Comparison of building construction systems to implement photovoltaic - PCM facades

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1. List and description of the different constructive solutions used in facades in Ireland and Spain.

The construction of facade for housing in Ireland consists basically in masonry walls with cavity air and timber frame with outer masonry wall. The requirements about facade in Ireland are the high degree of thermal isolation due to the climate characteristics of the region and the protection against moisture. Irish regulations (BRE) about energy saving in building show clearly the importance of the thermal insulation in the façade, with a required U-value of 0.27 W/m^2K for dwellings in all the country and thickness of insulating materials about 15 cm. It can be concluded that the type of construction systems for housing are homogeneous enough in all the region due to the homogeneity in climate and therefore the regulations for energy saving are applied with little difference in all the region.

The temperatures along the year are always below 20ºC, not often a cooling system for façade is required. Since cooling is not a main requirement, ventilated façade are not often used. Ventilated façade is rarely found in Irish construction of dwelling and therefore there is a lack on information about this systems, both in regulations and standardized systems.

In the Spanish context, there are many different typologies for façade, due to the difference in climate in the Peninsula and therefore the different requirements for each region. These typologies can differ from one layer wall, with brick, stone or concrete, to multilayer wall which combine these materials with insulating materials and external finishing layers of ceramic, mortar or stone. The Spanish regulations about thermal insulation requirement are different for every region, establishing 12 different climatic areas for determining the U-value of the façade. The most of climates in Spain require higher U-values than in Ireland, therefore the insulating materials are used in minor thickness (normal values would be 4-6 cm). Since the cooling it is an important requirement mainly in summer period but in some regions even in winter period, ventilated façade used is much more used than in Ireland. Different typologies of ventilated façade are found and the regulations are considering them as feasible solutions.

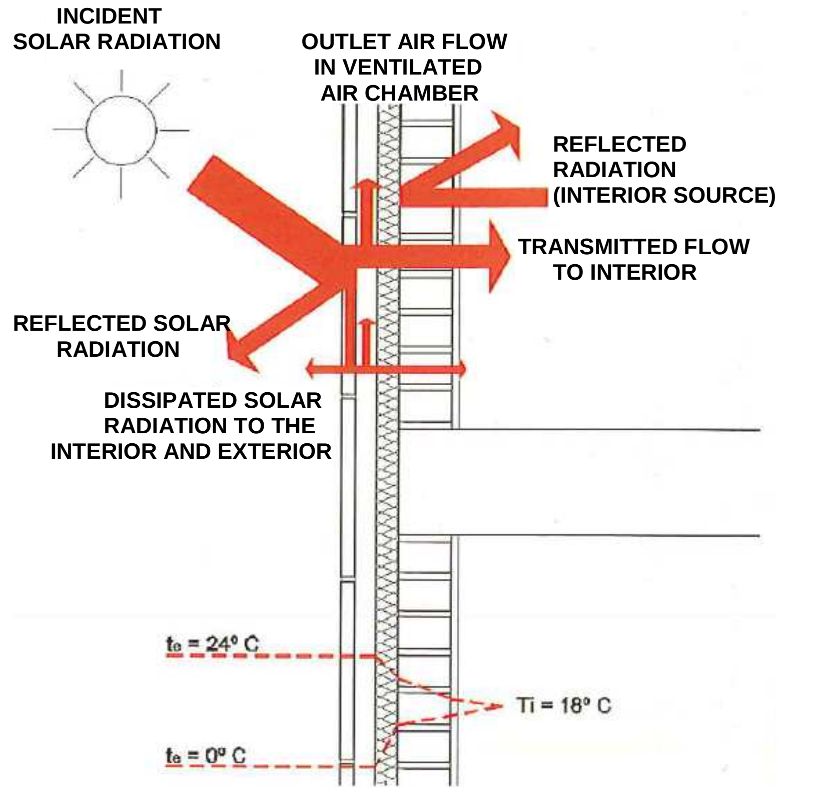
2. Study of the constructions systems about ventilated façade in Ireland and Spain.

2.1. The Ventilated facade

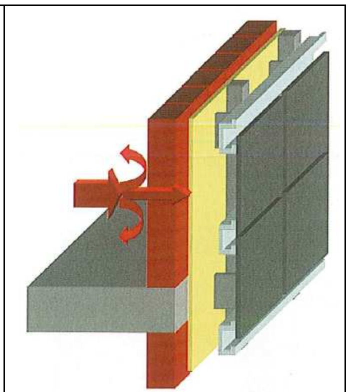
Ventilated facade is conformed by two separated layers allowing the pass of air in between.

