TECHNOLOGICAL EVOLUTION OF PHOTOVOLTAIC ENVELOPE. CONSTRUCTIVE INTEGRATION AND PARADIGMS OF INNOVATION

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1. Abstract

The building integration of photovoltaics (BIPV), as a key strategy of the forthcoming "Net Zero Energy Building", now promises unprecedented opportunities for the expressive language of the building and open to innovative technological scenarios the project of the building elements.
The "Technology transfer" of these systems is one of the "causes materialis" of innovation in architecture and outlines important aspects of conceptual and performance evolution of eco-friendly envelope, subject of a growing functional accumulation and technological complexity, and increasingly multi-capacitive and interactive. The part of the research presented, it aims to outline some key aspects of the process of technological-constructive innovation of the building organism, connected to the use of photovoltaics (PV). The proposed contribution, starting from the definition of introductory *classes of integrability* of reference for the theme of BIPV, reports the study of specific sub-classes useful for evaluating the degree of constructive integration of photovoltaic systems in the building constructive elements.
This work focuses on the schematization of different constructive approaches of BIPV, from those based on the principle of adaptation, optimization and stratification of the vertical enclosure or roofs with PV elements, up to those who represents the most advanced forms of innovation like unitary, multi-functional and polyvalent building elements. It follows a critical reading addressed by narrowing the main strategic forms of technological development of envelope with a brief summary of new concepts and emerging trends in the PV contemporary envelope, both in relation to innovation of morpho-typological and constructive nature, with the reference to some design experiments that show unprecedented spatial, functional and technological features of the building (luminescent shells, media facade, ultra-thin membrane).

2. Introduction: BiPV

The acronym BIPV (Building Integrated Photovoltaics) refers to a design principle according to which the PV system is conceived not only from the standpoint of energy supply but including the role of architectural and constructive element (dual function) of the building envelope. The PV integrated module, no more thought of as a *collages concepted* component, applied or superimposed on the building, becomes a technological element part of the constructive equipment of the building and at the same time, tool of *solar design* for the expression of the architectural language. In general, the concept of BIPV is translated into "architectural integration" of photovoltaics, but this definition is partial to a more detailed analysis, as summarized below. In literature, the theme of the BIPV finds space for several years in research of international level that have defined criteria and different levels of integration. From 1997 to 2001, the Task 7 of the *International Energy Agency* (IEA PVPS, Photovoltaic power systems in the built environment) has conducted a specific study, *"aimed to improve the architectural quality, technical quality and economic sustainability of photovoltaic systems in the built environment to remove barriers to their introduction as a significant energy option"*. This research had as its outcome, in addition to the preparation of a comprehensive database of BIPV products and projects, the list of *criteria of "architectural integration"* (Nagel & Zanetti, 2008).

Since the end of 2008 the Task IEA-SHC 41 (IEA, 2008) renewed the research *"Solar Energy and Architecture"* putting the basic theme to promote *"the architecture of high quality for buildings that integrate solar systems."* With the aim to achieve this objective, the research was organized into three main parts:
- Guidelines for quality criteria for architects and for development of new industrial products;
- Development of tools for preliminary assessment, useful in the design phase for the choice of various integration technologies;
-Collection of design examples for architects.

To a more depth analysis of the relationship between the PV system, building organism and context, now required by an increasing quality of the built environment that demands disciplinary interactions between the different actors and experts involved in the design process, emerges the need of coordination of the various cultural areas of the project, which go beyond the aspects of only energetic nature, that too often take precedence over other issues.
The project of BiPV should be recognized as the place for discussion and mediation of different, and often conflicting, levels of complexity and scale of reference and observation. In this dialectical context, often emerge aspects at the same time, both to the landscape scale and at the scale of construction or figural detail, or the need to compromise between *scientific parameters* (efficiency, power ...) and *interpretative aspects* (aesthetic, spatial, visual, cultural values...) that, at the planning stage, they need unitary solutions with respect to a contextual and requirements fixed framework. It emerges in this context the need for a multiparametric assessment and a cross-disciplinary interpretation of various factors and fields interacting, as outlined below.

