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Active building envelopes

An integrated solution for solar cooling and heating

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ABSTRACT: Solar thermal collectors are traditionally applied on roofs of low buildings to cover the domestic hot water and heating demand. Nevertheless, for high buildings the roof surface is not sufficient to satisfy such demands and consequently the entire envelope should be exploited.

In this study an innovative system of solar thermal façade has been designed for the application on an existing apartment tower in order to satisfy the energy needs for winter heating and summer cooling. The tower, built in the 80s, is placed in Sicily, a region which may be considered representative of mild Mediterranean climate.

The proposed system consists of evacuated tube solar collectors assembled on modular panels, designed to reduce the overall costs.

Also the aesthetic instances have been properly considered, taking care of both the design and the composition of the panels on the façade.

Depending on specific requirements, each panel can be flexibly equipped with optional accessories, such as insulation layers, sun-tracking mirrors, PV-modules, maintenance and cleaning devices.

Results show that this active façades can be effectively used in the case study, that is representative of high rise residential buildings, but it may have convenient application also on new constructions.

Keywords: active façade; evacuated tube solar collectors; Mediterranean climate; modular panels

INTRODUCTION

Solar thermal technologies are nowadays well-established [1-2], as well as absorption chillers are a widely tested solution [3-4].

Nevertheless, the use of solar thermal technologies in highly urbanized environment seems still to find several obstacles, even if the site is climatically favourable, as in the case of Mediterranean countries.

This is due to the specific territory and urban texture configuration, characterized by compact and morphologically dense urban areas.

The greater obstacle to the diffusion of solar thermal systems mainly lies on their intrinsic rigidity and on the lack of technologies which can be morphologically integrated with the traditional components of the building envelope.

The issue of system integration into built environment, although widely recommended, is in fact still unresolved. This difficulty is due on the one hand to the urban morphological complexity and on the other hand to the huge variety of building types, in particular the residential ones, which definitely constitute the greater part in the urban context.

It is necessary, therefore, to deal with the integration of solar technologies into the building envelopes, in order to achieve the goals of energy saving and carbon emission reduction.

The research focuses on built environment by the 70s, which is quantitatively significant in the European cities of the Mediterranean area.

That building stock has often no formal value, is poor in technology and energetically inadequate.

It could be therefore an important field of application for urban morphology modification strategies and energy retrofitting at urban scale.

In order to achieve the integration of energy-producing systems into the architectural building scale, we have to transform the traditional envelope components in active elements, which can be able to control the heat flow between the internal and external environment in an efficiently and flexibly way.

Since long time many technologies are available, such as insulation systems and ventilated walls, manual and automatic shading devices, photovoltaic (PV) panels and solar collectors.

Despite that, it is still absent an integrated solution able to adapt such technologies to the variety of

morphological configuration of residential building façades.

This is definitely the aim of this study, which will focus on a tower building located in Catania, Sicily, a region that can be considered representative of mild Mediterranean climate countries, where usually the summer energy demand exceeds the winter one.

SYSTEM DEVELOPMENT

Solar energy could be used to produce cooling through different technologies, such as by providing thermal energy for absorption chillers. There are many installations of these systems around the world and in particular in Europe: they work since some decades [5] and use many types of collectors, chillers, heat storage tanks, etc. In all the working solar cooling facilities, solar collectors are positioned on horizontal surfaces in order to maximize solar gain. Nonetheless, recent studies show that better energy performances could be gained by coupling PV to traditional electrical compression chillers [6]. Moreover, in high rise buildings the flat covering is small as compared to the total floor area, strongly limiting the overall effect of any system that could be set on such surfaces. There are some attempts on the integration of active solar systems in buildings façade of [7], but aesthetics emerges as the main issue.

Energetic issues

The main restriction to any design proposal is solar energy availability during useful periods. As shown in Fig. 1, in Mediterranean climate flat roofs have the highest overall available solar energy, which is mostly concentrated during summer. A correct inclination angle of sun collectors on flat surfaces or sun tracking allows for higher solar energy collection. South façades have higher daily solar energy available during winter than in summer. On the contrary, eastern and western exposures have mean daily available energy with distributions similar to horizontal surfaces. Therefore, façades that should be used to collect solar energy for cooling are East and West, while South façade could be used for winter heating.