The advantage of this kind of facade is the reduction of energy consumption in the building and the increase of the thermal interior comfort. The interior wall must be conformed by isolating materials. The air chamber acts isolating thermally and acoustically. The ventilation of the facade is achieved by natural, mechanical or mix convection. The natural convection is reached by the "chimney effect" due to the heating of the air. This makes possible the evacuation of the overheated air by solar radiation and decrease the interior temperature. Often, interior solar protection elements are installed in the chamber of air when the walls are made of glass, as an element of regulation of direct solar radiation. This allows modifying the solar factor, the luminous transmission, superficial temperature and the thermal transmission coefficient [Technal 2003].

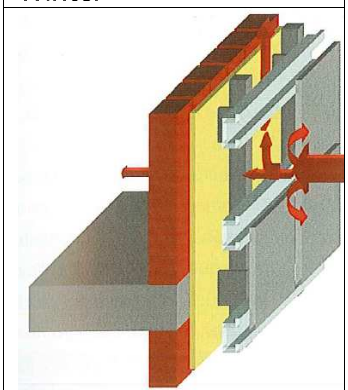
In the case of ventilated glass facade, the exterior glass can be half-reflective monolithic or even serigraphic glass. This allows controlling the intensity and quality of the incoming light. The interior glass should be double or triple glass in order to improve the thermal and acoustic isolation (figure 1).



Thermal flux in ventilated facade. [



Winter



Summer

Figure 1. Thermal flux in ventilated façade for summer and winter period.

2.2. Photovoltaic facade use in Ireland

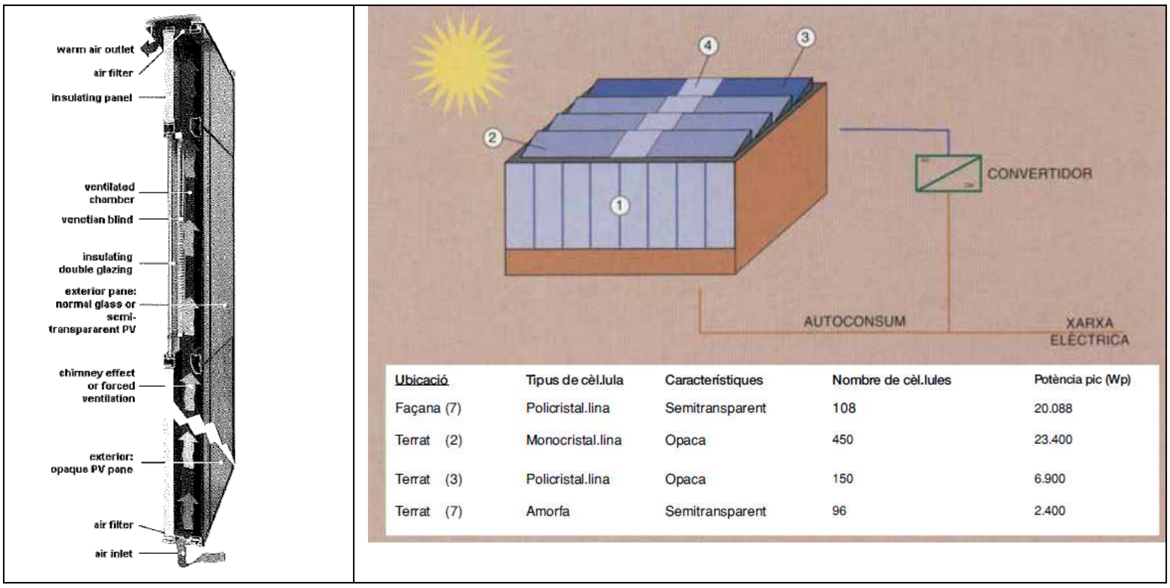
The Building Energy Rating (BER) in Ireland has a scale from A to G, to define the energy efficiency of buildings. This recently regulation will be required in the next years. In effect, BER certificates will be compulsory for almost all new homes by mid-2008. According to the BER, solar photovoltaic improves the BER level, by reducing the kWh of primary energy of the building.

2.3. Photovoltaic facade use in Spain

Currently, the use of photovoltaic panels in buildings is increasing in Spain. The systems are becoming more easily integrated in the buildings enclosure, as the light façade and the cover [Technal 2003].

<u>The Pompeu Fabra library Mataro, in Barcelona</u>

This is a 53 kW_P grid-connected building with integrated PV-thermal multifunctional modules. The building is the first of this kind in the European Union. Large-scale prefabricated multifunctional architectural modules producing both electrical and thermal sola energy were designed for industrial production. Various shapes and degrees of transparency were developed for curtain walls, roofs and blinds; solar thermal energy generated by solar absorption in the modules may be used for heating or evacuated via a ventilation chamber. The building is rectangular in shape with the largest façade facing south. The PV-thermal modules are the major innovation of the building, as they provide versatile and aesthetic possibilities for the building envelope while generating electricity and warm air which is fed into the gas heating systems for further heating if necessary. The prefabricated PV-thermal modules include the complete electric connection system and are installed in the structure of the building using curtain wall construction methods. The building can produce abut 125% of the calculated electricity needs (figure 2).