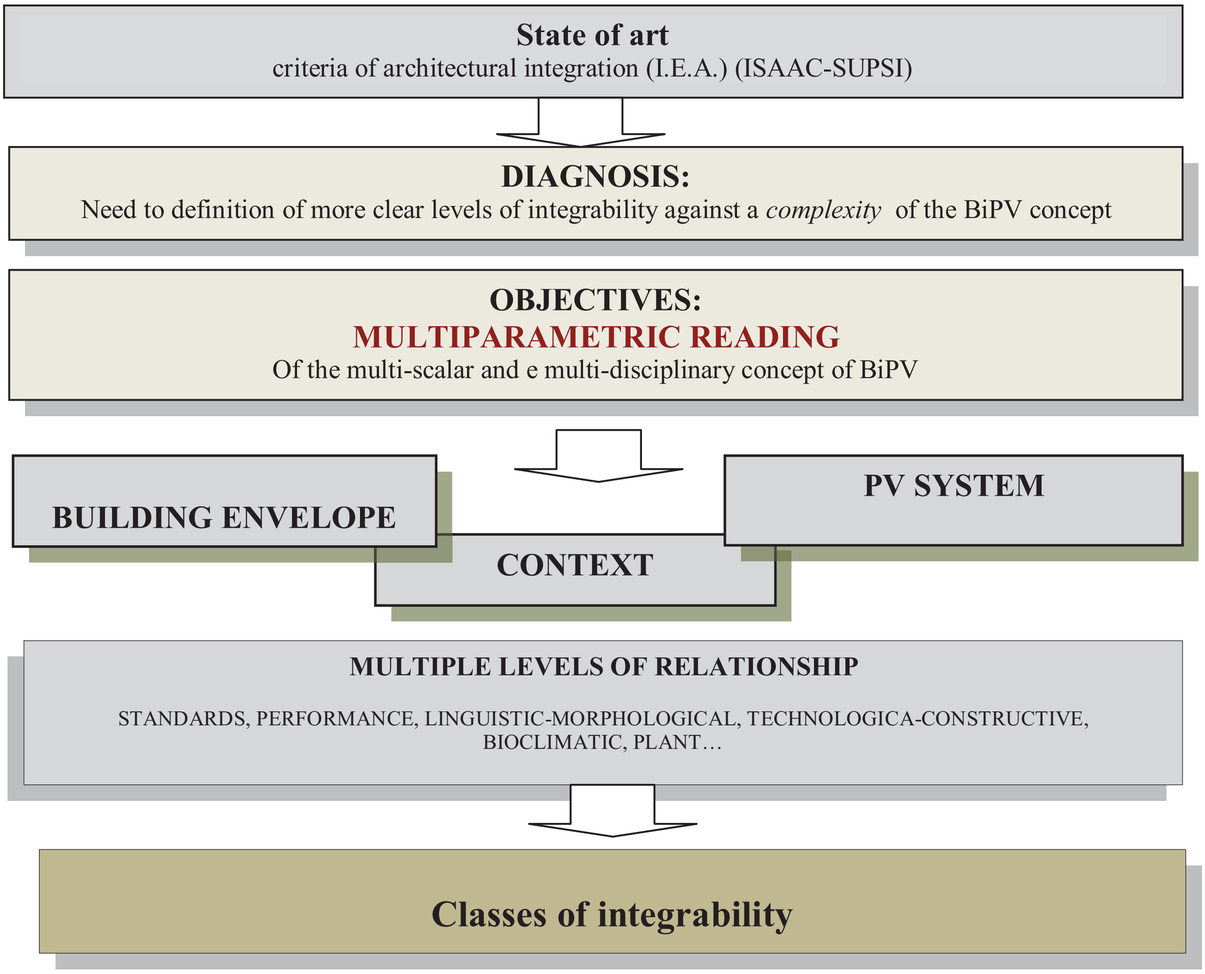


Fig. 1: Ideogram for defining classes of PV integrability

3. Classes of integrability and technological integration of photovoltaic

With the aim to outline the complexity of this relationship which is articulated around the concept of "PV integration " into the building envelope, has been structured a simplified grid of reading that defines some ***classes of photovoltaic integrability***, as a synthesis of the major functional and hierarchies relationships found in the analysis of existing studies and built examples :

Objetc of table: **Scheme of the different class of Pv integrability**	
class 1	1 **PROCEDURAL** *Object:* Regulatory and legal system that addresses procedural and operational conditions, limits and incentives
class 2	2 **MORPHOLOGICAL-FIGURATIVE** *Object:* Quality of perceptual and formal characterization of the architectural language of the building envelope
class 2	3 **BUILDING-PERFORMANCE** *Object:* requirements of optimization of energy production and construction-technological requirements of the building.
class 4	4 **TECHNOLOIGCAL-CONSTRUCTIVE** *Object:* levels of integration in the elements of building constructive equipment
class 5	5 **BIOCLIMATIC -ECOLOGICAL** *Object:* PV system integration in the bioclimatic and ecological design of the building in its life cycle.
class .6	6 **ENERGY-PLANT** *Object:* Parameters for the optimization of electrical function of the plant system.
class 7	7 **LANDSCAPE-CONTEXTUAL** *Object:* aspects of acceptability in sensitive context of historical and environmental value
class 8	8 **ON EXISTING** *Object:* aspects of integrability in the redevelopment of existing buildings.

