




# Innovative technologies, certification and assessment tools for a sustainable building heritage

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**Abstract:** It's clear that good results in the field of environmental sustainability can be obtained by energy efficiency policies for buildings - mostly undertaken or *in itinere* - built for more than 50% before the disregarded law 373/76 that provided, in the period of the European oil crisis, constraints for design, installation, operation and maintenance of heating systems and requirements for thermal insulation of buildings to contain consumption. On the other hand, it is less clear the part of buildings subject to conservation (in accordance with the Legislative Decree 42/2004 or former regulations on the subject) or listed buildings *ope legis* (art. 12 of italian legislative Decree 42/2004, asset belonging to the State, regions, public territorial authorities, as well as any other public body and institute and private non-profit legal entities and which are the work of an author who is no longer alive and whose execution dates back to more than seventy years) for which it would not be possible to apply the limitations of the decrees 192/2005 and 311/2006, which relieve the buildings "in which compliance with the requirements would entail an unacceptable alteration of their nature or appearance, with particular reference to historical or artistic features" of the energy efficiency obligations. In this paper we want to justify and illustrate some choices made by international research institutes regarding the difficulty in reconciling the new requests of sustainability related to the need to reduce consumption (especially from fossil fuels) with those of the historical value of the buildings subject to intervention, presenting evaluation criteria that can provide an objective method for quantifying the compatibility between new and existing, criteria that – in order to have predictive capacity and therefore be able to guide choices ex ante and not measure them ex post - use digital design tools (BIM, GIS, etc).

**Keywords:** Sustainability; Heritage; Innovative technologies; Assessment method.

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## 1. Introduction

Compared to the main avant-gardes of the past, our era is characterized by both a much greater quantity of pre-existing buildings than those currently in progress (or recently built), and a significant (or at least desired) increase in standards of comfort, accessibility and sustainability, and - and this is not a negligible aspect - with a cultural attitude that ranges from an excess of preservation of the architectural heritage to a shameless lack of attention to historical values.

The strategy shared at supranational level towards policies of energy saving and the use of renewable energy sources revealed the inevitable dichotomies concerning the attempt to bring the historic or historicized buildings into the twenty-first century- as in the recent past - with the introduction of major technical systems and mandatory changes for accessibility.

To these sufficiently complex issues must be added those of revising and adapting regulations to facilitate smart working, as well as training and cultural integration of new communication technologies. If it is true that the problems related to the introduction of "physically" evident components (ducting and electrical systems, photovoltaic or solar thermal panels, etc.) have produced some attempts (not many actually) to identify objective criteria to classify their impact (and their coherence with the existing buildings), the introduction of new information technologies has so far been underestimated because of the apparent simplicity of its "overlapping" without taking into account the obvious and unnatural historical contrast.

In this paper we want to justify and illustrate some choices made by international research institutes regarding the difficulty in reconciling the new requests of sustainability related to the need to reduce consumption (especially from fossil fuels) with those of the historical value of the buildings subject to intervention, presenting evaluation criteria that can provide an objective method for quantifying the compatibility between new and existing, criteria that – in order to have predictive capacity and therefore be able to guide choices ex ante and not measure them ex post - use digital design tools (BIM, GIS, etc).

## 2. Cognitive and cultural preliminary remarks for sustainable planning

It's clear that good results in the field of environmental sustainability can be obtained by energy efficiency policies for buildings - mostly undertaken or *in itinere* - built for more than 50% before the disregarded law 373/76 that provided, in the period of the European oil crisis, constraints for design, installation, operation and maintenance of heating systems and requirements for thermal insulation of buildings to contain consumption.

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Since the State is the primary owner of these assets, the enormous benefit in terms of reduced energy expenditures would amortize costs for requalification.

In particular, energy retrofit actions - generally more conservative in Mediterranean areas and more radical in Northern European countries (Cabeza et al., 2018) - may cover the building envelope, windows and doors, air conditioning and heating systems, and the use of renewable energy sources. In order to meet the new requirements imposed by European directives, and regarding the reduction of energy consumption, it will no longer be sufficient to reduce heating needs through insulation of the building envelope, but it will also be necessary to plan and implement new long-term strategies for energy production.

The subject of electrical systems is one of the most complex to deal with, not only for energy efficiency and indoor comfort, but also and above all for integration of the plant system with the existing machines and networks. Certainly, it is not possible to propose univocal solutions because each building represents a *unicum* in terms of opportunities and operational criticality: the problems arisinge forom the passage of canalizations, in buildings originally designed to be without them, are not always solved in the best way for the strong impact with the existing historic buildings. If water and electricity ducts have minimum sections, the problems are different for air systems because they require supply and return ducts with no minimum sections. Moreover photovoltaic and solar thermal systems have a strong impact and the ducts are generally visible and put on the roof.

The re-functionalization of historic buildings requires not only the ability to adapt the spaces and the existing morphology to the new intended use, but above all the design of an adequate system that allows to carry out activities in optimal conditions of thermo-hygrometric and acoustic comfort, whatever the choice of conservation or intended use for the building. This would allow future generations to appreciate not only the original building form and structure, but also subsequent modifications and/or additions that have taken place over time, recognizing the value of these stratifications in cultural development and in historical identity of a society.

