Recent Patents on Engineering, **2012,** ***6*, 137-148**

New Configurable Low-Cost Solar Roofs: Developing a New Paradigm for More Sustainable Houses

Luis Juanicó*

Bariloche Atomic Center, (8400) Bariloche, R. Negro, Argentina

Received: March 07, 2012 Revised: April 26, 2012 Accepted: April 27, 2012

Abstract: A new design of roof-integrated water solar collector is presented. It takes advantage of new synergies found between collector and roof. Its main concept is based on the use of water redistribution for changing the roof configuration. This system is completely suitable for inclined roofs, since it is based on waterproofed plastic chambers. This design provides a universal low-cost system for household heating and natural cooling that could be even cheaper than conventional roofs with similar (high) thermal qualities. This novel design has been claimed in an Argentinean invention patent application and also it has been internationally claimed.

Keywords: Natural Cooling, solar heating, solar roof, passive solar, roof-integrated solar collector.

1. INTRODUCTION

1.1. Perspectives for Using Economical Solar Technologies on Houses

The photovoltaic panel is today by far the preferred solar technology in developed countries to obtain the future indigenous energy supply from renewable sources. Meanwhile wind energy has the higher percentage of power installed by far, the number of PV projects are undoubtedly growing faster. However, the economic performance of PV has not improved hand in hand with this tremendous increase on the PV industry. Specific installed costs of about 5,000 U$/kW and annual capacity factors down by 15% on average are still true world-wide, and have remained essentially unchanged for the last 20 years. For example, these average numbers around the world for wind turbines are 1,500 U$/kW and 25% respectively. This figure shows us that PV remains an expensive option even within the portfolio of renewals.

On the other hand, there is a huge potential for energy savings in relation to buildings. Even today and after thirty years of developing low-energy homes, almost 40% of the total primary energy consumed in developed countries is related to building acclimatization, mostly related to space heating demand. This way, it is possible to improve our use of energy by saving instead of generating. Hence, it is feasible to improve the buildings sustainability in a more affordable manner, considering that a solar collector for heating water can produce energy about five times cheaper than PV installed on the same roof.

It is well known that a small solar collector (4m^2) can satisfy the domestic hot water demand of a single family in many places worldwide. Hence, we can expect that extending the collector onto the whole roof could provide the household with heating as well. As Hassan and Beliveau [1] have demonstrated, this can still apply close to 40° latitude. However, at present, large solar collectors are rarely used due to high costs involved. Whereas the specific costs for solar collectors are between 150 to 250 dollars per square meter of roofing area, the cost for a whole solar roof can easily scale up 25,000 U$D. On the other hand, the specific cost for standard roofs varies from 100 to 250 U$D/m^2, mostly relating to the quality of its thermal insulation, which is built-in on the back side of every solar collector. This is a starting point for our work: if it could be possible to achieve an economically feasible solar roof by means of integrating a solar collector into the roof.

Many feasible designs of roof-integrated solar collectors have been developed in the last 50 years, but at present high costs have delayed their massive application [2]. Many roof-integrated collectors have been proposed, such as hybrid systems with photovoltaic [3] or thermoelectric [4] panels. These integrated designs have contributed to improved collector performance, but they did not change the actual roof paradigm. On the other hand Medved [5] proposed a roof-integrated unglazed solar collector by building the water coil within the undulated metal roof, in a just architectonic way of integration. There are few designs proposing substantial changes to the basic roof concept, leading to further cost reductions.

The use of water ponds on roofs for house cooling in arid regions is well known [6, 7]. Jain [7] states that a shallow water depth of just 5cm is enough for keeping the roof temperature within comfort level. It is interesting to note that Jain also suggests the inverse procedure could be used for household heating in winter, although this feature has not be used up today in any commercial roof technology.

This brief discussion illustrates one of the motivating ideas in this paper: architecture is a deeply-rooted science. We notice that the technology of building construction has suffered a great evolution throughout time, but this remarkable evolution in construction techniques and new building materials has not been accomplished by a similar one on

---

*Address correspondence to this author at the Bariloche Atomic Center, (8400) Bariloche, R. Negro, Argentina; Tel: +54-294-4461669; Fax: +54-294-4445299; E-mail: juanico@cab.cnea.gov.ar

2212-4047/12 $100.00+.00

conceptual designs. Our old-fashion paradigms relative to low-energy buildings (that is, to build an almost adiabatic envelope walls and roof in order to minimize the heat losses) are still running. This paper is focused on discussing paradigms of roof in order to propose new designs based on a new paradigm: to build the most thermally configurable roof by means of creating many water chambers and by means of water redistribution [8].

1.2. From the Concept of the Classic Roof to the Configurable Roof

The classic concept of roof has prevailed without changes for many centuries. Classic roofs are designed following two main goals:

- To prevent rain or snow infiltration.
- To provide good thermal insulation.

The traditional way to fulfill these two objectives with high quality roofs has been to overlap several internal layers of different materials (low thermal conductivity, high reflectivity, etc.) between air gaps or chambers, under the waterproof exterior layer that provides physical protection as well. This whole system constitutes a good-quality roof, but at high costs in relation to materials and labor. On the other hand, low quality roofs (with fewer intermediate insulating layers) usually have lower costs but are ‘‘warm in summer and cool in winter”, as they do not reach the ‘‘almost adiabatic” category of the previous ones.

Summarizing, the traditional roof concept can be described as a fixed roof in which the greatest adiabatic degree is intended, as the single strategy used in order to minimize the energetic demand for indoor acclimatization. This concept fits the current architectural trend to design low-energy buildings, but with the drawback of having to pay high costs in order to achieve this adiabatic goal [9, 10]. Thus, whereas in developed countries an average roof with overall heat transfer coefficient U about 1,2W/m^{2}K can cost around 150 U$D/m^2, the cost for a low-energy roof (U down 0,5W/m^{2}K) doubled this value.

The single approach beyond the ideal for an “almost adiabatic roof” is to minimize the household energy consumption by minimizing the heat losses through the building envelope. In this way, the thermal quality of two different roofs can be compared by using their U values as the unique merit figure. This true has not been questioned for centuries, and it is supported on the classic roof concept that essentially states that an actual roof must be a passive and fixed system. Therefore, as much as the outside conditions cannot be controlled and the roof response cannot be adapted to it, from here it is inferred that the indoor ceiling temperature cannot be controlled (which is the actual ultimate interface with house dwellers), actually being this one the key factor for determining the overall heat exchanged by indoor space through the roof.

But this statement is no longer valid when the roof is thought as an active and configurable system. For example, the roof overheating during summer days could be reducing by blocking sun rays by using opaque awnings, and besides, the solar gain during winter days could be enhanced by using transparent awnings. This way, by folding and unfolding different kinds of awning, it is possible to obtain effective thermal gain, as it has been proposed by Fernandez-Gonzalez [11] and Juanicó [12]. But despite the success from the thermal point of view of these new configurable designs based on rolling awnings, they are weak regarding mechanic issues such as maintenance, reliability and durability. Indeed, these concerns are the ultimate reason for why the fixed roof still is prevailing. And hence, this fact pushed our work toward exploring other choices for configurable roofs, which is not based on any mechanical movable system. Our present choice is based in building a water roof by using the water redistribution (by filling and draining different water chambers) as the single mechanics for getting a smart solar-gain water-cooled roof.

