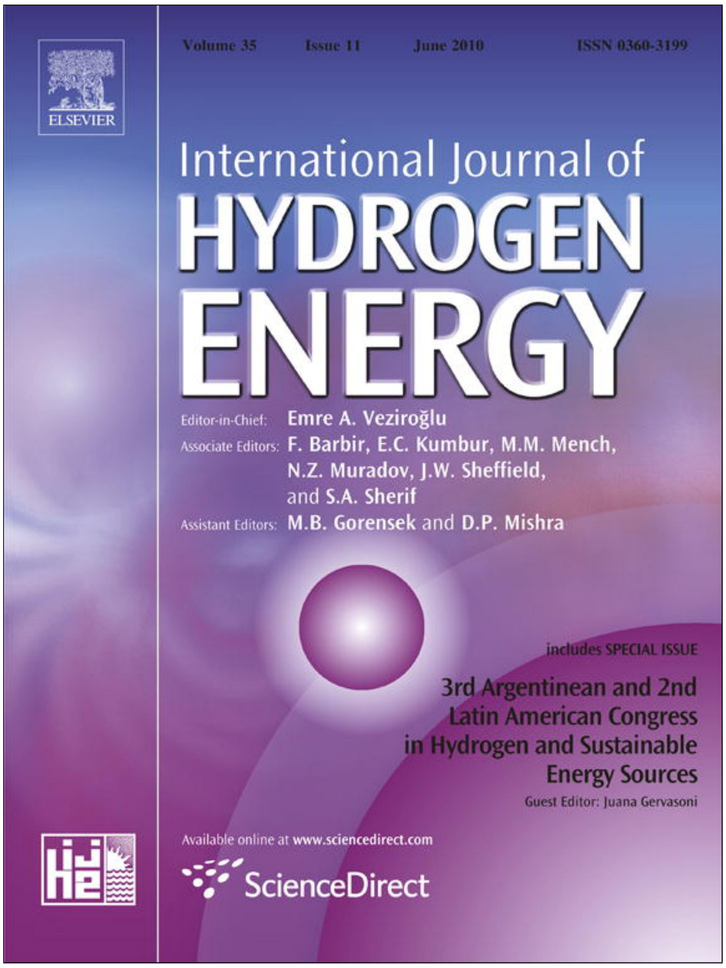
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New design of solar roof for household heating and cooling

L.E. Juanicó

Conicet (National Scientific and Technologic Research Council), Centro Atómico Bariloche, 8400 Bariloche, Argentina

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ABSTRACT

A new design of solar roof is presented. It is a roof-integrated solar collector that is configurable by water redistribution. This way, this active system can provide household heating and cooling. Its thermal performance and cost were studied. It is found that total cost is similar to standard roofs and significant energy savings could be achieved.

1. Introduction

Many solar roof designs have been developed in the last fifty years. Although all of them are technically feasible, their application has been limited due to high costs [1,2]. On the other hand, large solar collectors mounted onto the whole roof have shown that they can satisfy the household heating demand even at 40° latitude [3]. In addition, it is clear that thermal solar systems are cheaper than solar electrical generation. Although several solar thermal and hydrogen hybrid systems are been proposed for the supply of electricity to houses, at present they are expensive [4–6]. Considering that almost half of the total primary energy consumed in developed countries is related to building acclimatization, we can point out that there is a need for an economical roof-integrated solar collector, which is the more affordable path to solar widespread utilization.

As Hay [7] has demonstrated with Skytherm, a configurable roof can provide building acclimatization by taking advantage of Nature's thermal cycles. This pioneer design uses water bags mounted onto a metallic roof collecting solar irradiation during winter days and dissipating heat during summer nights. In addition, an awning with thick thermal insulation is unfolded during winter nights and summer days. Hence, by just folding or unfolding a cover this roof can obtain four different working configurations, providing household heating and cooling. However, this awning was too expensive due to its mechanical complexity, related to the additional thermal insulation panels added.

The drawback of Skytherm has been overcome by a new approach to the configurable water roof [8]. Instead of insulating the water pond during winter nights; it proposes removing the water from the roof and this heated water is used by a standard hot-water infloor heating system. This

E-mail address: juanico@cab.cnea.gov.ar
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system has been proposed as an economical choice for horizontal roofs [8]. However, its cost is appreciably higher for inclined roofs, due to the waterproof requirement of the glass–metal chambers. This paper presents for the first time a new design specially suited for the solution of this issue.

