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EXTERNAL BUILDING FACADES BY PHOTOVOLTAIC CERAMIC TILES

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Abstract

The building cladding is considered a way to mediate between indoor and outdoor. The shape and the materials constituting these coverings have always been related with different items like: i)environment climate; ii)materials availability; iii)inhabitants needs; iv)status of the materials knowledge.
Since obviously not all problems related with the building management can be faced and/or solved through the building covering, the remaining problems should be solved by the building service plants.
So, it is necessary an integrated approach starting from a systemic vision of the building (considered as covering+service plants) integrated with the environment characterised by well defined climate conditions.
This requires a good efficiency of the covering that can be realised in different ways, both traditional and advanced ones, nevertheless all aiming at the reduction of the energy consumption needed for building management.
The use of tiles having a surface functionalised with photovoltaic cells brings in this direction and represents a possible solution to be considered on the basis of the interesting developments that can be attained.

1. Introduction

1.1. The concept of building covering

Traditionally, the building covering has been considered as the interface between the external and internal climates. This "just separating role" undergone to change towards less active role, since the building construction gradually introduced the need to heat-up internal ambient and later on to reach full air conditioning. During many years it has been expected from designers and constructors to meet all comfort requests of building users who live, work, and relax within internal ambient approximately 90 % of own time.
The mentioned "new" although "not advanced" approach to the building covering remained the same until, due to political and economic changes, serious problems related with energy resources, particularly the non-renewable ones and above all crude oil and derivatives, had been faced.
Today appears inevitable to fully revise the approach to the buildings design bearing on mind the need to satisfy variety of end users needs, but consuming at the same time, the natural non renewable resources at lowest levels as possible: one could say "make more with less"[1].
Consequently, the contemporaneous buildings should aim to the main objectives of high energy efficiency and low environmental impact. Through development of the buildings coverings, one can meet the requested comfort and low cost maintenance, two strategically important issues of the buildings construction. This approach can be applied either to the buildings construction or renovation, giving so the fundamental contribution to reach the objectives of Kyoto agreement.
In Italy, and generically speaking in the other European countries where the buildings life duration is considered as an important parameter, the renovation related markets deal with very high numbers. The buildings patrimonies seek to be adequately retrofitted in order to "consume less and consume better".
To give a better comprehension of this scenario, some data concerning the Italian and European situation are reported in Figures from 1 to 4.

	2005	2006	2007	2008	2009	2010
New buildings	1,5	0,6	-0,9	-1,9	-2,1	-1,2
Renovation	-0,5	0,0	0,3	0,8	1,2	1,0
Investments	0,5	0,3	-0,3	-0,6	-0,5	0,2
Production value	0,4	0,2	-0,3	-0,4	-0,3	0,3

Fig. 1: Table reporting situation for buildings construction in Italy between 2005 – 2010 expressed as percentage variation in comparison to the previous year at constant value (Reference: CRESME) [3]

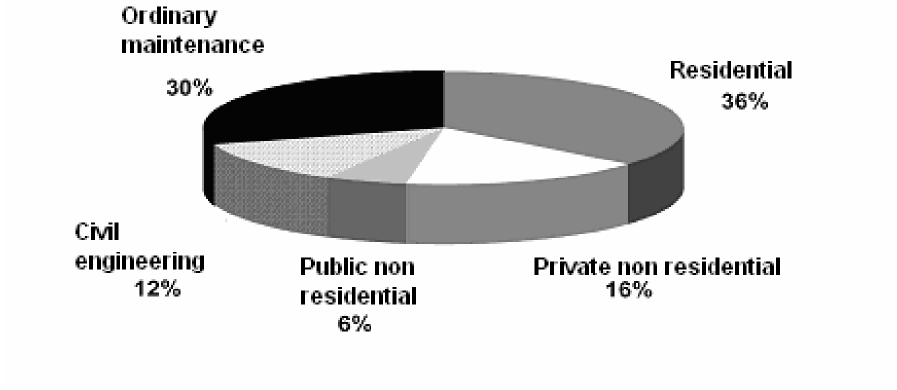

Fig.2: Building renovation figure: expressed as percentage of 2005 (Approximation and elaboration made by CRESME)