An example of integration of the plant system with the building is represented by the introduction of renewable energy sources in the building envelope, with particular reference to solar thermal collectors and photovoltaic modules, to be placed on roofs or infills. The perceptual alteration of the historical volume, materials, surfaces, the reversibility and invasiveness of the intervention, the difficult integration (Kandt et al., 2011; Kooles et al., 2012), the need for self-consumption,..., have created in the last decade a succession of legislative measures, ambiguously interpreted, to regulate the authorizations for the integration of photovoltaic and solar thermal components. To date, the installation of small photovoltaic plants is not exempt from the landscape authorization but is subject to the "simplified procedure" when the systems are located in areas or on properties subject to constraints *ex lege* (art. 142 of the Cultural Heritage and Landscape Code) or to constraints a) and d), art. 136. In the event that such plants are located in areas or on properties subject to restrictions pursuant to letters b) and c), art. 136, Presidential italian Decree no. 139/2010, attachment 1, no. 28 does not provide for liberalization but rather the submission to the "ordinary procedure" landscape authorization (art. 146 of the Cultural Heritage and Landscape Code). The "subjectivity" of the regulatory interpretation about the authorization by the Soprintendenza dei Beni Culturali e Ambientali (Superintendency BB.CC.AA.) is demonstrated by the appeals, which reached the Council of State, where the judgments annul the measures of the Soprintendenza BB.CC.AA. and the TAR (Tribunale Amministrativo Regionale) with reasons that go beyond the technical and landscape assessments "characterized by broad technical discretion" instead going into the "illogical and disproportionate limitations" such as the request to install photovoltaic panels on the north facing slopes "beyond the actual technical absurdity and economic unsustainability of the operation" in order to ensure a "totally photovoltaic coverage" (cf. CdS italian Sentence no. 00856/2017 published on 23/02/2017).

In the world there are several research projects, fundced by the European Commission, aimed at reducing the energy consumption of historic buildings making use of renewable energies and energy efficiency technologies; several retrofit strategies have been proposed and results achieved. The research activities of *Efficient energy for EU cultural heritage*, 3ENCULT (October 2010 - March 2014), promoted by twenty-one partners from ten European countries, focused on eight historic buildings (3 located in Italy, 1 in Denmark, 1 in Austria, 1 in Germany, 1 in Spain, 1 in Switzerland). For these buildings, technical solutions that could be generalised and replicated in other contexts (such as the semi-transparent photovoltaic double-glazed window) were developed together with the owners of the buildings, representatives of the local offices for the protection of historical monuments and other interested local authorities, professionals involved in the renovation works, local sponsors and, possibly, a representative of a local organisation involved in heritage conservation. The technical solutions developed in this project - with the involvement of: building owners, representatives of Environment Protection Bureau and other local authorities, professionals involved in the renovation works, local sponsors and possibly a representative of a local organization involved in heritage conservation - could be generalized and replicated in other contexts (such as the semi-transparent double-glazed photovoltaic window).

The project *Energy Efficiency for EU Historic Districts Sustainability*, EFFESUS (September 2012 - August 2016), sponsored by twenty-three partners from thirteen European countries, was concerned with identifying solutions for the energy retrofit of seven architectures (located in Italy, Hungary, Turkey, Germany, Spain, Sweden, Scotland) built in different historical periods and with different materials. The research aimed to determine a methodology for the evaluation and selection of feasible intervention, test new non-invasive technologies, assess the criticality of the regulatory apparatus on energy rehabilitation of historic buildings and to propose solutions for the integration of photovoltaics.

In the project *NewSolutions4OldHousing*, LIFE10 ENV/ES/439 (September 2011 - November 2015), the buildings subject to intervention are two social housing located in the historic center of Zaragoza. The design choices, already implemented, contributed to improve the passive behavior of the building without increasing the financial costs related to energy consumption as a function of the low income of the occupants.

The energy rehabilitation planned for the public and private buildings selected by the Methodology of energy rehabilitation of heritage buildings 2 project, RENERPATH (January 2014 - November 2020), in the central area of Portugal, includes innovative non-invasive interventions such as those of the Energie und Baudenkmal project, ENBAU (January 2014 - November 2020), which also addresses the problem of achieving high levels of sustainability at competitive prices.

The different actions proposed by several researches (Giombini *et al.*, 2015) share historical knowledge, building conservation assessment, the need to propose well-integrated solutions, energy diagnosis with evaluation of building performance,..., but do not quantify in depth the energy and economic benefits that the intervention produces, given the architectural and technical constraints due to the historical value of the building.

In addition, all solutions examined and then implemented did not lead to a certification of the building in question because many criteria for optimizing energy performance were not met and the adopted certification protocol lacked specific issues related to the intervention on the historic building.

The paper, after considering the opportunities and limitations of sustainability protocols, results in the definition of theoretical assumptions and operational references that can facilitate the integration of the photovoltaic component in historic buildings, in some cases converted into museums, libraries, stores, showrooms, for private or public use (Balocco *et al.*, 2013). Finally, the advantages, in terms of performance, offered by the experimentation of innovative solutions of the photovoltaic component in the building envelope are analyzed.

