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Isadora Pauli Custódio

The Art and Science of Integrating Photovoltaics in the Built Environment

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Isadora Pauli Custódio

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Thesis submitted to Programa de Pós-graduação em Engenharia Civil of Universidade Federal de Santa Catarina to obtain the degree of Doctor in Civil Engineering.
Advisor: Prof. Ricardo Rüther, Ph.D.
Co-advisor: Profª Ísis Portolan dos Santos, Drª.

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Isadora Pauli Custódio

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This doctoral level work was evaluated and approved by an examining board composed of the following members:

Prof. Roberto Zilles, Ph.D.
Universidade de São Paulo (USP)

Prof. Roberto Lamberts, Ph.D.
Universidade Federal de Santa Catarina (UFSC)

Profª Joára Cronemberger Ribeiro Silva, Ph.D.
Universidade de Brasília (UnB)

_____

Coordination of Programa de Pós-graduação em Engenharia Civil of Universidade Federal de Santa Catarina

_____

Prof. Ricardo Rüther, Ph.D.
Advisor

_____

Profª Ísis Portolan dos Santos, Drª
Co-advisor

Florianópolis, 2021.

“Indeed, with tremendous effort and immense joy, we must strip away the cultural taboos we have inherited. We must track them down one by one in our minds and desanctify them.” (ZEVI, 1978)

RESUMO

Com a tendência de integrar tecnologias de geração de energia renovável em edificações e utilizar a energia de maneira mais eficiente, os envelopes dos edifícios tornaram-se mais complexos e multifuncionais. A utilização de módulos fotovoltaicos (FV) em edificações surgiu deste contexto, para produzir energia e compor o envelope arquitetônico como um material de construção. Portanto, os módulos FV estão se tornando mais visíveis e alterando as formas dos nossos ambientes construídos e das paisagens. Com toda a informação técnica disponível e a expansão do mercado de energia FV integrada a edificações, é possível alcançar uma qualidade de integração arquitetônica. Entretanto, para explorar o potencial total da tecnologia é necessário criar uma ponte entre as comunidades do design e FV. A tradição da arquitetura FV é objetiva e explora a construção, ou a matéria concreta da arquitetura, quando, na realidade, a essência da disciplina de arquitetura é o vazio abstrato do espaço, do qual os homens experimentam. O objetivo geral deste trabalho é, portanto, estudar como a integração de sistemas FV em edificações influencia a experiência dos espaços arquitetônicos, e avaliar como a interpretação espacial se relaciona com as interpretações tradicionais. Embora apresente uma investigação disruptiva na estética da arquitetura FV, este trabalho não pretende contrapor todas as investigações que foram realizadas até agora, as quais são essenciais para a disseminação da tecnologia, mas ir além desta tradição e relacioná-la também à essência da arquitetura. Sendo uma integração FV eficaz o resultado de um ótimo trabalho interdisciplinar em equipe, os resultados servirão de inspiração para aprimorar a aceitação de arquitetos no uso de FV em edificações, assim como fornecerão aos engenheiros e arquitetos uma visão melhor de como a integração FV pode ser interpretada a partir das teorias de percepção arquitetônica, estreitando a lacuna que existe entre as comunidades.

Palavras-chave: Energia solar fotovoltaica em edificações. Avaliação estética. Interpretações da arquitetura. Integração solar no entorno construído.

ABSTRACT

With the trend of integrating renewable energy generation technologies on buildings and use energy more efficiently, building envelopes have become more complex and multifunctional. The use of photovoltaic (PV) modules in buildings emerged from this context, to produce energy and compose the architectural envelope as a construction material. Therefore, PV modules are becoming more visible and changing the forms of our built environments and landscapes. With all the available technical information and the expansion of the building-integrated photovoltaic (BIPV) market, architectural integration quality can be achieved. Still, to explore the technology's full potential it is necessary to create a bridge between the design and the PV communities. The tradition of PV architecture is objective and explores the construction, or the concrete matter of architecture, when, in reality, the essence of the architectural subject is the abstract void of space, which men experiment from. The general objective of this work is, thus, to study how the integration of PV systems in buildings influences the experience of architectural spaces, and evaluate how the spatial interpretation relates with the traditional interpretations. While it presents a disruptive investigation on the aesthetics of PV architecture, this work does not mean to contradict all the investigations that were carried out so far, which are essential to the dissemination of the technology, but to go beyond this tradition and relate it also to the core of architecture. Being successful PV integration the result of optimum interdisciplinary teamwork, the results will serve as inspiration to improve the acceptance of architects on the use of PV in buildings, as well as give engineers and architects a better insight of how PV integration can be interpreted from theories of architectural perception, narrowing the gap that exists between the communities.

Keywords: Solar photovoltaics in buildings. Aesthetics evaluation. Interpretations of architecture. Solar integration in the built environment.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANEEL Agência Nacional de Energia Elétrica

BAPV Building Applied Photovoltaics

BIPV Building Integrated Photovoltaics

CdTe cadmium-telluride

CE Current Era

CIGS copper-indium-gallium-diselenide

CTC/UFSC Centro Tecnológico da UFSC

c-Si mono-crystalline silicon

EPBD Energy Performance of Buildings Directive

GIS Geographical Information System

IEA PVPS International Energy Agency PV Power Systems Programme

IEA SHC International Energy Agency Solar Heating and Cooling Programme

LESO-QSV Laboratoire d'Energie SOlaire – Qualité-Sensibilité-Visibilité

LIPV Landscape-integrated PV

MCDM Multi-criteria decision-making

MCTIC Ministério da Ciência, Tecnologia e Inovações

m-Si multi-crystalline silicon

NUS National University of Singapore

NZEB Nearly zero-energy building

CAPES Coordenação de Aperfeiçoamento de Pessoal de Nível Superior

PEB Positive Energy Building

PF Productive façades

PPGEC/UFSC Graduate Program of Civil Engineering of UFSC

PV Photovoltaics

R&D Research and Development

SAM Self-Assessment Manikin

UFSC Universidade Federal de Santa Catarina

VF Vertical farming

ZEB Zero Energy Building

µc-Si microcrystalline-silicon

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PRESENTATION

Some facts about my academic history are important to understand where the determination of the theme of this thesis came from. In 2011, I started an undergraduate course in architecture and urbanism at Universidade Federal de Santa Catarina (UFSC). I was awarded my degree in 2016 and started a Master's of Science in Civil Engineering, which I completed in 2019. In 2013, during the undergraduate course, I started working at the Solar Energy Research Laboratory at UFSC (Fotovoltaica/UFSC Laboratory, www.fotovoltaica.ufsc.br) at the Centro Tecnológico of UFSC (CTC/UFSC), which installed the first grid-connected, building-integrated photovoltaic (PV) generator in Brazil in 1997. I began working at the laboratory at the beginning of the construction of its new buildings, which were completed in 2016, so I participated in the team responsible for detailing the architectural project and all the process of procurement for the new buildings. It was a huge opportunity to learn how construction works in practice. At the same time, my colleagues (mostly engineers and engineering students) and I worked on other PV projects, focusing on the form and function of PV systems. The course of architecture and urbanism has a hybrid character, comprising human and exact sciences, as the architectural subject itself includes technical, functional, and aesthetical aspects. During the course, we made field trips where the professors would give talks about the subjectivities and historic features of the places. These trips had an artistic character that fascinated me, and I would always ask myself how I could bring this important part of architecture to our studies at the laboratory, to show my colleagues what the architectural subject is as a whole. However, during the master's course I focused on engineering disciplines, and that is why my dissertation was very technical and entitled "Analysis of technical and economic feasibility of a mini solar photovoltaic generator integrated on university campus building envelopes". Civil engineering and architecture are similar subjects; however, they lead to divergent paths that could be more consonant. This discrepancy distresses many architects that choose to take graduate courses in engineering, as their architectural identity tends to fade away due to the lack of more holistic approaches in the disciplines. Fortunately, I have always had artistic hobbies, which are a great contribution into opening my mind to look at and understand things and situations with other perspectives. Becoming a mother in 2019 right before I began my doctorate degree has also turned on a more reflective part of myself, which was emphasized by the pandemic scenario in 2020 and 2021. These last facts have made me rethink about the core of architecture and its relation to the use of PV in the built environment.

1 INTRODUCTION

1.1 A DOCTORATE IN SOLAR PHOTOVOLTAIC ARCHITECTURE

The original project of this thesis, which I had written in the end of 2018 to participate in the selection process of the Programa de Pós-graduação em Engenharia Civil of UFSC (PPGEC/UFSC), was entitled "Method for simplifying the study of compromises between form and function of PV systems integrated on buildings". It had the aim to assist architects, engineers, and designers to use solar PV energy in their projects, through the creation of a method to quantify the compromises between form and function, aesthetics and performance, of PV systems in buildings. A universal tool would be created by identifying aspects that influence the form of the PV systems and how this affects their energy generation, performance, and economic viability. Relationships and dependencies between the aspects would be set and illustrated in abacuses for the Brazilian state capitals (in order to demonstrate the tool), so that the feasibility of PV integration could be easily understood by professionals who are not specialists in the field of PV.