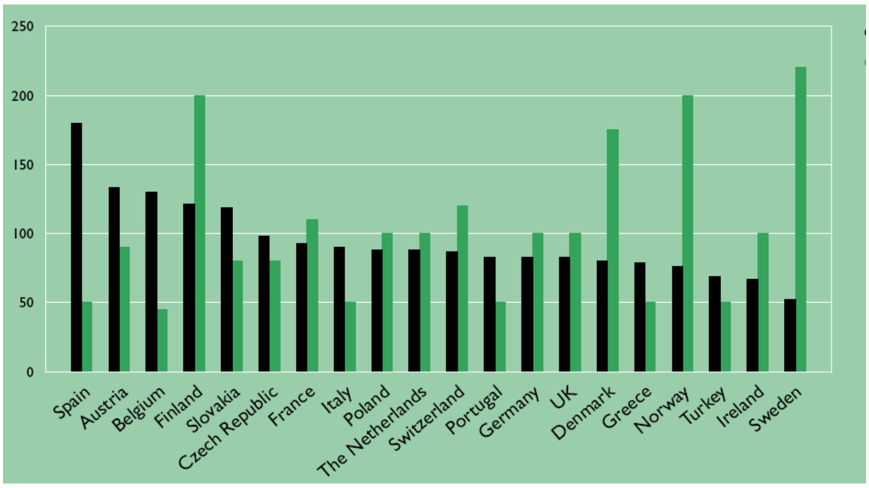

Fig.3: Building walls and energy consumption, data from some European countries: a) Thickness of thermal insulation (green); b) Energy losses through walls for heating and air conditioning (black) (*Reference: Rockwool*)

From these data it is possible to see that to make energetically oriented intervention, one should adopt suitable solutions to take into account the need to reduce heat losses, during winter season, and warming up, during summer, and to beneficiate of cost-less contributions especially through the control and use of solar irradiation. One could obtain very important advantages through interventions on the so called non-transparent closing parts, like roof and walls, which contribute up to 80 % of total heat exchanges of building. It is possible to guarantee, in the different seasons of the year, the control of heat exchange between outdoor and indoor by using coverings made of high-insulating materials, to lower heat fluxes, or by exploiting thermal inertia, through phase shifting of the thermal wave or delay of heat transfer. By proper designing of the building covering, through adequate type selection and distribution of functional layers, it is possible to reduce significantly the heat dispersion, approximately 30 %.
So, for energetically efficient renovation one should consider the different societal request. In Figure 4 the levels of renovation requests are reported and the particular sector on which we concentrated our attention is evidenced.

Fig.4:Levels of renovation requests (Reference: CRESME)

Among the building covering solutions, the so called "building coat"[4] and the ventilated wall should be mentioned.
Based on the use of extraordinary insulation components, the building coat, applied outdoor the building so maximising its effectiveness, contributes to limit the heat transfer bridges. Beside this, the building volume is not significantly changed and the building coat can be easily applied within modern constructions, with exception of those of great value.
The ventilated facade offers in practice a great number of advantages like:

a. ventilation of internal surfaces and, consequent elimination of moisture and condensed water from the walls;
b. reduction of the wind pressure on the internal layers and better control of infiltrations;
c. high efficiency in reduction of the heat transfer during summer,
d. reduction of maintenance costs.

One should notice that the realisation of ventilated facade requests higher costs than the "building coat".