1.3. Previous Designs of Configurable Roofs

In the pioneer work of Harold Hay [13, 14] and his patented Skytherm system, plastic black-painted water bags are mounted over a simple metallic roof that is protected by a folding cover with excellent thermal insulation. This system provides the household with heating by infrared radiation in winter, and cooling by free convection in summer. As Hay showed in the 1970s, this system can provide a comfortable temperature all year even in arid climates [15]. Hay’s design works under four configurations, combining the summer–winter and day–night options. By just moving the insulator cover it collects or stores solar energy during the day or night respectively in winter, and does the opposite in summer.

Although Hay could be considered a pioneer in the configurable design of roofs, he did not see the potential of his innovative idea, and neither did his followers, like Hammon [16], who were more interested in improving details in Hay’s design, such as the holding cover. This issue is a major concern on this design, because one of the main drawbacks of the Skytherm was the extremely high cost of its movable cover and thick insulation layer mounted over a very bulky mechanical system. Hammon has proposed to use folding windows, as a conventional way to reduce the cost of the awning.

According to the actual climate where it is applied and its low graduation ability, other disadvantages of Skytherm that can arise are the uncomfortable effects caused by the infrared heating overhead in winter, and vapor condensation on the cold ceiling in summer. Both issues are solved by our design by means of water redistribution. Hence, instead of a built an active system but with very limited options (indeed, only the awning can be folded or unfolded), the built of a fully configurable and active system is proposed in this paper, in which the water chambers could be partially or totally filled and drained. The use of multi interconnected water chambers integrated into the roof, enhanced by the use of modern microcontroller digital system, will allow us to optimize the performance of the system under any weather condition, as will be discussed after.

Although other solar collector systems that use flowing water connected to heating and cooling systems were developed in the past, such as Thomason’s designs in the sixties [17-19], and more recently, the Cool-Cell and Di-Thermal of

Baer and Mingenbach [20], they belong to a different category. Recently, there are many new designs published and claimed by invention patents, showing that this subject is an active research area [21-25], many of these innovations regarding new plastic materials with improved solar and thermal properties, which could be useful for our present purpose [21, 22]. However, the approach common to all these designs is to mount a device onto the roof, but they do not change the present roof concept neither do they achieve new synergies between collector and roof, as the Skytherm and our new designs do.

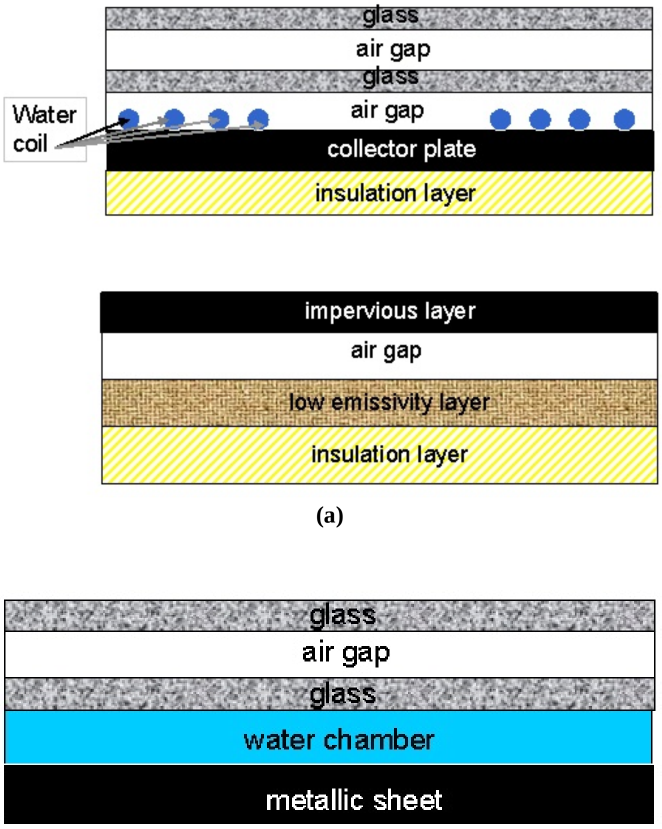
2. THE NEW APPROACH FOR CONFIGURABLE ROOFS

2.1. General Conceptual Analysis

Figure **1a** presents a flat-plate solar collector and a conventional roof. Observe that both systems have essentially a black metallic layer with a back layer for insulation. But whereas the collector has several glass layers and air cavities above in order to achieve good thermal insulation, the roof places the insulation and air cavities below the metallic layer. These alternative designs can be joined by reorienting the roof as a solar collector, joining both in a single system making the internal insulation layers unnecessary. This way, it is possible to use the metallic ceiling as a heating device for the household indoor space as the Skytherm does, and allows also to obtain saving in material and labor. Figure **1b** illustrates conceptually our first configurable roof, showing its main goal: to create a whole water chamber onto the black layer instead of the standard water coil used on flat solar collectors in order to collect solar energy.

This choice for a main water chamber allows many new features forbidden on the solar collector design, being:

1) During summer days this chamber becomes a water pond useful for keeping the roof not too hot. Whereas the household requirement of hot water is null in this season (or it is minimized so that can be satisfied by using a small part of the roof surface), this large water inventory on roof is useful for reducing effectively its temperature increase.
2) The previous feature can be extended by connecting this water chamber to the household demand of flush water. This way and according to the family consumption, this water inventory would be regenerated every day. Indeed, there are other complementary solutions suitable to use here, as:
    a) Using this water inventory for heating a swimming pool, or
    b) Combining this water inventory with a garden pond. This way the heated water during days into the roof can be cooled during nights in the garden pond.
3) During winter days this water inventory is used to collect the solar irradiation as in any solar collector. But instead of heating a very small part of the water inventory (usually reserving the main part into a thermally isolated tank), in the water pond system the whole water inventory is warmed simultaneously all together.


(a)

(b)

Fig. (1). a). Schematic drawings of a flat-plate solar collector and a conventional roof". **b**). Schematic drawing of the new roof-integrated solar collector.

