 1000 W/m^2 of incident solar radiation.

6 CONCLUSIONS

The experimental evaluation of the CoPVTG prototype unit indicates that the concept is performing as expected and is applicable for larger scale implementation and further research and development. The CoPVTG prototype was able to produced significant amounts of thermal and electrical power with overall efficiencies reaching 75.4%. By extrapolating the calculated power outputs to a 1m^2 unit, 318.8 W of heated air and 26.4 W of electrical power are predicted for solar radiation incident at a 55° angle and with an intensity of 760 W/m^2 (measured on the horizontal). The experimental results for the 30 and 55 incidence angles of illumination are in-line with the performance predicted by the ray-trace diagrams of Figure 2. The concentrating lens design provides a mechanism for passive control of the amount of incident beam solar radiation that can either be collected by the PV/T absorber or can be transmitted as daylight into the building. A 10.2 °C maximum rise above ambient temperature is predicted at 1000 W/m^2 solar radiation intensity. The output air temperatures can be increased by improving the thermal insulation of the unit. This can be done by introducing an outer third pane of glass. Convective heat transfer can be eliminated by evacuation of the resulting cavity or by filling up the cavity with using inert gasses.

The CoPVTG technology is easily building integrated as demonstrated by the prototype unit fitted into a conventional window frame. Whilst the technology has only reached a readiness level of 4 (TRL 4) its unique modular design and flexibility presents a great commercial opportunity.

NOMENCLATURE

A	aperture area (m^2)
c_p	specific heat capacity of air (J/kgK)
E	electrical power produced (J)
I_{in}	incident illumination intensity (W/m^2)
m	mass flow rate of air (kg)
Q	thermal power produced (W)
T	temperature (°C)
η	efficiency

SUBSCRIPTS

electrical	electrical power produced
in	inlet air temperature
out	outlet air temperature
thermal	thermal power produced

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