## 3. Sustainability protocols and operating methodologies

In order to ensure the sustainability of the historical heritage, in 2014 the Green Building Council (GBC) Historic Buildings (Boarin et al., 2014) introduced a certification system for the restoration, redevelopment or renovation of buildings - surveyed by the Superintendence and built before 1945 (or after 1945 if a pre-industrial building process is identified and there are recognized and proven historical, testimonial or cultural values) - which allows to simultaneously meet the objectives of deep energy environmental renovation according to European indications, and preservation and enhancement of specific construction characteristics. The GBC protocol is the normative transposition of the original LEED® New Construction & Major Renovation version of 2009, where a new thematic area, regarding sustainable intervention in the field of conservation, has been added. This area, called "Historic value" (VS), through the identification of precise investigation methodologies and specific operating principles, aims at preserving what is recognized as "material witness having the force of civilization".

In particular, it is possible to achieve a maximum score of 20/110 if, in addition to the mandatory preliminary investigations, advanced cognitive investigations are carried out (energy audit, 1 to 3 points; diagnostic tests on materials and degradation, 2 points; diagnostic tests on structures and structural monitoring, 2÷3 points), the project reversibility is recognized (1÷2) and compatibility is ensured (compatible end-use, 1÷2; chemical and physical compatibility of integrated materials, 1÷2; structural compatibility, 2), a scheduled maintenance plan (2), a sustainable restoration site has been set up (1), and specialists in architectural and landscape heritage are employed (1).

Additionally, the minimum programme requirements (CER_HB16_M_RMP_R01, issued on 25-03-2016) were determined, i.e. the minimum characteristics that a project should have in order to be certifiable with GBC Historic Buildings (compliance with current building legislation, territorial definition of the certification boundary, minimum area, minimum number of occupants, obligation to provide water and energy consumption, minimum index of buildable area in relation to the site area).

It would have been appropriate to include, in the "Historical value" thematic area, some items concerning the integration, compatibility, reversibility, impact,..., of the installation system, in order to assess in detail the role played by the installations in the recovery/restoration of historical architecture.

The actions of "optimization of energy performance", "renewable energies" and "enhanced commissioning" (ensuring that all systems work synergistically according to the design intents and operational needs of the client) are part of the "Energy and Atmosphere" area - already existing in the LEED® New Construction & Major Renovation version and reported in the GBC Historic Buildings version. This section deals with environmental efficiency without giving credit for the impact on valuable buildings.

The "identity card of the historic building", obtained through certification, analyzes all the typological, functional, structural and material characteristics of the building in order to have a complete analytical and cognitive system, while neglecting the plant system.

**Fig. 1** | Buildings with GBC Historic Building certification: 1) National Museum of Italian Judaism and the Shoah, in Ferrara, 2) the stables of the Benedictine monastery of the Rocca di Sant'Apollinare (PG), 3) palazzo Gulinelli in Ferrara.

To date, few rehabilitation and redevelopment projects have followed the criteria of sustainability and eco-compatibility (Castaldo et al., 2017), making the building eligible for international GBC Historic Building certification: MEIS, the national Museum of Italian Judaism and the Shoah in Ferrara, was awarded gold certification in 2016 with 65/110 points (3/20 VS thematic), the stables of the Benedictine monastery of the Rocca di Sant'Apollinare (PG), gold certification in 2018 with 72/110 points (3/20 VS thematic) and Neo-Renaissance Gulinelli Palace located in Ferrara, gold certification in 2019 with 61/110 points (13/20 VS thematic).

In the MEIS (Energy and Atmosphere thematic score 19/29), transformation and partial renovation of the ex-prison of Ferrara built in 1912 and decommissioned in 1992, energy optimization was ensured by high performance heating, air conditioning and HVAC ventilation systems. Control and automation systems such as sensors and dimmable lighting were also installed. In the new building, which is part of the complex, photovoltaic sunshades and integrated roof panels will be installed to meet an estimated energy demand of 90 kW.

As for the project concerning the stables of the Rocca di Sant'Apollinare (Energy and Atmosphere thematic score 29/29), built in the 10th century as a fortress - carried out by a team from the University of Perugia and coordinated by Lucia Castaldo and Franco Cotana - the building is completely self-sufficient thanks to a trigeneration plant fuelled by biomass (vegetable oil from the thistle, oil biomass from the surrounding countryside) and biogas from wet waste. Particular attention was given to the correct positioning of the electrical panels, to minimize the impact of laying cables according to the available space: the identification, above the barrel vaults, of an empty space to be used as a cavity facilitated the necessary operations.