Although they are also crucial the financial aspects in monitoring of a BIPV solution, they are not considered in this scheme to avoid reflections of financial nature, depending on the laws of the market and incentive schemes, little relevant in the scope of study. The following is the deepening of the specific "class" of *technological-constructive integration.*

3.1. Technological-constructive integrability

The study, considered the various themes related to the BIPV, has the objective of deep the specific aspect of technological-constructive innovation (class 4) of the building envelope. The path of innovation that has accompanied the technological transfer over the years for photovoltaics in architecture, has gone from a components initially governed by its own logical (not very different from that used on space satellites), to a production as more congruent with the peculiarities of technical elements for the building. This evolution was driven by the objective of improving the constructive "coexistence" between the new components and traditional technological elements, gradually solving the problems of various kinds on the "*how*" to integrate: the type and quality of physical connections between the building and photovoltaic components; the physical, chemical and constructive compatibility between the materials and components, frames, supports and connections; the integration of old and new functional requirements, etc ....

Over the years, this primary research to *compatibility* and *adaptation* was later joined by a path of progressive innovation of the PV building envelope, both in expressive languages and in the technological properties. Studying, specifically, the theme of technological-constructive integration of photovoltaic, it was decided to define some basic areas of inquiry, whose larger content are included in the research (Bonomo, 2008-11), which can be synthesized with identification of the following *sub-classes* (Fig. 2):

- A first, with the definition of a general abacus of ***typological alternative*** representative of the various possibilities of PV integration in the elements of the building envelope, referring to the three constructive sub-systems of *roofs, vertical enclosures and special envelope's elements* (Fig. 3).
- A second, ***the degree of building integration***, as the recognizing of the level of satisfaction of the building requirements provided for technological units, by the PV building system, like a performance index of integration that can be expressed through the four conditions (Fig. 4):
    - Independent application;
    - Overlapping application;
    - Complementary integration;
    - Total integration.

- A third, which coincides with the ***class of constructive element***, as a recognition of the hierarchical level of the PV system in the various sub-systems of constructive apparatus, which can configure:
    - basic constructive element (or basic material);
    - functional-constructive element;
    - unit of building fabric;
- A final class, on the definition of specific requirements of the ***constructive compatibility*** that is the attitude of the PV system to "interface" dimensionally, functionally and physically with the technical elements of the envelope, in respect of levels of quality required, which can be summarized in two categories:
    - *"combinability",* understood as the satisfaction of the geometric-dimensional interactions between the PV and the constructive systems, in order to ensure proper geometrical, morphological and dimensional coordination aimed to a good relationship;
    - *"coupledability",* understood as a demand for material, performance and mechanical compatibility of the union between the two systems, in order to ensure an adequate quality of the constructive coupling, in the light of requirements request.

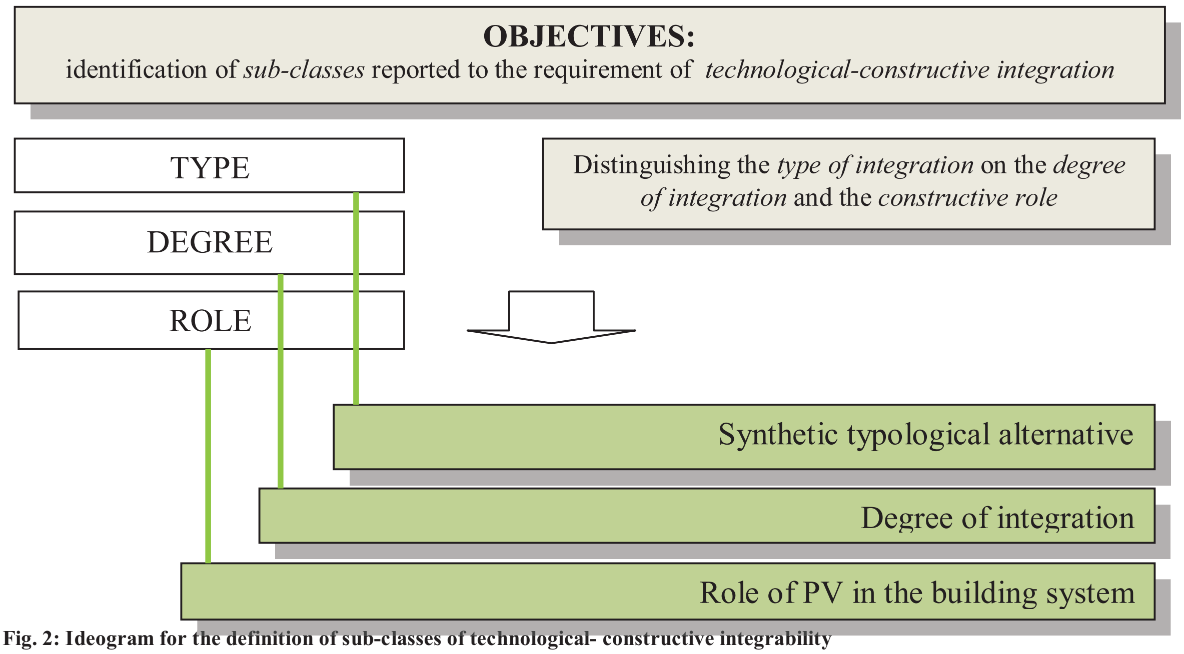


Fig. 2: Ideogram for the definition of sub-classes of technological- constructive integrability