After some months into the graduation program, I started to read more on the aesthetics of PV in buildings. These studies were mostly on classifying PV architectural aesthetics in objective ways. That fascinated me, as from the undergraduate days I had the idea of bringing to the lab more architectural concepts. The objectivity of the studies would help me on that since my colleagues are mostly engineers. The idea became, then, to create a method for evaluating the coherency of the formal aspects of the architectural integration quality of PV systems, being architectural integration quality "defined as the result of a controlled and coherent integration of the solar collectors simultaneously from all points of view, functional, constructive, and formal (aesthetic)" (IEA SHC, 2012). In particular, the formal aspects include the coherence of the system's geometry, materiality, and modular pattern, in relation to a building (IEA SHC, 2012; MUNARI PROBST; ROECKER, 2019). During this process, even an article entitled "A worldwide approach to the LESO-QSV method for assessing the visual impacts of solar systems in built environments" (CUSTÓDIO; ZOMER; RÜTHER, 2020) was published in the Elsevier journal Solar Energy. Still, after a while I was again not satisfied with the theme of the thesis, as it did not include the whole concept of the architectural subject. This concern can be noticed in the articles "Energy balance and performance assessment of PV systems installed at a positive-energy building (PEB) solar energy research centre" (ZOMER

et al., 2020a) and "Performance assessment of partially shaded building-integrated PV (BIPV) systems in a positive-energy solar energy laboratory building: Architecture perspectives" (ZOMER *et al.*, 2020b), where the design of the constructions of the Fotovoltaica/UFSC Laboratory are described in a holistic approach:

> "Buildings A and B clearly show contemporary architecture characteristics, such as the strong emphasis on geometric shapes, the asymmetrical lateral façades, the use of sustainable materials, the different mixed materials on the exterior (bricks, metal, and glass), the abundant daylight use, and PV systems building integration for energy generation.
>
> Their solar rooftops were their main design basis: the large curved PV rooftop in Building-A […] works as the building's shelter, since it englobes the entire construction, and its blue colour and curved shape relates directly with the adjacent water mirrors' colours and shapes. The straight lines of the building's walls and green roof slabs break the curved features, which helps to highlight the solar rooftop in the architecture. The curved characteristic was also built in order to study the behaviour of different inclinations in the same PV system. In Building-B, the big tilted straight PV plane also shelters the entire building and its highest part points out to Building-A. This straight plane that grows toward Building-A gathers the laboratory's main buildings, bringing the idea of a unit, since both constructions are part of a whole PV complex."
>
> In the solar carport, "the entire system is formally composed by disjointed linear groups of four PV modules, aiming to give the architectural composition a more dynamic aspect. This characteristic also enables the carport's projection shape to follow its parking lots' shape and area, which, in turn, follows the terrain's limit line.
>
> The design of the bus stop […] is composed by straight lines that flow continuously from its flower bed to its chair, and up to form the platband that embraces the roof's PV system. An orange wall that relates to the eBus' symbol and design colour also breaks the dominant grey colour. The PV system cannot be seen from ground height from 3 sides of the building due to its platband. There is no platband in the back of the PV system, so it is possible to see it from the ground from that perspective, also enabling rainwater to flow. Modules were installed almost horizontal to follow the bus stop roof's formal shape.
>
> The façades' PV modules […] provide a visual colour connection of the adjacent water mirror with Building-B's rooftop PV system. Also, the system was divided in two groups of four modules that were mounted in different ways, in order to show the different possibilities that building PV integration offers: one is a ventilated air gap and the other is a non-ventilated (closed) air gap installation." (ZOMER *et al.*, 2020a).

As the existing evaluations on PV architectural aesthetics mostly assess the quality of integration in objective and formalistic ways, I decided to "go back" and start from a previous step. Hence, I read three books about architecture on its pure structure: "The Classical Language of Architecture by John Summerson (SUMMERSON, 2009), "The Modern Language of Architecture", and "Architecture as Space: How to Look at Architecture", both by Bruno Zevi (ZEVI, 2002, 2009). It was this last book that made clear to me what I was looking for: the investigations on the architectural aesthetics of PV analyze the built concrete matters, while architecture's essence is the abstract void of space which men experiment from. Therefore, I

made a final decision regarding the theme of my thesis, to study how PV systems can influence the experience of architectural spaces.

1.2 AN OVERVIEW ON THE USE OF PHOTOVOLTAICS IN BUILDINGS

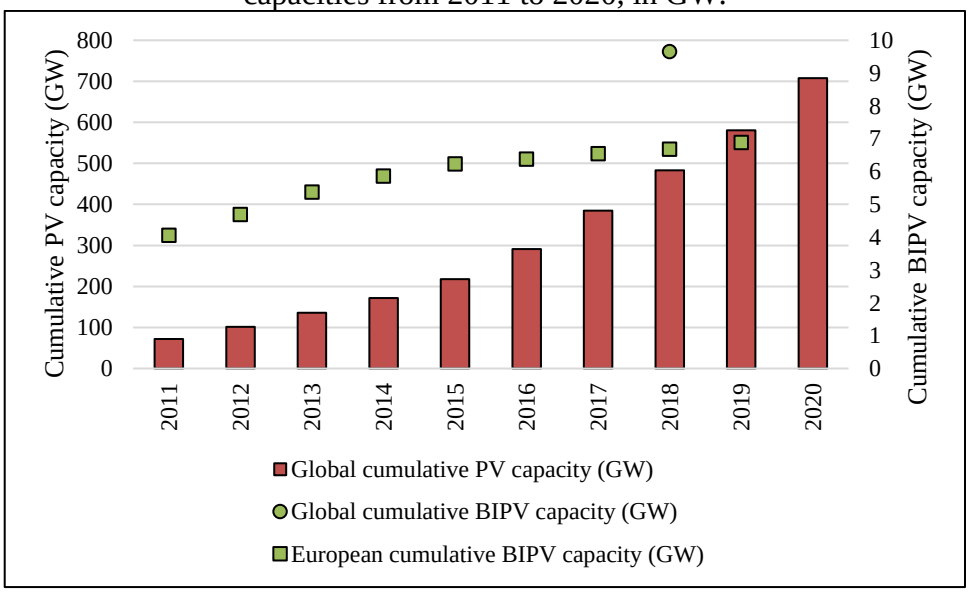
The integration of renewable energy generation technologies on buildings and the need of using energy more efficiently, have made building envelopes more complex and multifunctional. Accordingly, they became not only protection and shelter, or an interface between external and internal environments, but also comfort promotors, which contribute for reducing the use of fossil fuels and the consequences of atmospheric and noise pollutions. The implementation of active and passive strategies of solar energy became necessary to reach those objectives (HAGEMANN, 1996a). The passive use for heating or lighting has always been part of the architectural design process, whereas active technologies require the use of elements not yet fully thought of as part of the architecture (IEA SHC, 2012). The use of PV modules in buildings emerged from this context, to produce energy and compose the architectural envelope, enabling energy consumption in the same point of production, as well as saving and optimizing the net grid without using extra land areas. Photovoltaics in buildings is one of the most elegant and efficient ways of installing a solar generator, since the building skin doubles as the supporting structure for PV modules, and the building's electrical installation doubles as the electrical interface between the solar generator and the public electricity grid (RÜTHER, 2004). Furthermore, PV systems are resilient to extreme climate conditions, have a life expectancy greater than 35 years, and reduce pollution on the environment to visual impact on built environments and landscapes (TORRES-SIBILLE *et al.*, 2009). As a result, incentives as feed-in-tariffs and tax discounts to promote the use of PV in buildings have emerged and the solar industry has started presenting new products oriented to building integration (CRONEMBERGER *et al.*, 2014). This has enabled the use of PV modules on the envelope of buildings as shading systems, windowpanes, semitransparent glass façades, exterior paneling, skylights, parapet units, roofing materials, and roofing systems (HAGEMANN, 1996b), as well as on public open spaces as canopies/shadings, urban furniture applications/equipment, and transport facilities (KRSTIĆ-FURUNDŽIĆ *et al.*, 2020). This way, the cost of conventional construction elements can be offset, and new aesthetical features can be added to the environments (CRONEMBERGER *et al.*, 2014).