This last unique characteristic enhances noticeably the performance of the water pond considered as a flat solar collector, allowing it to obtain a good thermal performance although using low-cost materials. This is a key feature on this configurable design of solar roof. To understand this key factor, let us analyze the curve of thermal efficiency for a standard flat solar collector, described commonly by a linear function as:

$$\mu = a_0 - a_1 \frac{T_m - T_a}{I} \tag{1}$$

Where a_0 is the efficiency obtained for non-losses condition (well known as the optical efficiency), that is, the efficiency obtained if the mean temperature, T_m, is equal to the outdoor ambient temperature, T_a, a_1 is the linear coefficient related to heat losses and I is the normal flux of solar irradiance (W/m^2). The mean temperature T_m in a standard solar collector (built by parallel vertical water channels) is determined by the average between the inlet cold temperature, T_c, and the exit hot temperature, T_h in the collector. Since the water mass flow is only driven for free convection by the temperature jump (T_h -T_c), it is common that this jump rises up to 40°C [26]. So, for example if T_a = 10°C and T_c = 30°C, thus T_h = 70°C and T_m = 50°C. Hence, the jump of temperatures $\Delta T = T_m - T_a$ is equal to 40°C. On the other hand and according to this example, for the water roof case the temperature of the water pond would be equal to 30°C (that is, T_m), and thus, ΔT = 20°C, being a half of the previous case. According to the Eq. 1 the thermal efficiency is lower as much as the ΔT jump is higher, but its actual value is determined by considering the set of (a_0, a_1) collector parameters for each type of system. However, let us point out that this trend is noticeably higher in cheap low-quality collectors (that is, unglazed or glazed with plastic covers collectors) like is proposed here, and so, this ΔT reduction obtained by the water roof design is key for getting a suitable system, as we shall see now.

Tables **1** and **2** show the bibliographic values [26] of (a_0, a_1) for different kind of standard flat solar collectors and water pond respectively. Here, it is clear that by doubling the jump temperature is obtained a noticeable reduction in the collector efficiency, and this reduction is higher according to lowering the collector cost. So, let us study cases of simple and double-glazing low-cost collectors on an average flux I = 400W/m^2. The different results (the efficiency and maximum achievable temperature) are summarized in Tables **1** and **2**.

We shall see here in this comparison that the maximum achievable temperature is noticeably higher in the water pond design as much as higher the efficiency is. For example, even by using low-cost glazing materials, the water pond system can heat the water to 60°C or more, and can reach this level faster that in the solar collector case, since its efficiency is noticeably higher.

The Fig. (**2**) illustrate the efficiency curve as function of the temperature jump $\Delta T = T_m - T_a$ for different kind of solar collectors built with the worse quality (plastic glazing) glazing materials, according to the set of parameter of Table **1**. It is observed here again that the temperature jump $\Delta T = T_m - T_a$ could reach almost 50°C in a double-glazing design, a very useful value for the water pond collector in which the water inventory would reach almost 60°C. On the contrary, a similar-quality standard collector could heat the water inventory up to 47°C.

Note also that the double-glazing type gets always better efficiencies that the single glazing one, relates to the case studied, based on typical winter cold-climates conditions in many mid-latitude temperate-climate locations, like Buenos Aires (38°S). To be able of heating enough water (by collecting the solar resource over the whole roof) so that it can be used to satisfy (at least, partially) the household demand of space heating, that is the main goal intended here. This could be perfectly achievable if we could heat 5,000 liters of water up to 60°C for a 100m^2 living-area house (that is, by heating a 5cm deep water chamber) and this hot water inventory is used by an infloor water heating system, which works in the low-temperature (down 35°C) range. The balance of energy for this case in relation with the collector efficiency and the solar resource will be explained in a next section.

Concerns about the insulation obtained on multi-glass roofs can be solved in this new roof easily by applying new materials. Note that while all technologies developed for windows can be useful for transparent roofs, we can also explore other cheaper choices, since we do not need to satisfy the requirement of high optical quality, as the window does. For example multilayer Mylar windows that have been recently developed can maximize roof insulation [27]. The use of new plastic materials with low thermal conductivity instead of glass can be useful here, especially when transparency and optical properties are not major concern [28, 29].

The use of low-density polyethylene (LDPE) bubble-air films is a good example of this approach. This thin film gives us as very good transparent layer (solar transmittance above 90% in the visible and IR spectrum) with very good insulative characteristics (U=0,75W/m^{2}K and solar transmittance of 80% according to Wallner [29], achievable together with its ultra-low costs down 0,25 U$D/m^2. This material has a long life if the UV radiation is blockaded from sun. Besides and for the protective upper glazing, UV-inhibited polyethylene at 5 U$D/m^2 will be used as low-cost transparent plastic material with good mechanical resistance and water proofing [11]. This choice provided an excellent

Table 1. Characteristic parameters and results for standard flat solar collectors. results (efficiency and maximum T_c achievable) calculated for: T_a=10°C, T_c=30°C, T_m=50°C and I=400W/m^2°C.

Collector Type	a_0	a_1 (W/m^2°C)	µ (%)	T_c Maximum (°C)
Unglazed	0.85 – 0.90	16 – 20	<0 – <0	13 – 7
Single glazing	0.75 – 0.85	7 – 9	15 - <0	39 – 23
Double glazing	– 0.80	4 – 6	40 – 10	70 – 37

Table 2. Characteristic parameters and results for the water pond collector. results (efficiency and maximum T_m achievable) calculated for: T_a=10°C, T_c= T_m = 30°C and I=400W/m^2°C.

Collector Type	a_0	a_1 (W/m^2°C)	µ (%)	T_m Maximum (°C)
Unglazed	0.85 – 0.90	16 – 20	10 – <0	33 – 27
Single glazing	0.75 – 0.85	7 – 9	50 – 30	59 – 43
Double glazing	0.70 – 0.80	4 – 6	60 – 40	90 – 57

mechanical layer but with minor transparency that the thin bubble-air film suggested here. Hence, we are proposing here to add many bubble-air films wrapped by an upper protective layer provide a better solution, regarding the optical and insulative points of view. Besides, this assembly allows us to “tune up” the system for working under different locations by means of simply varying the number of LDPE layers.

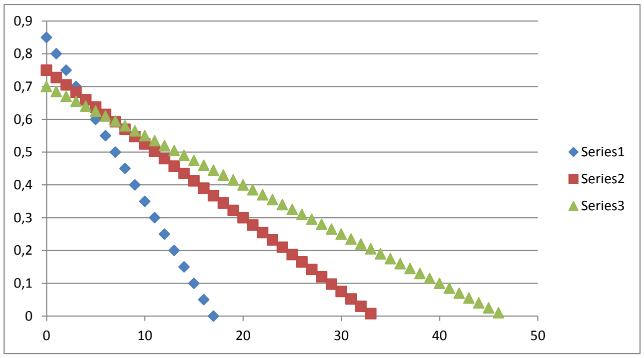


Fig. (2). Graphics of efficiency vs. (T_m -T_a) for different types of flat solar collector (#1: unglazed, #2: single glazing and #3: double glazing) by using the worst (a_0, a_1) set of values according to Table **1** and for I =400W/m^2.

The extremely low cost of the bubble-air film and its long life when it is not exposed to sun rays, suggested us to use this material also for constructing an insulative collector back layer with superlative insulation by means of placing many LDPE layers under the main water chamber. In addition, concerns about its infrared losses due to the high solar transparency of this material (90%) can be avoided by placing a first reflective (aluminum foil) layer. Combining these two, it is feasible to get a very insulative roof (that is, with a very lower U factor) with low-cost materials.