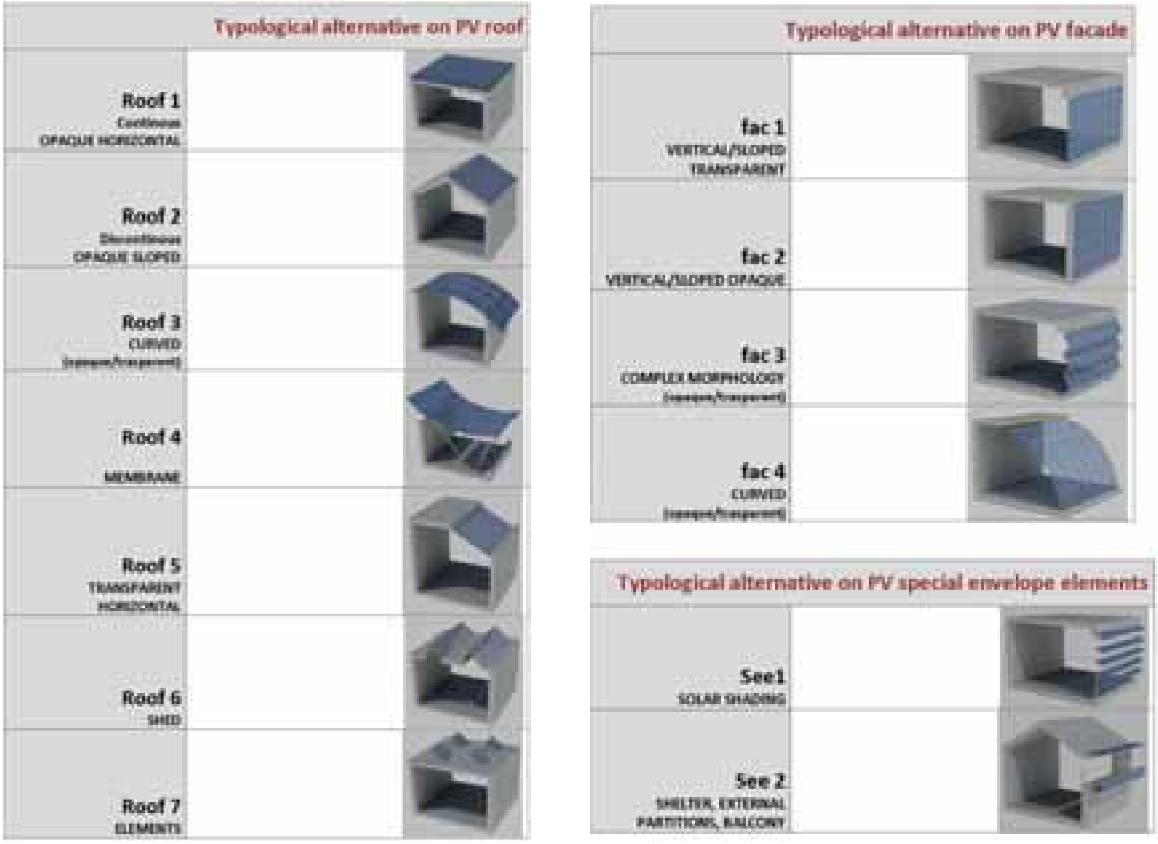


Fig. 3: Sub-class 1: Classification of different types of integration constructive alternatives