In this perspective, the IEA SHC Task 41 A.2 (2012) defined Building Integrated Photovoltaics (BIPV) as structures that include the PV modules, and all electrical components and mounting systems that are necessary to connect and integrate the PV products on a building. Therefore, a BIPV product is characterized as a non-divisible PV unit that acts as a building material, and its replacement can only be made by another construction product. The BIPV system is then a building layer which is physically and functionally integrated to a building, acting as a multifunctional envelope material, which also gives chances for innovative building envelope designs (IEA SHC, 2012; KAAN; REIJENGA, 2004; POLO LOPEZ *et al.*, 2014). Differently, Building Applied Photovoltaics (BAPV) are stand-off or rack-mounted systems, superposed on the envelope, and prioritize power generation. Stand-off systems are mounted above the roof surface, parallel to its tilted surface, while rack-mounted systems are usually installed on flat roofs and positioned at an optimum orientation and tilt for energy generation. Even as part of the architectonical composition of the building, they do not replace or perform as a construction component (CRONEMBERGER *et al.*, 2014; PENG; HUANG; WU, 2011; SÁNCHEZ-PANTOJA; VIDAL; PASTOR, 2018). However, BAPV, even in retrofit projects, have a great architectural composition potentiality that can result in more original and justifiable solutions than BIPV. The classification of BIPV and BAPV seems simple, but in practice they are not that obvious and can lead to ambiguity. First, BAPV becomes BIPV when PV modules are integrated tightly to buildings surfaces (PENG; HUANG; WU, 2011). Also, PV systems can be either installed in/onto the envelope or into/onto external partitions, as well as located in the building footprint, on site, or off site. Therefore, the nomenclature of BIPV and BAPV is no longer sufficient to describe all the possibilities (SCOGNAMIGLIO; GARDE, 2016).

In the European context, guidelines for the transformation of the building sector into nearly zero-energy buildings (NZEBs) are being traced. The Energy Performance of Buildings Directive (EPBD) 2010/31/EU, for example, establishes that all new public buildings must be NZEBs since 31 December 2018, and all new buildings need to be NZEBs since 31 December 2020 (EPBD RECAST, 2010). PV is an indispensable technology for meeting the net zero energy target (SCOGNAMIGLIO; GARDE, 2016), hence it is evident that the global cumulative BIPV capacity has been increasing. However, there are several barriers when estimating it: the definition of BIPV has changed over time and varies from country to country, and many national administrations do not keep track of these specific installations. That being understood, the Becquerel Institute estimated that about 2% of the global cumulative solar PV capacity corresponded to BIPVs in 2018 (BECQUEREL INSTITUTE, 2019), that is, about 9.7

GW, being 6.7 GW only in Europe. **Erro! Fonte de referência não encontrada.** shows, in GW, the global cumulative solar PV capacity from 2011 to 2020 (IRENA, 2021) and the global cumulative BIPV capacity in 2018 (BECQUEREL INSTITUTE, 2019). The cumulative BIPV capacity in Europe from 2011 to 2019 (SUPSI; BECQUEREL INSTITUTE, 2020) is also presented.

Figure 1 – Global and European (EU-27 + UK + CH + NO) cumulative solar PV and BIPV capacities from 2011 to 2020, in GW.



Sources: Becquerel Institute (2019); IRENA (2021); SUPSI and Becquerel Institute (2020).

Architects and designers are essential during this progressive growth, as the form of buildings and cities might change radically (SCOGNAMIGLIO; RØSTVIK, 2012), taking new architectural expression possibilities (DE BERARDINIS; BONOMO, 2012). Thus, energy should start to be seen as a permanent component of building envelopes and therefore part of their forms. Furthermore, aesthetics provided by PV can be affected in different scales, going from a single building to an entire city, that is, the architectural and the urban scales (SCOGNAMIGLIO; RØSTVIK, 2012). As PV modules are becoming more visible in our built environments and landscapes (KRSTIĆ-FURUNDŽIĆ *et al.*, 2020), this growth needs to be oriented in a way to protect their architectural quality (MUNARI PROBST; ROECKER, 2011). Moreover, distinct interests lead to a debate on the acceptability of these systems (MUNARI PROBST; ROECKER, 2011): engineers and building owners mean to improve energy generation and reduce costs, which usually leads to a negligence regarding the building's design; architects chase compromises between formal aesthetics and energy performance

(URBANETZ; ZOMER; RÜTHER, 2011; ZOMER *et al.*, 2014, 2020a, 2020b, 2013); and heritage protection departments pursue the conservation of historic building images (PELLE *et al.*, 2020; ROSA, 2020; XU; WITTKOPF, 2015; XU; WITTKOPF; ROESKE, 2017). Also, the acknowledgment of the PV technology by citizens, as users of the cities, is also of great relevance and, to accomplish it, the systems must be used without disturbing architecture (SÁNCHEZ-PANTOJA; VIDAL; PASTOR, 2018). The process of each project for the integration of PV in buildings is unique and the final design should reach an optimal compromise between all relevant factors (KOSORIC; WITTKOPF; HUANG, 2011).

In this context, the IEA SHC Task 41 A.2 (2012) established "architectural integration quality" of PV systems as the result of building coherent PV integration, regarding functional, constructive and formal (aesthetical) aspects. The evaluation of the coherency of functional and constructive features is more technical, as there are exact functions and durability that should be considered for the building envelope (IEA SHC, 2012). Some of these characteristics include mechanical resistance and stability, structural integrity, safety, and protection against weather, fire, and noise (POLO LOPEZ *et al.*, 2014). However, when it comes to formal aspects, the evaluation of integration quality becomes subjective: the system geometry (field's size, shape, and position), the system materiality (modules' colors, textures and reflexivity), and the modular pattern (PV modules plus mounting system) must be coherent with the overall building design in order to achieve integration quality (IEA SHC, 2012; MUNARI PROBST; ROECKER, 2019). Furthermore, a wider perspective about the aesthetics of PV in buildings is addressed. Since new ideas are learned and accepted faster when they are visualized and directly experienced, the design of PV technologies in buildings should be exhibited to the public. This way, either high-tech or eco-tech building designs can be reached and the use of PV in buildings is encouraged (CELADYN; FILIPEK, 2020).

Looking back at history, PV technology was a new and suspicious device for architects. Today, however, the aesthetics of the technology is already well accepted by these professionals, which use PV as an innovative building material to sustainable buildings, as they now know how to use it both aesthetically and technologically. As PVs has become a symbol of sustainability, many architects have started using the technology to attract the public (SCOGNAMIGLIO; PRIVATO, 2008; SCOGNAMIGLIO; RØSTVIK, 2012). Nonetheless, many have never thought about using it as means of architectural expression (KAAN; REIJENGA, 2004); they do not see PV as a creative challenge, but as a necessity imposed by legislators (SCOGNAMIGLIO; RØSTVIK, 2012). The gap that still exists between the

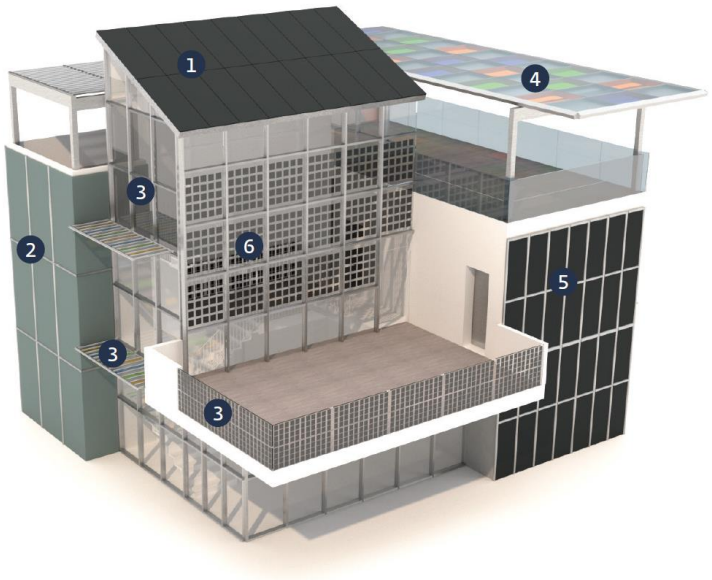
scientific knowledge and architecture's practice is believed to be the main cause for the rejection of using PV in buildings (SCOGNAMIGLIO; RØSTVIK, 2012), together with the complexity of the built environment which requires experimental application and advanced simulation methods (KRSTIĆ-FURUNDŽIĆ *et al.*, 2020). By the integration of PV modules from the early design phases and the development of the PV market, it should be easier to overcome these barriers (CRONEMBERGER *et al.*, 2014; KRSTIĆ-FURUNDŽIĆ *et al.*, 2020).

The concern of achieving architectural integration quality within a solar expansion scenario must come from architects, engineers, and public authorities that need to establish incentive policies. Also, PV product manufacturers need to improve the market offer with products for architectural integration (FLORIO; ROECKER; MUNARI PROBST, 2015). To fully explore the market potential, it is necessary to include structural, electrical, and esthetical design issues into the BIPV products (HAGEMANN, 2004), hence it is important that scientists and architects work together to understand each other's languages (SCOGNAMIGLIO; PRIVATO, 2008). Architects should not only apply the available solutions, but also take a leading role in the development of the PV market, contributing on the improvement of new, more functional, and aesthetically advanced products (KRSTIĆ-FURUNDŽIĆ *et al.*, 2020).