2. Analyses of different roof techniques

2.1. The evolution of the classic roof

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

- To prevent rain and 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.) under the waterproof exterior layer. This whole system constitutes a good-quality roof; but at high costs in relation to materials and labor. So, the traditional roof concept can be described as a fixed roof in which the greatest adiabatic degree is intended. This approach follows the current architectural trend for low-energy buildings, but with high costs [9]. We, on the other hand, are proposing to maximize the building degree of adaptability to the environment.

2.2. General description of the new concept of configurable roof

Fig. 1 illustrates the general operational scheme of the new system developed previously for horizontal roofs and Fig. 2 its cross section drawing [8]. Summarizing, this system consists of a metallic base with an upper-level step (trapezoidal or square profile) where all the joints to the supporting structure are placed. Hence, a solid watertight metallic base for the water chamber is obtained. This water chamber may be covered with a double glazing cover similar to that of a flat solar collector, providing a watertight chamber by simply keeping the water level below that of the glass. The large water inventory on the roof is connected by piping to the storage tank that feeds a standard hot-water infloor heating system. This system includes a boiler, useful on cloudy days when the solar energy collected is not enough to satisfy the heating demand. A rolling awning is extended above the previous assemblage on summer days and winter nights. Then, a third air chamber is created, together with the double glazing that provides suitable thermal insulation on the roof. Note that this awning does not need insulation panels as Skytherm does. In addition, a new design of a configurable solar awning with mechanic improvements has been developed [10].

2.2.1. Working configurations of the new concept

1. *Winter-day*. The water pond generated on the metallic base collects solar energy and simultaneously warms up the living areas.
2. *Winter-night*. Hot water is sent in the twilight hours to the tank and from there it is pumped through the heating system. This way, three air chambers are created on the roof including the awning. Besides, a small amount of hot water can be pumped onto the metallic roof in order to keep the ceiling temperature above the minimum comfort level (18 °C). Thus, indoor comfort can be maintained although the thermal insulation of this roof is lower than that of a conventional one, this is a completely new feature.

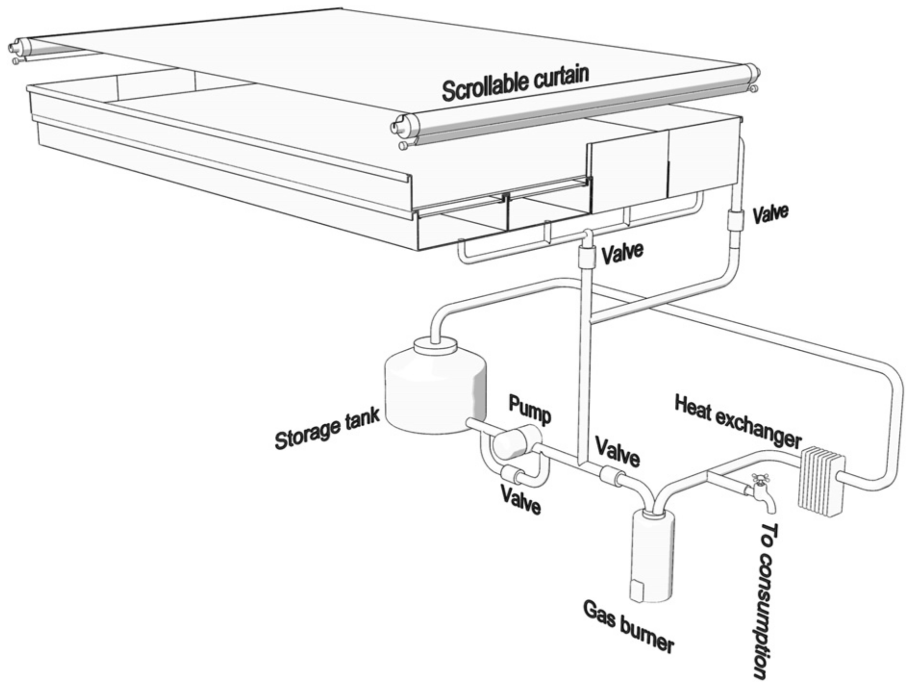

Fig. 1 – General scheme of the horizontal water roof.

