Simulation of the Renewable Energy Production Potential of Building Integrated Photovoltaics on Residential Buildings in Naples

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Abstract. In Italy buildings alone are responsible for 49 million toe of energy consumption, the most energy-intensive sector responsible for almost half of the national total and, despite the modest population growth recorded in recent decades, energy consumption has increased by + 45% since 1990. European and national decarbonisation goals and the growing demand for energy production from renewable sources requires a pervasive use of integrated photovoltaic (PV) systems and components. Innovative multifunctional building integrated photovoltaic (BIPV) systems enable the widespread integration of such solutions into the building sector. BIPV solutions on the market differ not only in technology, but also in their visual appearance and different integration methods, with features ranging from modularity and simplicity of assembly to lightness and structural safety, with the possibility of including insulation or micro-ventilation components. The study presented aims to evaluate the applicability of BIPV solutions on a sample of residential buildings in Naples (Italy), with the goal of assessing the most effective integration methods according to different urban contexts and typological-morphological features, but also to discuss the critical aspects of the pervasive use of these solutions.

Keywords: Building Integrated Photovoltaics (BIPV) · Energy transition · Decarbonisation

1 Introduction

Several crises in recent years - including climate, pandemic and energy crises - have highlighted how they affect urban settlements. These have shown how cities and lifestyles, as well as housing stock, are no longer able to withstand multiple and converging impacts. If with the 2020 lockdown there was a strong contraction in energy demand, the generalised economic recovery of 2021 and the subsequent expectations - which in our country fuelled a GDP growth of about + 4% - induced a spike in demand for electricity that translated into a surge in costs.

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On this growth ground, for the world's economies and in the wake of the challenge induced by the energy transition of Next Generation EU[1], in February 2022, the profoundly critical geopolitical tensions in Europe were triggered. This suddenly aggravated the security of supply of fossil fuels (mainly gas) with a contagion effect on electricity prices, which, in our country, is produced through a significant share from fossil fuels [1].

Given such a complex and evolving framework, it becomes even more necessary to implement large-scale building renovation actions, adopting operational and management strategies that can rapidly reduce dependence on fossil fuels. The need for a reduction in fossil fuel consumption should rely on renewable energy sources and energy efficiency in line with the 2030 climate and energy package Fit for 55[2].

According to the European Commission, the most interesting priority fields of action for the building sector include efficiency, energy saving and the reduction of energy consumption in buildings on the one hand, and the development of the value chain in technological innovations for renewable energies and building technologies on the other hand. It will be necessary to diversify energy sources and to focus on renewables considering the three joint climate, energy and security goals, also in the context of a revision of some of the National Recovery and Resilience Plan (NRRP) missions.

In the recent REPowerEU[3] outline plan, the European Commission has set the goal of increasing Europe's energy independence and energy resilience not only on the basis of diversifying gas supplies, but also by more rapidly reducing the use of fossil fuels and energy consumption, by intensifying decarbonisation, aiming at energy efficiency, increasing renewable energies, transitioning to the predominant use of electricity in buildings, shortening the time and facilitating the approval process of projects for the installation of Renewable Energy Sources (RES) plants.

1.1 The Role of BIPV Systems in the Energy Transition Scenario

The operations of buildings account for 30% of global final energy consumption and 26% of global energy-related emissions (8% being direct emissions in buildings and 18% indirect emissions from the production of electricity and heat used in buildings) [2]. In Italy buildings alone are responsible for 49 million toe of energy consumption, the most energy-intensive sector responsible for almost half of the national total and, despite the modest population growth recorded in recent decades, energy consumption

[1] EC—European Commission (2020), A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, COM/2020/662 final, Brussels.

[2] EC—European Commission (2021), 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, COM/2021/550 final, Brussels.

