Chapter 29
Photovoltaic Breakthrough in Architecture: Integration and Innovation Best Practice

Guido Callegari, Eleonora Merolla, and Paolo Simeone

Abstract In the new context of the trialling and the development of the materials, buildings systems and innovative processes required to meet new challenges posed by environmental transition in Europe and across the globe, the construction sector urgently needs to define more sustainable development models to achieve decarbonisation, as is the case in other sectors. In this context, recent experiences of incorporating photovoltaics into architecture are a clear sign of a change in focus on how systems are integrated into architectural design: a new way of viewing the technological innovation of PV modules which is ever more closely linked to the architectural design right from the initial concept stages. The study we present is based on a critical analysis of the current international state of the art of architectural design incorporating photovoltaics, selecting case studies which illustrate best practice for technological innovation to demonstrate possible scenarios for future developments. Therefore, all the principle approaches identified by the international research will be described as well as the impact that these technological developments are having on architectural style and quality of life in cities. With regard to the aesthetic and formal properties that are the dominant feature of recent practice for the integration of photovoltaics, the study will highlight further areas of research with a view to defining a component of the building shell in which the generation of energy from renewable sources represents just one of the potential components of a system integrated into the architectural style. In addition, the intention is to demonstrate that the architectural designs analysed can be considered to be the result of a close relationship between designers, applied research and the industrial sector; therefore, technological innovation of photovoltaic products will inevitably be linked to a deeper and fundamental innovation of processes leading to these results.

G. Callegari · E. Merolla · P. Simeone (✉)
Polytechnic University of Turin, Turin, Italy
e-mail: paolo.simeone@polito.it

G. Callegari
e-mail: guido.callegari@polito.it

E. Merolla
e-mail: eleonora.merolla@polito.it

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29.1 Introduction

The aim of this paper is to provide some observations that have emerged from research into the impact of technological innovation processes in defining new formal paradigms in architecture (Conato and Frighi 2018). The research in question is specifically focussed on interpreting the impacts of form on the perception of architecture, and in particular the building envelope, deriving from energy and environmental "transitions" paradigms introduced in Europe beginning with the Green Deal. Will the objectives of the European policies lead to new generations of architecture in which formal characteristics are an expression of new potential ways of interpreting the concept of environmental sustainability? We can already see that change is happening in terms of the perception of architecture and in particular in terms of building systems when analysing certain specific areas where there have been recent regulatory and market developments, such as Building-integrated photovoltaics (BIPV). This paper concisely sets out the findings of in-progress research focussed on how photovoltaics are incorporated into architecture by analysing the evolutionary process from the 1970s to the present day and outlines an initial framework of approaches to design through an atlas of "energy transition architecture" in Europe in order to produce a taxonomy of BIPV design.

The strategic role of the energy sector in European decarbonisation is fundamental for achieving climate neutrality by 2050 (IRENA 2021). The shift to energy communities has also been supported by new regulatory standards which in some cases also have implications for architecture. One example is the standard Photovoltaics in Buildings EN 50583:2016 which was the first to include the integrated photovoltaic module in a multifunctional construction component, in accordance with the Construction Products Regulation (EU) CPR 305/2011. This new interpretation has assisted with the move from PV to smart BIPV systems as innovative technological components contributing to tackling current decarbonisation challenges (IEA 2020, 2021). These processes have stimulated the market through R&D to produce new generation smart materials which can generate electricity, extending the surface area of the building envelope used for this purpose. This approach has led to a change of interpretation in how building systems are incorporated into the architectural design, as shown in the case studies analysed in this paper.

29.2 Investigation Outline

29.2.1 Research Field

The work of the research group at the Politecnico di Torino Department of Architecture and Design is centred on developing and designing smart BIPV system building envelope components characterised by prefabrication, recyclability and modularity.

The background to the work features two areas of research which are linked but separate: an industrial development project for a private client (Department of Architecture and Design 2020) and contributing as a partner on the Green Deal project H2020-LC-GD-2020 to develop a BIPV component for a demonstration project (ARV-Climate Positive Circular Communities 2020). The aim of the paper is to illustrate the results obtained from the state-of-the-art analysis in order to show new scenarios regarding the current AEC and BIPV sectors in the European context.