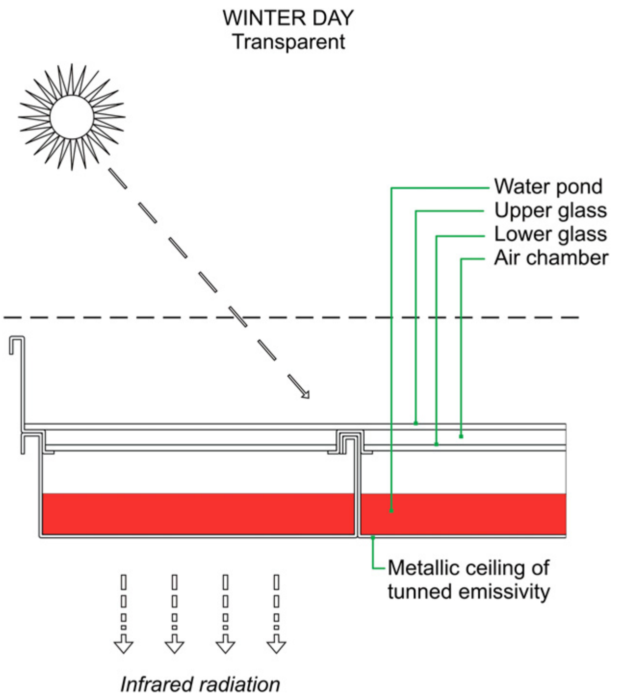

Fig. 2 – Cross section drawing of the horizontal water roof.

3. *Summer-night*. A secondary water pond is generated onto glass panes in order to cool it by evaporation and thermal radiation to the sky. This way the temperature can drop down to 10 °C below ambient temperature, according to Nahar [11].
4. *Summer-day*. The water cooled is pumped onto the metallic roof to get indoor cooling by free convection. Meanwhile, this water pond is protected from solar radiation by extending the rolling awning; eliminating more than 50% of house heat load, according to Jain [12].

3. The new design for inclined roofs

We have already studied a new solar roof that has advantages related to the Skytherm design. While both use water ponds, the new design eliminates the awning complexity, and it creates two more air chambers that enhance the roof insulation. On the other hand, regarding concerns about water proofing the chambers, we must recognize the simplicity of Skytherm, which can be built easily for inclined roofs.

From this starting point, we have created a new design that comprises the advantages of these two previous designs. We are proposing now a new roof that uses thin flat water bags (about 3 cm thickness) interconnected by piping to a reserve tank and from there, to the conventional household infloor heating system. Besides, in order to keep the capability of creating an air chamber when the water bags are drained, we can use a home air vacuum to fill the empty bags with air. The number of fittings and pipes can be minimized if the small individual bags are substituted with large cushions. These large cushions could be manufactured with internal transparent layers, in order to improve the roof's thermal insulation similarly to the previous multi-glazing solar roof. By applying this new design to inclined roofs it is possible to increase the solar gain appreciably in comparison with the horizontal one. In the next section we will study the thermal performance of both options. This design has been recently patented [13].

4. Energy analysis

Let us first analyze the energetic behavior of the solar collector. This analysis can be carried out easily as there is abundant scientific literature available, and it is supported by the previous study of the horizontal roof [8]. Let us consider, a one-family house ($A = 100\ m^2$, living area) sited in two locations: i) Bariloche (latitude 42°S), a cold Patagonian town close to Los Andes Mountains; ii) Buenos Aires, a city with moderate climate on the Atlantic Coast (latitude 34°S). The monthly average of the daily solar irradiation flux on level surfaces (G'') for both locations in the colder (July) month, are 1.5 and 2.0 kWh/m^2 respectively. The daily energy collected (Ed) for the horizontal roof can be calculated as:

