ABSTRACT

There are currently various universities and institutions developing research into the integration of photovoltaic systems in buildings, internationally known by its abbreviation in English, BIPV (Building Integrated Photovoltaics). Within this technology, one aspect stands out, considered innovative, the integration of hybrid models or cogeneration. This technology, which we shall call BIPVT (Building Integrated Photovoltaics Thermal), integrates a hybrid module in the building, which not only generates electricity, but also uses residual energy that is lost in the form of heat or light, to increase the energy efficiency of the building, in applications with low temperature. However, the methods to test the efficiency of this investigation and evaluate its cost benefit, are not clear, and constitute a challenge for the investigation within an architectural framework.

1. Introduction

It was examined the different methods of research used to evaluate buildings with integrated photovoltaic cogeneration systems (BIPVT), it’s advantages and disadvantages. We’ll focus on examining published articles related to research carried out in universities and research centers. Due to its importance in the field, reports published by programs from the International Energy Agency of the European Community, such as PV Hybrid PAS Project and Task 35 PV/Thermal Solar Systems.

Ten articles and studies between 1996 and 2008 were chosen. Parameters for the evaluation of the studies were chosen, based on subjects observed individually in different previous studies. In each document a brief description of the methodology used and results obtained is given.

2. Photovoltaic cogeneration technology

Currently, efficiency in the photovoltaic conversion in modules varies from 6% to 26%, depending on the technology used. This means that for each 1,000W/m² of incident solar energy in a photovoltaic module, between 850-940W/m² are lost in sensitive heat or reflected into space in the form of light. It’s a known phenomena that the efficiency of the crystalline silicon cells diminishes with respect to its nominal value of around 0.4% to each centigrade above 25°C (Wenham et al.,1998). Other photovoltaic technology performs in a different way and are less affected by higher
temperature, such as amorphous silicon. In photovoltaic systems integrated in buildings, the modules usually work in lower temperatures, and what has been a limitation, can also be viewed as an opportunity. These factors have been the motor for the idea of recovering the heat from the back face of the modules and using it in the generation of thermal energy.

These systems are generating a growing interest from research centers and from the industry, and now a few patents and products can tentatively be found on the market. Up to now, photovoltaic cogeneration systems have been applied in a varied range of buildings, from all sectors, although not widely spread.

One of the most important reasons for research in photovoltaic cogeneration systems is that they can increase the economic viability of photovoltaic systems integrated in the building. Equally, taking out the heat from modules, by radiation, convection or conduction, brings additional benefits of reducing the thermal cycles and strain on the materials they are made of.

In a photovoltaic cogeneration system integrated in a building, you can expect the heat recovered from low or medium temperatures to be transferred through heat recuperation systems used mainly for:

- Production of DHW,
- Heating using with a heat pump,
- Heat storage with a system of phase changing materials,
- The preheating of air in HVAC systems.

2.1. Types of PVT collectors

- Liquid PVT Collector
  The photovoltaic cells work as the heat absorber for the thermal collector (Fig.1), like a conventional flat plate liquid collector. This way, the heat that would be lost or warm the module, is transmitted directly to the working fluid, which will be used in other applications. These systems can represent a significant saving in the costs and physical space of the installation.

![Fig.1 “scheme of a PVT Liquid Collector” (AIE, PVPS Task 7)](image)

- Air PVT Collector
  Similar to a conventional underflow air collector with a PV laminate working as a cover for the air channel (Fig. 2).
- Ventilated PV with heat recovery
It is the type of PVT most used in building integration, in conventional PV façades or PV roofs, by recovering the hot air off the back rear of the modules. It is done using the natural convection of the warm air, or with ventilators, by chimney effect. Those PVT systems more than producing electricity, helps to extract the warm air of the interior of the building in summer, preheats the air of heating in winter, and allow natural lighting.

- PVT Concentrator
It is a result of a PV concentration system, which is cooled by active means (Fig. 3). Those systems may be rather bulky, and due to technical characteristics - concentration technology requires tracking and produces different optical effects and reflections, makes building integration a difficulty issue.

3. Research in photovoltaic cogeneration
Research in the use of residual energy in photovoltaic systems goes back more than 30 years, to the 1970’s. Most research has been academic or governmental, almost always with official financing. Specific projects have been financed by the European Union such as the Joule and Thermie Program, PV in the US and NEDO in Japan.