Note that new piping technologies can be used to minimize leakage problems. The construction of continuous flexible pipelines is now available. Therefore, at present, the application of multi-pipe systems does not imply excessive costs in materials and labor. Thus, water redistribution is a feasible technique that can be applied to new roofs built by means of many water chambers.

Other technologies available now that can be used for our configurable designs are:

- High reflectivity layers (such as aluminum foil or aluminum paint), which provides a useful way to minimize infrared radiation losses.
- Microcontroller systems allow us to design a “water roof” in which the water redistribution (filling and draining the water chambers) can be self-controlled. Moreover, this issue could be enhanced by using many complex techniques that have already been explored, such as adaptive control techniques and internet weather forecasts [30].

These technological evolutions open an opportunity technology window for new designs that involve water chambers and water redistribution. These ideas are the main concepts that we propose here for obtaining a configurable roof that works also as a solar collector. This design combines new materials and new designs for developing an innovative roof system. It fully uses water redistribution for changing the roof configuration, creating a deeply configurable system.

2.2. The Configurable Solar Design for Horizontal Roofs

This first design was fully presented in a previous work [30] and so will be summarized here focusing in relation with the new design presented in this work by first time. The condition of level-surface roof allows us to develop a simple solution, suitable for building the main water chamber by using standard metallic roof with a trapezoidal profile. Figure **3** illustrates the general operational scheme of the system under the winter-day configuration, and Fig. (**4**) shows a transversal cut of the roof. It consists of:

- A metallic base with a ‘‘U” profile so that it provides an upper-level step. All the joints of the roof are made on this upper level, and thus, we get an impervious metallic base for the main water chamber.
- The previous water chamber is covered with a first glass pane placed at an intermediate level between the previous two, providing us with a water-tight chamber by simply keeping the water level below that of the glass. This glass rests between two neighboring steps, as shown in Fig. (**4**). As the water level will always be lower than these joints, they do not need to be waterproof.
- A second glass layer will rest on the previous upper rung forming a double-glass water collector. A shallow water layer contained between the metallic roof and the first glass will capture the solar energy absorbed by its black metallic base.
- This large water inventory (for 4 cm water depth and a 100 m^2 roof surface, a water volume of 4,000 liters is obtained) is connected by piping with the storage tank located near the house.
- This water tanks feeds into the conventional circuit of hot water used to heat the house (preferably a floor with radiant heat).
- Normally, this floor system has a standard pump that will also serve to pump the stored water to the roof.
- On cloudy days, the heating system is reinforced with a standard water boiler.
- A rolling awning is arranged above the previous assemblage. Then, another air chamber above the second glass is created when the awning is extended, so that with the air chamber between glass layers provides the overall heat insulation.

This roof works on four different configurations as the Skytherm does, matching the season (winter & summer) and day & night options by filling or draining two main water chambers onto the metallic roof together with folding or unfolding an upper rolling awning. So, this roof is capable of heating (during winter days) or cooling (during summer nights) this water inventory, as the Skytherm does. But in-

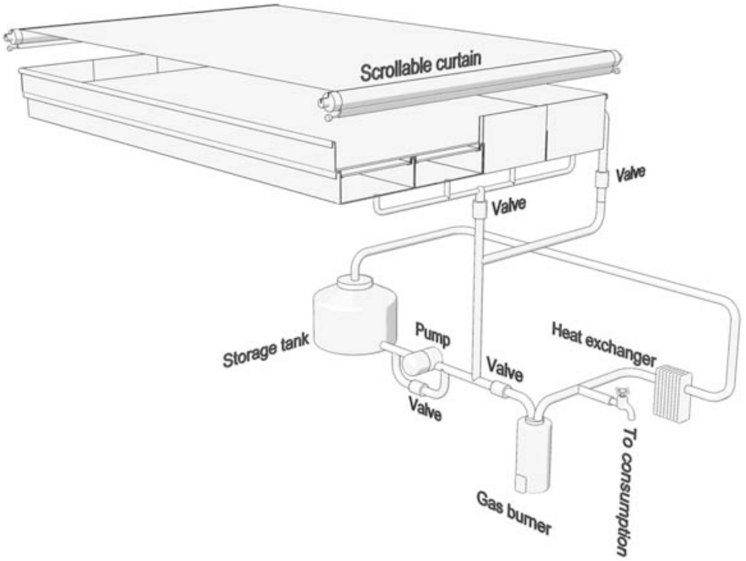


Fig. (3). Perspective of the general scheme of roof system with accessories.

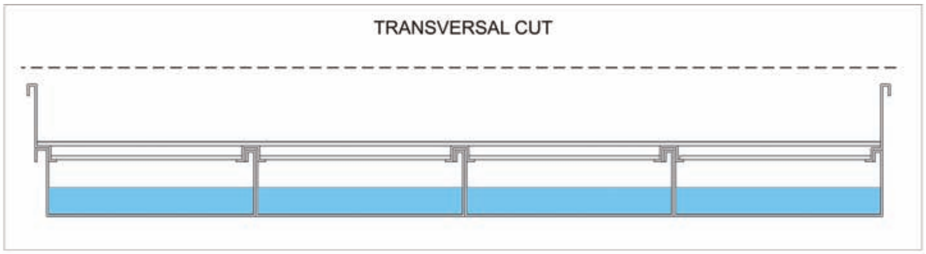


Fig. (4). Cross section drawing. It shows the ‘‘U” profile that supports two glasses.

stead of thermally protecting this water pond onto the roof during summer days and winter nights like Skytherm (that implies the use of a high insulated awning), this new design follows a different approach that is to drain the water roof to a storage tank. This way, two main advantages are obtained simultaneously:

- A new air chamber is created into the roof, which in turns improve its insulative quality.
- This heated water inventory can be used for space heating purpose during winter nights by means of a moderate-temperature heating system, like an infloor hot water system, and of course, for supply the domestic demand of hot water.

Moreover, the feature of this configurable roof could be enhanced by using the configurable rolling awning presented in a previous work [12]. This complementary system is based in a new design for rolling awnings. In this design, the rolling cover is always extended between two rolling axes placed in both roof extremes. But its special characteristic consist in that this cover is built with three different blankets (one transparent, a second one opaque and a third one with open mesh), each one of similar size that roof. So, just by moving simultaneously both rolling axes, it is possible to select which one blanket is extended onto the roof:

- By using the transparent cover during winter days.
- By using the opaque cover during summer days and winter nights.
- By using the open mesh cover during summer nights.

This way, this configurable foldable awning can enhance noticeably the performance of our previous configurable roof, as it was demonstrated [12].

Let us analyze in detail the four working configurations of this combined roofing system.

2.2.1. Winter-Day Configuration

The water pond generated between the first glass and the metallic base collects solar energy and simultaneously warms up the interior of the building by radiation during winter days (see Fig. (**5**)) whereas it is protected by the transparent cover. Considering a daily solar flux of 3,600 W/m^2, this water pond can reach a peak temperature between 50°C and 70°C at some moment in the afternoon [31]. This behavior is commonly observed in low-cost solar collector as it is founded in the scientific [32, 33] and well as in the non-scientific (see for example http://www.builditsolar.com/Experimental/experimental.htm) literature.