BIPV currently represents a minor portion of the PV and construction markets (BECQUEREL INSTITUTE, 2019). However, it has already a great miscellany of components and mounting systems with different forms, colors, sizes, and functions, from which architects and designers can choose or even customize. There are, for example, glazed semi-transparent BIPV solutions with thermal properties; opaque glazed solutions without thermal protection; opaque no glazed solutions without thermal protection; products with colored/patterned interlayers and/or special solar filters; products with colored and/or semi-transparent PV-active layers (thin film, OPV); products with colored polymer films (encapsulant, back sheet); products with coated, printed, specially finished or colored front glass covers; and products with colored anti-reflective coatings on solar cells (c-Si) (SUPSI; BECQUEREL INSTITUTE, 2020). These variety of visual features increase the possibilities and acceptance of the PV technology in the built environment, especially in architecturally sensitive areas where the technology must have low influences on the design of the buildings (PELLE *et al.*, 2020). Figure 2 shows the technological systems of the available BIPV products, illustrating how they can be applied in the building envelope (SUPSI; BECQUEREL INSTITUTE, 2020). This variety of BIPV products and technological systems leads to a greater complexity of PV systems

design. However, one can start from the notion that, usually, single family houses will require standard PV modules and their mounting systems; on the retrofitting of average buildings, prefabricated BIPV components could be used and even include insulation; valuable buildings will mostly require customized PV modules; and NZEBs will demand the integration of prefabricated BIPV products as part of a whole energy solution set (KRSTIĆ-FURUNDŽIĆ *et al.*, 2020). Regarding heritage protected historical buildings, low-visual impact is usually needed, what can already be reached by the products available in the market (ROSA, 2020).

Figure 2 – BIPV products' technological systems, being (1) discontinuous roof, (2) rainscreen, (3) external integrated devices, (4) skylight, (5) prefab system, and (6) curtain wall.

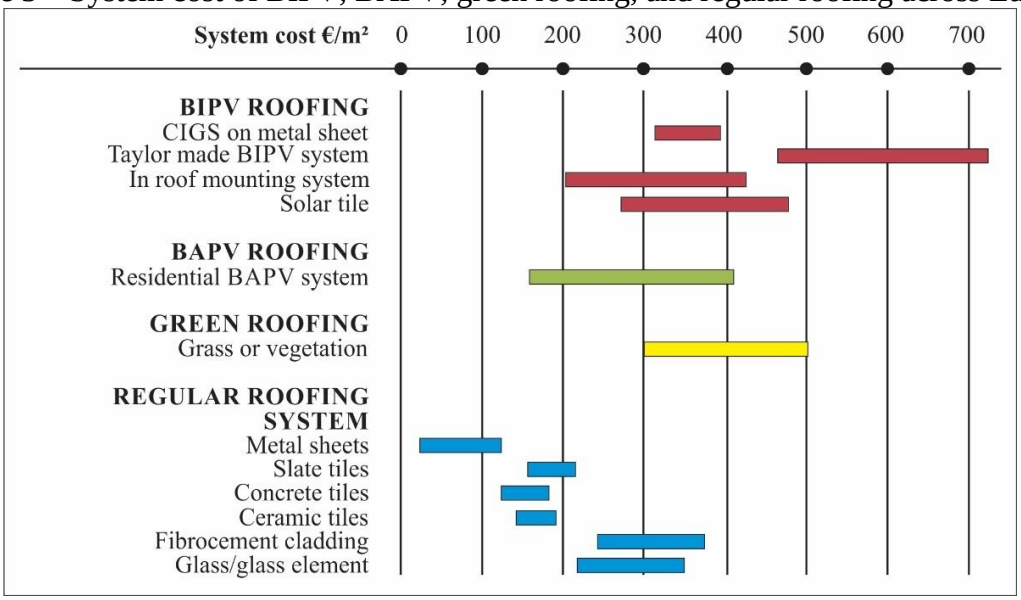


Source: SUPSI and Becquerel Institute (2020).

Historically, what has kept the initial investment on BIPV products higher than conventional building materials is the cost of PV modules (BECQUEREL INSTITUTE, 2019). However, in the last years this value has dropped significantly and BIPV products have started to be economically competitive with other construction materials (SORGATO; SCHNEIDER; RÜTHER, 2018). Figure 3 shows a comparison of the system cost of BIPVs, BAPVs, green roofing, and regular roofing in Europe, and Figure 4, a comparison of the system cost of BIPV, green, and regular façades in Europe (SUPSI; BECQUEREL INSTITUTE, 2020). The BIPV system's cost includes the end user cost of the solution as a whole: the BIPV modules and all the other anchoring and mounting parts that are necessary to ensure the complete functionality, safety, and performance/normative conformity of the structure (SUPSI; BECQUEREL

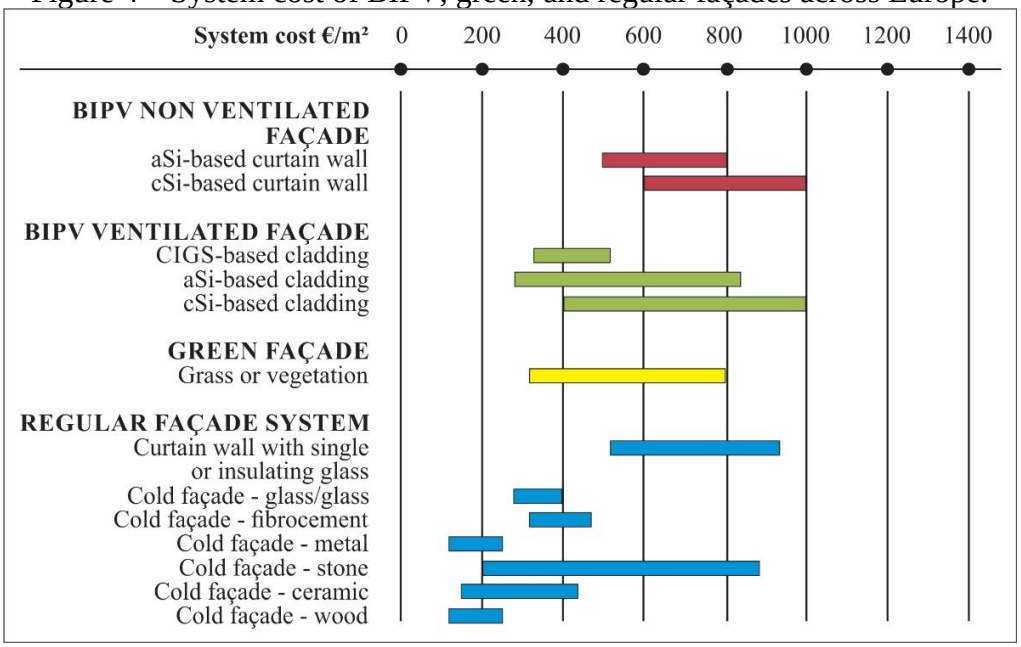
INSTITUTE, 2020). Market drivers such as financial incentives, technology and technical standards, demand from designers for retrofit projects, acceptance by stakeholders, requests from certification schemes, policymakers, environmental conscience, increasing efficiencies, cost-effectiveness, optimization of the BIPV process (from manufacturing to installation), digitization of the products, and the EPBD 2010/31/EU can contribute to boost even more the BIPV sector (BECQUEREL INSTITUTE, 2019; SUPSI; BECQUEREL INSTITUTE, 2020).

Figure 3 – System cost of BIPV, BAPV, green roofing, and regular roofing across Europe.



Source: Adapted from SUPSI and Becquerel Institute (2020).

Figure 4 – System cost of BIPV, green, and regular façades across Europe.



Source: Adapted from SUPSI and Becquerel Institute (2020).

The development of the PV technology, together with users' preferences, has led to changes on the architectural features of PV building integration over time. Around the year 2000, traditional blue crystalline modules were mostly used, while currently thin film black and colored modules are preferred, as they look like traditional façade materials. Also, about 20 years ago, tracking systems were considered ideal, while at present fixed systems facing the most different directions are mostly seen. Moreover, the advancement of energy saving solutions (vacuum insulation, thermoactivated components with Phase Change Materials – PCM, heat pumps) and solar thermal collectors has also facilitated the combination of these products with the PV technology (BECKER *et al.*, 2017).

Still, to explore the technology's full potential it is important to create a bridge between design and the PV communities (SCOGNAMIGLIO; PRIVATO, 2008). Architects and designers must use all the available technical information to improve their knowledge about PV. However, to achieve successful architectural integration quality, engineers and architects need to get a better insight of how PV integration can be interpreted from theories of architectural perception. Non-technical problems should be considered to obtain the highest potential of PV architecture (HAGEMANN, 2004). Independently of the market expansion, architects should use PV modules as means of architectural expression. That is, cognitively, the technology should be treated as any other material of the building envelope (SCOGNAMIGLIO, 2021).