1.2 The concept of ventilated facade built of PV materials

In the last years there was a growing tendency to integrate the PV devices into the building, coupling the use of a renewable source to produce electricity to aesthetic effects.
In the Building Integrated Photovoltaic installations (BIPV), the solar modules are assembled becoming elements for roofs and facades, combining various functions, namely electricity generation, thermal insulation, shading, and even fulfil the aspects of architectural design.
The first installation of building-integrated photovoltaics (BIPV) was realised in 1991 in Aachen, Germany [5]. Today, photovoltaic modules for building integration are produced as a standard building product. Since then building integration is one of the fastest growing market segments in photovoltaics[6].
To produce electricity by photovoltaic effect various technologies can be used, so many ways to integrate the PV devices to the architectural elements may be realised.
The integration of BIPV materials is preferably possible on roof or on façades. Focusing attention on the last one, the PV ventilated facades. are double façade constructions which combine the advantage of cooling the PV modules using ambient air with the potential to use the so produced hot air for other services of heating and cooling of the building. The first European building using such a concept is the public library at Matarò, near Barcelona (Lloret et al.1997 and 1998). [7].
Concerning the PV technologies, the multi and mono-crystalline Silicon modules may be used for BIPV.[8,9]. Besides them, thin film technology based on amorphous silicon for BIPV is supported by a number of attractive features that apply to the technology in general, and to BIPV in particular.[10]

1.2 The new concept of PV ventilated facade

The external layer materials used to build ventilated façades belong to very different types. The ceramic ones offer particularly large number of products being adequate for variety of needs of the both designers and end users. These materials are offered in different sizes and colours, high frost resistance and long life span. Thanks to the studies of

CECERBENCH, laboratory within Italian Ceramic Centre and specialised to study and develop ceramics having a functional surface, one can notice that it is possible to create new characteristic of ceramic external materials: production of electricity through photovoltaic effects. To achieve this objective were studied different materials able to substitute the glaze layer and to deliver photovoltaic electricity and were developed the procedure to create, preferably during the ceramic tiles production cycle, the coating in the form of solar cells.
Practically, this type of ceramic tile opens the new field of building industry activities introducing the possibility to make Building Integrated Photo Voltaics in ventilated facades and without being counterbalanced to covering but synergetic with them adding the advantages within building architecture and energy consumption.
One can easily presume that the ventilated facade built by PV building ceramic materials and under favourable geographic orientation accentuate the need to study and develop the solutions of high energy efficiency for the large size and relatively new constructions without particular historical interest, like the buildings of European cities suburbs built during the second half of the 20^{th} century.

2. Experimental

During the recent period of the CECERBENCH Laboratory activities, the prototype of photovoltaic ceramic tile has been developed. The 10 x 10 cm prototype was produced by a thin film technique that enabled the creation of a photovoltaic surface layer replacing the glazing one.
As a structural support the porcelain stoneware tile was used on which the conductive and photosensitive layers were deposited. The unit photovoltaic cells (4 cells, size 7x1cm) are connected in series to create a device similar to a PV module, and the photocurrent is afterwards directed toward the tile incorporated plug-sockets enabling an easy interconnecting with the neighbouring tiles.
By using nine of these prototypal tiles, a device like a PV module has been assembled: the tiles have been electrically connected among them and inserted into a steel frame, locked within an aluminium structure.
It is well known that the modules of c-Si cells are composed of cells having similar or even equal electrical characteristics to guarantee the best performance level. Unfortunately, our prototypal cells were not in this situation, so we decided to use a series/parallel configuration enabling the cells to work as much as possible near their maximum power point. The tiles have been connected in such a way to form three raws (each composed by three tiles) which were then connected in parallel among them.
The so obtained PV module has been exposed to sunlight by fixing it at a wall exposed to south and no shadowed. The fixing arrangement intended to simulate a ventilated facade and a distance of approximately 10 cm between the wall and the module was left.
The electrical and thermal parameters have been monitored during two weeks (from 16/07/2007 until 27/07/2007), eight hours per day, performing the measurements roughly each hour.
The current intensity and voltage have been recorded related to a 250 Ohm resistive charge, connected to the PV module.
The measurements carried out were: cell temperature, temperature of tile surface (both “as received” and coated by PV layers), back temperature of the tile, wall temperature (by a pyrometer mod. PhotoTemp MX, Raytek, USA equipped with a type K thermocouple), module generated current intensity and voltage (by two digital multimeters mod. UT60 series, UNI-T, China). Finally, the illumination of the plane on which the module was mounted (by a luxmeter mod. ISO-TECH ILM350,Germany) and the environment temperature and humidity were recorded, also.