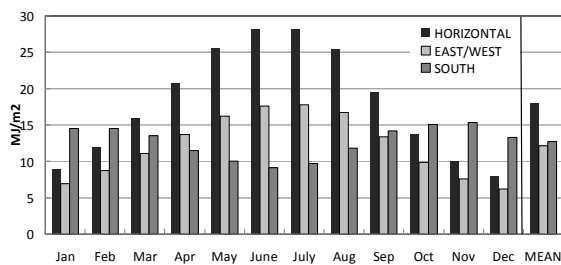


Figure 1: Mean daily available solar energy in Catania (37°30'N)

Efficiency of solar collectors is a decreasing function of the heat-loss factor T^* :

$$\eta = (\eta_0 - a_1 \cdot T^* - a_2 \cdot G \cdot T^{*2}) f(\varphi) \cdot f(\theta) \quad (1)$$

$$T^* = \frac{T_m - T_a}{G} \quad (2)$$

where η_0 is the efficiency without heat loss, a_1 and a_2 are characteristic coefficients of each device, $f(\varphi)$ and $F(\theta)$ are the correcting factors for sun incidence angle, G is the sun specific power, T_m is the mean fluid temperature, T_a is air temperature. Even though most collectors used for solar cooling in South Europe are flat ones, vertical positioning lead to a doubling of the heat-loss factor (2) as sun power halves, making almost mandatory the use of evacuated tube collectors that have smaller coefficients a_1 and a_2 .

The energy demand of buildings depends on climatic conditions and on the different uses. Commercial and industrial buildings with high electricity demand have high internal gains, that make loads almost insensitive of external conditions. In the climatic conditions of Catania specific cooling loads could be as high as 75 W/m² in midwinter, meaning that no heating is really needed. Moreover, energy demand for cooling depends on the specific daily use period: for tertiary buildings it corresponds to opening hours, for residential it is usually limited to late afternoon and evening time. This situation leads to very different mean energy demands for cooling as illustrated in Fig. 2. Comparing the values of energy demand per floor area to solar energy availability per collecting area shown in Fig. 1, as the conversion factor of solar energy to cooling energy, obtained by absorption systems, is approximately 0.35, it is clear that solar cooling is more applicable for residential buildings than other uses. Moreover, cooling demand for residential and low load tertiary buildings is the main cause of the electricity peak load increase that stresses electricity suppliers in summer, making it strategic in energy demand planning.

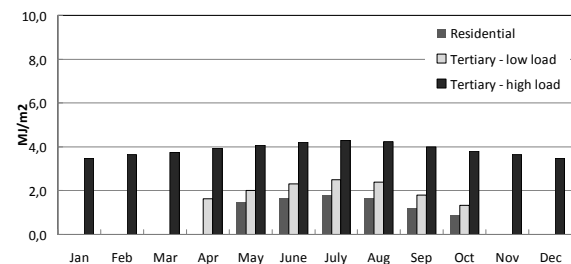


Figure 2: Mean daily cooling energy demand per floor area

Construction issues

The main component of the designed system is a modular panel, consisting of a steel frame, supporting evacuated tube solar collectors along with their mirrors. Each panel is independently linked to the whole circuit,

so it is possible to exclude one or more panels for maintenance purposes, without interrupting the system operation. The panels are connected to the outer walls of the building through a steel substructure.

The construction process of the modular panel is divided into the following phases:

- production of the basic components;
- assembling of the panels;
- installation of the panels and circuit connection.

In the first phase the basic components are produced: evacuated tubes, mirrors, frame sections, and connection hardware. For these components an elevated accuracy and an advanced know-how are requested, so they should be made in a line production.

In the second phase the panel are assembled, using the basic components produced in the first step. The panels are made to order, with requested sizes.

The third and last phase consists of panel installation at the building site. It needs at least two crews: one responsible for steel substructure and panel fixing, the other for all electrical and hydraulic connections.

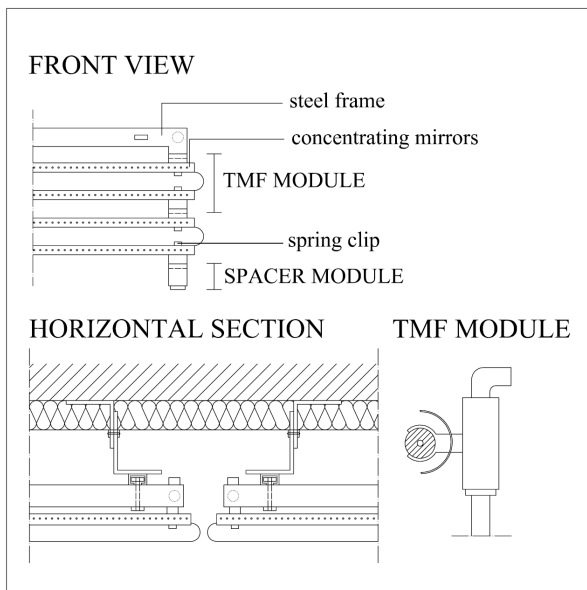


Figure 3: Design of a panel made by TMF modules.