1.3 SYSTEMATIC INVESTIGATION ON SOLAR PHOTOVOLTAIC ARCHITECTURE

This section describes the procedure of the literature review on the aesthetics of PV architecture, which was divided in two parts. The first one consisted of systematic investigations in the databases of Scopus from Elsevier and *Portal de Periódicos da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)*. In both databases, the investigated descriptors included "BIPV", "BAPV", or "PV" plus the words "architecture" and/or "aesthetics" and/or "integration quality" and/or "quality" and/or "evaluation". More than a thousand results were found, but most of the papers considered the technical part of PV architecture, such as how the form of the PV integration influences its performance, or how the integration of PV systems influences the energy efficiency of buildings. After a careful selection, 30 papers were considered relevant for the thesis. The second part of the study on the state-of-the-art was on the research tasks of the International Energy Agency PV Power

Systems Programme (IEA PVPS) and the International Energy Agency Solar Heating and Cooling Programme (IEA SHC). Although many tasks relate to PV in architecture, for the state-of-the-art investigation only IEA PVPS Task 7 – PV power systems in the built environment, IEA SHC Task 41 A.2 – Solar Energy Systems in Architecture: integration criteria and guidelines, and IEA SHC Task 51 C.3 – Lessons Learnt from Case Studies of Solar Energy in Urban Planning, were contemplated, as they present methods, guidelines, and/or criteria to consider for achieving aesthetically coherent PV integration (IEA PVPS, 1997; IEA SHC, 2012, 2018). Additionally, a doctoral thesis entitled "Desenvolvimento de Ferramenta de Apoio à Decisão em Projetos de Integração Solar Fotovoltaica à Arquitetura[1]" was also added to the review of literature, as it contributes for disseminating the integration of PV in architecture (SANTOS, 2013).

The literature review on PV architectural aesthetics demonstrated that there is a desire to achieve objectivity on the establishment of a method or on the definition of criteria that should be considered to create, judge, or describe the aesthetics of PV systems on buildings. These types of contribution are effective as they broadcast a connection between PV and architecture. However, architecture as a whole is much more than these objective methods. There is a need to go over the core of the architectural subject and relate it to PV.

1.4 ARGUMENTS AND CONTRIBUTION

Architecture, painting, and sculpture have been denominated as "fine arts", or art forms that have aesthetic values and are involved with the beauty that delights our eyes. Different from painting and sculpture, though, architecture is a functional art that defines spaces where we can live and be at. Although its representation through plans and sessions is cold and abstract, no other art is so closely linked to humanity's everyday life. Therefore, shapes are built around men not merely to be seen from the outside, but to live in the conceived spaces. Understanding architecture is therefore not the same as being able to determine its visible features. Indeed, it should not be seen, but experienced, as not even the most accurate description of the visible features will give the idea of what the essence of architecture is. Through words, however, it is possible to help others feel these experiences (RASMUSSEN, 2015).

[1] Our translation: Development of a Decision Supporting Tool in Projects of Solar Photovoltaic Integration to Architecture.

Architecture has a three-dimensional vocabulary that includes man. Paintings, for example, work mostly with two dimensions, and sculptures with three, but, in both, man remains outside just as an observer. Differently, architecture allows man to participate, enter, walk inside, and experience its spaces; hence it cannot be debated with the proper terms of painting and sculpture critical languages, which regard the matter of those arts. The space is the protagonist of the architectural fact and can only be known and lived through direct experience. Therefore, to understand buildings we must become masters of spaces by learning how to see them. When we understand the theory of spaces and apply it in the architectural criticism, the pleasure provided by architecture will be reached and we will be able to feel it in a concrete way. **Meanwhile, we will continue to debate about buildings with the proper critical terms of painting and sculpture, complimenting their function, technique, plastic, and pictorial data. These explanations are certainly very useful, but ineffective in making the value of architecture understood, once its essence, the space, is forgotten**. Architecture's spatial experience can happen in wherever man's work has created closed spaces. Therefore, it can be achieved either in interior spaces, which are defined by the architectural work, or in exteriors or urbanistic spaces, which are enclosed in this work and in the adjacent ones. (ZEVI, 2009).

Despite the space being the center of architecture, the tradition of criticism is practical. It is fixed on the tangible matter, which are the shapes and materials that we can see. Space is a void that comes by itself, or a denial of what is solid, so it is ignored, even though it is what gives us the pleasure we get from architecture. Of course, works of art only exist in function of their material (COUTINHO, 2001 apud SANTOS, 2014): in painting, this material is the color, in sculpture it is the volume, while in architecture it is the void of space (SANTOS, 2014). The architectural space, in turn, depends on the construction itself to exist. Therefore, architects should work both with the solid matter and the void spaces of architecture, as they depend on one another. Rasmussen (2015) illustrates this relationship through Rubin's vase, a known image of optical illusion, shown in Figure 5. This type of illustration is used in the Gestalt theory, much adopted in architectural criticism, which regards the notion of perception and interpretation of elements as a whole (not from the analysis of the parts in isolation), through five principles: proximity, similarity, common fate, objective set, continuation, and closure (WERTHEIMER, 1923 apud VEZZANI; MARINO; GIORA, 2012).

Figure 5 – Rubin's vase.



Source: Adapted from Schooler (2015).

If we paint a black vase on a white background, we consider as figure what is in black, and as background everything in white. However, if we consider the white part as the figure, and the black as background, or as a cavity in the picture, we will notice that the vase disappears and two faces in profile emerge. We can transfer our perception from one thing to another by seeing vase and faces alternately. Nevertheless, each time there must be a complete shift in perception, we cannot see vase and profiles at the same time even if they depend on one another to exist (RASMUSSEN, 2015). The architectural subject should be understood in the same way: it is determined both by the constructed parts and the spaces, that depend on one another to exist, but we either see the concrete matter, or we see the void space. Furthermore, construction and space should be studied separately because the concrete matter of the buildings is susceptible to time deterioration, while the space is timeless as it does not suffer degradation. Temporary uses occur in spaces, so it constitutes and preserves a time (SANTOS, 2014). Architecture should, then, be interpreted in both concrete and spatial terms. Furthermore, architectural evaluation should consider the surroundings and landscape, expanding space to larger areas, views, and experiences.

Existing investigations, that is, the tradition of PV architecture, involve the concrete matter of this art. These investigations are done either by architects and engineers, since the construction itself, or the concrete matter of the buildings, is a common knowledge they have. The present work includes the spatial interpretation as to provide a full understanding of PV architecture. Being successful architecture the result of optimum interdisciplinary teamwork (HAGEMANN, 1996a), the results will serve as inspiration, improve the acceptance of architects on the use of PV in buildings, as well as give engineers and architects a better insight of how photovoltaic integration can be interpreted from theories of architectural perception, narrowing the gap that exists between these two professional groups.

1.5 OBJECTIVES

In the context of the introduction presented so far, this section establishes the general and the specific objectives of this thesis. A literature review is presented in the next chapter, to further contextualize the thesis, followed by chapters on the method, results and discussions, and a final conclusion.

1.5.1 General objective

This work aims to show how the integration of PV systems can influence the experience of architectural spaces, and to understand the relationships between the traditional and the spatial interpretations of the aesthetics of PV architecture. Even if the study on the spatial interpretation is disruptive regarding PV architectural aesthetics, this work does not mean to contradict all the investigations that were brilliantly done so far, which are essential to the dissemination of the technology. The idea is to go beyond this tradition, to complement and compliment the studies. Architects and designers need to improve their knowledge about PV using the vast information that is already available. However, both engineers and architects need to get a better insight of how PV integration can be interpreted from theories of architectural perception. This is the main objective of this work, and the results should give inspiration and improve the acceptance of architects on the use of PV in buildings, and bring the PV and the design communities together.

1.5.2 Specific objectives

The specific objectives of this thesis are as follow:

- To summarize the existing investigations on the aesthetics of PV architecture, in order to understand how it has been interpreted so far.
- To delineate the concept of the architectural subject on its essence, to understand the gap that exists in the literature regarding the interpretation of PV from theories of architectural perception.
- To clarify the notion of the traditional interpretations of architecture, as to relate them to the existing research on the aesthetics of PV architecture.

- To explain the concept of the spatial interpretation of architecture, which will be considered in the methodology.
- To select 20 worldwide case studies of PV integrated in the built environment to be interpreted by the adoption of both the traditional and the spatial interpretations.
- To establish a general methodology for both traditional and spatial interpretations of PV architecture, in order to apply them to the 20 case studies.
- To understand the relationships between the traditional and spatial interpretations of PV architecture, to narrow the gap that exists between the PV and the design communities.

2 LITERATURE REVIEW

This section presents, first, a literature review on the aesthetics of PV in buildings. In fact, in general the studies aim to evaluate not only PV, but more accurately the multifunctional influences of PV in buildings, as only such understandings should be considered as the "overall performance" of these systems (ERANKI; MANI, 2020). Second, an overview on the interpretations of architecture is presented. Finally, a discussion on the gaps that exist in the literature is provided, outlining the theme of this thesis.

2.1 RESEARCH ON THE AESTHETICS OF PHOTOVOLTAIC ARCHITECTURE

Many studies have discussed about the influences of PV systems in the built environment, demonstrating different appeals to describe and/or evaluate the integration quality of these systems regarding aesthetical, technical, and constructive aspects. From the published literature, it was noticed that research can be divided in four groups: (i) works that establish methods or criteria evaluation for PV building integration; (ii) works that describe the features of PV building integration; (iii) works that deal with the integration of PV plants in landscapes, and (iv) works that regard all the previous categories. Even if the scope of this work regards PV in the built environment, research on PV plants in landscapes was also considered. They bring interesting discussions that could contribute to this thesis, also emphasizing the relation between PV integration on buildings with its surroundings and landscapes.