However, as far as only passive designs are allowed for water-pond solar collectors, this temperature peak can scarcely be useful since the hot water domestic demand is often mainly at evening. Let us for example, the daily temperature curve of a low-cost water-pond collector built by means of a long LDPE black hose (2" diameter) surrounded by recycled soda PET bottles, that is a common design intended for low-income rural families. This case is illustrated in Fig. (**6**) for a test performed in Salta, Argentina (25° S), during summer (2nd January, 5.5 kwh/m^2/day of total daily solar irradiance on a level surface, average T_a = 20°C with amplitude +/- 10°C). Although the peak temperature reaches 80°C, the water is barely useful (35°C) at 8 p.m. This is the main reason for what this kind of low-cost solar collector are rarely used, even considering its extremely simplicity and universal availability. On the water pond design the collecting surface and the "tank" surface are the same. Therefore, the water heated during the morning and afternoon is after that quickly cooled during the evening.

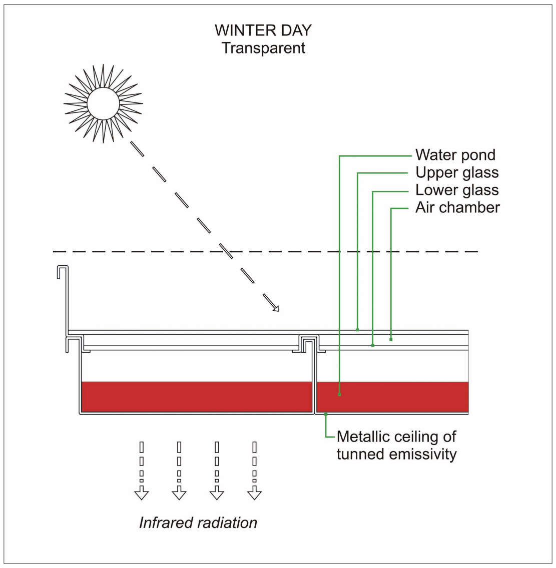


Fig. (5). Working scheme for the winter-day configuration.

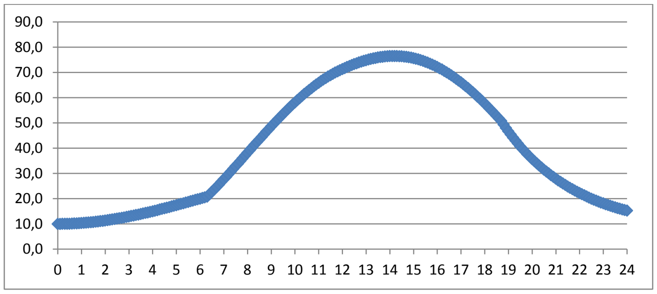


Fig. (6). Daily temperature curve (°C vs. hour) for the 2-inch hose solar collector.

Regarding this behavior, our present proposition follows a completely different approach that the passive water pond system. The use of a microcontroller allows that the system can drain the hot water pond after its peak temperature is observed, concretely in the twilight hours. This way, the heated water is stored in the insolated tank during the evening and night, remaining useful for two different purposes:

1) First, providing space heating by means an infloor heating system, by using the useful temperature jump above 35°C (for example, from 70°C to 35°C).

2) Second, keeping the ceiling temperature above the minimum comfort level (18°C) by using the range from 35°C to 18°C by means of partially filling again the water pond onto ceiling. Note here one remarkable advantage of our design (comparing with Skytherm): the heating losses of the water roof to environment are noticeably reduced, due to its lower jump of temperature and its shorter time of exposition.

2.2.2. Winter-Night Configuration

This warm water is sent in the twilight hours towards the storage tank and from there it is pumped and recirculated through a standard hot water system for household heating, preferably by in-floor hot water radiation. Together with the unfolded opaque rolling awning, (see Fig. (**7**)) three air chambers are created, providing good thermal insulation during the night, as we have already discussed.

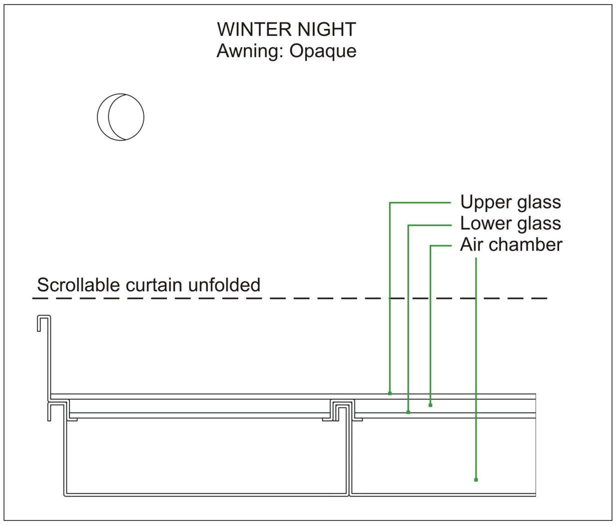


Fig. (7). Working scheme for the winter-night configuration.

2.2.3. Summer-Nights Configuration

During summer-nights (see Fig. (**8**)) a shallow water pond is generated onto the upper glass, (open to the environment), in order to cool it by evaporation, and by thermal radiation emitted to the sky. In this way the temperature can drop up to 10ºC below ambient temperature [7].

Although this cooling method has been extensively tested for arid regions, it has the drawback of exposing the water inventory to environmental conditions. Thus, problems such as smog pollution could contaminate this water up no usable levels. For this reason and considering other practical issues as the feasibility of building a water chamber onto a multiple-glazing surface, this configuration is avoided in our present design that will be presented in section.

2.2.4. Summer-Day Configuration

During the day the water is pumped to the main chamber to provide indoor cooling by free convection as shown in Fig. (**9**). Meanwhile, this water pond is protected from solar radiation by extending the rolling awning. This way more than 50% of the house heat load can be reduced, as Jain pointed out [8]. Note that according to Jain a shallow 5 cm water pond can provide enough cooling power to satisfy the household demand.