In this project, which obtained the highest score in the Energy and Atmosphere theme, energy efficiency and retrofit are considered as forms of protection of the historic building and not as alterations to the original material texture. "*Questo principio consente di superare la logica, ormai obsoleta, alla base delle principali direttive e leggi inerenti la valutazione delle prestazioni energetiche degli edifici che escludono qualsiasi intervento su immobili ricadenti nell'ambito della disciplina del codice dei beni culturali e del paesaggio, nei casi in cui il rispetto delle prescrizioni implicherebbe una alterazione inaccettabile del loro carattere o aspetto con particolare riferimento ai caratteri storici o artistici*." (AA.VV., 2017)

The introduced principle of improving the performance of the historic building, even modestly, and not of adapting it to fixed and rigid performance levels, is an important step towards reducing energy consumption. It is important to consider the overall energy performance of the building-installation system and not that of individual elements. "*La visione parcellizzata della sostituzione del singolo componente o dell'adeguamento prestazionale del singolo elemento tecnico è estremamente pericolosa nel caso dell'intervento sull'edificio storico, sia per motivi legati alla coerenza e uniformità del prodotto finale dell'intervento, sia per motivi legati alle prestazioni energetico-ambientali (asimmetrie termiche, presenza di ponti termici difficilmente risolvibili, ecc.)*." (Pisello et al., 2016)

The project of Gulinelli Palace (Energy and Atmosphere, score 11/29), a "fusion" of pre-existing buildings built between the end of the 14th century and the second half of the 19th century, is characterised by an installation system in which the original ventilation ducts are used for air-conditioning the rooms; a heating/cooling system with radiant floor panels, dry laid and/or nailed were also included. In the examined examples,

*(Table 3 continued from previous page)*

due to prior negative opinions of the Superintendency or design choices, the retrofit strategies were not achieved through the integration of the photovoltaic component on the roof or in another space of the building (except for MEIS where the photovoltaic component was integrated in the new building and not in the existing one).

In agreement with the local authorities and if it was not possible to install the system on the building envelope, in the analyzed buildings it would have been possible to locate the renewable energy systems in alternative and accessible spaces, in close proximity to the site. Parking spaces with photovoltaic pergolas could have been installed on the land surrounding these buildings, which would certainly have contributed to increasing the sustainability of the site and thus the certification score. The protocol guidelines do not allow for the complex integration of renewable energy sources, "*sia per il valore storico-artistico del manufatto che risulterebbe danneggiato da tali inserimenti, sia per la scarsa efficienza conseguibile a causa delle condizioni al contorno (ad esempio, ombreggiamenti causati da edifici adiacenti oppure non corretta esposizione delle coperture nel caso di integrazione di dispositivi fotovoltaici)*". For these reasons, they consider off-site renewable energy production feasible, "*mediante contratti di fornitura certificata (energia verde), in alternativa o a completamento di una ridotta quota di energia rinnovabile prodotta in loco*." (AA.VV., 2017).

The expression used in the GBC Historic Building protocol guidelines, which describes a building in which a photovoltaic component has been integrated as "damaged", is still not very sharable. Instead, this "'new architectural element" can contribute to the preservation of historic architecture by combining it effectively with the conservation of the building and a high value of the design quality of the adaptations. Research, experimentation and testing of various design solutions can make the building heritage sustainable.

This limitation seems to have been overcome by the methodology, developed by the EPFL Lausanne Polytechnic, which not only assesses the esthetic impact of photovoltaic panels on buildings but also defines minimal local levels of integration quality, according to some criteria derived from the literature, and identifies the factors needed to establish smart solar energy policies that preserve the quality of pre-existing urban contexts while enabling solar energy use (Dessì, 2013).

The methodological model, called *Laboratoire d'Energie SOlaire - Qualité-Sensibilité-Visibilité*, LESO-QSV (Munari Probst & Roecker, 2011, 2015), is based on the concept of "architectural criticality" of city surfaces and establishes the qualitative level of acceptability of solar panels (based on the "visibility" of the modules and the "sensitivity" of the building).

The concept of "criticity" of city surfaces is at the basis of the LESO-QSV approach.

If the level of 'criticity' is higher - as in the case of the installation on the façade of a historic building - there is more need for a qualitative integrated planning. If the level of 'criticity' is lower - as in the case of the installation on the terrace of a factory in an industrial area – there is less need for a meticulous integration.

If the photovoltaic modules are visible (Florio *et al.*, 2018) from a public space, this influences, proportionally, the impact on the "criticity" of the building; as for the context sensitivity, visibility (Fig. 2) is divided into three levels (*high*, *medium*, *low*) and two sub-levels (from close range, close visibility and from far away, remote visibility).

The QSV method proposes to classify the "sensitivity" of existing contexts into 3 categories: high (for protected or meaningful heritage/buildings), medium (contexts/buildings with no specific architectural/urban qualities, but with a meaningful identity for the community), low (contexts/buildings with poor urban/architectural qualities and no specific identity). The crossing of the levels of visibility and sensitivity defines (Munari Probst et al., 2015) a 3x3 matrix that identifies nine different criticity situations for which quality expectations will have to be set. The characteristics useful for establishing the integrative quality of the system have been grouped into: geometric (position, size and shape of the photovoltaic field in relation to the building), coherence of the system materiality (reflectivity, texture, module colour), layout (juxtaposition of modules and their joining system). For each of these three characteristics (geometric, materiality, layout), the coherence of the installation with the building is assessed through a coloured arc of a circle (green if fully coherent, yellow if partially coherent, red if not coherent). For example, considering the whole photovoltaic field, the coherence of the shape, size and position is assessed in relation to the roof of the building where the modules would be installed. The combination of the coloured arcs gives a three-sector circle that expresses the overall quality of integration (Figg. 3-4).