The main areas studied so far have been ventilation systems to use the hot air in the back face of the modules and the transmission of light through the modules in different levels for interior lighting, the simulation of thermodynamic models for PVT modules, the use of thin silicon layers in PVT modules and the evaluation of the module efficiency.

Regarding PV cogeneration through the recuperation of air from the back face of the modules, research in Japan and the US have led to products that are currently in commercialization, such as OM Solar and Solarwall. In the European Union, although there are buildings constructed with the technique, such as the Biblioteca Mataró in Barcelona, and even in research projects, there are few products available. One of
the conclusions of the PASSYS research program, a project related to passive architecture, now finished, was that a fundamental problem for the use of hybrid systems is the quantity of heat that can be used, which would vary greatly according to the type of building and its location.

In each of the ten documents studied, numbered form 1 to 10, different parameters observed in separate research studies have been highlighted:

- Interior comfort: referring to the interference of the PVT systems in the interior conditions of temperature, humidity, acoustic and lighting comfort.
- Cost benefit: referring to the confrontation between costs and the perceived benefits of the implementation of the PVT system.
- Environmental benefits: emission reduction EPBT, LCA emissions and water savings
- Climate analysis: referring to the evaluation of the influence of the climate and local geography on the PVT system.
- Empirical experimentation: applied to experiments carried out empirically, using test cells, in exterior conditions or not.
- Theoretical experimentation: applied to experiments carried out with computer simulations, without the help of experimental cells.
- Commercialization aspects: referring to component manufacturing costs, marketing and commercialization of the modules
- Aspects of architectonic integration: referring to visual aspects, adaptability to colors and shapes, dimensional compatibility and adaptation to the building.
- Interface with the construction industry: referring to installation conditions, maintenance, durability, regulation codes, etc.
- Interface with the solar industry: referring to collaboration in the development of products in cooperation with the PVT module industry.
- Overall performance – electrical and thermal: referring to the efficiency of the conversion of solar radiation to electrical and thermal.

4. Research and documents studied


Published by the PV-Hybrid-Pas Joule Project, this paper is part of the development of a standard scheme for the performance evaluation of hybrid PV building components, whose objective is to approximate the technology developers and the building industry. It states that the performance evaluation of a hybrid component is a very complex task.

The building industry needs to know not only about the electric and thermal performance of the component, but also how it works as a construction component – Is it possible to compare it to another similar product? Is it possible to predict how it works on different sites and know the impact on the energy consumption in winter and in the summer time? Are there any conflicts related to building codes? What about maintenance and durability?

In order to integrate a PVT component in a building a comprehensive assessment procedure is proposed that should include: electrical performance, thermal processes
at component level, thermal performances in winter and summer time, ventilation performances, visual performances and maintenance and durability.

This work, coordinated by the European Economic Interest Grouping PASLINK and JRC Institute for Advanced Materials, was organized though four tasks, to be done in three different levels: on component level, at room level and at the level of the real building, through scale and replication.

Test activities were made on several outdoors centers of PASLINK throughout Europe, with the major aim of obtaining an efficient and reliable standard test procedure for PVT components. Also simulation activities were carried out to predict performance in real buildings, using “scaling and replication” concept, in order to define adequate applications for the PVT components.

Preliminary results indicate that at component level, it is possible to achieve higher thermal efficiency rather than electric. Another important preliminary conclusion states that at building level, a PVT system may not be adequate for many building types and climatic conditions.


Study of a 200m² single house, located at Iwaki, Japan, Latitude 37°N. A Southern oriented c-Si multi PVT array of 4,8m² (PV and Air) provide 4,2kWp of electricity and hot air for a heat pump and a PCM heat storage system.

It states that this house has estimated cooling and heating loads one third of a house model with the insulation standard for the locality. It is due to its construction characteristics, such as high thermal insulation, shading and natural ventilation, thermal storage etc. PV/T array provides electric power almost entirely for lighting and appliances, and helps to meet part of the heating load by means of the heat pump and PCM system.


This paper reviews the state-of-the-art in PVT at that moment, from a building perspective, through research projects and built examples. It also presents an evaluation method for PVT components considering the energy and economic performance of the PVT systems, and possible niche markets for different applications.