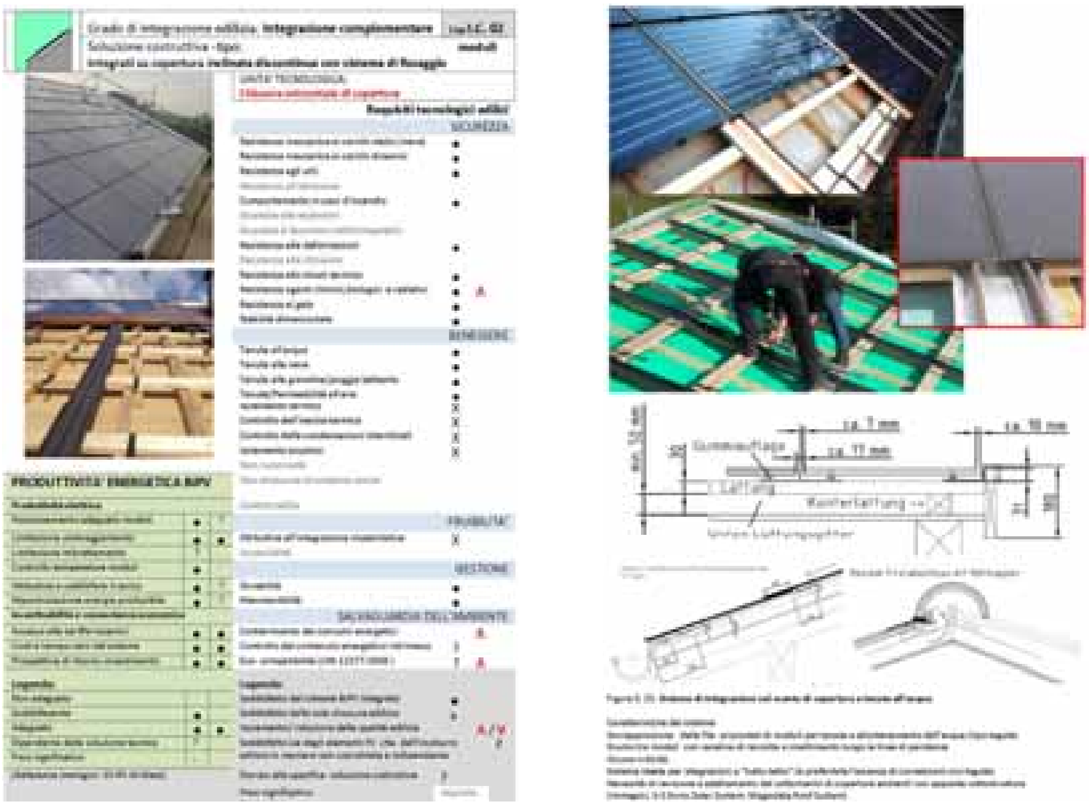


Fig. 4: Sub-class 2: Evaluation sheets of constructive-integration degree of BiPV in roof. The analysis of the level of satisfaction of different building requirements, by Pv system, determines the degree of integration.

Fig. 5: Sub-class 2: Example of evaluation sheets of the degree of constructive integration of PV façade.

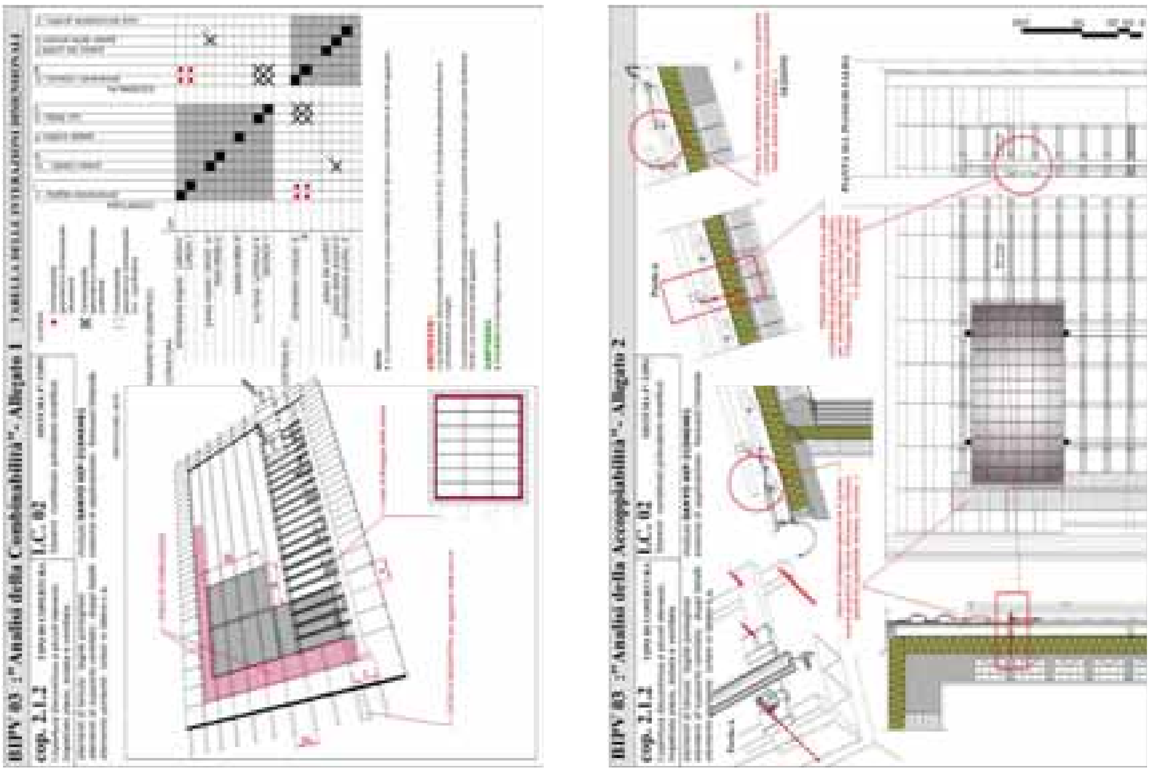


Fig. 6: Sub-class 4: Example of evaluation sheets of the *combinability* and *coupledability* of a PV system on roof, with analysis of the geometrical, dimensional and constructive critical.