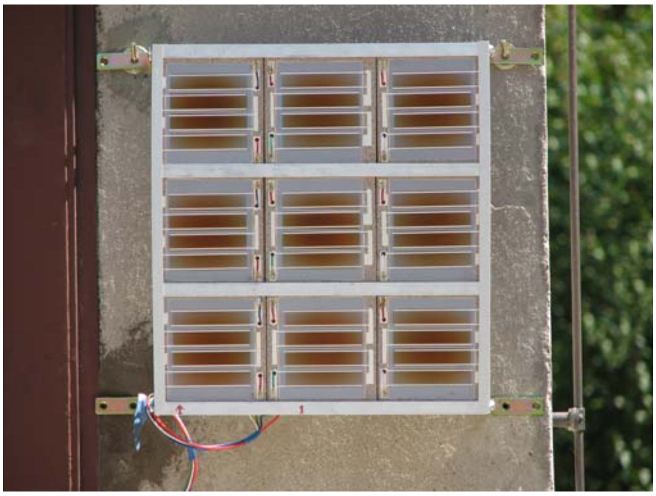	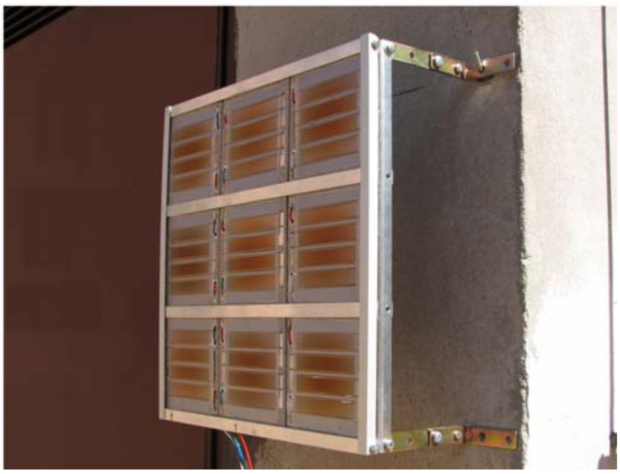
Fig.5 : Front view of the PV ceramic tiles module	Fig.6: Side view of the PV ceramic tiles module installed to simulate ventilated wall

3. Results and discussions

3.1 Monitoring of PV module

Preliminary measurements of surfaces temperature

To be better acquainted with illumination levels and related temperature distribution over PV module, the temperature measurements of different surfaces were carried out and typical obtained results are given in Figure 7.