Ubicació	Tipus de cèl.lula	Caracteristiques	Nombre de cèl.lules	Potència pic (Wp)
Façana (7)	Policristal.lina	Semitransparent	108	20.088
Terrat (2)	Monocristal.lina	Opaca	450	23.400
Terrat (3)	Policristal.lina	Opaca	150	6.900
Terrat (7)	Amorfa	Semitransparent	96	2.400

Figure 2. The public library of Mataró as an example of PV ventilated façade. Source: ICAEN.

3. Implementation of the PCM in the photovoltaic ventilated facade

The macro encapsulated PCM can only be implemented in opaque facade or at least in the non-window part of the facade. The two layers that are containing the PCM are made of opaque material (aluminum) and the PCM in itself is also opaque. Therefore the translucent solutions are discarded and the implementation is focused in the solid part of the facade, no windows. As it is going to be shown, PCM can be implemented in opaque ventilated facade with different options.

The PV panels are used as the exterior layer of a ventilated facade, placing a ventilated air chamber between the PV panel and the interior wall. Previous research of Brinkworth et al. (1997) found that providing a ventilated air gap behind a PV panel is an effective way to limit increases in PV module temperature, which otherwise result in a decrease in electrical output. Yun et al. (2007) demonstrate the reduction in the temperature of the PV module with the placement of a ventilated air gap and at the same time an increase in the electrical generation. These results show a reduction in the temperature from 1ºC in December to 5ºC in April and increase of the PV electrical generation from 0.97% in December to 4.60% in April (figure 3). It establishes a general annual electrical energy loss of the PV facade placed directly over the wall without ventilated air chamber about 2.5% compared to the ventilated PV facade. According to Markvart (2000), the encapsulating materials can be broken down when the cell temperature is above a certain limit (85–100 ºC), which can cause the hot-spot formation, degrading the performance of entire modules.

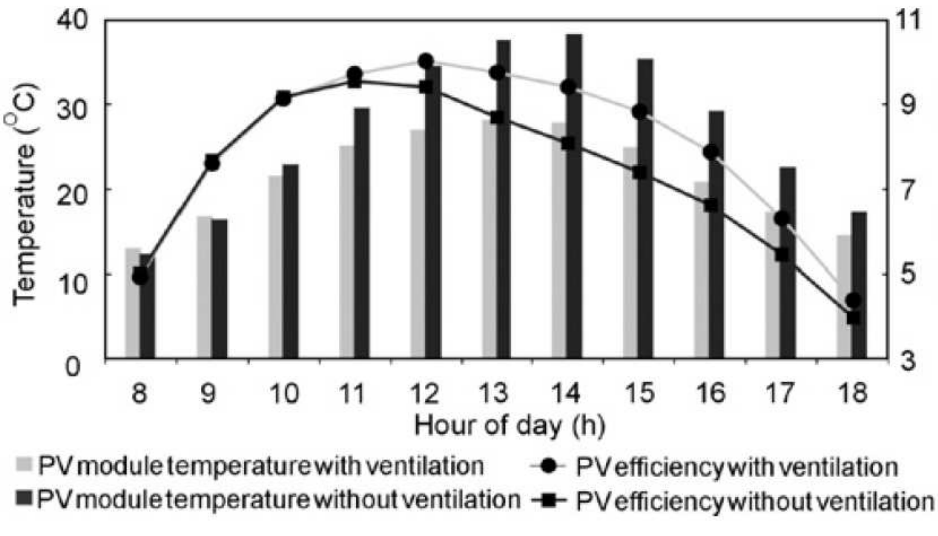


Figure 3. PV efficiency and module temperature during the day when the hottest PV module temperature occurs. Source: Yun et al. (2007).

With the implementation of PCM in the photovoltaic ventilated facade a reduction of the excess of heat in the module is expected and at the same time the thermal energy can be stored and used for regulating the interior temperature of the building.

The design of the PV-PCM ventilated facade for both summer and winter period is crucial. While in winter period, the gain of heat in the PV modules can be used for heating the interior of the building, in summer period the heat should be dissipated through the air gap and not transferred to the interior of the building.

The PV-PCM ventilated facade is used for winter period as a preheating device of the airflow coming into the building. In summer period is used as a natural ventilation system for cooling the building. The PV facade plays an important role in modifying solar radiation and heat transmission to the inside of the building. If an air gap is left behind the PV panel, it can play a central part in providing natural ventilation to rooms (figure 4) [Yun et al. 2007].