4. Technological innovation of photovoltaic envelope

The path of innovation of the building envelope, read through the use of photovoltaic devices, it was in principle dedicated to improving the constructive "coexistence" between "new solar array", before only of standard type, and the traditional technological units of the building, coping, gradually, to solve problems of various kinds on *"how"* to install the panel. In this original research of ***adaptation*** of the plant on the building envelope, the growing awareness of the technological and expressive potential of PV, has led to a conceptual revolution that has passed from the vision of the solar module as a terminal installed, like a *body added* to the buildings, to that of a component of the technological and architectural system of the building envelope. The industry's next step was therefore to reconsider the ***stratification*** of the "complex" building enclosures with the interposition, on the outer surface, of the PV module, thus ***optimized*** to the dual function of component of the plant and of the construction. This "proximity" to the building opened as a result, a research in several fields of architectural language and constructive role of the solar elements, thus elevated to the rank of protagonist of the construction quality. The entrance of PV in the system of *"multiple-body"* building elements, has thus helped to stimulate a specific industrial research on the building integration, resulting in many successful technology solutions on the international scene. In many cases, the research has raised the paradigm of integration at a further higher step, ie with the inclusion of PV material as an integral part in a *unitary and multifunctional building element*. In this case, the full technological integration in the envelope, becomes an essential part of the constructive and energy strategies of the building concept, and directly affects important quality like the control of thermal comfort, or the visual and thermodynamic properties of the envelope. The *multi-functionality* and versatility, along with other paradigms such as interactivity and lightness, combined with the growing development of new materials "custom made" with higher performance, constitute the current landscape of research on technological systems in which the photovoltaic almost disappear as an autonomous entity and become an ingredient "melted" within new concepts of materials and components, at the same time synthesis of advanced technology and eco-sustainability.

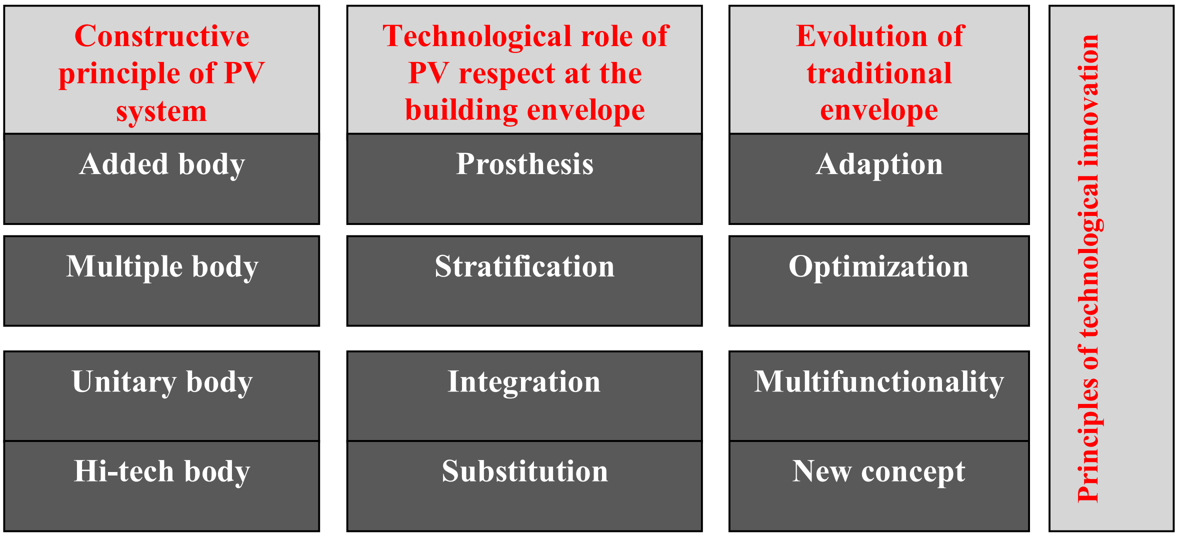
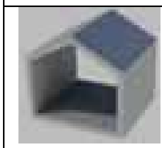
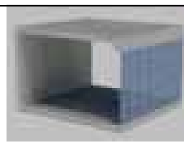
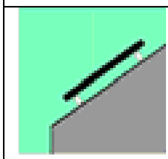
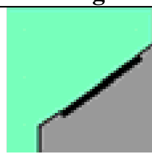