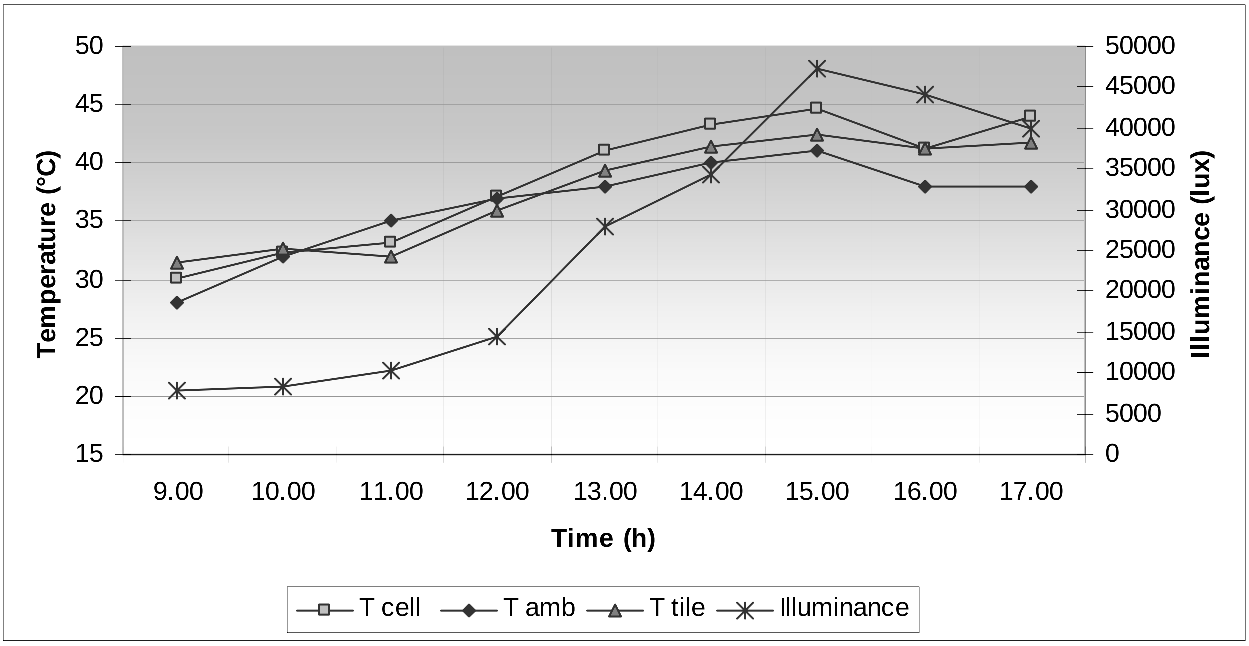

Fig.7: Interdependence of PV module surface temperatures and illumination levels in time

One can notice the expected interrelationship between solar illumination intensity and all the measured temperatures like the ambient one, that of the “as received” ceramic tile surface and that of the tile surface covered by PV cells.
If more detailed analysis is carried out through the comparison of PV cells temperature, ambient temperature and solar illumination level, it is possible to see that these parameters are, in first approximation, correlated linearly; here are presented the measurements performed during typical “hot sunny day” and “hot cloudy day”(see Figure 8).
It is important to carefully evaluate these results since the received solar energy increases all temperature levels but, due to the accentuated influence on PV cells temperature, could alter the PV cells efficiency. One can forecast a significant influence of module temperature on PV cells efficiency, and consequently on whole PV ventilated facade, so the detailed temperature measurements of various tile surfaces were repeatedly performed.
Since the PV prototype module were not built into the full size ventilated façade, the obtained data did not offer necessary reliability to reach sound conclusions. Nevertheless, the up to now performed measurements show that the tile maintain a quite homogeneous thermal behaviour: the average difference measured between tile surface uncovered or covered by a PV cell is approximately 0.5 °C, whereas the maximum difference recorded is + 3.7 °C (“hot sunny day”, 15:00 h, T_{amb}= 39 °C). Qualitatively speaking this rather limited temperatures difference is consistent with literature data reporting that the a-Si thin cells are less sensitive to over-heating than c-Si solar cells [12], and this holds also in this case where the PV cells are on a ceramic support instead of glass support.