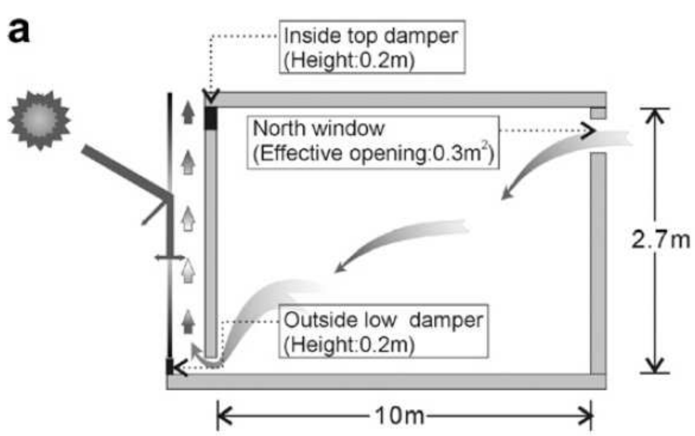
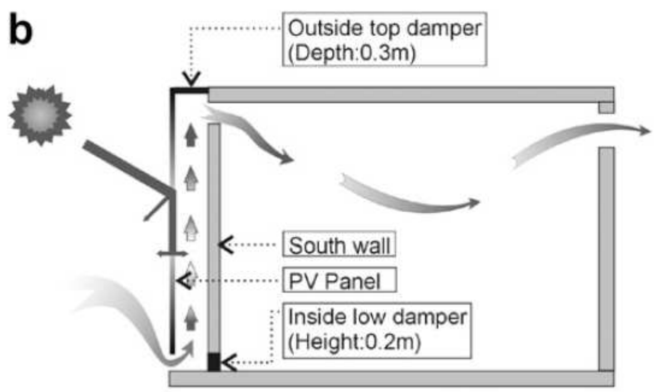
SUMMER PERIOD  	Airflow from the inside of a room may be induced through an air gap. Stack effect within an air gap behind PV modules boosts natural ventilation through the building. The PV panels heat the air within the gap since the absorbed solar radiation in the PV cells not converted to electricity is transmitted by radiation and convection. This leads to a temperature difference within the height of the air column and creates an upwards airflow, which induces buoyancy driven ventilation of the room, causing room air to be exhausted through the vents.
WINTER PERIOD  	Air warmed from an air gap can be supplied to the room. Outside air enters at the bottom of the PV panel and provides the necessary fresh air to a room to maintain good indoor air quality. Low temperature fresh air is preheated by PV panels and can thereby potentially reduce a draught risk.

Figure 4. Diagram of a base case building illustrating the operation strategies for summer and winter seasons: (a) summer and (b) winter. Source: Yun et al. (2007)

Therefore, for making possible the difference of operation of the facade in summer and winter, different factors should be taken into account:

- The U-value of the facade, taking into account the properties (thickness, conductivity) of the materials of each layer in the facade (with especial attention to PCM behavior and the ventilated air chamber).
- The possible thermal bridge caused by the supporting frame of PV modules.
- The exterior and interior conditions of temperature in the building along the year.
- Incident solar radiation over the south facade along the year.

- The previous modeling and analysis of the airflow through the ventilated air chamber and its interaction with the interior airflow of the building.

In order to determine:

- The dimension of the interior air gap and the location of the opening for regulating the airflow from the air gap to the interior of the building.
- The position of outlet-inlet holes in order to control the airflow through the air chamber and the interior of the building.
- The position of the layer of macroencapsulated PCM in the facade.

A previous work about computer simulation using Computational Fluid Dynamics (CFD) Modeling is necessary for designing the PV-PCM ventilated facade. Yun et al. (2007), used for their study the Environmental Systems Performance for research (ESP-r). It is an integrated modeling tool that can simulate a thermal and fluid flow phenomenon in a building, by solving the thermal model and a fluid flow network (figure 5).

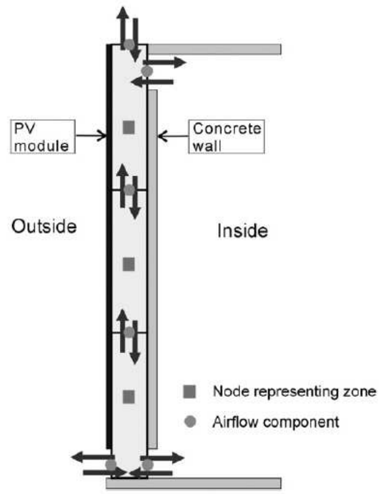


Figure 5. Vertical zone configuration connected with thermal and mass flow models. Source: Yun et al. (2007).

3.1. PV-PCM ventilated façade in Ireland.

Pre-heating device with PV ventilated facade, thermal energy storage with PCM and electricity production with PV panels.