[3] EC—European Commission (2022), REPowerEU: Joint European Action for more affordable, secure and sustainable energy, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, COM/2022/108 final, Strasbourg.

has increased by + 45% since 1990. Regarding greenhouse gas emissions, buildings alone account for 113 million tCO2eq, the second largest sector in Italy responsible for 27% of national emissions. Approximately 60% of these emissions come from housing and the rest from offices, public and commercial buildings [3].

The challenge that can be played by integrated photovoltaic (PV) systems for building renovation should be implemented with rapid and well-structured technical retrofit actions of housing, buildings and building complexes, verifying their environmental, technical and economic feasibility. This involves planned actions to achieve contributions to the resolution of critical energy issues by integrating the objectives of decarbonisation and green transition.

Achieving complete decarbonisation of the electricity sector requires a widespread deployment of photovoltaic installations. Households are essential in this development, with levels of competitiveness that mostly depend on electricity prices and taxes. Developing new PV on building envelope, especially for households, will contribute decisively to decarbonise the electricity sector thanks to smart self-consumption policies, new business models for cross-cutting applications like electric mobility, solar-based heating and cooling, and emerging applications [4].

1.2 Evolutionary Trends in BIPV Systems: Product Innovation for a Widespread Architectural Integration

Contemporary research in the production of cutting-edge Building Integrated Photovoltaic (BIPV) systems and products is focused on the development of flexible, colourful solar cells or modules that offer high efficiency even in partial light exposure or cloudy conditions, or on improving the performance of a photovoltaic technology that can also be used inside homes. Although the typical efficiency of solar panels ranges from 15% to 23% for residential systems, continuous improvements in scientific research are moving towards the production of increasingly low-cost and highly efficient photovoltaic devices.

BIPV modules on the market differ not only in technology, but also in their visual appearance, varying in cell, background and frame colour, cell and module shape, type of grids for electrical contacts, optical reflection of the module, transparency and flexibility. The characteristics that are most decisive for designers when selecting integrated photovoltaic products and systems relate to specific visual aspects:

- *cell colour*: the blue colour of mono- and polycrystalline cells is the most used solution, but there is a wide choice of possible colours on the market. The reduction in yield of coloured cells can be offset by the positive effects on the architectural quality of the chosen BIPV solution;
- *background colour*: while in traditional modules the background is white or black, it is possible to opt for different colour alternatives by changing the colour of the encapsulating material (normally EVA - Ethylene Vinyl Acetate or PVB - Polyvinyl Butyral). The use of glass in the module stratigraphy makes it possible to change the colour, characteristics and create screen-printed designs. The use of transparent backgrounds also allows for semi-transparent modules that are particularly versatile in construction;

- *frame colour:* the most common frames are made of natural or coloured anodised aluminium, which improves the mechanical resistance of the module and facilitates its installation, but several manufacturers now provide frameless catalogue solutions that facilitate integration into the architecture, especially with respect to specific applications such as curtain walls or sunshades;
- *patterns and shapes:* the cells can have different shapes and sizes, but the most common ones are 10x10, 12.5x12.5, 15x15cm. The distance between the cells, for energy yield purposes, is minimal, but for aesthetic reasons it can vary, also creating special patterns in the assembly of the product. The dimensions of the modules are also no longer standard, making it possible to select from numerous variants;
- *optical reflection*: this characteristic varies with respect to the choice of front protection material and the treatment, if any. For the purpose of energy yield, optical reflection should be minimised to allow maximum capture of solar radiation;
- *transparency*: this is a fundamental characteristic in architecture because in some cases it could affect both visual comfort and thermal gains. Semi-transparency of the cell can nowadays reach thresholds of 40% (standard 20%), but with proportional reductions in energy efficiency;
- *flexibility*: there are also different types of modules on the market that can be integrated into curved or flexible components (such as curtains, curved glass, aluminium covers, etc.).

In addition to the described visual aspects, the installation system is also decisive in the choice of BIPV solutions. Today's market presents evolved and specific systems for different integration methods with features ranging from modularity and simplicity of assembly to lightness and structural safety, with the possibility of including insulation or micro-ventilation systems [5].