The system has been tested in academic and professional courses, specific seminars and training meetings, resulting in consistent and objective evaluations (Munari Probst & Roecker, 2011, 2015).

To obtain a qualitative assessment of the integration of the photovoltaic, a multi-purpose software simulation

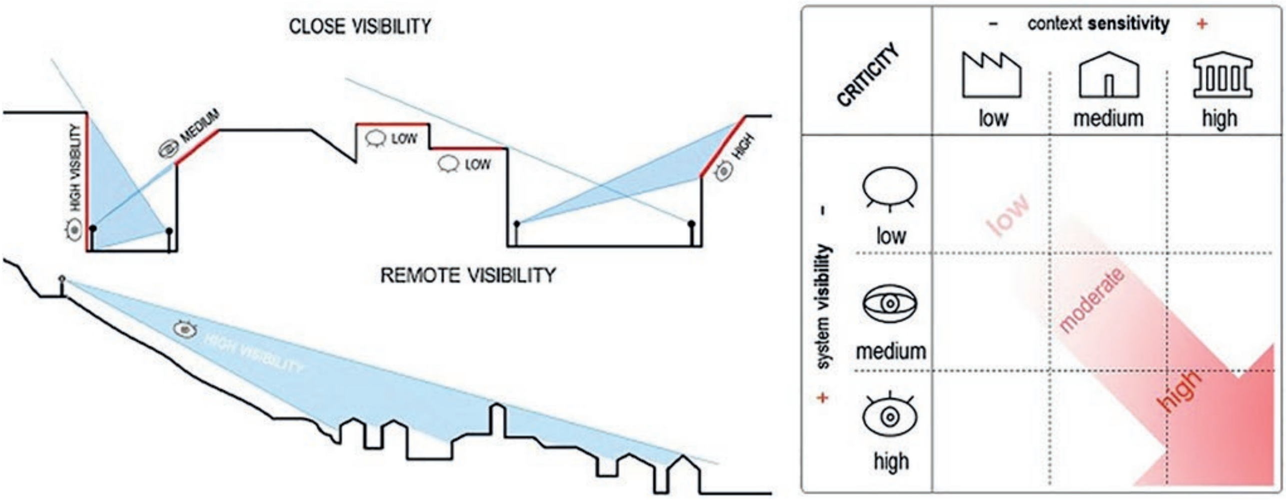


Fig. 2 | Visibility of photovoltaic surfaces from public spaces (close visibility) and from hills (remote visibility); criticity matrix and gradient (diagram: M. C. Munari Probst & C. Roecker).


Fig. 3 | Integration quality evaluation method: criteria grouping – sectors evaluations– resulting quality circle (diagram: M. C. Munari Probst & C. Roecker).

Fig. 4 | Different levels of "system geometry" coherency (photo: M. C. Munari Probst, C. Roecker).


**Fig. 5 |** Different levels of "System materiality" coherency (photo: M. C. Munari Probst, C. Roecker).

tool has been developed, called LESO-QSV GRID; in order to valorize the educational potential of the database, more then 150 cases can be accessed and downloaded as separate case sheets classifying and describing in detail each installation example (Munari Probst & Roecker, 2019).

This method was used to evaluate three Swiss buildings - Manetti house in Bironico, 1600; Hôtel de La Sage in Avolène, 1890; Anatta house in Monte Verità Ascona, 1904. Finally, a solar glass façade was built in the Anatta house; in the Hôtel de La Sage a photovoltaic shutter was recommended; and in the Manetti house photovoltaic cells were integrated into the roof tiles.

Another example of good integration is the Kirchgemeinde Carlow church in Germany, with its brick façade and cruciform single-nave floor plan; the partial replacement of the medieval slate roof with specially designed polycrystalline photovoltaic panels was non-invasive and respectful of the historical value. Each module, whose dimensions correspond to six existing elements, matches the colour and shape of the roof so that it is perfectly integrated. Eighty-eight panels were installed in 2001, forming a parallelogram, whose arrangement takes into account the following problems: shading (created by the adjacent roof and the bell tower); inclination of the upper roof (40°); constraints imposed by the monument protection authority. Although the photovoltaic system does not fully meet the energy needs of the church, it contributes to a reduction in consumption of more than 35%. If the additional quality level had been measured using the LESO-QSV model, only the geometric characteristics would not have been fulfilled due to the size and position of the photovoltaic field, which are not consistent with the geometry of the roof.

This innovative digital methodology stimulates the cultural revolution that, for many years and not particularly successful, has concerned the integration of new plant technologies for energy retrofit in full recognition of the material and immaterial values of the historical built heritage.

The necessary integration of the photovoltaic component in all historical architecture is evident in the prototype (Sibley, 2006) developed for the solar lighting of the Seffarine and Moulay Idriss hammām buildings (Fez, Morocco). In these buildings, the natural lighting and ventilation of spaces, provided by the round holes (traditionally covered by blown glass bulbs) in the domes and vaults, are not always adequate to the needs of the users, especially in afternoon and evening hours when the hammams are still operating.