The Spanish and the Irish requirement for a facade are completely opposite. While in the Mediterranean climate the main requirement is the cooling by means of the air gap in the north-Atlantic climate the requirement is to isolate the building from the low temperatures and the moisture (see annex figure 1). Therefore the application of the ventilated facade for the Irish context would have a stronger requirement of isolation as well as of production of heat, the opposite to the Spanish ventilated facade that would be basically required for cooling and not heating.

The next proposal are focused in the restoration of the existing buildings, taking in consideration the traditional construction systems of masonry walls with cavity wall and timber frame, in order to improve the energy efficiency in the existing buildings.

The idea of the application is that the facade is not just used as an isolation envelope between the exterior and the interior but also is used as a energy generator of electricity and heat (figure 4).

The solar radiation affects into the south facade. Part of this solar radiation can be used to generate electrical energy and part of it heats the materials of the facade and this energy could be stored in those materials during the day for using the heat during the night. The utilization of Phase Change Materials (PCMs) plus the trombe wall system can improve the thermal energy storage of the facade.

The photovoltaic-ventilated facade in Ireland can be implemented with the current typical masonry constructive solutions, by adding a exterior layer of photovoltaic panels separated from the wall to create an air gap and providing the airflow from the air gap to the interior of the building. Solar radiation heats the air in the interior gap, which is mechanically distributed to the interior of the building.

Traditional Irish construction systems

+

PV panel / Trombe wall

+

PCM / thermal energy storage 1 day-night

Figure 6. Concept of the proposal.

Trombe wall.

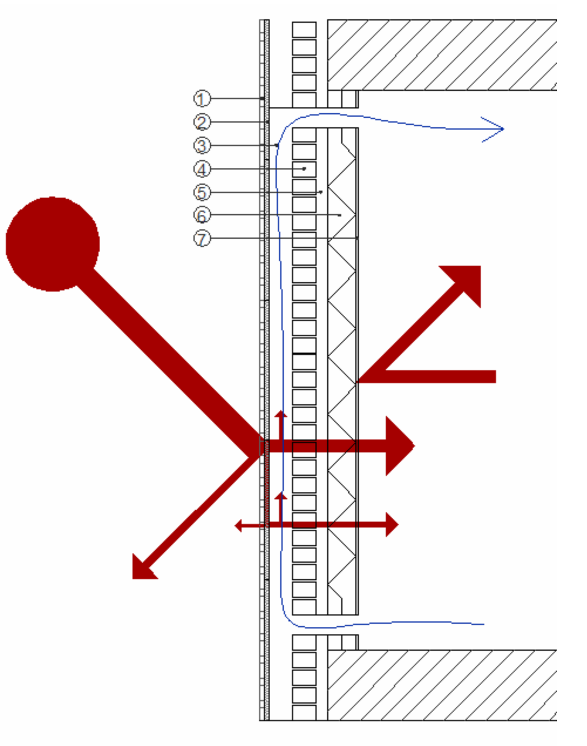
The trombe wall is a indirect gain system for design of passive solar buildings in which the thermal storage mass is separate from the main building envelope. It acts as a collector-storage wall. Part of the south-facing wall is glazed and inside the glazing there is a thick layer of thermal mass such as concrete, brick or water tanks with black surface to absorb and store the transmitted solar radiation. In the proposal the glazing is substituted by the PV panels and the heat is absorbed by the PCM. It may have vents at the top and bottom to permit transfer of some of the stored heat by convection from the face across the glazing, which may reach a high temperature (e.g. 70ºC). Most of the stored heat is transferred by convection and radiation from the interior surface to the room interior, but a portion is lost through the glazing to the exterior, in this case the PV panel. Night insulation and high thermal resistance fenestration systems reduce this loss. In this case the PCM is used as a way of keeping the thermal energy at night. Effective use of thermal storage in buildings will result in significant energy savings, but more importantly it will lower the peak demand for electrical power. In the case of the ventilated facade, the solar energy is stored in the building envelope. Solar energy stored during the daytime is then used at night to reduce peak heating loads [Athienitis & Santamouris 2002].

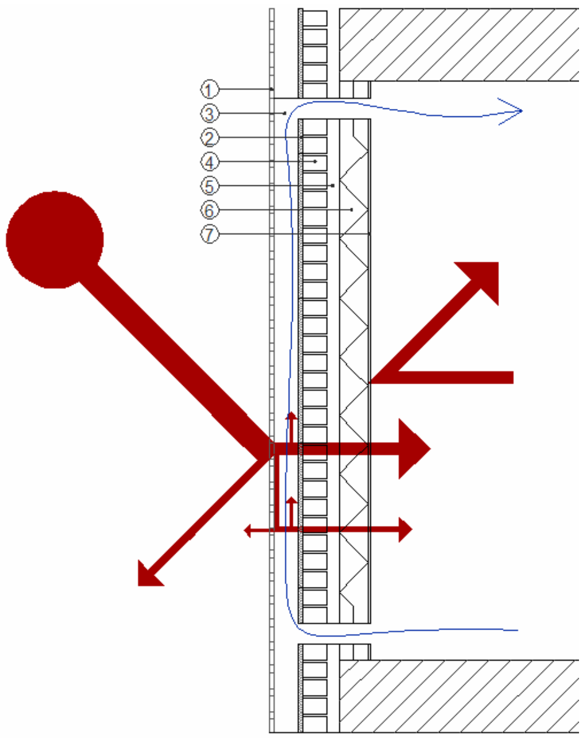
Significant amounts of thermal mass are required to store the excess solar gains without causing large room temperature swings. The use of PCMs in building products has rendered it feasible to store significant amounts of thermal energy in the building envelope without the uncomfortable temperature swings and large structural mass associated with sensible heat storage [Athienitis & Santamouris 2002].