In the building sector, both for new construction and retrofit, the main categories for the application of BIPV refer to:

- *solutions for roofs*, through products such as tile modules, PV sheathing or floor systems;
- *facade solutions*, mainly through cladding modules;
- *integrated external devices* such as sunshades and PV parapets.

The solutions most widely developed on the market are aimed at flexible and versatile solutions with specialisation and complex performance response of individual products and multifunctional systems. It is interesting to observe how the trend towards mimicry of architectural materials is one of the main focuses of product innovation, through e.g. glass treatments (printing, sandblasting, etc.), coloured filters and inter-layers in the module layering. In particular, the market penetration of BIPV modules from 'invisible' photovoltaic technologies contributes to increasing the social acceptance of photovoltaics in sensitive areas, where they have often been considered unsightly by planners and end users [6]. The focus in the coming years will be on developing new photovoltaic cell technologies, improving the performance of existing ones and expanding the fields of application of the technology.

2 Testing on a Case Study: The Municipality of Naples (Italy)

The study presented here reports part of the results developed within of the research activity carried out in the framework of the collaboration agreement between ENEA and the Department of Architecture of the University of Naples Federico II entitled "Technological innovation and design of BIPV systems for energy transition processes at the building and urban scale", within the framework of the PTR 2019–2021 Electricity System Research, Project 1.1 "High efficiency photovoltaics" [7].

Thirteen reference buildings were chosen within the metropolitan city of Naples, Italy, combining the characteristics of the urban fabric, building types, building morphology, architectural value and orientation. Buildings are mainly located in the east and west areas of the city—in the neighbourhoods of Fuorigrotta, San Giuseppe, Poggioreale and Barra—and in the historic centre.

In an initial metadesign phase—i.e. a synthesis phase between the activities of data collection and analysis of cognitive aspects—the identification of the main project strategies and the evaluation of the potential energy producibility of the choices made were carried out. Following the metadesign phase, it was possible to define the methods of integration of photovoltaics in the parts that constitute the building envelope through the choice of specific technical solutions, systems and BIPV products in order to define, through the choice of pattern, colour, transparency, non-visibility of the cell, flexibility, customisation of formats, etc., the architectural character of the building.

The main objectives of the testing can be summarised as follows:

- recognise the contextual conditions and type-morphological aspects in order to define the metadesign choice factors that are most consistent with them for the architectural integration of BIPV systems and products;
- identify the main strategic options that characterise the project with BIPV;
- identify the characteristics of the built environment that influence the energy producibility of BIPV systems;
- understand the most common ways of integrating BIPV in buildings and the related technical solutions.

3 Materials and Methods

A three-stage methodological approach—analytical and knowledge-based, simulation, output collection and systematisation - is adopted in the design process, aimed at assessing the opportunities for integrating BIPV systems on the set of reference buildings and evaluating their energy potential [8].

3.1 Analytical and Knowledge-Based Phase

In the analytical and knowledge-based phase, the aspects related to the urban context, the typological-morphological aspects and those related to the different levels of architectural value are taken into consideration to identify a set of sample buildings that are representative of the conditions and contexts most observable in the metropolitan city of Naples. The analysis of the urban fabric and that of the morphological characteristics