The geometric arrangement of the holes crossed by the light, which are concentrated in the central area of the roof - in Arabic language *qamarriyats*, small moons, or *shamasiyyats*, small suns – creates a incredible atmosphere and leaves the peripheral spaces (where bathers normally sit) in a state of semi-darkness, certainly less pleasant but in line with local traditions on respect for privacy.

Changing needs for comfort and demand for high quality standards by tourists are leading to the almost complete closure of hammams, now replaced with modern spas in hotels; in the buildings that are still operating, the poor lighting does not facilitate the use of the services in the evening, when tourist demand is higher.

The research project, funded by the University of Manchester, has led to the testing of a prototype,

**Fig. 6 |** Natural light in the hammams al Hussayniya in Cairo and al Basha in Acre; prototype hammam Seffarine and Moulay Idriss (Fez, Morocco)-

developed between August 2012 and March 2013, able to provide better lighting during daylight hours in support of natural radiation and at night by means of solar-powered LED lamps, appropriately inserted into blown glass bulbs positioned in the holes of the roof. The solar panel produces 18 Volt at 10Watt and is used to charge a 12 Volt battery pack. Control logic turns the LED light on at a predetermined lighting level and a dc-dc converter maintains the voltage from the batteries to the LED bulb at 12 Volt even when the batteries discharge. The light is turned off when the batteries reach a certain level of exhaustion (Sibley & Sibley, 2013). The results showed a clear improvement in the quality of visibility during the day and a range of about 8 hours of solar-powered electric lighting at night.

## 5. Performance improvement of BIPV panels

In many of the cases analyzed in the previous section, photovoltaics have partly or totally replaced or flanked materials and traditional building systems, becoming a characteristic element of the intervention on historic buildings rather than a superfluous addition. Together with the traditional integration of the modules on the roof, there are also the possibilities of installation in adherence to the façade (Building Added/Attached/Applied Photovoltaics, BAPV and Photovoltaics Curtain Wall, PVCW), through supporting substructures, or as prefabricated components of the building envelope (Building Integrated Photovoltaics, BIPV), able to meet precise technological requirements, such as water and air tightness, mechanical resistance, stability, safety in case of fire, etc. (Farkas *et al.*, 2015)

The current BIPV market (photovoltaic façades are a part) is 8.5 GW, about 2.5% of the global photovoltaic market, with Europe accounting for 40% thanks to government incentives, in particular from Italy, France and Germany (Delponte et al., 2015). However, BIPV technology has, as has been amply demonstrated (Chatzipanagi & Frontini, 2012), a limited thermal insulation performance due to its high solar factor and thermal transmittance values. The thermal transmittance of commercial double-glazed photovoltaic modules (5.7 W/m$^2$K, a similar value is also obtained in the presence of inert gas instead of air) could be reduced by minimizing conductive and convective heat transfer. This is possible with the introduction of a vacuum chamber, as has already been done for glass with vacuum insulation, achieving a U-value of approximately 0.86 W/m$^2$K (in the case of 4 mm double glazing and 0.7 mm vacuum) and excellent sound insulation performance.

The experiment conducted by Hong Kong Polytechnic University - based on the results obtained for photovoltaic curtain wall by Chinese authors in 2016-2017 (Wang et al., 2016; Zhang et al., 2016, 2017) – tested a small-scale prototype of a vacuum BIPV curtain wall, set up in the Hong Kong university campus.

The vacuum photovoltaic panel has a sandwich structure composed as follows: a layer of polyvinyl butyral (PVB) is placed between the first laminated glass (with amorphous or monocrystalline silicon cells and a light transmission of 12%) and the low-emissivity vacuum glass, which acts as a connection between the layers, keeping the vacuum created intact.