Fig. 7: Scheme of principles of technological innovation

ANALYSIS SHEET OF PV TECHNOLOGICAL INTEGRATION	
Traditional Integration on the roof	**BiPV in multifunctional Façade (rif: Schueco Energy[2])**
Typological Alternative:	
 Opaque discontinous roof	 Vertical transapent enclosure
Degree of constructive integration:	
 Overlapping	 Total Integration
Constructive principle of Pv System:	
Added body	Unitary-hi-tech body
Technological role of PV towards envelope	
Prosthesis	Integration- substitution
Evolution of traditional envelope	
Adaption	Multifunctional
Class of building elements:	
None: Plant	Maximum: Building element
Constructive compatibility: **Combinability**	
Low Low geometrical and dimensional coordination and low modularity	High Complete geometrical and dimensional coordination and modularity on the façade design
Coupledability	
Traditional/low: mechanical point fixing	Maximum: Unitary element with a PV part not materially and functionally separable
Innovative aspects in BIPV concept	
None	Concept of energetic and multifunctional interactive facade with control of thermal, humidity, visual and energetic requirements.

Tab.1: Scheme of analysis of PV technological integration on building envelope

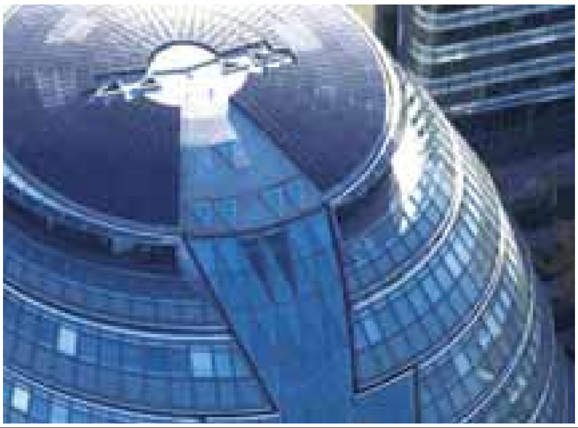
In the comparison between systems of different technological generation, it is clear that innovation is essentially linked to radically different concepts generated by the evolution of constructive principles, in which the photovoltaic becomes increasingly a component of "melted" within constructive apparatus and an indispensable element to the functionality and efficiency of the building system. In other cases, such as those listed in next paragraph, the innovation connected to photovoltaic is linked to a more complex integration approach, which involves more specifically the primary role of the architectural design.

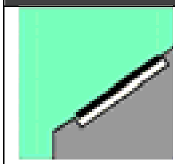
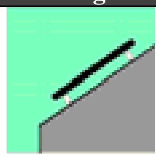
Fig. 8: Different principles of technological innovation of BiPV systems: (top left) The PV as a added body. Oskar Von Miller Forum, Thomas Herzog+Partner, Monaco (photo author); (top right) Example of stratification of roof with basic photovoltaic building elements that replace the traditional roof covering. Creaton AG "Solesia"; (bottom left) Intelligent facade Schueco Energy 2 at BAU 2009 in Monaco; (bottom right) "Green Pix Zero Energy Media Wall" in Beijing (China), Simone Giostra & Partners Architects + Arup Engineering, 2008.

4.1. Technomorphism and new spatial requirements

A paradigmatic situation of "technological innovation in architecture" related to the use of photovoltaics, is that of ***technomorph*** building solutions (Nardi et al, 1996). The strategy of integration in this case, shifts the focus from expressiveness of the building skin and from the texture design to the study of morphogenesis of the architectural organism and of its constructive parts; the building born in these cases, as synthesis of morphological parameters of PV integrability (eg. optimum orientation and tilt, the absence of shading ...), surpassing the use of formalistic or archetypal solutions. In several examples of high architectural and constructive integration of PV, in fact, the shape of the building is fixed at the start of the design process, and only after it has adapted and, possibly, optimized on the presence of the solar system and of its requirements. In this current case, therefore, the phenomenon of replacement of a material with another with PV, is accompanied by the *permanence* of formal references to the characteristics of the original material and pre-existing technologies.

In this historical process the appeal to the ancient forms and techniques, however, in general, is attributable to the "physiological" impossibility to have adequate facilities and tools appropriate to the innovation, that has not yet had time to be assimilated. Through the strategy of "technomophism" can be read instead an elaborate form of design innovation, which involves the creation of forms in a language coherent with its design and constructive concepts; it is the case, in the history of materials, of the steel and of the transition from the archetype of the arched bridge, first used in the infrastructure of cast iron (because of the permanence of the reference to the use of the techniques of stone and wood), to the cable-stayed or suspended bridge. Although today, in reference to the use of photovoltaic, this innovative process is highly hybridized and made not very evident by the functional accumulation and symbolic values of the contemporary building envelope, it is possible to find a *technomorph* approach when the architectural outcome of the entire building, becomes the synthesis of advanced PV design requirements with those of, for example, energy efficiency, through an innovative reworking of the project.