29.2.2 Criteria and Indicators

The research led to the definition of an analytical framework regarding the architectural, constructive and technological integration of BIPV components in the architectural design, based on the following analysis criteria:

- aesthetic and formal characteristics: the main technologies for customising the appearance of PV have been analysed;
- PV morphological integration: a classification of BIPV components that can be integrated on the vertical envelope has been identified; the main integration strategies will be explained;
- smart grids and smart buildings: selected case studies will be shown as virtuous examples of plus energy buildings.

29.2.3 Analysed Sources

Reports and scientific articles published by European research institutions have been analysed in detail, as well as major online databases for sharing BIPV best practices were consulted; interviews have also been conducted, as a means for comparison and critical analysis, with BIPV innovation technology researchers from a number

	scientific papers	selected content
1	D'Ambrosio V., Losasso M., Tersigni E (2021) Towards the Energy Transition of the Building Stock with BIPV: Innovations, Gaps and Potential Steps for aWidespread Use of Multifunctional PV Components in the Building Envelope	Product customisation
2	Attoye D. E., Tabet Aoul K. A., Hassan A (2017) A Review on Building Integrated Photovoltaic Façade. Customization Potentials	BIPV façade applications
3	Pelle M., Lucchi E., Maturi L., Astigarraga A., Causone F., (2020) Coloured BIPV Technologies: Methodological and Experimental Asses¬sment for Architecturally Sensitive Areas	Product and manufacturer overview
4	Sánchez E., Izard L., (2015) Performance of photovoltaics in non-optimal orientations: An experimental study	PV façade benefits
5	Munari M. C., Roecker C., (2019) Criteria and policies to master the visual impact of solar systems in urban environments: The LESO-QSV method	Visual impact of PV system
6	Norwood, Z., Theoboldt, I., Archer, D.E. (2016) Step-by-step deep retrofit and building integrated façade/roof on a 'million program' house	case study of BIPV façade for retrofit

	reports	selected content
1	Zanetti I., Bonomo P., Frontini F., Saretta E., van den Donker M.N., Verberne G., Sinapis K, Folkerts W., Vossen F., (2017) Building Integrated Photovoltaics: Product overview for solar buildings skins. Status Report 2017	Customized products overview
2	Corti P., Bonomo P., Frontini F., (2020) Building Integrated Photovoltaics: a practical handbook for solar buildings. Status Report 2020	BIPV case studies
3	IEA SHC (2013) Designing Photovoltaics System for Architectural Integration. Criteria and guidelines for product and system developers, Task 41.A.3/2	Product and project overview
4	Kraubitz, T., Scheibstock, P., Guillen, G. (2018) Plus Energy Buildings and Districts, keystone papers 1 for GIZ's Sino-German Urbanisation Programme	case study of plus energy building with BIPV
5	IEA PVPS (2019) Coloured BIPV: Market, Research and Development, Task 15, Subtask E, 2019	PV Aesthetic features and technology

	interview	topic
1	Pietro Florio / *JRC, Scientific Research Project Officer*	the role of applied research in BIPV technological innovation
2	Alessandro Virtuani / *Senior researcher at EPFL & co-founder Officina del Sole*	the importance of BIPV for European decarbonisation challenges
3	Pierluigi Bonomo / *Researcher- Head of BIPV Advanced Building Skin Team at SUPSI*	new formal configurations interpreted by architecture
4	Enrico Ferramondo Marchesi */innovation manager of living lab NEST, Zurigo*	collaboration between research, industry and architects to speed up the transfer of BIPV within the market and the architecture

database

1 solarchitecture.ch 2 bipv.ch 3 solaragentur.ch 4 bipv.eurac.edu/en

Fig. 29.1 Main analysed sources for this research

of European organisations, such as the NEST[1] research lab in Zurich, SUPSI[2] and EPFL.[3]

A comparison of the leading European producers of BIPV modules, such as SwissINSO, AGC Glass and Ertex Solar, has been made to complete the analytical framework. A summary of the sources consulted is presented in Fig. 29.1.

29.2.4 Selected Case Studies

As a result of the analysis, 78 BIPV integrated façades in Europe have been identified and analysed, of which 67% relate to the residential construction sector. Both first generation (c-Si), second generation (a-Si, CIGS, CIS, CdTe) and third generation (OPV, DSSC) PVs have been considered. It is relevant to show how—as a result of the technological innovation of the PV appearance started in 2010—39.4% of the surveyed façades adopt completely camouflage solutions or coloured PV cells (Fig. 29.2).