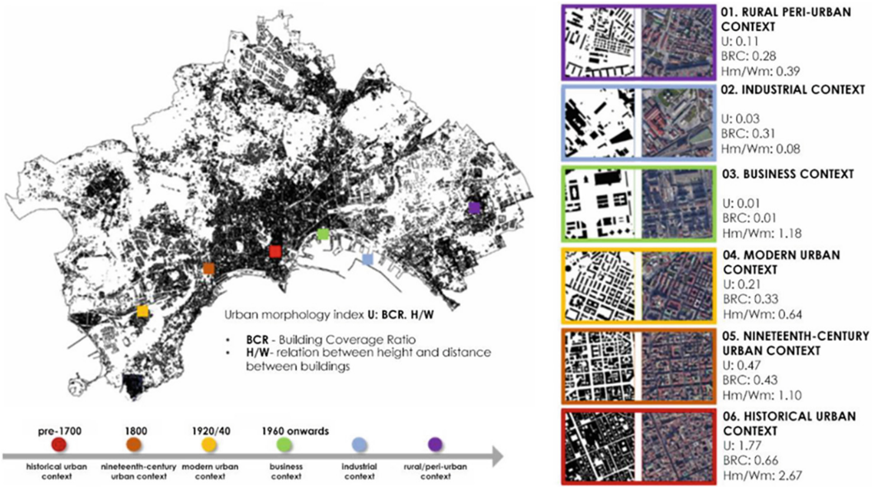


Fig. 1. Analysis of the urban fabric conducted through the assessment of the urban morphology index (U) [10] in sample areas within the Neapolitan context (500 x 500 m).

of the recurring buildings investigates the factors that will affect the quantity of surfaces appropriate for the installation of BIPV systems [9] (Fig. 1).

Three key parameters [10] - the average distance between buildings or street width (Wm), the average height of buildings (Hm) and the Building Coverage Ratio (BCR), the ratio of built to unbuilt area in a given area - are used to define six categories of urban fabric:

– *historic urban context*, pre-1700, characterised by a high ground cover ratio, irregular, small street grids and buildings of medium height;
– *19th-century urban context*, developed between 1700 and 1800, characterised by a medium-high ground cover ratio, regular, fairly wide street grids forming square or rectangular lots and buildings of average height;
– *modern urban context*, formed between 1920 and 1960, characterised by an average ground coverage ratio, regular and wide street grids forming square or rectangular lots and buildings of medium height;
– *business district*, developed after 1960, characterised by a low ground coverage ratio, very wide street grids and distances between buildings with very high heights;
– *industrial context*, developed after 1960, characterised by a medium coverage ratio, irregular street grids and very wide distances between buildings with very low heights;
– *rural/peripheral context*, developed after 1960, characterised by a medium to low ground cover ratio, irregular street grids, but with fairly wide distances between buildings and low heights.

According to different studies [11, 12] that have focused on the analysis of façade morphology to define recurring categories and considering the most common architectural solutions of façades and roofs found in the reference context, six types of recurring building morphologies have been identified.

Moreover, based on the prevailing dimensional relationships and linking building development along the three dimensions of length, height and width, three building types were identified (Fig. 2).

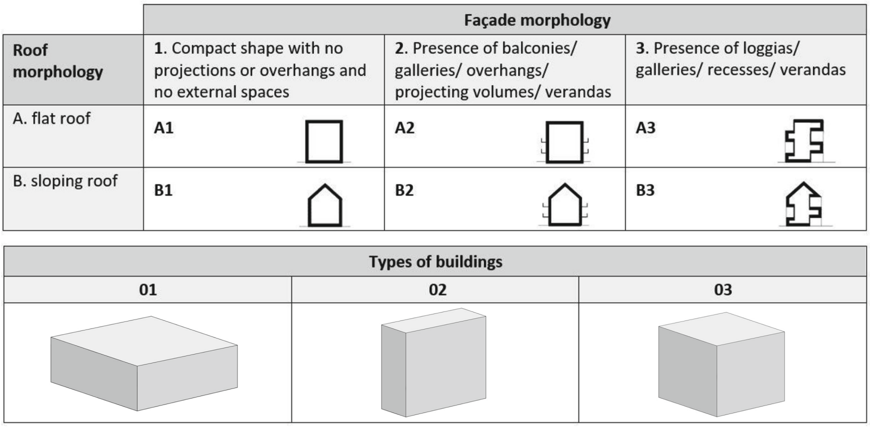


Fig. 2. Recurrent building morphologies and building types in relation to the prevailing dimensional ratios.