2.1.1 Research that establishes methods or criteria evaluation for photovoltaic building integration

The IEA PVPS Task 7 (IEA PVPS, 1997) – presents "not too subjective" criteria that need to be observed for the creation of high-quality PV integration projects, by which the integration of PV in buildings can be architecturally classified and evaluated. Chart 1 shows the aesthetic criteria set as essential to successful PV architecture, which can also be used as a guideline for both the design process and the architectural critic (KAAN; REIJENGA, 2004; SCHOEN *et al.*, 2000).

Chart 1 - Criteria for good PV architecture, as defined by IEA PVPS Task 7.

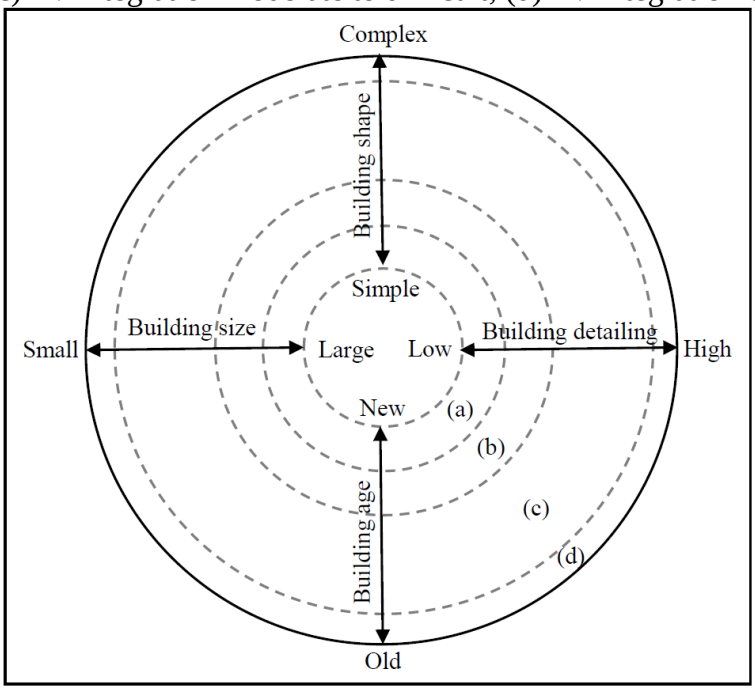
Natural integration	The PV system seems to be part of the composition, without which it would be lacking something: it completes the building. In renovations, the PV system should look as it was there before.
Architecturally pleasing	This is a very subjective issue: the design must be architecturally pleasing and attractive to the eye.
Good composition of colors and materials	The color and texture of the PV system should be in harmony with the other construction materials.
Grid harmony and composition	The dimensions of the PV system should match the sizing of the building.
Contextual coherency	The appearance of the building should be coherent with the PV system. On historic buildings, PV tiles usually fit better than large modules.
Well-engineered system and integration	This does not refer to the consistency of the construction, but to the elegance of the details. Have details been properly thought? Has the quantity of materials been minimized?
Innovative design	The architectural design of PV systems asks for innovative and creative thinking, as new ideas can boost the PV market and add value to buildings.

Sources: Kaan and Reijenga (2004) and Schoen *et al.* (2000).

The criteria could be applied to other construction materials and building components, but they were clearly formulated only for PV, as it is not considered an essential material on building envelopes. No matter how well it is integrated, PV modules will always be 'added' elements on buildings, as they are not considered indispensable materials in architectural terms. Buildings without PV systems are suitable, but buildings without windows or structural systems, for example, are unacceptable. Then, to encourage the use of PV in buildings, the PV community, architects, and engineers must develop and demonstrate high-quality integration concepts that meet the industry's objectives and the architectural needs of buildings (KAAN; REIJENGA, 2004). The notion that PVs are not essential should change with the new energetic requirements and public consciousness.

Bahaj, James and Jentsch (2007) stated that when proposing PV systems to buildings, architects and designers should understand the "sensitivity" of a building to the PV modules. The authors propose that the evaluation of 'sensitivity' should consider the shape, size, detailing (at façade and roof levels), and age of the building. Figure 6 shows a map that can be used to evaluate the appropriateness of a building for PV. In terms of "sensitivity", buildings that require low effort to good PV integration are ones where all four parameters sit near the center of the map, that is, appropriate buildings for PV integration should be large, new, and simple (BAHAJ; JAMES; JENTSCH, 2007).

Figure 6 – Ease of aesthetically pleasing integration of PV arrays into architecture as a function of building size, shape, detailing, and age: (a) PV integration easy; (b) PV integration fairly easy; (c) PV integration moderate to difficult; (d) PV integration very difficult.



Source: Adapted from Bahaj, James and Jentsch (2007).

Kosoric, Wittkopf and Huang (2011) created a multi-criteria decision-making (MCDM) design methodology for the integration of PV in buildings in the early design phase. With architectural requirements and design alternatives established, the MCDM tool can be used to revise subjective decisions and design assessment criteria to select an optimal design. To illustrate the application of the tool, the authors present a case study with eight design alternatives for a PV demonstration site at the National University of Singapore (NUS). Architectural requirements related to architectural values were established and used in the evaluation of the design possibilities, which also included a technical economic performance evaluation, as shown in Figure 7. From that, each requirement or criterion was given a weight coefficient that reflected the objectives of the design and the investor's requests, followed by qualitative and quantitative judgements. The authors believe that a systematic application of the method should reduce subjectivity in the qualitative judgments (KOSORIC; WITTKOPF; HUANG, 2011).

Figure 7 - Criteria categories, criteria function groups, and individual criteria functions with their weight coefficient for the evaluation of design possibilities of PV in buildings for the National University of Singapore (NUS) demonstration site.

Criteria category	Criteria function groups	Individual criteria functions	Units
Architectural value (0.5)	Effectiveness of integration (0.2)	Effectiveness of integration into existing architecture of the building (0.1)	Qualitative (1–5)
		Effectiveness of fitting in within NUS architectural environment (0.05)	Qualitative (1–5)
		Effectiveness of fitting in within architectural environment of Singapore (0.05)	Qualitative (1–5)
	Innovativeness (0.05)	Innovativeness (0.05)	Qualitative (1–5)
	Impressiveness from outside and inside the building (0.1)	Impressiveness from outside the building (0.05)	Qualitative (1–5)
		Impressiveness from inside the building (0.05)	Qualitative (1–5)
	Functional contribution (0.05)	Functional contribution (0.05)	Qualitative (1–5)
	Architectural coherence (0.05)	Architectural coherence (0.05)	Qualitative (1–5)
	Motivational effect on people and NUS students (0.05)	Motivational effect on people and NUS students (0.05)	Qualitative (1–5)
Techno-economic performance (0.5)		Electricity generation per year (0.2)	MWh
		Total system cost (0.2)	kSGD
		Complexity of constructional interventions (0.1)	Qualitative (1–5)

Source: Kosoric, Wittkopf and Huang (2011).

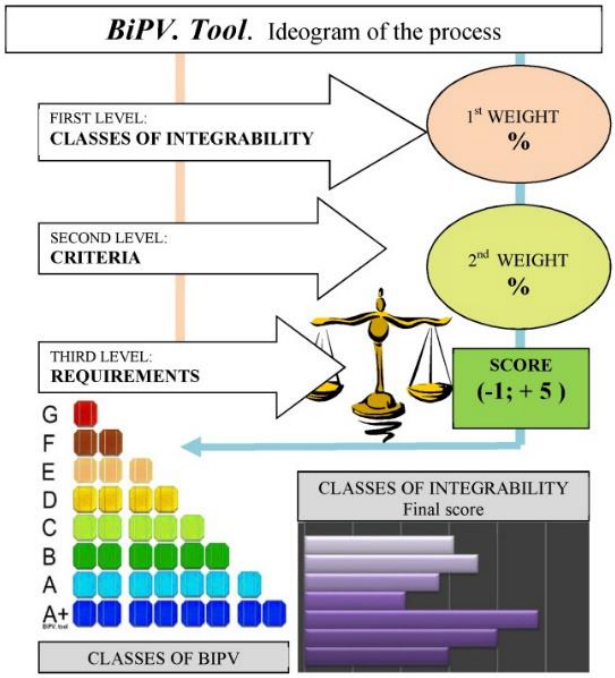
Furthermore, IEA SHC Task 41 A.2 presents examples of building integration of PV systems and a method of evaluation of their architectural integration quality. The analysis includes the functional/constructive and the formal criteria of “collector used as multifunctional construction element”, “field position and dimension”, “visible materials”, “surface textures”, “surface colors”, “module shape and size”, and “jointing”, which are evaluated as “+”, “+/-”, and “-”, respectively if they are fully coherent, partially coherent, or not coherent with the building. Finally, the document presents the “integrability” (flexibility for integration) of innovative PV market products, considering the features of “multifunctional element”, “shape and size flexibility”, “pattern choice”, “color choice”, “jointing/frame”, “availability of dummies”, and “complete construction system”, which as evaluated as “-” for negative, “+/-” for neutral, and “+” for positive appreciations (IEA SHC, 2012).