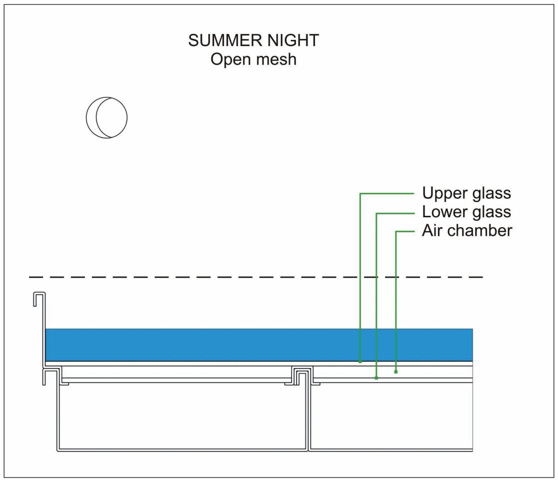


Fig. (8). Working scheme for the summer-night configuration

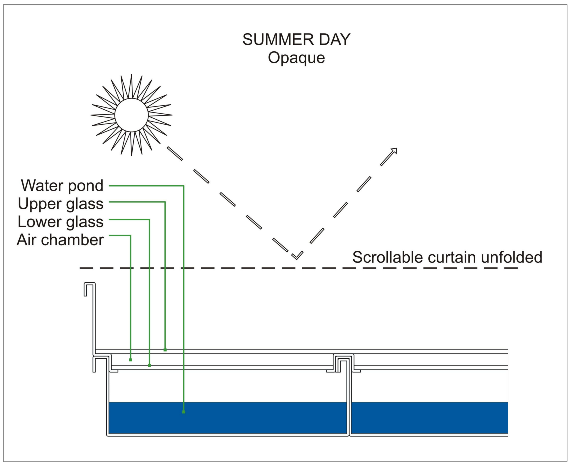


Fig. (9). Working scheme for the summer-day configuration.

Of course, this general description represents only one practical manner of building the present design. For example, one or both glass layers can be replaced with a low-cost transparent plastic material with good thermal properties, like transparent alveolar polycarbonate.

3. THE NEW CONFIGURABLE DESIGN FOR INCLINED ROOFS

Although the horizontal design minimizes the roof area, (and cost as well), it is interesting to adapt it to inclined roofs, for which must be ensured the water tightness of the main water chamber. But the requirement of waterproofing regarding a metallic roof causes strong limitation in the construction techniques and superlative costs due to the introduction of expensive construction techniques, as plasma arc welding. However, the performance of this design on inclined roofs has been already studied, showing that it is noticeably improved for high-latitude climates regarding horizontal roofs [34]. The construction of this design by means of overlapping several layers of plastic materials thermally sealed, as the way for getting feasible waterproofing chambers with affordable cost, is the new choice proposed here. Figure **10** presents the cross-section drawing of the new design of roof, illustrated in Fig. (**11**). It is assembled by:

1) The main water chamber (1) formed by a black base (a) and transparent ceiling (b).
2) The secondary water chamber (2) placed above the main chamber (1) and formed by its transparent base (b) and transparent ceiling (c).
3) In the back side of the main water chamber (1) are placed many air-bubble LDPE sheets (d) forming an insulative chamber (3) below an aluminum foil (e) used as infrared reflective layer.
4) Eventually for cold-climate high-latitude locations, the insulative quality of the secondary chamber (2) can be improved by adding several air-bubble LDPE layers (f) onto its transparent base (b). As we shall see, it is very important to put the (f) layers exactly in this position, in order to allow that the secondary chamber (2) can work as a water cooling device.

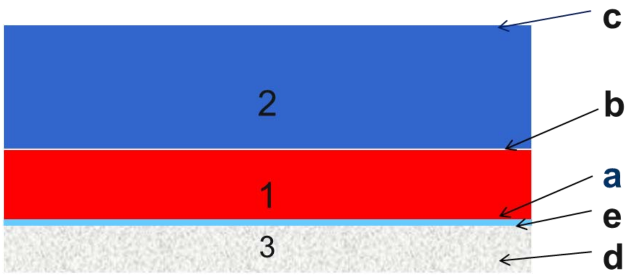


Fig. (**10**). Cross-section drawing of the new solar roof.

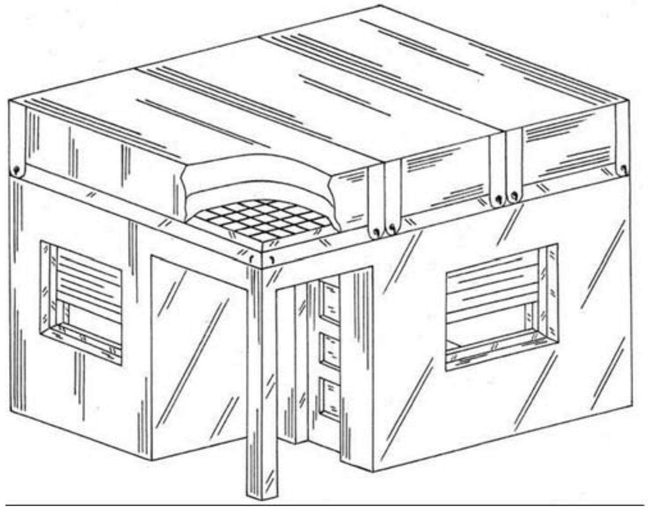


Fig. (11). General drawing of the new multiple-chamber water roof. Note that the metallic roof has been substituted by a metallic open mesh structure.

3.1. Different Working Configurations of the New Roof

3.1.1. Winter-Day Working Configuration

During winter days, the main chamber (1) is intended for working as a flat solar collector built with double glazing covers (b+c) and very insulative back side (3). So, the secondary chamber (2) will be air filled by means an electrical home vacuum cleaner working as a blower. Moreover, if two additional (f) layers are placed with the glazing chamber (2), the solar chamber (1) becomes a quadruple-glazing solar collector.

According to the energy balance performed in next section, it is suggested to design a thickness for the main chamber (1) around 5cm, but indeed, this parameter could be tuned up according to the local solar resource and even more, according to the current conditions of any particular day. For example, in a very cloudy day perhaps this chamber could be filled only partially, in order to achieve a more useful temperature. Again here, the use of a microcontroller enhances the features of this design.

3.1.2. Winter-Night Working Configuration

During winter nights (indeed from afternoon, when the water pond reaches its peak temperature) the hot water pond (1) is drained and storage into the tank in order to be used for indoor space heating. In this new design will not be necessary to pump some water again into the roof (1), since the insulative chamber (3) is enough for this purpose.

3.1.3. Summer-Day Working Configuration

During summer days both, the main (1) and secondary (2) chambers are water filled. So, the secondary chamber becomes an unglazed solar collector and therefore it gets major heat losses in order to limit its temperature increasing. As another method for reducing its peak temperature, a relative large thickness (about 10cm) is suggested for the secondary chamber (2). Although the main chamber (1) could be also heated too high during summer (but always less than the secondary chamber, that in turns is used then as its coolant device), the insulative chamber (3) is enough for assuring that the ceiling temperature be down the maximum comfort level, as we shall see in next section.

3.1.4. Summer-Night Working Configuration

During summer nights both water chambers (1 and 2) remain filled in order to be cooled by infrared heat losses to sky, as Skytherm uses. Perhaps close the sunrise, and precisely at the moment when the down temperature peak occurs, both chambers are drained and this water inventory is sent to the tank.