Two possibilities of placing the macroencapsulated PCM in the ventilated facade are proposed in the following figures. Both solutions should be modeled and experimentally analyzed in order to choose the best option from an energetically point of view.

a) PCM in exterior side of the air gap.
The PCM is placed next to the photovoltaic panel in order to control the overheating of the PV cell during the day. At night, the PCM acts as an insulation materials giving heat to the air gap.

b) PCM in interior side of the air gap.
Using the semi-transparent photovoltaic panel for improving the trombe wall effect.





1. Photovoltaic panel
2. Macroencapsulated PCM
3. Ventilated air chamber
4. Brick wall
5. Cavity wall
6. Isolation
7. Interior finishing

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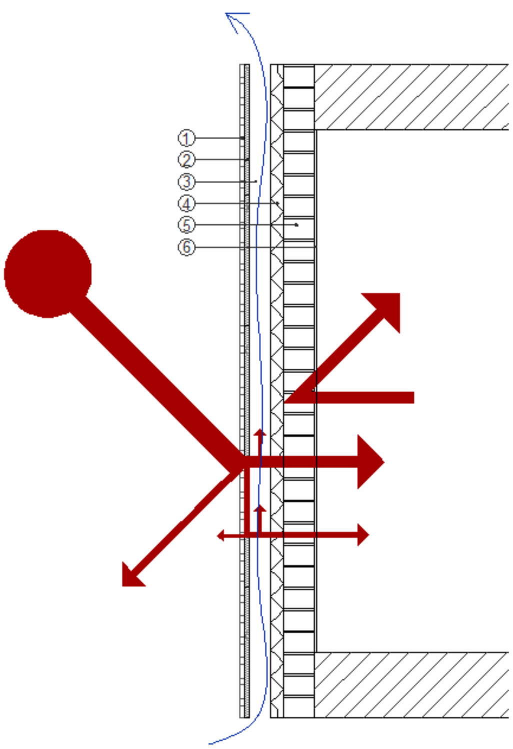
3.2. Spanish PV-PCM ventilated facade.

Cooling with PCM and electricity production with photovoltaic panels.

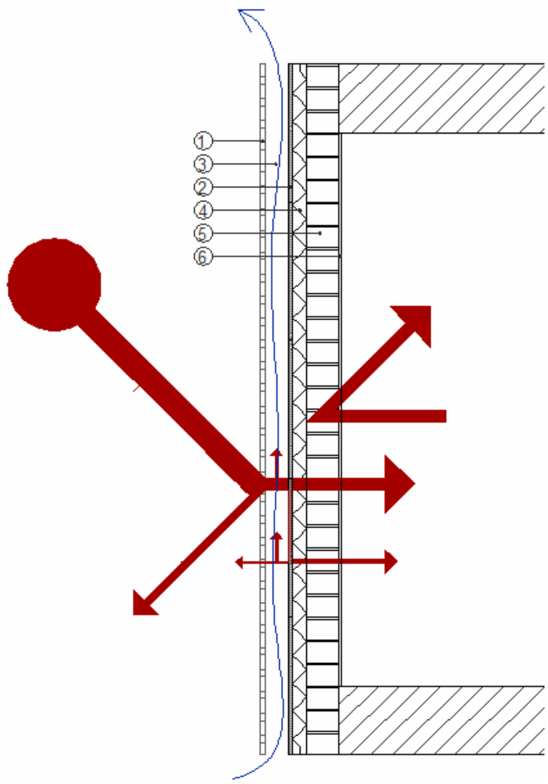
In the Mediterranean climate is required to dissipate heat in the building due to the higher temperatures and the longer exposure to the solar radiation. As it has been previously exposed, it exist already some examples of ventilated facade that are using photovoltaic panels. As a difference from the Irish proposal, the air heated in the gap is continuously ejected to the exterior in order to maintain the interior side of the ventilated facade as fresh as possible. The new proposal consist in substituting the current ceramic layer of the ventilated facade by the PV module and introducing the PCM in the air gap in order to reduce the overheating produced by the solar radiation in the PV panel and in the air gap.