$$\mathrm{Ed} = G'' \cdot \xi \cdot A \qquad (1)$$

where ξ is the collector efficiency. Assuming $\xi = 50\%$, average for actual flat solar collectors, Eq. (1) gives us Ed = 75 kWh = 0.27 GJ in Bariloche, and Ed = 100 kWh = 0.36 GJ in Buenos Aires. These energies collected can be compared with the household heating demands; the annual average heating demand for a single-family is 144 GJ in Bariloche, and 20 GJ in Buenos Aires [14]. Hence, by distributing these heating demands along six months (Bariloche) or three months (Buenos Aires) according to the duration of their cold season, the daily heating demand (Ea) is calculated as Ea = 0.8 GJ and 0.22 GJ, respectively. Thus, the horizontal solar roof could fully satisfy the average heating demand of the temperate location, but only about one third of the cold location. Let us point out that the heating consumption in Bariloche (1.5 $GJ/m^2/y$) [14] is about three times greater than developed countries with similar annual mean temperatures (8 °C), like Stockholm, with 0.5 $GJ/m^2/y$ [9]. This figure has been attributed to the low-thermal quality of the envelopes of buildings and supported by the low Argentinean natural gas tariffs (ranging from 1 to 2 U$D/MBTU). According to the Swedish specific consumptions guidelines, the horizontal roof could almost fulfill the household demand in Bariloche. In addition, it is possible to increase the energy collected with a steep roof. For a roof with a 60° slope we can use the solar roof on the sun-oriented gable, having $A = 100\ m^2$. This slope is usually chosen by architects in Bariloche due to snow concerns. This slope almost maximizes the

Table 1 – Annual savings according to local tariffs and type of roof selected.

Location	Natural Gas		LPG	
	Horizontal	Inclined	Horizontal	Inclined
Buenos Aires	U$60	U$60	U$600	U$600
Bariloche	U$80	U$240	U$1300	U$3900

Table 2 – Annual savings according to tariffs in Barcelona, Spain.

Location	Natural Gas	
	Horizontal	Inclined
Buenos Aires	U$800	U$800
Bariloche	U$1800	U$5400

energy collected during the winter solstice, in which the apparent sun trajectory rises only up to 24°30′. In this case, this inclined roof collects three times as much energy as the horizontal one, obtaining Ed = 225 kWh = 0.81 GJ. This amount would satisfy totally the large heating demand of low-quality houses in Bariloche. Finally, considering the actual solar source in Stockholm (0.5 kWh/m^2) which is about three times lower than Bariloche; the inclined roof could provide fully the heating demand of the Swedish houses.

5. Cost study

Based on actual high-quality roofs built in temperate regions of Argentina (U = 0.4 W/m^2 K), generally with lower slopes than in Bariloche (20°), we found total costs of about 150 U$D/m^2 of living area. For this solar roof in the horizontal version, we have already estimated similar costs, including the new rolling awning at 50 U$D/m^2 [10]. For the new inclined roof proposed here, the cost of the plastic water bags could be lower; however, considering that special cushions need to be manufactured (50 U$D/m^2), total costs were estimated ranging from 150 to 200 U$D/m^2, the higher cost similar to conventional roofs built in developed countries.

Moreover, appreciable energy can be saved in any location. Assuming an average efficiency of 60% for the most generalized heating system in Argentina [14], 900 m^3 of natural gas (NG) could be saved annually in Buenos Aires with both roofs, and 2.000 m^3 and 6.000 m^3 in Bariloche for the horizontal and inclined roof, respectively. Regarding the residential tariff of NG for Buenos Aires (0.07 U$D/m^3) and Bariloche (0.04 U$D/m^3), these values imply annual savings of 60, 80 and 240 dollars, respectively. These modest savings change noticeably when these are considered for the case of houses not-connected to the grid. In this case, regarding the LPG tariff (0.60 U$D/l) the annual savings are 600, 1300 and 3900 dollars, as illustrated in Table 1.

The Argentinean NG tariffs are very low in relation to international ones. For illustrating purposes, let us consider the residential tariff (R1) of NG in Barcelona, Spain (see: www.gasban.com), to 0.6125 euros/m^3, or about 0.9 U$D/m^3. Following the previous comparison, the annual savings estimated for Buenos Aires are around U$D 800, and up to U$D 5400 for Bariloche (see Table 2).

6. Conclusions

This work presents a new design of a solar roof intended to be a suitable option for inclined roofs. No doubt that it will need further work; however, regarding considerable bibliography and the simplicity of flat solar collectors, its performance can be roughly estimated within the conceptual level of this first study. In addition, since this roof uses mainly standard building materials and construction techniques, its cost and the complexity expected can be roughly estimated, with a good chance of being commercially feasible. The costs would be the same as those of actual conventional roofs of a similar (high) thermal quality. Therefore, this roof has a good chance of widespread success as it would be affordable in most countries; and it is especially suitable for developed countries with cold climates.

The energy savings that could be obtained in different weather patterns was estimated. It has been found that the whole household demand could be met at temperate medium-latitude locations for both, horizontal and inclined roofs, obtaining noticeable savings. In addition, the steep roof could also perform satisfactorily in cold high-latitude locations.

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