3.2. Energetic Analysis of the New Roof

3.2.1. Energy Balance for the Winter Configuration

In this case the system works as a double glazing collector (without adding any “f” layers), and thus a_0= 0,8 and a_1=8 W/m^2°C, according to Table **1** and the LDPE properties. The environmental conditions for Buenos Aires (38°S) during winter gives us a daily average solar irradiation, E_d = 2.0 kWh/m^2 on a level surface and a mean temperature T_a = 12°C with amplitude +/- 8°C. Modeling this water pond flat solar collector mounted onto an inclined roof, we can obtain the daily temperature curve, and the peak temperature. This standard procedure consists in a four-step method:

1) Determining the apparent sun trajectory for the day studied (1st July) by using the well-known trigonometric equations (see for example, [26]). This way the sun elevation angle and azimuthal angle are determined hour by hour.
2) Calculating the normal solar flux projected on the collector plane and the collector projected area, hour by hour.
3) Using Eq. (1) to determine the energy absorbed by the solar collector, hour by hour.
4) Using the balance of energy for the water pond, for calculating the temperature increasing of the water pond, hour by hour.

This iterative procedure can be solved hour by hour, starting with an initial condition of the water pond temperature T_m=T_a at the sunrise. Of course, this condition could be replaced for the actual value if the annual cycle is simulated (considering that one year is a periodic-stationary cycle, which indeed is barely true!), but now for preliminary analysis this boundary condition is reasonable. Hence, the daily temperature curve of the solar pond and the daily efficient curve can be obtained for any particular set of solar and environmental conditions, and also taking in account the roof inclination.

We study now the sensitivity of this last variable, regarding the fact that here we are not optimizing the annual collector yield (in which case is well-known the recommendation of latitude + 10°) or even the winter yield. Instead, now what we are looking for is to optimize the maximum temperature peak of this water pond, which is a rather than different objective. Regarding the fact that this moment is usually reached during afternoon, it is possible that the optimum inclination of roof is determined when the sun is normal to roof in the afternoon too. Regarding this point, the ambient temperature will be modeled by a sinusoidal curve as it is usual [12, 35] but with its peak occurring at 2 p.m. instead of noon.

Two different roof slopes were studied keeping constant the living area at 100m^2 and also the effect of the water pond thickness was studied. These results are summarized in Table **3**. Here, the last column shows a merit figure, the energy useful for space heating purpose by infloor water system. Since this system works above 28°C, the useful temperature jump ($T_{maximum}$ - 28°C) defines this figure together with the heated water mass.

These results show that a thin pond (between 2cm or 3cm) mounted onto an 60° inclined roof is the most convenient choice since the maximum temperature is accordingly higher (and so, more useful) and the storage tank is smaller. The useful energy obtained for all cases is enough to satisfy the heating demand for an average house, even in colder locations. For example, in Stockholm (57°N), there was an average heating demand of 53 GJ/year in one-family houses [36].

Table 3. Sensitivity analysis for winter conditions.

Roof Slope	Thickness (cm)	Water Mass (Kg)	T Maximum (°C)	E Useful (GJ)
60°	2	4,000	55	0.46
60°	3	6,000	51	0.59
60°	4	8,000	47	0.65
60°	5	10,000	44	0.66
30°	2	2,300	47	0.19
30°	3	3,500	43	0.22
30°	4	4,600	40	0.23
30°	5	5,800	37	0.22

3.2.2. Energy Balance for the Summer Configuration

Similarly to the previous case, we can use the same model with the right conditions in order to represent the summer conditions in the same location in 1st January (T_a=25°C +/- 10°C, E_d = 6.0 kWh/m^2), relative to a warm and sunny day. But now, since the secondary water pond (10cm depth) is filled together with the main chamber (5cm depth), this new solar pond can be modeled as a single pond having the total size (15cm depth) and having parameters according to an unglazed collector (a_0= 0,9 and a_1= 20W/m^2°C). The results are summarized in Table **4**. Here, it is observed that even a relative thin (1+2) chamber (about 5cm) is enough to keep the roof below a convenient level, regarding that the insulative chamber (3) can be assembled with many low-cost layers in order to achieve a high insulative quality.

4. CONCLUSIONS

An innovative concept of a solar roof that could satisfy the domestic heating and cooling demand has been presented. Being a new concept, it certainly will require in the future additional work on detailed engineering and to be field tested. Nevertheless, the vast bibliography available allows us to extrapolate its performance in this conceptual study, having a good chance of success in locations with low-latitude to mid-latitude climates.

This innovative design takes advantage of new synergies proposed between the collector and the roof. Its main concept is based on the use of water redistribution to change the roof configuration in a simple and practical manner, just by using the water redistribution. In addition, this new roof has eliminated the foldable awning proposed in our previous designs, which implied major concern about maintenance and durability.

This design could lead to low-cost roofs that also provide passive heating and cooling. As we have pointed out, the main drawback of large solar collectors is their high cost. This design provides a solution to this problem that could be widely applied. The practical solution proposed, by means of thermally sealed plastic bags, is a low-cost and feasible manner of construct the new roof. This self-supported solar roof could be manufactured in a large-scale by a factory, reducing the cost even more. So, we expect to obtain total cost about 100 U$D/m^2, that is very competitive.

This design has found new synergies intended to achieve the most configurable buildings, not the most adiabatic ones, which is the present paradigm for low-energy buildings. I believe that the generalized use of the U-factor as the main parameter for characterizing buildings thermally, actually reflects the conventional criterion. The U-factor would reflect properly the heat flux across a building surface only under stationary conditions. However, the actual condition

Table 4. Sensitivity analysis for summer conditions.

Roof Slope	Thickness (cm)	Water Mass (Kg)	T Maximum (°C)
60°	15	30,000	53
60°	10	20,000	58
60°	5	10,000	64
30°	15	17,500	52
30°	10	11,500	58
30°	5	5,750	65

for buildings is far from this case. Nature exists along cycles: summer and winter, day and night, and so, environmental conditions impose strong cycles on our buildings. Therefore, the question here is: why use a stationary factor as the main thermal parameter? Of course, a fixed passive roof can achieve better thermal performance only by means of better thermal insulation, but, as we have demonstrated here, for new dimensions of configurable designs there are many ways to achieve better thermal performance. We should always keep this fact in mind.

CURRENT & FUTURE DEVELOPMENTS

Regarding the simplicity of this design, it could have a good chance for achieving success. However, as in any novel design developed just up to conceptual level, it will need a whole further development until to demonstrate its feasibility under real working conditions. In this sense, it would be a common error to starting the experimental study by focusing in its performance as a solar collector and leaving underlying other main issues, like: 1) proper selection of materials; 2) mechanical testing and aging evaluation; 3) system reliability; 4) manufacturing process and quality controls, etc. Doing this, probably some first good "solar results" could be obtained on a functional prototype, but instead the next real-scale prototype could show new unpredicted troubles relates to materials concerns, leading to a closed path.

This analysis is not only speculative. We have followed the same path in our previous development of the horizontal solar roof [31] and also in the development of the configurable solar awning [12]. Based on this reason, and mindful of the long way to go yet for which is imperative to be able to add new skills and actors to this project, is that we have now followed a new approach. Our current study is focused in these previous underlying issues. So, and by adding new skills from other actors (the National Institute of Manufacturing Technology, INTI) in our team, currently we are developing a real-scale prototype regarding real materials and manufacturing processes from the plastic industry.