3.2 Simulation and Output Collection

The simulation focused on a sample of thirteen buildings selected according to different urban fabric pattern, façade morphology and building types in the urban context of Naples. The buildings sample is subdivided as follows:

– for the rural/peripheral context three in-line buildings with loggias and flat roofing, two towers, one with loggias, the other with balconies and flat roofing;
– for the modern context three in-line buildings including one with loggias and two with balconies, and one tower with balconies and one block building with balconies;
– for the business district the sample consists of two buildings, one of which is a compact form and one with balconies and a flat roof;
– for the historic urban context one building of compact form with sloping roof.

Many of the buildings identified in the sample have an authorial value and photovoltaic integration actions were considered in order to safeguard the architectural character and in line with the authorship of the building. In this sense, the simulations were not aimed at maximising the usable surface area for PV, but rather its coherence with the building, evaluating more or less 'evident' levels of integration on a case-by-case basis, with impacts of varying degrees with respect to the character of the building, opting for solutions not always visible.

Within the simulation phase, Building Information Modelling supported by the open source and interoperable tool PVSITES for estimating the energy characteristics of integrated photovoltaic systems allowed the identification of the most appropriate surfaces for BIPV integration, in relation not only to potential energy production, but also to spatial, morphological and linguistic-expressive results.

Uniform and comparable data sheets collect and systematise the outputs on the case studies. The main energy outcomes reported refer to the nominal plant power (kWp); the annual yield (kWh/kWp) and energy production (kWh per year) and per m^2 (kWh/m^2 per year); losses due to shadows and temperature effect (%)(Fig. 3).

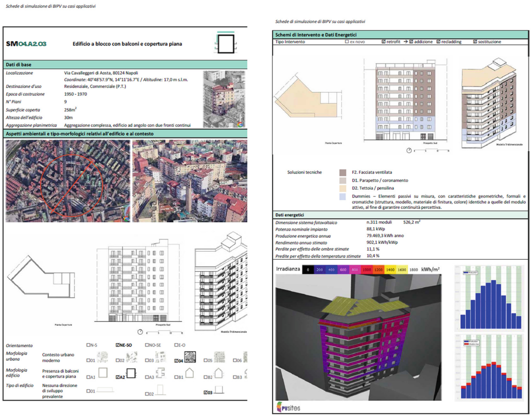


Fig. 3. Sample sheet containing simulation results on a residential building.

4 Test Results and Discussion of Strategies

Starting from the results of the testing, it is possible to elaborate some considerations on the applicability of BIPV systems with respect to different contexts and typological-morphological characters and on the energy results deriving from the integration of specific technical solutions.

4.1 Types of Urban Fabric

With respect to the urban reference context, the simulations carried out in the different scenarios show that according to the context some general indications on the integrability of BIPV solutions can be identified:

- in rural/peripheral and industrial contexts, façade surfaces suitable for solar potential are located at the first level and allow for a quantitatively homogeneous integration of roof and façade for buildings that are predominantly developed in length, while for those predominantly high, the possibility of using the façades for PV integration is limited to approx. 40% due to the frequent presence of overhangs, recesses or protrusions;

– in recently developed business districts, the predominantly high buildings, often characterised by compact shapes and the absence of balconies or loggias, allow up to 80% of the façades to be used for PV integration, while the potential integration of BIPV on the roof becomes minimal;
– modern and nineteenth-century fabrics are characterised by significant shadows on façades, allowing the application of efficient BIPV systems from the second or third level. In these fabrics developing mostly in length, BIPV on roofs prove to be the most applicable, up to 62%;
– the historical urban context, tested for only one case, proves to be unsuitable for the integration of BIPV technical solutions in the façade, not only due to the morphological complexity, but also due to the high presence of shadows cast. However, the possibility of application on roofs potentially reaches 80% [8] (Fig. 4).