The panel is realized starting from a preassembled basic module, whose sizes and configurations vary according to customer requirements. This basic module, called TMF (Tube-Mirror-Frame), consists of an evacuated tube and its mirror, both connected on two sections of the steel frame (Fig. 3). The TMF modules are stackable through a plug-in system and joined together with the upper and lower beam of the steel frame.

Panel height and tube distance can be varied as required by using special spacers between the TMF modules. The panels are connected to the walls through a steel structure system and hardware components easily

available on building market, as shown in the horizontal section of Fig. 3.

To collect the solar energy impinging between tubes, aluminium mirrors are used, in order to focus solar rays onto the tubes. This setup allows to reach stagnation temperatures well over 300°C, and operating temperatures about 120°C without significant efficiency loss, thus useful for absorption chiller operation. For aesthetic purposes, they can have different colours, but only in very light tones to avoid a performance decrease. Furthermore, to minimize wind load and to allow rain water drainage, the mirrors will have a perforated surface.

The described system refers to panels with tubes in horizontal position; nevertheless if the vertical direction is preferred, the production and assembly process is almost identical, even though mirror positions have to be rearranged.

To provide greater flexibility to the system, it is possible to consider solutions that are more or less complex and efficient, according to user requirements and economic availability. The idea is therefore to implement the standard solution of the basic model with a series of optional accessories – listed below – which make the system more efficient.

Exterior insulation. The possibility of assembling the panels on the façade allows to realize a ventilated wall. On the building side of the air-gap, a layer of thermal insulation could be attached to the existing façade. This option would allow to enhance energy efficiency by reducing thermal loads.

Sun-tracking mirrors. Rotating concentrating mirrors are more efficient than fixed ones. In fact they are able to follow and capture the sunlight according to daytime and season. They will be placed behind the tubes and will rotate automatically, actuated by a control system that detects the position of the sun. Panels equipped with sun-tracking mirrors will be supplied with a central control station (LCU), which manage the handling of the mirrors and the monitoring of characteristic parameters of the panel (such as the fluid flow and its temperature). The LCU can manage the above mentioned bypass system of the single panel in coordination with the supervisor system.

Brise-soleil with mirrors. It is possible to install movable and reflective shelves (thin strips in polished and treated aluminium) in order to increase the capitation and efficiency of the solar panels. It is possible to move them with a stepper motor, combined with a reducer and a crank gear. These shelves should be placed horizontally in the southern façades and vertically in the eastern and western ones, depending on direction of incident sunlight.

Integration with PV modules. It is recommendable to install PV modules (made up of blades) as fixed shading elements (PV brise-soleil), in order to protect from direct sunlight balconies or loggias.

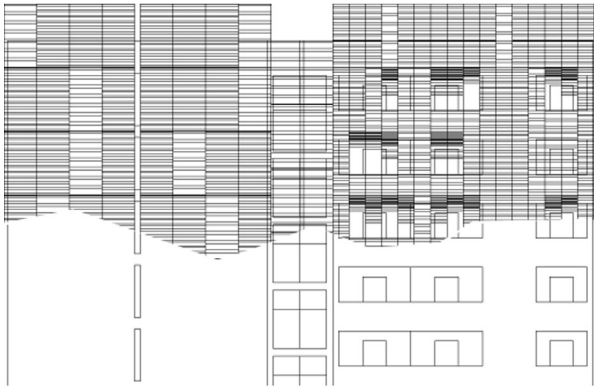


Figure 4: The “Concrete building” in Catania: current façade (lower part) and simulation of the new solar thermal coating (upper part).

Panels maintenance and cleaning. Dust, dirt and faults reduce significantly the efficiency of solar collectors. The accessibility to the panels, for cleaning

and maintenance, can be obtained by using Building Maintenance Units (BMUs), such as roof machines or crane-suspended man-baskets. Alternatively, it is possible to look for a cleaning robot sliding on vertical tracks (integrated to the steel substructure). At present BMU are the only commercial solutions, anyway, in the near future, market production of robots for walls cleaning will reduce drastically cleaning and maintenance costs.

CASE STUDY

The case study is the so-called “concrete building”, in Librino, the suburb of Catania (Sicily) designed by Japanese architect Kenzo Tange.