[1] Modular research and innovation building Next Evolution in Sustainable Building Technologies (NEST) of Empa and Eawag, Zurich, Switzerland.

[2] University of Applied Sciences and Arts of Southern, Lugano, Switzerland.

[3] Swiss Federal Institute of Technology, Lausanne, Switzerland.

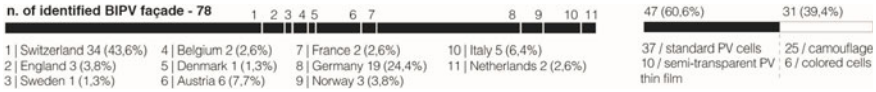

Fig. 29.2 Analysis of the current state of the art of BIPV integrated façades in Europe. Original graphics by authors

29.3 Output (or Results)

29.3.1 Aesthetic Evolution of BIPV

Recent experiences of PV integration into the building envelope represent the current culmination of a technology which has evolved over time, since the early trials in the 1980s and 90s. The research sets out the main stages of the evolution of BIPV, with a particular focus on façade integration. From the first instances of inserting PV cells into glass-glass modules to later colouring techniques, the evolution of PV has been driven by continuous scientific research and experimentation by architects, leading to examples of PV integration which are completely organic with the architectural design (Fig. 29.3).

The customisation of colourings, shapes and configurations of PVs has increased interest in technical innovation of photovoltaics in terms of integration into the architectural design. Whilst these designs must achieve ever more stringent decarbonisation targets, all stakeholders now have an enormous range of aesthetic and formal solutions available (Fig. 29.4).

29.3.2 PV Integration Forms and Strategies: Best Practices

Integrated photovoltaic systems offer new construction solutions which the architectural design can employ in order to interpret the increased energy efficiency requirements with an expressive architectural language that features a high degree of technological awareness. The conventional building elements such as cladding panels, sunscreen, parapets and accessories can today be enhanced with multifunctional components that are highly customised, generating electricity that can be fed to the energy community's network, fulfilling the building's energy requirements. The research has thus identified a series of PV façade integration categories: cladding system for cold façade, solar shading systems, balconies and solar glazing (Fig. 29.5).

Research has found that the most widespread integration approach involves the PV component being inserted into the architectural design in a bounded way, interacting with the other elements of the envelope and shaped by the system of solar shades and balustrades. In this way, the integrated photovoltaic system can cover part of the building's energy requirements (Fig. 29.6a). However, on the other hand, a fully

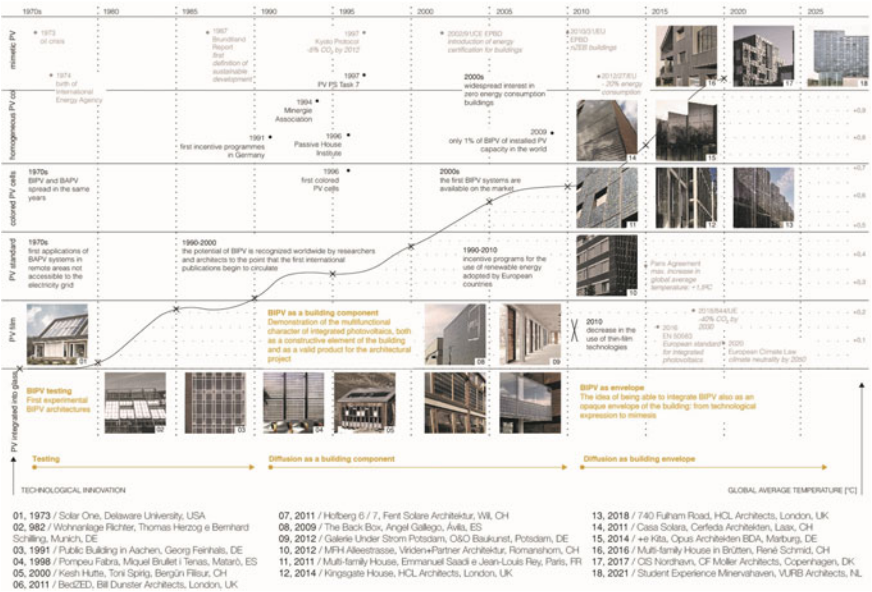

Fig. 29.3 Evolution in technological innovation of building-integrated photovoltaics. The graphic depicts the evolution of integrated PV in architecture, identifying the main stages and the respective dominant PV technologies. The relationship between the increasing global average temperature curve (NASA 2021) and the current BIPV experiences is shown. These reference buildings refer to the 78 surveyed façades cited in Fig. 29.1. Original graphics by authors

active envelope configuration can be highlighted where the photovoltaic component constitutes the main cladding material and, through camouflage components, it creates a more conventional architectural language or, through components which are identifiably as technological, a more innovative image with emphasised PV system.