ANALYSIS SHEET OF PV TECHNOLOGICAL INTEGRATION	
Office building "Energy Base" in Vienna (A), Pos Arckitecten, 2008	**London City Hall in London Foster & Partners, 2002**
Typological Alternative:	
 Complex morphology envelope	 Curved roof
Degree of constructive integration:	
 Integrazione complementare	 Sovrapposizione
Constructive principle of Pv System:	
Multiple body	Added body
Technological role of PV towards envelope	
Stratification	Prosthesis
Evolution of traditional envelope	
Optimization	Adaption
Class of building elements:	
Functional building element	Functional building element
Constructive compatibility: **Combinability**	
High: Good geometric-dimensional coordination	High: (trapezoidal module) Good geometric-dimensional coordination
Coupledability	
Traditional: mechanical fixing system	Traditional: mechanical fixing system
Tecnomorph solutions: Innovative aspects in BIPV concept	
Morphology of envelope and multifunctionality studied for energetic production, solar control winter/summer and daylighting comfort.	Morphology of the envelope designed to optimize exposure to the sun, the aerodynamics and the maximization of energy production on the roof

Tab.1: Scheme of analysis of PV technological integration on building envelope

In these cases, often, the concept of PV *integration* is not necessarily synonymous with a high degree of constructive integration, or with an innovative constructive principle or a relevant technological role of the solar component in the building equipment (see Table 1); it is instead the case of buildings where the presence of PV is never an end in itself, or disconnected from the process of morphogenesis of the architectural design and from its overall energy concept, but is an integral part of these design process or, in other words, an advanced synthesis of different integration themes, previously summarized as *integrability classes*.

Fig. 8: Examples of "technomorph" forms in relation to the use of photovoltaics. (left) Sunlight House II, Henry Troy Architect, (right) Building integration of stationary reflectors with PV or PVT absorbers tracking. Architectural concept of buildings with integrated systems PVT in combination with reflectors for lighting the interior (Cisbat Congress 2009)

In other ways, the spatial innovation connected to the photovoltaic involves, in addition to the results on the external form, the project of building **interior spaces**. With the growing functional accumulation that focuses on building perimetral enclosures, which meet all the main technological requirements of security, comfort, and energy efficiency (including artificial lighting, air conditioning, ventilation ...), the interior of the building are increasingly "lightened" by the presence of plant and from their primary requirements, so resulting increased distribution, spatial, functional and technological flexibility.

Fig. 9: "Future Cube". Concept design of multifunctional solar facade able to perform complex functions, such as solar control, the spread of natural light, artificial lighting, aeration and ventilation. Collaborative project developed by Behnisch Architekten, Zumtobel Lighting, Transsolar Energietechnik, Sunways, Bartenbach Lichtabor, 2010 (immages: The Plan).

4.2. New concepts of envelope: lightness, flexibility, interactivity and media.

While at widespread scale is still needed to disseminate basic criteria for the correct PV integration, in the most interesting examples at international level, the envelope seems to be able to meet the criteria of eco-sustainability in a spectacular way with advanced shapes and technologies, synthesis of innovative technological aspects and exploration of new sensory-perceptual forms. Thanks to solar, in some realization, the building acts as a self-sufficient organic system, harvesting solar energy during the day and using it to light up at night, offering unprecedented urban and architectural spaces, in which the building is dedicated to media and digital art, thus demonstrating a spectacular use of "sustainable" technology" applied to the contemporary envelope. In these cases it is evident that the presence of PV is so integrated into the "composition" process to be functional, not only at the creation of languages and architectural images as usual, but as to push in the characterization of space-perception through evolved concept, which often exceed the criteria of strictly architectural interpretation (or trends of trivial energy optimization) and tend to graze the fields of component design and contemporary art.

Fig. 10: (top left) *Boxenstopp*, Branschweig (D), Daniel Hausig, 2000. The envelope is made of, outside, solar cells and electroluminescent cells from inside (pictures: C. Luling) (top right) "Metabolic Media." Synthetic textile with micro LED powered by flexible organic solar cells or DSC. The traditional surface becomes dynamic, bright screens. (Photo: www.loop.ph) (bottom left)Solar Tensile in Intersolar 2011 Monaco; (bottom right) "Wrap ® Smart". Research by Stefan Kieran and James Timberlake Architects, 2003. Testing of innovative building multifunctional composite material. The printed thin film solar cells, storage energy and, in combination with OLED technology, enabling the lighting of the interior, where the phase change materials provide to microclimate control. (Photo: www.kierantimberlake.com)

5. Conclusions

The study discussed, through the determination of performance levels of constructive integration, allowed to establish some criteria for the evaluation of BiPV degree, useful in the analysis of built examples, and as a reference methodology for control the design process of new realizations of BIPV (Di Giovanni Bonomo, 2011). The general purpose of this study, still ongoing, has moreover been to reconcile the paradigms of BIPV stratified over the last years and the emerging trends according to an evolutionary logic of the building construction and "technology", trying to link the different forms of integration "through the continuous thread" of *technological innovation in architecture*.

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