It concludes from the whole panorama that is the basis for the PVT systems commercial viability has been done, but indicates that there is still a great amount of work to do. Examples of areas for further investigation should be:

- Considerable real work testing,
- Long term testing of the stagnation temperature effects of heat on a-Si and c-Si cells integrated on absorber plates
- Standardized methods for efficiency ratings
- Economic analyses, looking at the whole energy flows in the building.
- Market size and type studies, for different climatic conditions.
The evaluation method proposed, to Dutch conditions, defined ten criteria (Fig. 4) to validate eight different PVT systems, just for thermal and PV combinations. The main objective of his method is to show the technological and market values of the predefined systems.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unit</th>
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<td>Time to market</td>
<td>year</td>
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<td>Market potential</td>
<td>m²/yr</td>
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<td>Investment</td>
<td>Euro/m²</td>
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<td>Building integration</td>
<td>m²</td>
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<td>Thermal performance</td>
<td>GJ/year·m²</td>
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<td>Electrical performance</td>
<td>kWh/year·m²</td>
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<td>Energy consumption</td>
<td>kWh/year·m²</td>
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<td>Sustainable building</td>
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<td>Life time</td>
<td>year</td>
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<td>Effect on energy performance</td>
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Fig. 4 Criteria for the proposed method

The most important conclusions are that the PVT systems are especially adequate for low temperature applications, although the clear difficulty of matching in a building the supply and demand of electrical and thermal energy. It also states that PV cogeneration systems may play an important role in PV installations in buildings, mostly for daylight applications.


This document relates the experience and lessons learned from this research and product development program, with specific focus on PV and PVT technologies for residential and commercial buildings sector.

As a result of the program, five commercially available products were developed:
- PowerView Viewglass Curtain Wall and PV Sunshade – an insulated view glass functioning as a window and electrical producer, and a sun shade.
- HeatGuard^T and PowerTherm^T – an insulation PV roof tile and a flexible PVT roof panel.
- Phototherm module – a triple junction a-Si PVT module
- Flexible PV membrane – for roof applications.
- Electrochromic windows – an EC window with a PV powered variable control.

The products must meet requirements of safety and electrical performance, as well as of design, manufacturing and marketing, to have reliability, aesthetic design and low-cost installation.


This technical note relates an investigation where thermographic images were used to evaluate a PVT integrated roof, from building scale and component scale perspectives. Thermographic infrared technology converts IR radiation into visible
light, and transfer it to an electronic form of representation. An image produced this way may be used to describe and calculate the amount of energy being radiated by the object, and rendered using a scale of colors. It is a non-destructive and non-evasive method used on investigations that allows qualitative and quantitative analysis, to find surface temperatures and emissivities.

The PVT array was designed and experimentally tested in Sydney, Australia, formed by 20 BIPV roof modules integrated in an iron metallic roofing sheets. BP c-Si cells were used to produce electricity and a cooling/heating duct was installed on the back side of the array, insulated on the back and the sides. A fan was used to create a flow in the duct and a heat recovery unit used to capture it.

It was found that the interior temperature of the BIPV array was 11°C higher than the surround roofing on a clear day, a clear impact for the building envelope and the PV cell performance. Results were useful in calibrating the numerical models created to predict the system’s temperatures and also emissivities and temperature gradients.


It deals with the development of a double skinned glass facade with a photovoltaic system, which was effectively implemented in the renovation of a university building in Trondheim, Norway (Fig. 5). 192m2 of photovoltaic modules were installed with high efficiency cells, cSi mono BP type Saturn, facing southeast. The best use of natural light has been studied to lower lighting costs. The ventilation of the chamber, 80cm in width, can be mechanically controlled with ventilators in the lower and upper entrances, equipped with temperature sensors.

![Fig. 5 Building facade, before and after the completion.](image)

The building was monitored for a full year after construction. The data obtained was the production of electricity, air and surface temperatures, air speed in the chamber and wind direction. Furthermore, satisfaction surveys were carried out with the users of the building as well as lighting levels.

It was concluded that there was a heat saving of 7-8%, calculated with simulation programs. The outer façade was susceptible to infiltrations during periods of strong winds, which impeded the calculation of overall savings, although it’s considered that during winter there was a positive contribution from the chamber to the interior comfort. Graphs demonstrate that the difference in temperature between the external air and the air in the chamber reaches up to 10% in winter, however, in summer the ventilation conditions cause overheating and reversion of air direction, which penetrates interior spaces.
This paper describes a methodology used for calculating the thermal impact of an integrated PVT façade (PV and air) on building performance. It was applied successfully to the Spanish public library of Mataró, the first European building to use this concept. Then it was derived and calculated for the same façade transported to Stuttgart.