Again, two proposals in the position of the PCM in the air gap are shown and both solutions should be computer modeled and experimentally analyzed in order to choose the best option.

a) PCM in exterior side of the air gap.
The PCM during the day reduces the overheating of the PV panel.



b) PCM in interior side of the air gap.



1. Photovoltaic panel
2. Macroencapsulated PCM
3. Ventilated air chamber
4. Isolation
5. Brick wall
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4. Quantification of the required materials for the PV-PCM facade

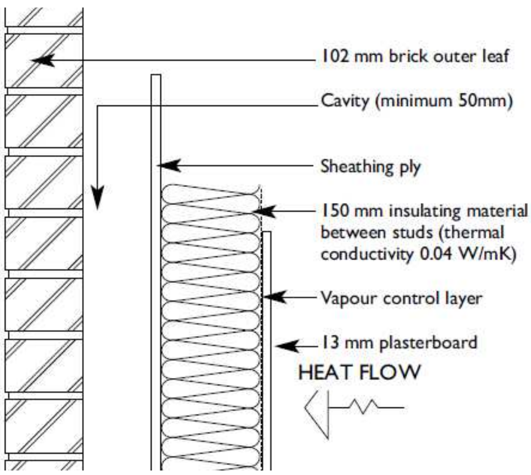
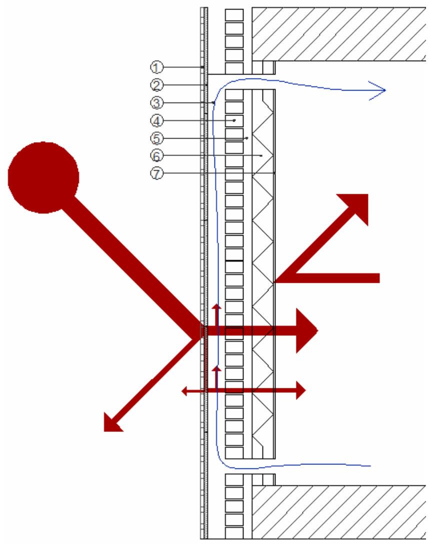
The proposal of implementation of the PCM in PV façade in chapter 3 has been analyzed. The PCM-PV ventilated facade in Ireland and Spain are composed of different materials in function of the materials used in each country. The facade in Ireland have as main components the timber frame and masonry wall construction with thick insulating material, while the Spanish solution is composed by masonry wall and thin insulating material.

The quantification has into account the current typologies of facade and makes a comparison with the proposed ventilated facade for both countries. Therefore, 4 different constructive solutions are analyzed (figure). The conventional facade and the ventilated façade with photovoltaic panels and PCM are evaluated and compared.

Maximum U-value

In order to accomplish the law regulations in each countries, the U-value for the facades have been calculated, and therefore the thickness of the insulating materials is determined. At it was exposed in chapter 1, for Ireland the maximum U-value for the façade is 0.27 W/m^{2}K. For the Spain, the diversity in climates requires deciding where the building is place and therefore what is the U-value for that region. As an example, for this case of study the climatic zone of Lleida has been chosen. This area corresponds to D3 (see figure 9 and table chapter 1). According to CTE DB-HE 1-2 table 2.2., the maximum U value for facades in Lleida is 0.66 W/m^{2}K [CTE]. Therefore, any adapted solution for ventilated facade with PV and PCM should have a thermal transmittance lower than this U value.

As a summary the figure 7 shows the analyzed construction systems, the thickness of the wall and the U-value for each one.

kg/m^2	Conventional facade	PV–PCM ventilated facade
Ireland	Timber frame + masonry wall (cavity wall) 32 cm, U = 0.28 W/m^{2}K < 0.27 (BRE)	Conventional facade + PCM-PV panel
		

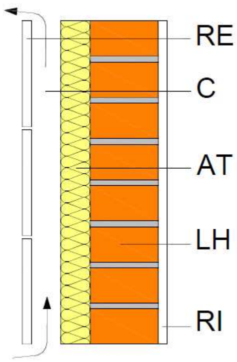
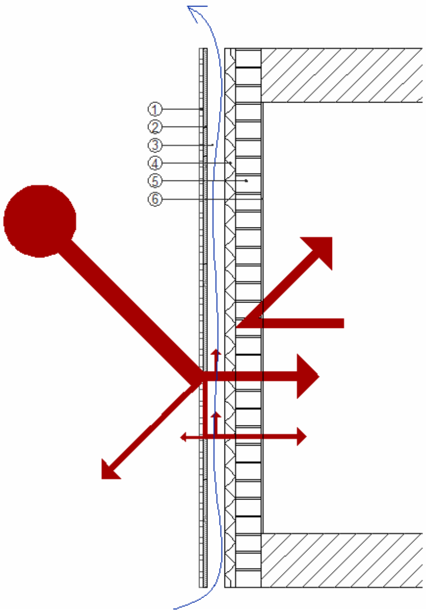
<table>
<tr><td rowspan="2">Spain</td><td>Ceramic ventilated façade
Exterior insulation 4 cm.
Exterior layer: ceramic piece 3 cm
Interior layer: ceramic brick 11.5 cm
22.0 cm, U = 0.62 W/m^{2}K < 0.66 (CTE)</td><td>PCM-PV ventilated facade
Exterior insulation 4 cm.
Exterior layer: PV-PCM panel
Interior layer: ceramic brick 11.5 cm</td></tr>
<tr><td>RE: Ceramic piece fixed with metallic frame