The choice of a building in the outskirts of Catania has led to a series of experimental considerations, both general and specific, due to the peculiarity of its architecture and geographic location. The first, and the main one, is focused on the architecture of the suburbs built in the last thirty years, architecture that is often banal and socially ghettoized. Another consideration was made on the building location – the sunny south of Italy – which, together with the building type – a residential tower – allows to assess the typological difficulties and positional advantages of the solar collectors arranged on its front.

The architecture of the selected building, although designed in the 80s, is still permeated by rationalism, a language already neglected some decades ago.

The value of this experimental design lies not only in the technical and architectural retrofitting, aiming to make the building energetically more sustainable, but also has the side – but not secondary – effect of creating a better architecture and a social improvement.

Architectural issues

The compositional theme of the “concrete building” is the full/empty syncopated rhythm of its recessed balconies. All the windows of the apartments are in fact contained within these balconies, thus freeing the building from any cantilevered structure. The façade consists of a visible concrete surface. Other compositional keys are: the height of the building, repetition and overlapping.

All this elements contribute to the image of an architecture that fails to rise altogether, even if going upwards.

The design idea then is to overlap a regular grid to the rhythm of solids and voids of the façades (Fig. 4). The grid is made of evacuated tube solar collector panels dimensioned within a module that matches the height of the balconies, i.e. the story height. The rectangular geometry, narrow and high, of the module (and even more of the half-module) gives the building a slimmer and lighter look. The combination of three modules

having different texture produces a façade system whose grid does not fall into a monotonous repetition of elements always equal to themselves, but allows to find many chances for variation.

The first variation is the distance of the tube collectors. A second variation is the integration with PV: brise-soleil panels are provided with PV blades on the moving parts of the façade.

The set of PV blades forms PV verandas, some of which have been already present in the building.

The panel abacus includes: two single-module solar thermal panels with different tube distance (2a and 3a), two half-module solar thermal panels, distinguished as the former, two half-module PV panels with movable blinds, each with different blade size (also 2a and 3a).

The multiplicity of modules allows not only to vary the monotony of the regular grid but also to compose, according to the exposure of the façade, combinations of PV and solar thermal panels to achieve greater energy efficiency.

Energetic issues

A simplified model of the case study has been carried out. The whole building has been modelled as a single thermal zone. Typical mean year data for Catania has been used for external dry bulb air temperature and sun radiance, while usual formulations for incidence angles on each surface has been used, with a 0.2 terrain uniform reflection for its contribution to radiation on vertical surfaces. A 3 W/m² constant internal gain has been accounted for, including both people and electric devices, as the floor area used is the gross value, including stairways, corridors, bathrooms etc. A mean 2 W/m² K thermal transmittance has been firstly used for the opaque part of the existing building envelope and a mean 5 W/m² K value for windows. Then, these values were changed to 0.7 W/m² K and 2.5 W/m² K respectively, assuming that building envelope will be insulated.

Table 1: Building data

	Total area [m ²]	Windows [m ²]
Roof	626	0
Permanent shadow façade	827	0
North façade	2.761	197
East façade	1.269	98
South façade	1.934	197
West	1.269	98

Solar gains are evaluated with a 0.7 absorption coefficient for opaque parts (concrete) while 0.1 is used for windows along with a 0.7 transparency coefficient. Finally, natural air-change rate is set to 0.5 vol/h.

Thermal inertia effects are evaluated only for opaque envelope as a 2 hrs delay and a 0.9 decrement factor for sol-air temperature. Heating period is set, according to Italian law, from 6.00 to 8.00 and from 16.00 to 22.00 from December 1st to March 31st. Cooling period is set from 17.00 to 23.00 from May 1st to October 31st, if external air temperature exceeds 28°C at least in one hour during the day.

The active portion of the outer envelope described is set to be 490 m² on each of the almost windowless East and West façades, and 450 m² on the South façade. Mean temperature of the fluid in the solar panels is set to 100°C for heat loss factor evaluation. Collecting efficiency is derived from data for an existing device with data from Table 2 and $f(\varphi)$, $f(\theta)$ shown in Fig. 5. Obviously sun power availability does not coincide with cooling load, therefore a heat storage is necessary. Energy loss from storage is evaluated in 3% per hour, while COP of absorption chiller together with hydraulic systems is set to 0.6. The whole solar energy is presumed to be useful, reducing flow rate in order to meet collected power. This would be necessary even to let panels – set on different exposure –work together.