The methodology to determine the energy transfer to the façade ventilation air is based on the $U$ and $g$ values. Due to the energy gains to the air, the conventional $U$ and $g$ values are divided into two components, corresponding to transmission and ventilation. It was also considered that these parameters need to be time variable. The energy balance equations are established at three nodes: at the PV absorber, at the ventilation fluid and at the inside surface of the rear glazing.

It concludes that the methodology can be used to characterize properly the thermal performance of a partially transparent ventilated façade, and might be a tool for engineers and architects designing a building with this kind of PVT integrated.

Study of a theoretical facade with PV integrated, carried out by The Martin Center for Architectural and Urban Studies, University of Cambridge and School of Architecture and Design, University of Brighton.

It works as a resource for preheating air in winter and as a ventilation system of the back face of the module.

It proposes a new indicator to evaluate the efficiency of the façade with PV integrated which aims to balance usable natural light and electricity production on one hand with electricity consumption for heating and refrigeration on the other.

It Works with variables such as the proportion of the Windows, the width of the building, thickness of insulation, thermal gain from artificial light and external shading of the facades, among others.

It concludes that the operation of the modules is sensitive to temperature increase, the production of electricity due to ventilation of the back face of the modules is low (without numerical data), and the position of air vents should be thought out to favor the natural ventilation with negative pressure.

The IEA SHC Task 35 "PV/Thermal Solar Systems" is a three year research work task initiated January 1, 2005, as part of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Program. Objectives are to catalyze the development
and market introduction of high quality and commercial competitive PVT solar systems and to increase general understanding and contribute to internationally accepted standards on performance, testing, monitoring and commercial characteristics of PVT systems in the building sector.

As for the short term, it seems that multifamily buildings may be an important market. For medium and long term, it seems to be DHW and space heating, using a combination of heat pump with PVT. Just for long term that will be a market for industry, agriculture, solar cooling.

It is still a challenge to agree on performance and reliability standards for PVT, although to have PVT on the market it also seems that financing and subsidies are necessary, to improve thermal efficiency and long term reliability and reduce the costs of the modules and installation. It concludes, stating that the most important factors are profitability and building integration.


In this Project, new types of facades and roofs are going to be developed to achieve an external finish of photovoltaic layers (opaque or semitransparent), a width variable air channel and interior finish, that can be opaque or transparent. New methods of examining hybrid systems and the energy performance of PVT integrated buildings will be examined.

This document looks at the work of the project that aims to establish the methodology and calculation procedures necessary to give support to the project developers, at the initial design stage, on the convenience of installing a FDVFC, from an energetic and economic viewpoint. A diagram has been developed to be used in a eventual decision support software, which incorporates the calculation methods necessary to obtain the energetic and economic output variables.
5. Comparison Chart

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<td>Climate analysis</td>
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<td>Empirical (indoor/outdoor)</td>
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<td>Aspects of architectonic integration</td>
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<td>Interface with the solar industry</td>
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<td>Overall performance – electrical &amp; thermal</td>
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Chart 1. Document comparison matrix

**Observed evaluation:**
- No reference on the subject -
- Almost no reference on the subject +
- Analysis on the subject ++
- In-depth analysis on the subject +++

6. Conclusion

On verifying the data in the comparison chart on the documents in discussion, there are aspects that clearly dominate all the research studies and others that are hardly mentioned.

As expected, interior comfort, climatic conditions, simulation programs and overall performance are the aspects present in all studies, almost always in-depth. However, subjects that you would expect to be treated with equal in-depth analysis, such as interface with the construction industry, aspects of architectonic integration, commercialization and cost/profit ratios are hardly touched at all. The environmental benefits of technology are not discussed.
We have seen that various methodologies have been developed, using different evaluation criteria, modeling software, which varied mainly according to the type of fluid and the use of recuperated heat. It can be observed that there is still no consensus in relation to the methodology that should be used to evaluate the integration of PVT systems in buildings.

The challenge of modifying the pattern of huge electricity consumption in buildings requires a rigorous analysis of the possibilities that technology offers, as well as its limitations. Therefore, the continuation of research into the optimization of PVT components is vital.

Parallel to this so that integrated photovoltaic cogeneration in buildings can contribute to energy efficiency, it’s important to clarify the impact of this technology on different types of buildings and climatic conditions, which provide architects with data and parameters, revealing its true benefits and advantages.

7. References