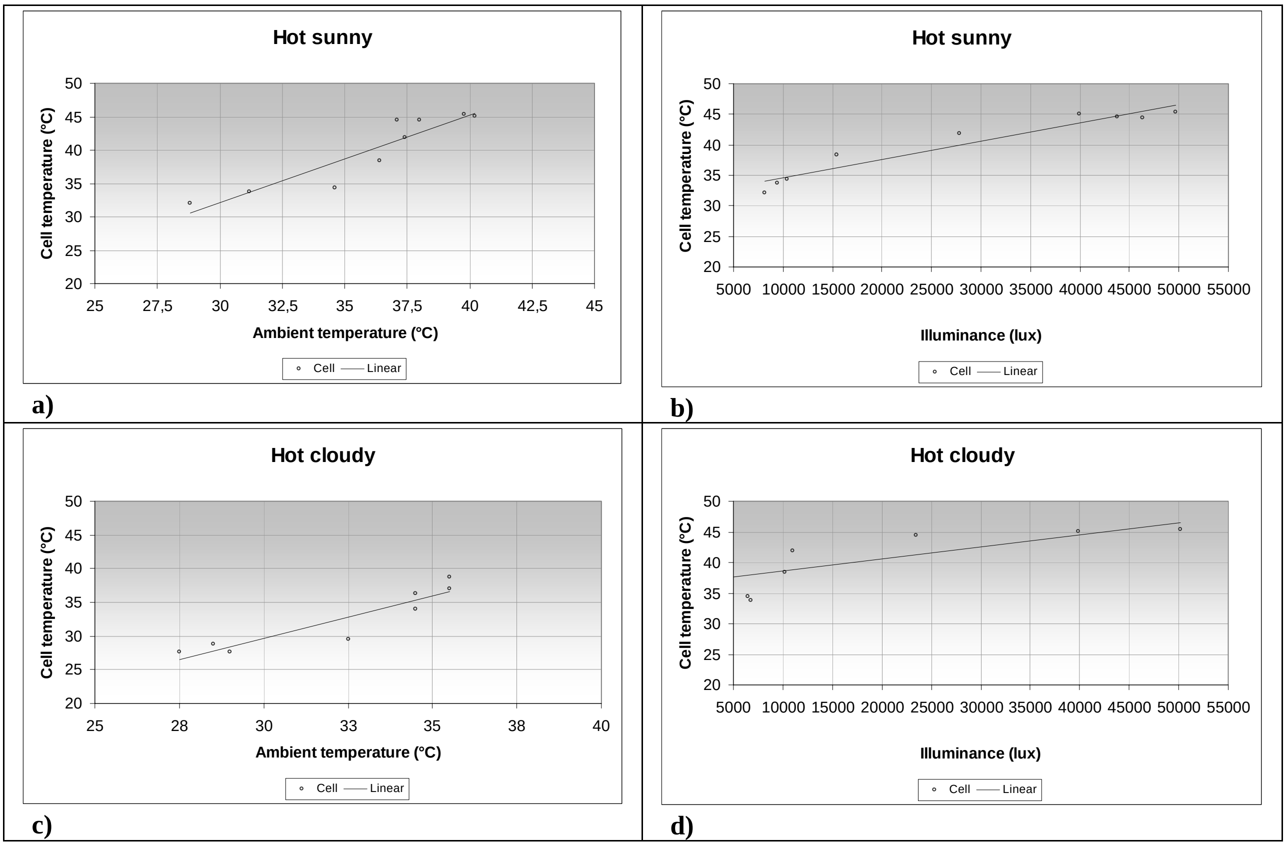

Fig. 8: relationships of PV cell temperature: a) and c) with ambient temperature respectively in a hot sunny day and in a hot cloudy day; b) and d) with solar illumination respectively in a hot sunny day and in a hot cloudy day

- ***Preliminary electrical measurements***

To get even initial information on electrical behavior of prototypal PV tile, the series of electrical measurements were done along last summer, although the sample mounting and measurements did not fulfilled the intended experimental orthodoxy. Nevertheless, several qualitative comments and explanations have been formulated wishing that could be applied during ongoing and future more sophisticated measurements.

Within this phase of the present work and without rigid ordering of specific importance several statements can be mentioned as given in the following presentation parts.