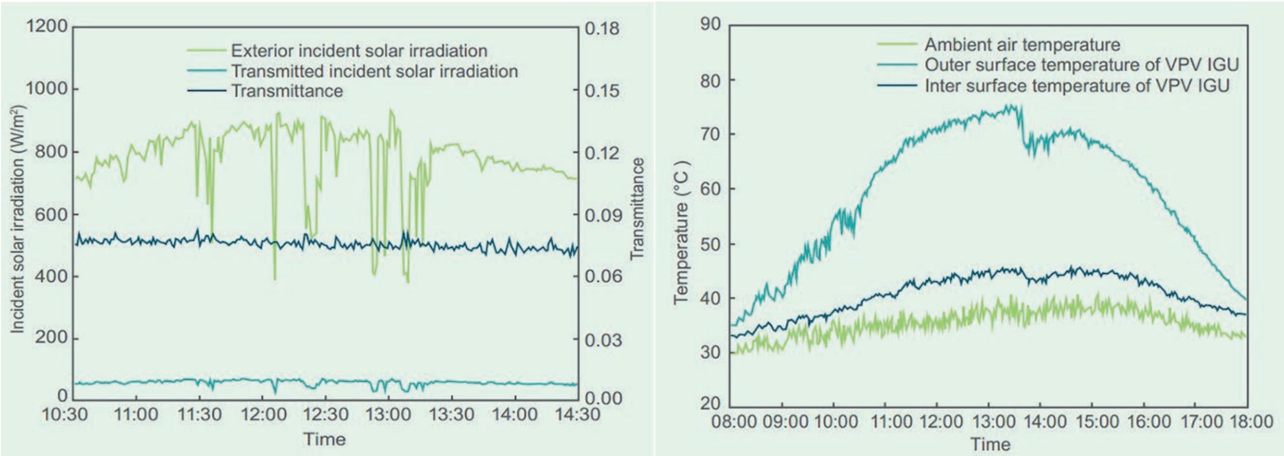


**Fig. 7 |** Transmission diagrams of incident solar radiation (source: YANG Hongxing).

The panel, whose size is 1300x1100 mm and thickness 20.87 mm, was monitored with pyranometric detectors, spectrometers, sensors for the surface temperatures reached by the glass. The I-V curves, the indoor temperature, the thermal performance of the glass, the production of electrical energy under standard STC conditions (air mass 1.5; solar irradiation 1000 W/m$^2$; cell temperature 25 °C) were then analyzed and the data were recorded by the GL840 Midi Data Logger at 1 minute intervals.

The graphs show that when the incident solar radiation varies, during the hours between 10:30 and 14:30, the average transmission of solar radiation, due to the vacuum, is approximately 0.08, and the temperature of the outer plate, in direct contact with solar radiation, is much higher than that measured in the inner plate.

During the hottest part of the day, at 13:30, the external plate reaches the maximum temperature of 75.3 °C, while, the temperature of the internal plate is 44.2 °C; the indoor air temperature undergoes slight variations that prove the effective mitigation of heat transfer in the indoor environment. So the photovoltaic glazing with vacuum insulation can contribute, compared to traditional single-glazing, to a reduction in cooling load and energy expenditure, improving thermal comfort. In addition, measuring the power generated by the photovoltaic cells, as solar radiation and exposure vary, shows the same consistency as production without the vacuum.

A further comparison, between PV vacuum glazing and traditional transparent glass, was made in order to evaluate the variation of indoor temperature: in the first case the temperature had an average value of 39.6 °C and a maximum of 40.3 °C; in the second case the values were 43.6 °C and 44.7 °C, respectively. The U-value of PV vacuum glazing was then evaluated, obtaining an average value of 1.5 W/m$^2$K, corresponding to a heat flux of 15.4 W/m$^2$.

Moreover, a study was conducted to investigate and compare the energy performance of the vacuum PV glazing and other commonly used energy-efficient glazing.

In the research methodology, a simulation model, based on EnergyPlus and WINDOW, has been developed to simulate the overall energy performance of different windows taking into account of their thermal and power performance. This model is used to simulate the overall energy performance of the vacuum BIPV curtain wall in comparison with other commonly used windows:

1_single-pane clear glazing; thickness 5.7 mm; U-value 5.541 W/m$^2$K; Solar Heat Gain Coefficient, SHGC = 0.817

2_double-pane clear glazing; thickness 24.1 mm; U-value 2.631 W/m$^2$K; SHGC = 0.703

3_vacuum glazing (low-e); thickness 11.5 mm; U-value 0.648 W/m$^2$K; SHGC = 0.391

4_single-pane PV glazing; thickness 8.0 mm; U-value 5.254 W/m$^2$K; SHGC = 0.489

5_double-pane PV glazing; thickness 25.7 mm; U-value 2.584 W/m$^2$K; SHGC = 0.354

6_vacuum PV glazing; thickness 13.8 mm; U-value 0.557 W/m$^2$K; SHGC = 0.143

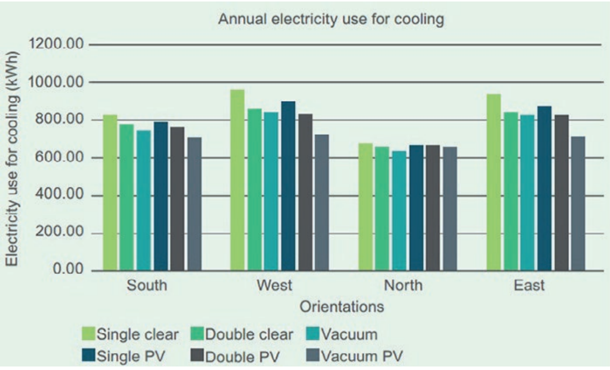


**Fig. 8** | Annual cooling electricity consumption with different types of glazing in Hong Kong (source: YANG Hongxing).

In order to simulate the annual thermal and power performance, a 'test chamber' was created (2.5 m × 2.3 m × 2.5 m) in Hong Kong. The different types of glazing described were applied in the external wall and simulations were carried out by orienting the glazing to the north, south, east and west. The graph in Fig. 8 shows the annual amount of energy used for cooling.

The cooling electricity consumption with vacuum PV glazing (type 6) is 705.56 kWh per year and it is 14.2%, 9.8%, 8.4%, 7.1% and 4.1% lower than that obtained with glass types 1, 2, 3, 4, 5, respectively the vacuum PV glazing has the lowest U-value and SHGC among all types of glazing.