This strategy ensures that the building generates power more uniformly across the whole day, thanks to the variety of PV exposure to the transit of the sun, sometimes even achieving a positive energy balance so that the surplus can be fed back to the grid (Fig. 29.6b).

The research has selected best practices which represent the different strategies for PV façade integration, extended and bounded, respectively, to demonstrate the quality of the architectural design. A few case studies selected by the authors are examined in more detail below (Figs. 29.7, 29.8, 29.9 and 29.10).

29.3.3 Buildings as Small Power Plants

The active envelope concepts of BIPV architecture can change the distribution model for the local power network, viewing buildings as energy community power stations.

a / MAIN PRODUCTS CONSULTED FOR THIS RESEARCH

product	manufacturer	PV technology	color*	dimension [mmxmm]	shape	cells visibility	efficiency ** [%]
Kromatix™	SwissINSO	c-Si	C1	custom	rectangular	NO	16,5-17,5
Solaxess	Solaxess / CSEM	c-Si / CIGS	B2	custom	custom	NO	11,4
VGS Design PV	Ertex Solar	c-Si	A1-C2	custom; max 2400x5000	custom	NO	n/a
ColorBlast	Kameleon Solar	c-Si	C2	custom	custom	NO	8-15
Kaleo	CSEM	c-Si	B2	custom	custom	NO	n/a
DSD-PV	Dutch Solar Design	c-Si	C4	900x1200	rectangular	NO	n/a
SunCol	Glassfer&Sunage	c-Si	C5	custom	custom	NO	n/a
Lacobel T Active	AGS Glass	c-Si	C2	n/a	n/a	NO	n/a
eForm unichrome	Sunovation	c-Si	C4	max 3500x1500	rectangular	NO	15
colored PV cells	LOF Solar	c-Si	A1	custom	n/a	YES	15
a-Si module	Onyx Solar	a-Si	A2	custom; max 4000x2000	n/a	/	n/a
PS-CT-series	PolySolar	CdTe	A2	standard 1200x600	rectangular	/	6-12
PS-ASG-series	PolySolar	a-Si	A2	standard 1400x1100	rectangular	/	5-10

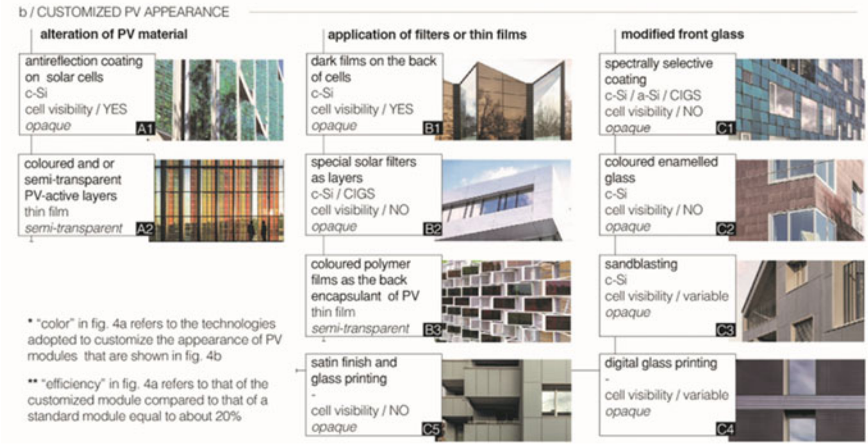

Fig. 29.4 PV products overview. The table shows the main available products and related aesthetic and technological features (**a**). The graphic illustrates the current colouring technologies for PV components and the range of different formal interpretations (**b**). Original graphics by authors