a. The electrical parameters of the PV prototype demonstrated a deterioration during the very initial period of measurements. As the measurements proceed the electrical parameters tended to stabilize within the limits of testing conditions and no PV tile inactivity was revealed at all. This can be related with intrinsic phenomenon of amorphous silicon cell efficiency losses under sunlight exposure, Staebler Wronsky effect [13].
b. Beside the spectral irradiance distribution, the temperature level has a crucial influence on the a-Si PV module performance. The information on PV device surrounding and environmental conditions, like ambient temperature, are decisive for its evaluation [14]. One can expect that PV tile assembled into real size ventilated façade, and consequently kept at fairly stabilized conditions, will function much advantageously.
c. The previous issue obtains much deeper importance if the curves shown by Figure 9 are examined: one can notice that the curve of the delivered electric power quickly increases when the cell temperature exceeds, as in the present case, 35 °C. Although here should be taken into consideration the advantageous insolation angle, one can expect that, through an appropriate design of ventilated façade, the thermal parameters permitting a PV tile to be at conditions close to the optimal temperature can be achieved. Moreover, since in literature one can find that the curve of the delivered electric power of a-Si modules begins to increase even at lower temperatures, from our results one can say that the delivered electric power increase very probably is due to the modification of the illumination conditions: this is confirmed by the observation that, in a “hot sunny day”, this phenomenon is always observed after 11 a.m.

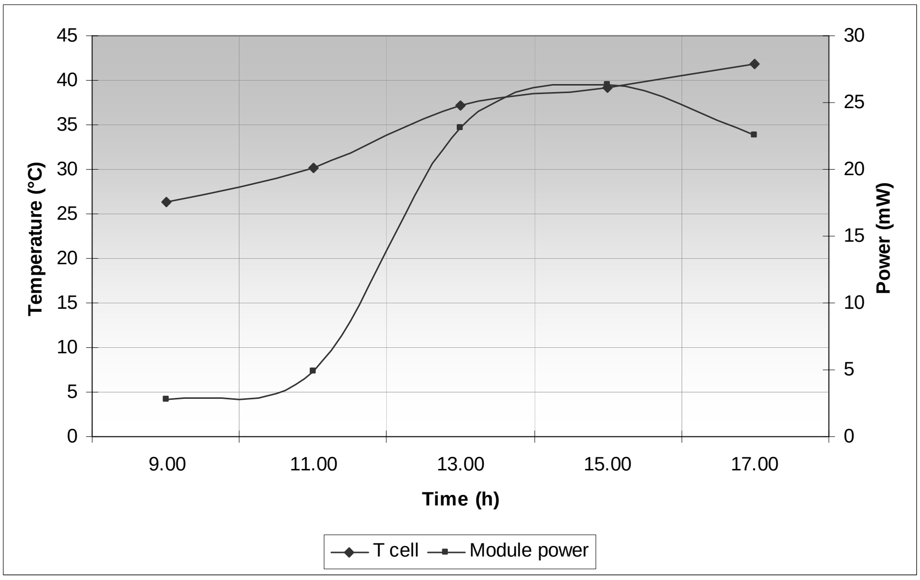

Fig. 9: Current delivery in function of PV tile temperature ("hot sunny day")

d. Comparing the curves of PV module power and illuminance, vs. time, one can notice that both curves are characterized by maximums. Comparing them a shift between them is evident (see Figure 10). Although the effects of spectral variation has been already met by the c-Si devices, the here obtained response is more pronounced, as a consequence of intrinsic behavior of a-Si [15]. Also, the influence of other parameters like temperature, insolation angle and so on should be here taken into consideration.