In the developed prototype, the visible light transmission is 12%, which could cause a higher power consumption, however, the light transmission can be adjusted to a value higher than 20% during the panel construction phase according to the actual area occupied by the photovoltaic material.

Certainly BIPV technology, highly revolutionary in its way of approaching or replacing the existing buildings, is more suitable for historic buildings for which a radical renovation of the building envelope is essential or an addition, with new volumes, is needed to increase the potential of the property.

If, on the other hand, a low-impact intervention is desirable, a restyling (Chen et al., 2012) that does not affect the state of the curtain wall, it is advisable to use PVCW technology, which is able to combine aspects relating to decorative features with the production of electrical energy for air cooling/heating and lighting. In this case the photovoltaic curtain wall becomes a second skin able, as shown by recent experiments (Zhou et al., 2017), to reduce heating energy demand by 16% and cooling energy demand by 17% (Li et al., 2015; Peng et al., 2013), in case of southern exposure and under certain conditions of solar radiation, ambient temperature, hours of sunshine, shading of nearby objects, weather conditions. These values were obtained by applying a photovoltaic façade, consisting of monocrystalline silicon modules (power 160 W, efficiency 19.8%, size 1560 mm × 880 mm), to the south wall on the Institute of Building Energy (Dalian, China).

## 6. Conclusion

The data on Italy's energy-consuming building heritage, more than 30% built before 1945 (18.3% before 1919 and 11.8% between 1919 and 1945), should make us consider which strategies to adopt to improve the performance of the building envelope. In the restoration and redevelopment of this building context, the sustainability of processes technological solutions requires deeper reflection due to the complexity of the many variables.

The known interventions of insulation, plant adjustments, installation of high-efficiency air conditioning systems, photovoltaic systems, solar thermal systems,..., must be properly evaluated according to the indications proposed by the sustainability protocols adopted in Italy - with particular reference to those dealing with historic buildings (Green Building Council Historic Buildings) - and by the operational methodologies tested in other countries (Laboratoire d'Energie SOlaire - Qualité-Sensibilité-Visibilité of the EPFL Polytechnic of Lausanne).

The dichotomy between aesthetic-testimonial and energy-environmental requirements has not yet been overcome at national or EU level, so that even today, with rare exceptions, photovoltaic systems are considered as an architectural superfetation of the building and not as an architectural element that can be integrated.

This "mistrust" of photovoltaic technology, in particular, has allowed some exemptions from energy efficiency targets in the case of " (…) buildings officially protected as heritage or by reason of their special architectural or historical value, where compliance with requirements would result in an unacceptable alteration to their character or appearance" (italian legislative decree 2010/31/UE, art. 3, paragraph 2a).

Instead, the sustainability of photovoltaic integration in the building envelope must be promoted through innovative reversible solutions; these solutions must also respect, not contradict, the testimonial value of the historic building and represent the architectural language of the 21st century.

Although the Superintendence Authorities have authorized the integration of photovoltaics even in symbolic buildings in some cases - for example in the roof of the Paul IV Hall in the Vatican, designed in 1970 by Pier Luigi Nervi - in other contexts, such as the Aeolian Islands, these interventions are still not allowed or feasible under strict restrictions.

Experimentation with photovoltaic technology can facilitate integration: Building Added/Attached/Applied Photovoltaics, BAPV; Photovoltaics Curtain Wall, PVCW; Building Integrated Photovoltaics, BIPV, are added to the traditional systems of modules installed on the roof, when current regulatory limits can be overcome. The solutions, such as vacuum photovoltaic modules, ensure not only the production of electrical energy but also a reduction in energy requirements for heating and cooling and in thermal transmittance of opaque vertical closures.

The problems and solutions addressed in the paper implicate not only the solution of technically and technologically complex problems (which are relatively easy, given the current state of theoretical knowledge, the technologically advanced level of the market and the potential of simulation and shared design programes), but also require a deep reflection on the very meaning of "architecture", which is very difficult to solve. Some aspects that cannot be ignored probably need discussions and cultural approaches that are not easy to analyze and specify in the short timeframe required by the situation.

It is necessary to emphasize the clear prevalence (in the "old" continent) of existing buildings in which techniques, materials, types and styles differ considerably from one another and for which it is difficult, if not impossible, to identify a single line of thought and sustainable intervention; as was restated in the paper, the assessment of cultural compatibility is, in fact, much more aleatory than the technical assessment of achieved or attainable performance. Similarly, we could underline the need to accelerate our action, at planetary level, to reduce not only polluting emissions but also solid waste, which requires an additional wealth of knowledge and technical-legislative tools (e.g. maintenance plans, demolition projects, minimum environmental criteria) that are perhaps not yet sufficiently applied or even developed (and unambiguous).

The current state of design and construction probably needs to abandon as soon as possible the drive to specialization that was predominant in the cultural models of the last half century without the mentality of shared and participatory design having spread at the same pace, in order to put back man, and not economy, at the centre of the world, paraphrasing a Renaissance model in which Vitruvian man becomes modern man and the world becomes the globalized, multi-ethnic world to which all societies are now tending.

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