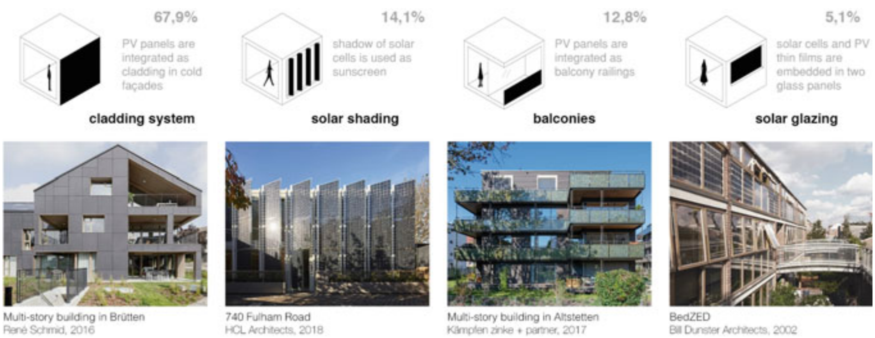

Fig. 29.5 PV façade integration forms. The percentages refer to the 78 studied façades. Original graphics by authors

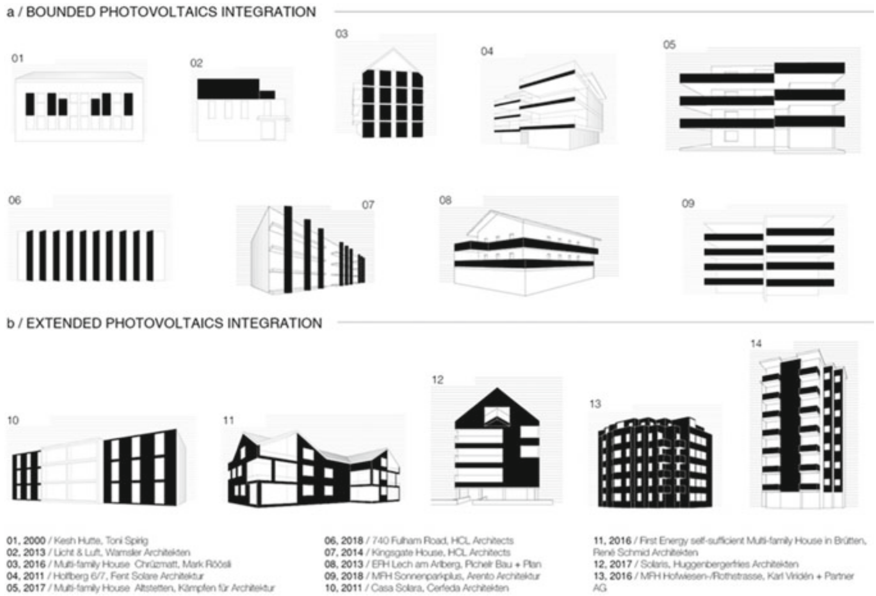

Fig. 29.6 PV façade integration categories. The areas shaded darker denote PV integration strategies in the architectural design, such as claddings, balconies and shades. Original graphics by authors