C: ventilated air chamber
AT: thermal insulation (water-repellent) 4 cm
LH: masonry wall, perforated brick 11.5 cm
RI: gypsum lining</td><td></td></tr>
</table>

Figure 7. Four different constructive solutions are evaluated current and proposal solution for Ireland and Spain.

About the required materials for PV-PCM facade in both countries Ireland and Spain, All the solutions accomplish the U-value established by the regulations for each country. The implementation of a PV module and a layer of PCM with a ventilated air chamber are not substantially changing the results about the thermal conductance.

Due to the restoration conception of the PV-PCM ventilated façade in the Irish case, the implantation of the new layers mean an increase of the thickness of the facade of almost 5 cm and an increase in the global weight of 13.1kg/m^2 or and addition of 4.7%.

In the Spanish case, the substitution of the layer of ceramic by the PV-PCM module means a reduction in the thickness of 1.2 cm. This substitution also means a reduction of the global weight of the facade of 5.5 kg/m^2, or a reduction of 2.5% (table 1).

	Thickness (cm)	**U-value**	**Kg/m^2**
Ireland			
Conventional facade	32.7	0.27	277.56
PV-PCM ventilated facade	37.5	0.27	290.65
Spain			
Conventional facade	23.0	0.62	222.13
PV-PCM ventilated facade	21.8	0.61	216.67

Table 1. Summary weight, thickness and U-value for both typologies and countries.

5. The benefit of implementing a PV-PCM ventilated façade in terms of energy consumption

The benefit of having a PV-PCM facade has to be evaluated in terms of energy efficiency considering the following points:

1- The electrical energy produced by the PV modules, clean energy without CO2 emissions.
2- The energy saving in heating and cooling in the building due to the control of the airflow through the ventilated facade with trombe-wall effect and to the thermal energy stored due to the PCM.
3- The energy saving in artificial lighting in the interior of the building due to the natural light obtained through the windows in the facade.
4- The embodied energy in the materials that are composing the facade and their span life.

The last point, related to the embodied energy of the materials, is evaluated and shown in table 2.

	Weight per m^2 of facade kg/m^2	**Embodied Energy (MJ/m^2)**	**CO_2 emissions ($kgCO_2/m^2$)**
Ireland			
Conventional facade	277.56	2,273.52	232.29
PV-PCM ventilated facade	290.65	5,444.18	405.41
Spain			
Conventional facade	222.13	1,091.24	87.07
PV-PCM ventilated facade	216.67	3,671.62	225.39

Table 2.Summary embodied energy and CO2 emissions for both typologies and countries.

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6. Conclusions: Comparison and evaluation between Ireland and Spain and final

The PV-PCM ventilated facade can be implemented in both countries but the design should consider the summer and winter requirements for each country. While in Ireland the heat gain for being used in the conditioning the building would be the main requirement along the year in Spain the cooling of the building is the basic requirement.

Previous researches have already evaluated the benefit of placing a ventilated air chamber behind the PV module but not yet the improvement of placing PCM in the air gap. For both countries, the introduction of an air chamber behind the PV module and the macroencapsulated PCM in that gap can reduce the excess of heat in summer period and it can be used for heating the interior air of the building through the trombe wall effect and the storage of thermal energy in the facade.

A computer modeling is required for analyzing the behavior of the ventilated facade air flow, the PV modules and the PCM in the air gap in order to optimize and determine the dimensions and position of these elements in the facade.

The implementation of PV-PCM ventilated facade in Ireland would mean an increase of the total thickness of the façade but just an addition of 4.7% in the total weight. If the restoration component is considered, the material addition would be good for the total material balance, because of the conservation of materials -not substitution, prolonging its useful life time- and the possible energy saving in the interior of the building due to the addition of PV-PCM modules.

In Spain, the substitution of the layer of ceramic by the PV-PCM module results in a lighter facade but with higher embodied energy. For both countries, the implementation of the PV module means a considerable increase of the embodied energy of the total facade.

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