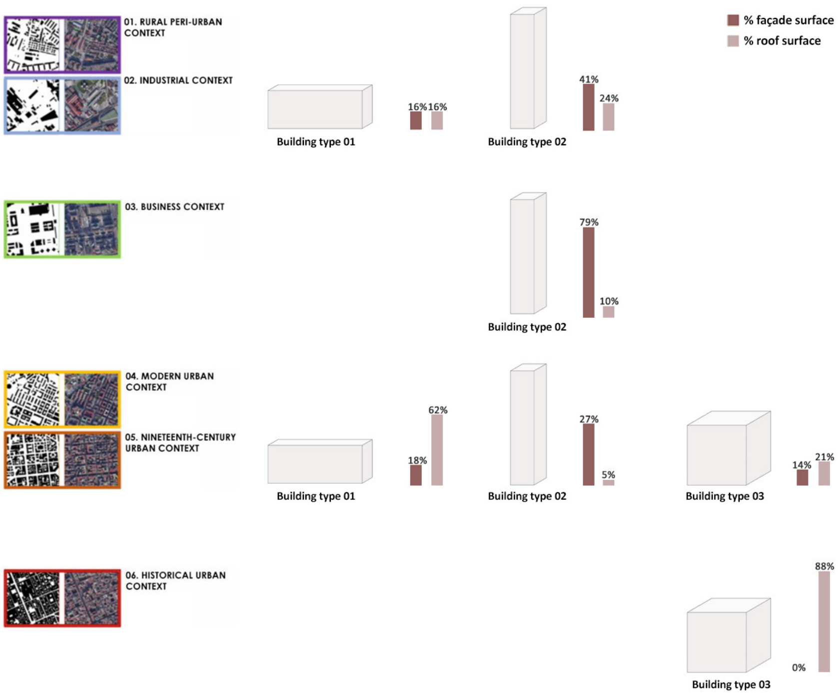


Fig. 4. Variation in the average percentage of surfaces suitable for the installation of BIPV on façades and roofs in relation to building types identified in urban contexts.

4.2 Building Morphology

With respect to the morphological characteristics of the buildings analysed, it is possible to note how buildings with a compact shape, without projecting elements, recesses and overhangs, will provide the highest integration of BIPV systems in the façade, up to more than 80%. The presence of balconies or loggias tends to significantly reduce the area in which the integration of BIPV solutions is effective, reaching in the case of balconies less than 56% of the total façade area, while loggias allow for a higher integration, with percentages between 56% and 83%.

In general, in cases where the complexity of the architectural elements in the façade is high, a detailed analysis of the irradiation in selected critical areas allows the identification of the best solar technologies adapted to the local conditions, such as exposure to direct or diffuse and reflected irradiation, shading and orientation of the building envelope elements (Fig. 5).

Fig. 5. Suitable areas (in red) for PV integration. on balconies (top) and loggias (bottom).

From the simulations carried out on the sample analysed, three main PV integration approaches emerge: the first, mainly used in the refurbishment of buildings of poor architectural quality or in degraded contexts, in which technological integration is emphasised and made 'evident', becoming characteristic of the architectural language and aimed at maximising energy production.

A second approach aims to integrate photovoltaic systems with minimal visual impact, according to a 'mimesis' approach in relation to the character of the building, with the adoption of industrialised technologies and products that integrate without significantly impacting the appearance of the building. This approach is appropriate not only in case of buildings of historical and cultural value, but also in sensitive environmental contexts, where a particular compatibility of the interventions is required. The design choices consider the available technological options, favouring those most suitable to reduce the impact on the environment, while maintaining a high efficiency of the proposed interventions. This is done in line with the objective of preserving the environmental, architectural and constructive characteristics of the context in which the intervention takes place.

The third approach refers to a type of integration that can be defined as 'hidden', characterised by a photovoltaic presence that is not always visible, but has a significant impact on the building in terms of performance. Such solutions are pervasive and affect the building in a diffuse manner, using materials and systems that are apparently simple and of low visual impact, but which achieve high energy and environmental performance. The low-impact appearance of these solutions can be an added value, as they integrate harmonically into the existing architecture, contributing to the lightness and dematerialisation of interventions. This approach favours uniformity of performance in many parts of the building, thus contributing to an overall improvement in efficiency and sustainability (Fig. 6).