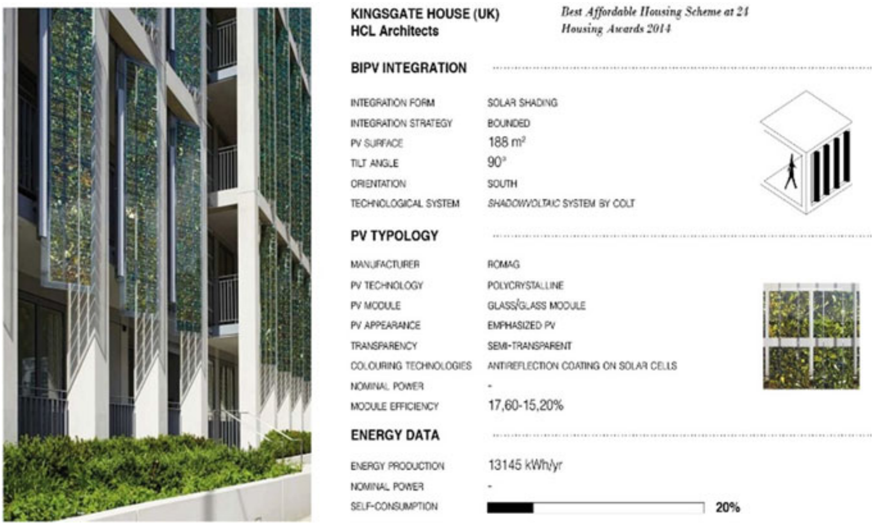

Fig. 29.7 Kingsgate House—case study. Original graphics by authors

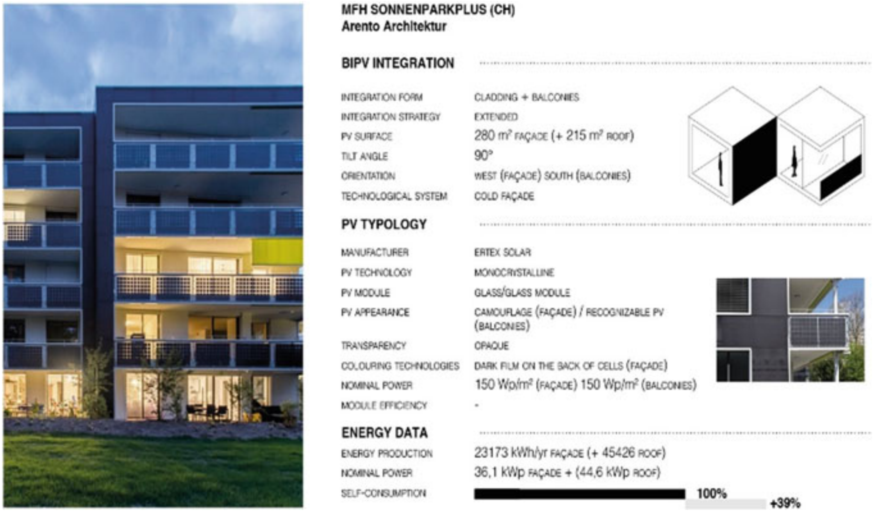

Fig. 29.8 MFH Sonnenpark Plus—case study. Original graphics by authors

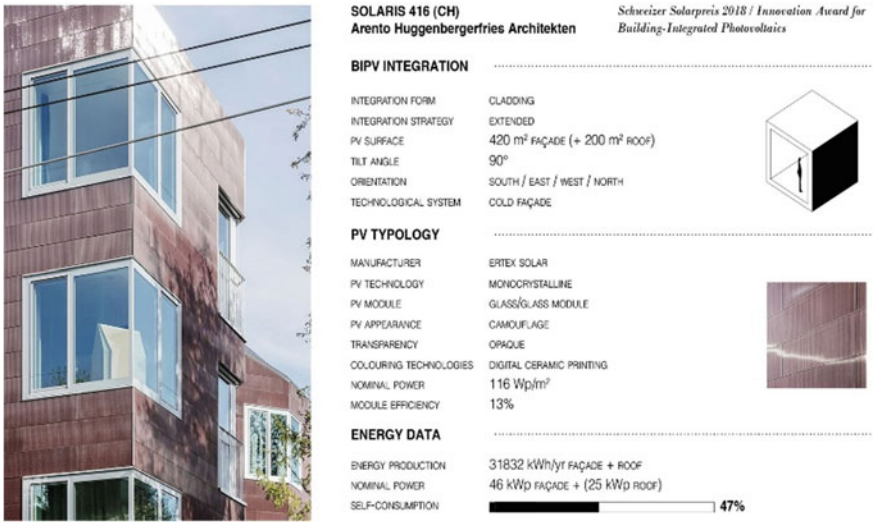

Fig. 29.9 Solaris 416—case study. Original graphics by authors

With this smart grid principle, the power surplus generated from buildings can be used to recharge electric vehicles or fed back to the network from which these buildings receive electricity when they cannot generate it independently.

Aktiv-Stadthaus (Fig. 29.11). The *Aktiv-Stadthaus*, a building designed by HHS Planer + Architekten in Frankfurt (2015), is based on the Effizienzhaus Plus energy