ACKNOWLEDGEMENTS

Argentinean Du Pont enterprise is acknowledged for its support by means of funds obtained for the experimental development given by the national Prize Du Pont to Clean Energies 2009.

CONFLICT OF INTEREST

None declared.

REFERENCES

[1] M. Hassan and Y. Beliveau, “Design, construction and performance prediction of integrated solar roof collectors using finite element analysis”, *Constr. Build. Mater.,* Vol. 21(5), pp. 1069-78, 2007.

[2] M. Belusko, W. Saman and F. Bruno, “Roof integrated solar heating system with glazed collector”, *Sol. Energy,* Vol. 76(1-3), pp. 61-9, 2004.

[3] G. Vokas, N. Christandonis and F. Skittides, “Hybrid photovoltaic thermal systems for domestic heating and cooling. A theoretical approach”, *Sol. Energy,* Vol. 80, pp. 607-15, 2006.

[4] S. Maneewan, J. Hirunlabh, J. Khedari, B. Zeghmati and S. Teekasap, “Heat gain reduction by means of thermoelectric roof solar collector”, *Sol. Energy,* Vol. 78(4), pp. 495-503, 2005.

[5] S. Medved, C. Arkar and B. Cerne, “A large-panel unglazed roof-integrated liquid solar collector-energy and economic evaluation”, *Sol. Energy,* Vol 75, pp. 455-67, December 2003.

[6] N.M. Nahar, P. Sharma and M.M. Purohit, “Studies on solar passive cooling techniques for arid areas”, *Energy Convers. Manage.,* Vol. 40, pp. 89-95, 1999.

[7] D. Jain, “Modeling of solar passive techniques for roof cooling in arid regions”, *Build. Environ.,* Vol. 41, pp. 277-87, 2006.

[8] M. Wall, “Energy-efficient terrace houses in Sweden. Simulations and measurements”, *Energy Build.,* Vol. 38, pp. 627-34, 2006.

[9] L. Juanicó, “Solar roof”, Ar Patent Appl. P060104453, October 10, 2006, and internationally claimed by SUNROOF PCT/IB2007/054116, April 17, 2008 and WO/2008/044209, on October 9, 2007. Also claimed in: 1) Mexico (MX/E/2009/020490); 2) USA (US/1244755); 3) Europa Union (PI 0715308), on April 8, 2009.

[10] J. Smeds and M. Wall, “Enhanced energy conservation in houses through high performance design”, *Energy Build.,* Vol. 39(3), pp. 273-8, 2007.

[11] A. Fernandez Gonzalez, “Economic analysis of the cost effectiveness of passive solar heating strategies in the Midwest of the US”. *In Proceedings of the 2005 World Solar Congress,* Orlando, Florida, U.S., August 2005.

[12] L. Juanicó, “A new design of configurable solar awning for managing cooling and heating loads”, *Energy Build.,* Vol. 41(12), pp. 1381-5, 2009.

[13] H.R. Hay, “A passive heating and cooling system from concept to commercialization”, *In Proceedings of the Annual Meeting of the American Society of ISES,* 1977

[14] H.R. Hay, *“Process and apparatus for modulating temperatures within enclosures”*, U. S. Patent 3,563,305, 1971.

[15] H.R. Hay and J.I. Yellott, “International aspects of air conditioning with moveable insulation”, *Sol. Energy,* Vol. 12(4), pp. 427-30, 1969.

[16] R. Alves and Ch. Milligan, “Living with energy”, MacMillan London Limited, London, 1978.

[17] H.E. Thomason, *“Solar heated home”*, U.S. Patent 3,254,703, 1966.

[18] H.E. Thomason, *“Apparatus for cooling and solar heating a house”*, U.S. Patent 3,295,591, 1967.

[19] H.E. Thomason, *“Flat roof solar heating building”*, U.S. Patent 3,910,253, 1975.

[20] S. Baer and W. Mingenbach, *“Passive heating and cooling system”*, U.S. Patent 6,357,512, 2002.

[21] R. Rhodes, *“Thin film solar collector”*, U.S. Patent 8,161,963, 2012.

[22] Barton, N. Torr and A. Carl, *“Thin film solar collector”*, U.S. Patent 8,137,814, 2012.

[23] M. Fuur, F. Fogh and P.C. Boldsen, *“Solar water heater”*, U.S. Patent D652,494, 2012.

[24] W. Colson, *“Solar heating blocks”*, U.S. Patent 8,082,916, 2011.

[25] V. Palmieri, *“Vacuum solar thermal panel”*, U.S. Patent 8,161,965, 2012.

[26] J. Duffie and W. Beckman, “Solar engineering of thermal processes”, 3rd ed., N. Jersey: John Wiley & Sons, Inc., 2006.

[27] P.T. Tsilingiris, “Comparative evaluation of the infrared transmission of polymer films”, *Energy Convers. Manage.,* Vol. 44(18), pp. 2839-56, 2003.

[28] G.M. Wallner, W. Platzer and R.W. Lang, “Structure-property correlations of polymeric films for transparent insulation wall applications”, Part 1: Solar optical properties, *Sol. Energy,* Vol. 79, pp. 583-92, 2005.

[29] G. M. Wallner, R. Hausner, H. Hegedys, H. Schobermayr and R. W. Lang, “Application demonstration and performance of a cellulose triacetate polymer film based transparent insulation wall heating system”, *Sol. Energy,* Vol. 80, pp. 1410-6, 2006.

[30] A. Guillemin and N. Morel, “Experimental results of a self-adaptive integrated control system in buildings: A pilot study”, *Sol. Energy,* Vol. 72(5), pp. 397-403, 2002.

[31] L. Juanicó, “A new design of roof-integrated water solar collector for domestic heating and cooling”, *Sol. Energy,* Vol. 82(6), pp. 481-92, 2008.

[32] P.T. Tsilingiris, “Towards making solar water heating technology feasible-the polymer solar collector approach”, *Energy Convers. Manage.,* Vol. 40(12), pp. 1237-50, 1999.

[33] P.T. Tsilingiris, "Back absorbing parallel plate polymer absorbers in solar collector design", *Energy Convers. Manage.*, Vol. 43(1), pp. 135-50, 2002.

[34] L. Juanicó, "New design of solar roof for household heating and cooling*", Int. J. Hydrogen Energy*, Vol. 35(11), pp. 5823-6, 2010.

[35] W. Chen and W. Liu, "Numerical and experimental analysis of convection heat transfer in passive solar heating room with greenhouse and heat storage", *Sol. Energy*, Vol. 76, pp. 623-33, 2004.

[36] A. Carlsson-Kanyama, R. Engström and R. Kok, "Indirect and direct requirements of city households in Sweden", *J. Ind. Ecol.*, Vol. 9 (1-2), pp. 221-35, 2005.