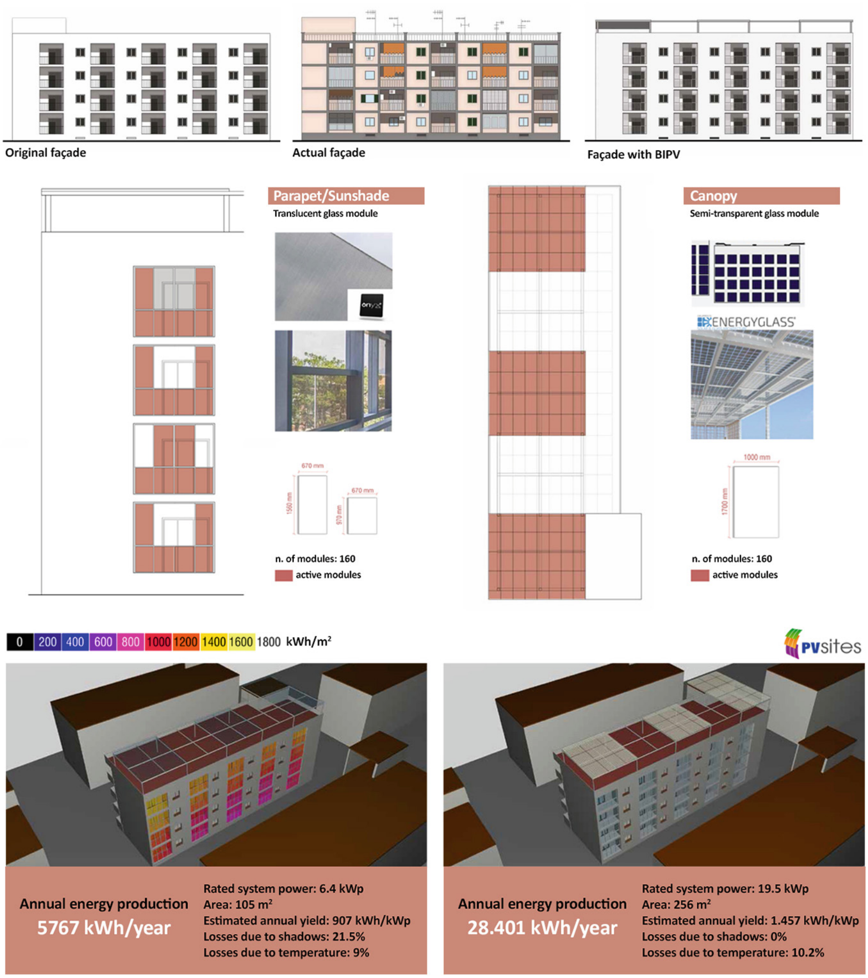
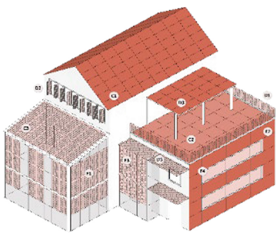


Fig. 6. Simulation of the integration of BIPV solutions on a building in the Rione D'Azeglio neighbourhood by Luigi Cosenza: integration of translucent parapets and PV shelters on the roof. Image from A. Giordano.

A further consideration can be developed regarding the aspects of design innovation in technological retrofit interventions: various degrees of transformation can be identified, ranging from the simple integration of surfaces or volumes to the more radical transformation of buildings [13] through subtraction or addition of volumes. There are several examples, especially in the international field, that adopt these methods to simultaneously improve the technological performance and architectural quality of existing buildings, when there are no specific constraints of context or authorship. In the absence of such constraints, innovative architectural and technological solutions can be adopted, for example to increase the surfaces exposed to solar radiation to overcome the problems related to the non-optimal orientation of buildings. Other solutions include surface additions (recladding), creating a second skin able to give a different architectural character and performing multiple functions in addition to those of energy production, such as micro-ventilation, thermal insulation, protection from rain and direct solar radiation [14]. Regarding the technical solutions that were found to be the most integrable in the case studies (Table 1), non-practicable continuous roofs (C2a) and parapets or crowns (D1) appear to be the most viable, as well as cold façades (F2) that not only allow to produce energy from renewable sources, but also to improve the thermal performance of the envelope.