Table 2: solar collector coefficients

η_0	0.764
a_1	1.02
a_2	0.0053

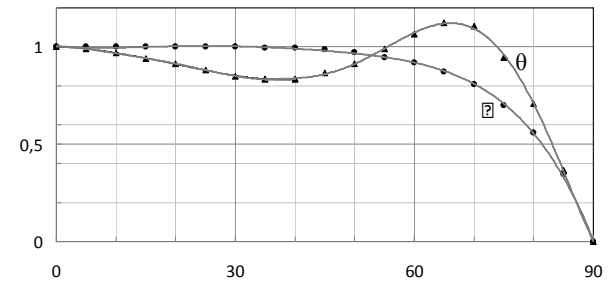


Figure 5: Longitudinal (φ) and Transversal (θ) factors

With the parameters set for the specific building, the model shows that the proposed solar system can fulfil about 26% of heating demand and 69% of cooling demand (Fig. 6), without considering any effect on the heat transfer performance of the new envelope. Evaluating the loads reduction due to the insulation of the building envelope and the shading on both windows and walls, 69% of the original heating energy demand is fulfilled by solar heating (Fig. 7) while up to 95% of cooling demand could be ensured by solar cooling.

It is a little bit unexpected getting better performances during cooling rather than heating period,

but this seems to be due to some features of the model used:

- solar panels are exposed almost evenly East, South and West, but in winter just the southern ones are really effective, thus in winter solar collecting area is a third of the summer one;
- heat storage is presumed to discharge wholly during night-time, thus no solar energy is available during morning heating period;
- during heating period, solar energy availability occurs when heating loads are lower.

As this study was done to verify the feasibility of such a solution, these aspects has not been integrated in the model, leaving this integration for further developments.

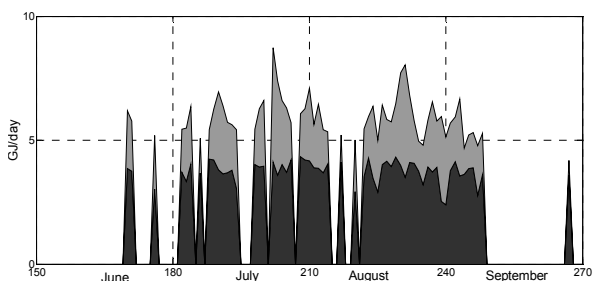


Figure 6: Cooling load (light-grey) and solar cooling (dark-grey).

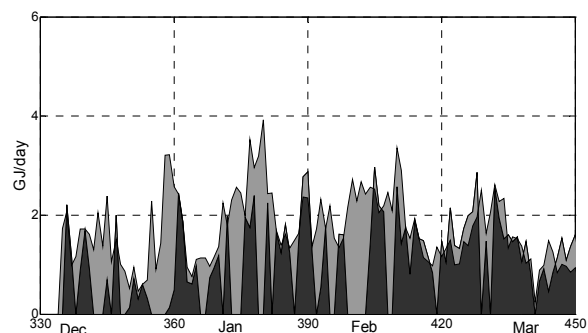


Figure 7: Heating load (light-grey) and solar heating (dark-grey).

CONCLUSIONS

Integration of solar cooling and heating with tower apartment buildings in mild Mediterranean climate is not only possible but also convenient.

In the existing building considered in this paper, evacuated tube solar collectors assembled on modular panels have been virtually applied on the South, East and West façades. The case study confirms that the proposed solar façade significantly increases energy efficiency of the building, being able to cover about 70% of heating energy demand and up to 95% of cooling demand. These values drop to about 25% and

70% respectively, without enhancing meanwhile the building envelope insulation.

Moreover, the multidisciplinary approach adopted has allowed to confirm the constructive feasibility of the proposed system and to satisfy the aesthetical instances, which are particularly relevant in the poor context of south Mediterranean suburbs.

This innovative system configures itself as an active façade, made of modular panels, which can be flexibly and effectively applied on different building types. The use of different optional accessories permits also to match better the specific user requirements.

Such modular components can be conveniently used also on new constructions as well as on tertiary buildings, which generally present a more uniform façade, well suited for the application of an external solar thermal envelope.

However some negative aspects and improvement needs should be remarked, such as the uselessness of façades shadowed by close buildings or by other obstacles, and the difficult application of the solar panels on buildings with a complex envelope or with many cantilevered structures (balconies, bow-windows, etc.).

Obviously further analyses and designs are needed to ensure an effective operation of the system. A specific design of collecting panels is needed in order to preserve efficiency on each façade, as usual panels are designed for symmetrical solar radiation. The whole system and each other component should be optimized too. Moreover, apart from specific case studies, design tools for a wide diffusion of active façades should be developed along with the technology of the components involved.

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