De Berardinis and Bonomo (2012) have proposed the BiPV.tool, a multi-criteria method to evaluate BIPV rating, which was validated by Bonomo, de Berardinis, and Frontini (2013) by its application on case studies. The tool’s evaluation process ideogram is illustrated in Figure 8. The goals of the method are to disseminate the meaning of the word “integration”, as it is often mentioned regarding diverse themes, levels of complexity, and scales of reference

and observation, as well as to reassure higher architectural quality of PV systems design. Regarding the definition of "integrability", for example, other studies outline it as a methodology to evaluate only the quantifiable functionalities of PV systems: electricity generation, energy required for thermal comfort, building energy demand, and economic feasibility (AADITYA; MANI, 2017; ERANKI; MANI, 2020).

The tool from De Berardinis and Bonomo (2012) consists of a grid which is structured in different scales of scoring and weighting criteria, including architectural, constructive, and energetic aspects, as shown in Figure 8. Qualitative and quantitative requirements are given a score, leading to a final score for the whole BIPV project. The tool aims to draw an operational methodology for a more objective assessment of the PV integration quality through a labeling system with classes of integration that go from A+ to G (BONOMO; DE BERARDINIS; FRONTINI, 2013; DE BERARDINIS; BONOMO, 2012).

Figure 8 – Evaluation process ideogram of the BiPV.Tool.



Source: de Berardinis and Bonomo (2012).

The process of the method consists of seven classes of integrability, having each of them a list of evaluation criteria, which in turn have their own requirements (143 in total). Each class of integrability, as well as each evaluation criteria have different weighting conditions. A score from -1 to +5 must be given to each requirement of the evaluation criteria. Scores resulting from the analysis of these qualitative and quantitative aspects lead to final weight percentages

for the criteria and for the classes of integrability, leading to a final score for the project which can be formalized in a class from A+ to G. The list of the classes of integrability with their relative weight are presented in Figure 9 and the list of evaluation criteria for each class of integrability, also with their relative weight, are shown in Figure 10 (DE BERARDINIS; BONOMO, 2012).

Figure 9 - Classes of integrability of the BiPV.tool with their relative weight.

Class of PV integrability	Object of assessment	%
PROCEDURAL	Regulatory and legal system that addresses procedural conditions, limits and incentives	5%
MORPHOLOGICAL FIGURATIVE	Quality of aesthetic and formal characterization of the architectural language	30%
TECHNOLOGICAL CONSTRUCTIVE	Constructive role in the technological system	15%
BUILDING PERFORMANCE	Level of satisfaction of technological requirements	15%
BIOCLIMATIC ECOLOGICAL	Energy saving and environmental efficiency throughout the building lifecycle	15%
ENERGETIC PLANT	Principles of solar design and electrical efficiency	15%
LANSCAPE CONTEXTUAL	Coherence and acceptability with a system of contextual values to be protected	5%

Source: de Berardinis and Bonomo (2012).

Santos (2013) developed a design decision support tool to assist architects to use PV integration in their projects. The tool considers the location of the project, the percentage of irradiation to be received at the position of installation of the PV system, shading losses, the selection of desirable integration features to view similar reference projects, definition of the available area for the PV system, selection of the type and quantity of the PV modules, definition of the PV installed capacity and of the performance of the system, estimation of energy generation and avoided CO_2, definition of the cost of the installed capacity unity (Wp), estimation of the system's initial investment, indication of the average monthly consumption, and estimation of the annual energy balance (SANTOS, 2013).

Figure 10 - Evaluation criteria of the BiPV.tool with their relative weight.

1	PROCEDURAL	5%
	Criteria	Weight
1.1	Possibility to access to incentives	50%
1.2	Possibility to access to bonus tariffs	20%
1.3	Compliance with special rules	30%
2	**MORPHOLOGICAL-FIGURATIVE**	**30%**
2.1	Linguistic-morphogenetic PV role	20%
2.2	Recognizability of the PV skin and dialectical relationship with the building envelope	15%
2.3	Dimensional-morphological coordination of PV surface	20%
2.4	Linguistic and aesthetic control at component scale	15%
2.5	Innovation in design	15%
2.6	Figurative role of other parts	
2.6.1	*wiring, connections, cables*	5%
2.6.2	*structures and application systems*	5%
2.6.3	*Inverter, batteries*	5%
3	**TECHNOLOGICAL-CONSTRUCTIVE**	**15%**
3.1	Type of integration	40%
3.2	Constructive role	30%
3.3	Couple ability	30%
4	**BUILDING-PERFORMANCE**	**15%**
4.1	Degree of satisfaction of building requirements	60%
4.2	Interference on technological quality	25%
4.3	Strategy of technological innovation	15%
5	**BIOCLIMATIC-ECOLOGICAL**	**15%**
5.1	PV effectiveness in global energy efficiency	
5.1.1	Ability to satisfy the energetic electrical demand	40%
5.1.2	Contribution of PV in the global energetic demand	40%
5.2	PV environmental impact	
5.2.1	Recycling	15%
5.2.2	Embodied energy in PV plant	5%
6	**ENERGETIC-PLANT**	**15%**
6.1	Choice of PV material	10%
6.2	Maximising and optimizing the producible energy	20%
6.3	Adequate placement of PV modules	20%
6.4	Limitation of shading on PV modules	10%
6.5	Limitation of dirt on PV modules	10%
6.6	Control of module temperature	20%
6.7	Control of albedo factor	10%
7	**CONTEXTUAL-LANDSCAPE**	**5%**
7.1	Landscape character of context	30%
7.2	Intervention on contextual quality	70%

Source: de Berardinis and Bonomo (2012).

Polo Lopez *et al.* (2014) performed a multi-criteria analysis to compare BIPV solutions with other construction materials in building façades in terms of technological, architectural,

energetic, environmental, and economic requirements. The assessment methodology was based on the criteria shown in Figure 11 (POLO LOPEZ *et al.*, 2014).

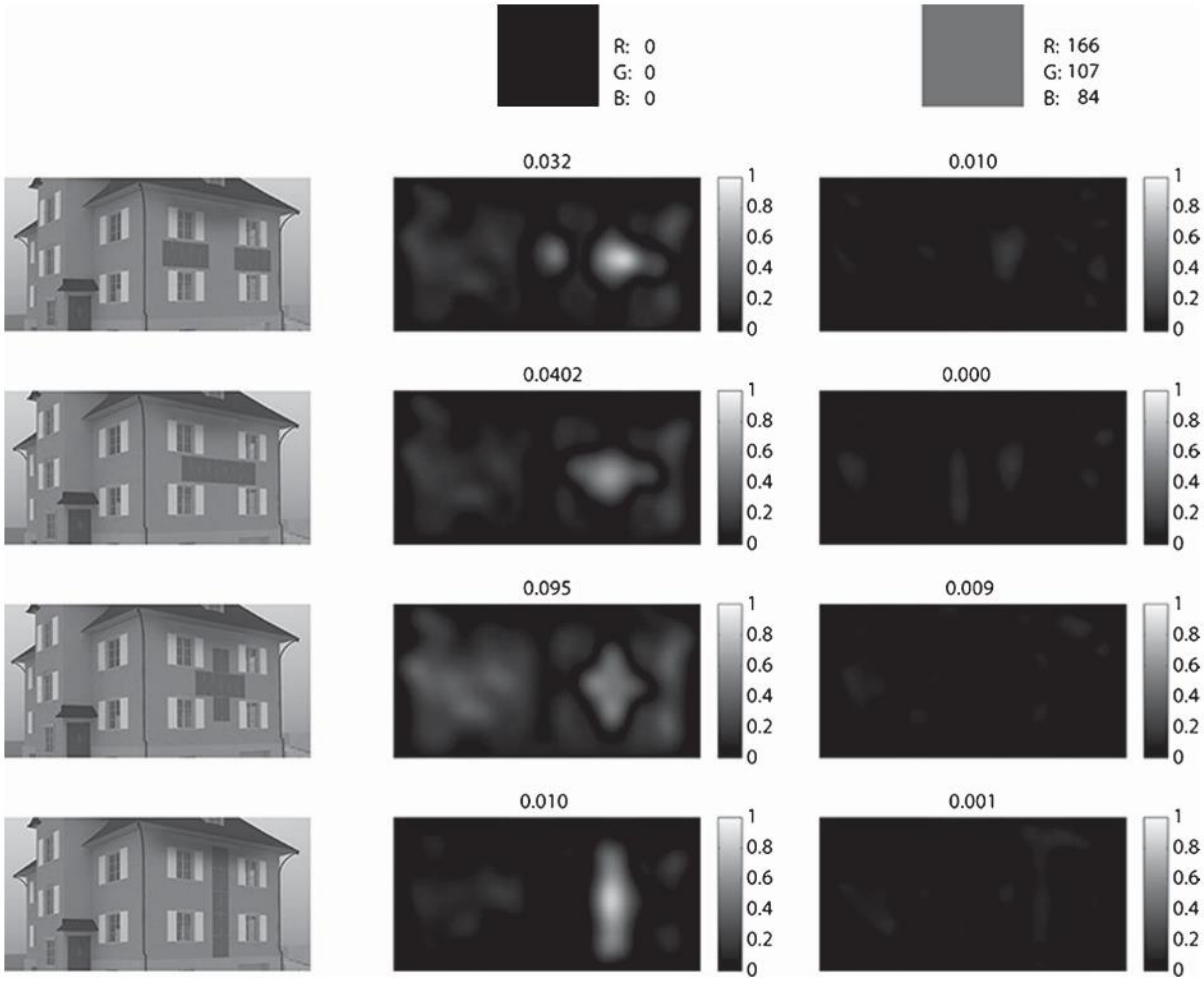
Figure 11 – Evaluation criteria for the comparison of BIPV solutions with other building materials in façades.