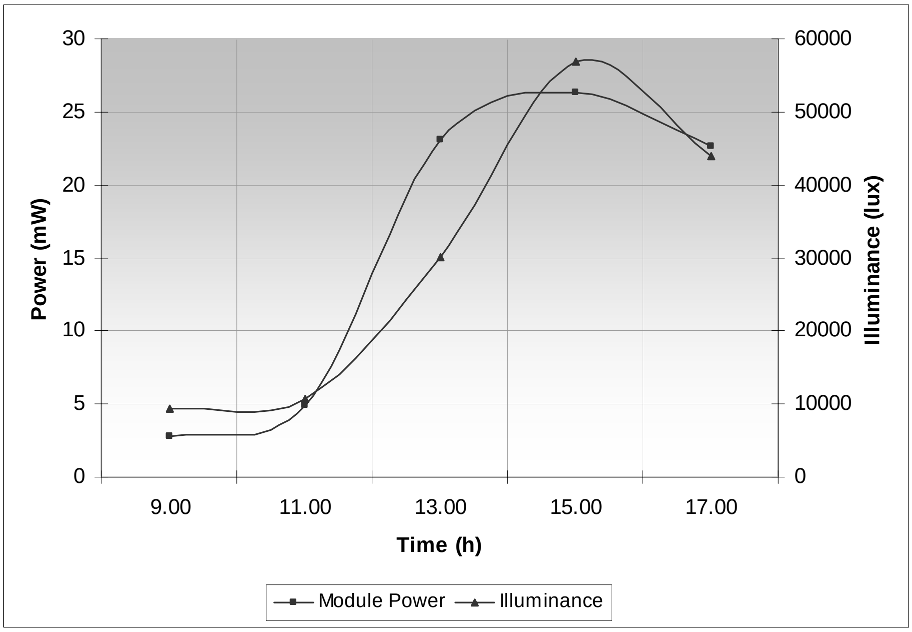

Fig. 10: Current delivery in function of PV tile luminance ("hot sunny day")

e. Additionally, the broadly known effect of vertical inclination on PV device efficiency was followed in this series of experiments. It was demonstrated that current delivery of PV a-Si tile prototype is slightly more vulnerable than traditional c-Si devices. When assembled at angle of 90 ° it looses approximately 40 % of power able to produce at most favorite inclination of 45° (c-Si device remains at 65 % if compared at efficiency at angle of 30 %). Enhancing the devices efficiency, one can expect that the losses due to vertical placement decrease below those of c-Si, since the a-Si has a higher sensibility to diffuse solar radiation
f. This experimental work was done on prototypal PV ceramic tile and the measurements were not executed within strictly defined conditions, so semiquantitative and not definitive data were obtained. However, one can presume that large size of building facades, together with the fact that, power installed being equal, the thin films of a-Si have an energy annual yield better than that of c-Si [16], will enable to exploit the advantages of PV ceramic tiles use.

3.2 On -going work on the building energy balance and introduction of façade PV tiles

The experimental work and related calculations of practical interest will be attained through the present study performing following activities:

- Energy balance of typical building constructed during the years after 1970,
- Analysis of energy balance of previously mentioned building with tailor designed and assembled ventilated façade built in PV ceramic tiles,
- The previous study lines are under realization through specific issues dealing with:
  - --- Consumption of primary energy
  - --- Consumption of electricity
  - --- Carbon dioxide emission, case study.

4. Conclusions

An “as received” porcelain ceramic tile of Italian provenience, after its characterization, has been used as support for photovoltaic device. Instead of an eventual glaze layer, the thin PV cells and related electrical connections were deposited by ceramic traditional and advanced techniques.
Various preliminary measurements were performed with PV prototypal ceramic tiles assembled within “ventilated façade like” structure and in particular: the temperature measurements of different surfaces, illumination levels and voltage-current measurements were carried out within a month long summer period.
An evident deterioration of PV tiles efficiency was noticed during the very initial measurement days, in full accordance of theoretical findings related with amorphous silicon cells, but after relatively short time their characteristics became fairly unchanged. The measurements of “as received” tile surfaces and those covered by PV cells revealed limited differences, not over 0.5 °C, that can be ascribed to the nature of the support, i.e. a ceramic one and not a glass as usually employed, and to the lack of all thermodynamic parameters of real size ventilated façade. One can notice that tile temperature, logically bound with illumination level, influences the PV tile efficiency and, in present PV prototypal tile, the delivered electric power quickly increases when the cell temperature exceeds 35 °C
Since the present work dealt with prototypal PV ceramic tile and the measurements were not executed within strictly defined conditions semiquantitative and not definitive data were obtained. However, useful information on this topic were achieved enabling to plan future activities to develop the approach for building of ventilated façades made of PV ceramic tiles.

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