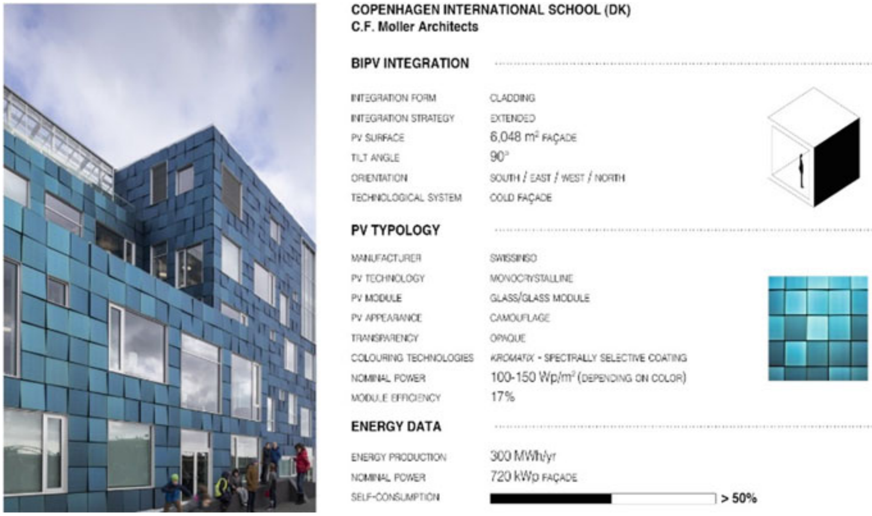

Fig. 29.10 International School—case study. Original graphics by authors

efficiency standard and complies with the requirements imposed by the German Federal Ministry of Transport, Building and Urban Development (BMVBS). The electricity generated by the PV components integrated into the south façade, along with the photovoltaic system on the roof, is collected in storage systems and used to charge electric vehicles or fed back to the network. The project falls under the subsidy scheme launched by the Federal Office for Building and Regional Planning (BBR), which finances research and development projects relating to the energy consumption of buildings (Kraubitz et al. 2018).

MFH Hofwiesen/Rothstrasse (Fig. 29.12). The same active envelope approach, generating electricity to meet the requirements of users and for the community,

Fig. 29.11 Newly built apartment building Aktiv-Stadthaus

has been adopted in a Swiss pilot project to demonstrate a possible renovation and energy efficiency improvement method for existing building stock; the *MFH Hofwiesen-/Rothstrasse* residential complex in Zurich (2016), designed by Viridén + Partner AG (SD, Pd 2017), financed by the Canton of Zurich as part of the Federal Energy Office's (UFE) programme, is notable for the use of camouflaged photovoltaic modules integrated on all sides.

Stacken (Fig. 29.13). The renovation work carried out on the *Stacken* residential complex (2017) in Gothenburg (Norwood et al. 2016) in Sweden, also supported by public and private financing, demonstrates the potential of integrated photovoltaic systems for renovating the existing building stock through the application of a BIPV façade with external insulation retrofit.

Fig. 29.12 Renovation of an apartment building

Fig. 29.13 Renovation of Stacken apartment building

29.4 Conclusions

The recent shift to energy communities for the generation of power represents a conversion for end users too, who become “generators” rather than “consumers” of energy via a decarbonisation, digitalisation and decentralisation model; for the authors, this model is also evidence of a social evolution which architecture is beginning to interpret and translate to new formal configurations; the potential relations between the building envelope and the building systems mean that architecture can be equated to energy infrastructures of high architectural quality.

In addition, this research paper seeks to demonstrate how the move over the last 20 years from the European target for a high energy efficiency building stock to the current aim for NZEB low carbon footprint buildings represents not so much a challenge as a change of paradigm in the AEC sector, with many consequences on potential innovation models that the market, the research sector and the profession are still seeking to interpret. It is based on this approach that researchers, manufacturers and designers are collaborating to pursue common objectives, representing the stakeholders in a technological innovation process which is having repercussions on the construction sector.

The construction sector—slower in innovation compared to other industrial sectors (Bellicini 2019)—now therefore has a greater opportunity of technological innovation that the market is gradually accepting. Within this transformation scenario, the contribution of the research has tried to highlight further directions of technological innovation aimed at contributing to an increasing industrialisation and prefabrication of the construction sector and in the specific case of the BIPV market. Among these, the authors support the thesis that integrated PV systems can move away from the dry construction systems to which they now belong in order to be conceived as three-dimensional prefabricated components belonging to Industry 4.0, integrated with additional systems and directly installed on the building envelope in an off-site production logic. Based on this reflection on the relationships between the building envelope, plant components and architectural languages—and within the broader framework of digitisation and technological innovation outlined above—the applied research activity is conducted by the Politecnico di Torino Department of Architecture and Design for the development and industrialisation of smart BIPV systems solution.

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