Table 1. Overview of the most frequently used BIPV technical solutions in the case studies. Image edited from: IEA PVPS Task 15 [15].

BIPV Technical solutions in the case studies		USE
	**C1** Discontinuous roofing	1/13
	C2a Continuous roofing non-walkable	10/13
	C2b Continuous roofing walkable	4/13
	F2 Cold façade	9/13
	D1 Parapet	10/13
	D2 Sunshades/Shading	2/13
	D3 Shelter/Canopy/Pergola	3/13

5 Conclusions

The increasing environmental awareness, together with the challenging target of zero net emissions by 2050, outlines a common objective of progressive decarbonisation of environmental systems. Every building will have to be carbon neutral and this goal places integrated photovoltaic systems at the centre of a renewed design effort that looks towards buildings conceived more and more as 'semi-permeable membranes' for energy storage, cells of a large technological organism linking a large number of communities collectively engaged in complex economic, social and political relationships. [16, 17].

The transition needs to focus on renovating existing buildings to increase their energy efficiency and incorporate renewable energy capture systems as much as possible in different parts of the building. Technological retrofit interventions will have to foresee more or less dense degrees of transformation with interventions by subtraction or addition as well as by integration of surfaces or volumes. Where there are no restrictions due to the presence of constraints, it will be possible to opt for innovative solutions in terms of architecture and technological experimentation [14]. BIPVs need to be included in a balanced decision-making system that helps to perimeter a convergence between 'passive' components (orientation, thermal insulation, thermal storage systems, etc.) and 'active' components (plant elements, PV systems, etc.).

BIPV systems must therefore be part of project approaches through which the issue of savings, efficiency and the use of renewable energy sources can be managed, and which take into account the effective compliance of the project with the topics of energy self-production but also of the overall architectural quality. Facing the complexity of design, due to the onset of unpredictable conditions linked to the control of the relationship between energy outcomes and performance responses, the world of production must propose flexible packages and customised solutions linked to the technological and morphological specificities of the built environment, capable of adapting to different types of buildings and contexts. BIPV products capable of specifically responding to the needs of users are favoured, so that the possible variations in constituent elements, appearance, performance, represent a designable modality and therefore integrated in the product offer.

Starting from the observation that it is often not possible to intervene on the built with standard products and modules, given the many specific needs that vary from case to case, the need emerges to select products characterised by a lower formal pre-determination and by the possibility of being modelled 'tailor-made', through a custom-fit conception (variations on standard products within reasonable ranges and not very costly in terms of production and marketing).

The morphological quality of architectural integrability represents one of the greatest challenges for the spread of BIPV products, which have not yet fully entered the building sector in terms of language, requirements and approach. The integration of photovoltaic modules or systems in buildings - as building components—has implications not only on the performance of the building, but also on its spatial quality and on morphological and linguistic-expressive outcomes. From the point of view of the evolution of the use of photovoltaics in buildings, while the pioneering use cases of photovoltaics in buildings have been strictly influenced by the aesthetics of photovoltaics aimed at achieving maximum efficiency, recent technological developments allow for greater design freedom, proposing BIPV components for the cladding of façades and roofs that are very similar to conventional building elements.

The role of industrial product design favours the competitive positioning of morphologically or aesthetically characterised BIPV products. It constitutes a differentiating factor between various products, which are alternative to each other due to small details related to textures, surface treatments, formats, colours, material consistency, combinatory and integration possibilities, and connections. It is therefore an evolution in a technical-productive sphere that refers to a necessary updating of technical thought and the culture of the project, claiming the centrality and the unavoidability of the technological and environmental approach to architectural design.

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