Technological features:
- Safety and reliability: robustness and durability; - Weather protection, hygiene, health and environment; - Durability and maintenance during operation phase.
Architectural features (aesthetical & functional):
- Dimensional aspects of materials and components, also considering fixing and fastening systems; - Aesthetical aspects: material, shape, color;
Energy properties & comfort:
- Energy issues and aspects related to human comfort.
Construction methods & manufacturing System:
- Constructive aspects: weight, type of supporting structure and ideal system installation and fixation; - System flexibility: quick & easy construction; - Customizability of manufacturing;
Environment properties & other issues:
- Environmental aspects: ecological and sustainable; - Plus accessories, smart-media properties or others;

Source: (POLO LOPEZ *et al.*, 2014).

Xu and Wittkopf (2015) and Xu, Wittkopf and Roeske (2017) present a technique to evaluate the visual impact of BIPVs, where the visual saliency of an image (the probability of a particular image region to attract visual attention in comparison to its surrounding) is calculated and represented in saliency maps. It considers PV layout and color variations and compares the buildings with and without the PV integration proposals. This way, it is possible to objectively assess and quantify the visual impact of PV installations and judge whether they are ‘significantly’ influencing the envelope of a building or not. In Xu and Wittkopf (2015) the influence of different PV systems on the façade of a heritage-protected historical building was evaluated, in order to find the option with the least visual influence, since the architecture of the building needs to be kept as original as possible. Figure 12 illustrates the difference of the saliency values between the saliency maps of the building with and without PV integration. In the example, the single horizontal line PV integration in grey would be the one with the least impact in the architecture.

Figure 12 – Difference of the saliency values between the saliency map of the building as it is and each ‘new’ saliency map.

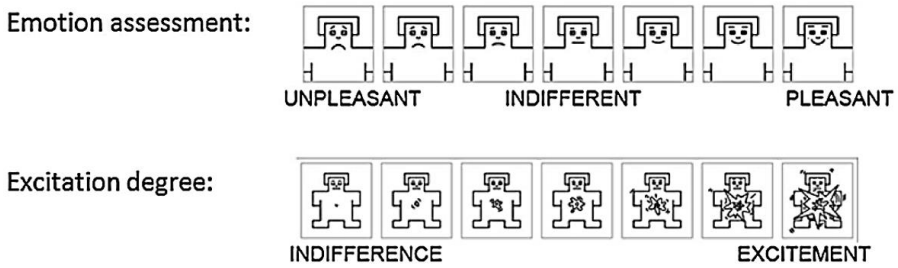


Source: Xu and Wittkopf (2015).

Sánchez-Pantoja, Vidal and Pastor (2018) collected data on the aesthetic perception of the use of PV technology in the buildings of the Solar Decathlon Europe competition in Versailles 2014, directly from the citizens, through a survey. The objective was to identify society’s acceptance or non-acceptance of the PV technology. The research analyzed how 10 prototypes of BAPV and 10 of BIPV are perceived by citizens, considering BAPV as systems that are superposed on the envelope and prioritize power generation, and BIPV as fully architectural integrated systems. 505 surveys were done, being some in situ and others online (where participants could only see images of the buildings). The evaluation of the aesthetic perception used the Self-Assessment Manikin (SAM) method, a non-verbal instrument that includes a pictorial scale for assessing emotional reactions when facing different situations. Two dimensions were considered: hedonic valence (pleasant-unpleasant) and arousal (level of

excitation), as shown in Figure 13. Participants were supposed to mark in the figure the expression that best represented their feelings when they saw each building. The sociodemographic profile of the participants was also considered to see if this had any influence on the aesthetic perception of the systems (SÁNCHEZ-PANTOJA; VIDAL; PASTOR, 2018).

Figure 13 – Illustration of the survey using the SAM method to score the parameters "hedonic valence" and "arousal".



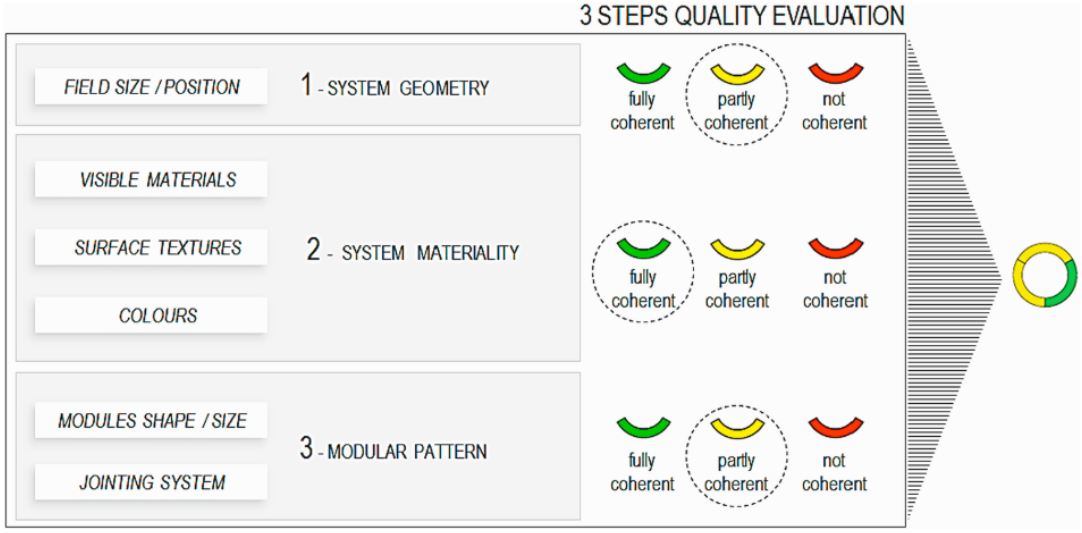
Source: Sánchez-Pantoja, Vidal and Pastor (2018).

Results showed that the use of PV in buildings is well accepted by users. BIPV cases had greater aesthetic acceptance with higher values for both hedonic valence and arousal when compared to the BAPV cases. The range of scores, however, was not very wide and the difference could be reduced if the respondent considered the economic investment of the BIPV, which is higher. Moreover, it was noted that the more a person can see and perceive the PV system, the lower is the hedonic valence. Regarding the sociodemographic profile, the only parameter that had influence on the variables was age. Younger people usually gave higher scores to arousal in both BAPV and BIPV cases, and higher scores to BAPVs regarding hedonic valence, in relation to the older participants. This indicates that older people are less impressed and less inclined into accepting the aesthetics offered by BAPV solutions (SÁNCHEZ-PANTOJA; VIDAL; PASTOR, 2018).

Furthermore, the LESO-QSV (for Laboratoire d'Energie SOlaire – Qualité-Sensibilité-Visibilité) method was created to bring objectivity to the debate of the urban/architectural acceptability of PV and solar thermal systems, ensuring that the integration quality of the systems, as defined by IEA SHC Task 41 A.2, is acceptable for their given environment. Therefore, the LESO-QSV method establishes formal acceptability conditions regarding context sensitivity, system visibility, and socio-political context. To do that, first the architectural integration quality is quantified, then it is related to the concept of "criticity" of city surfaces which is established by the "criticity" grid (FLORIO; ROECKER; MUNARI PROBST, 2015; IEA SHC, 2012; MUNARI PROBST; ROECKER, 2011, 2015, 2019).

A three-level qualitative scale (fully coherent, partly coherent, or not coherent) is used to quantify architectural integration quality. The coherency of the system geometry (field's size, shape, and position), the system materiality (modules' colors, textures and reflexivity), and the modular pattern (PV modules plus mounting system) are evaluated considering the design of the building. A three-sector circle is used to present the global system quality, where each arc of the circle represents an individual evaluation. Fully coherent characteristics are represented in green arcs, partly coherent in yellow, and not coherent in red. Figure 14 illustrates the evaluation method of architectural integration quality, where two of the characteristics are partly coherent with the overall design of the building (yellow arcs in the quality circle) and one is fully coherent (green arc) (FLORIO; ROECKER; MUNARI PROBST, 2015; MUNARI PROBST; ROECKER, 2015, 2019). According to Munari probst and Roecker (2019), a validation of the approach has been conducted with students from classes devoted to solar integration. Participants individually evaluated integration cases and, although not totally uniform, the evaluations showed good overall coherency, validating the method.

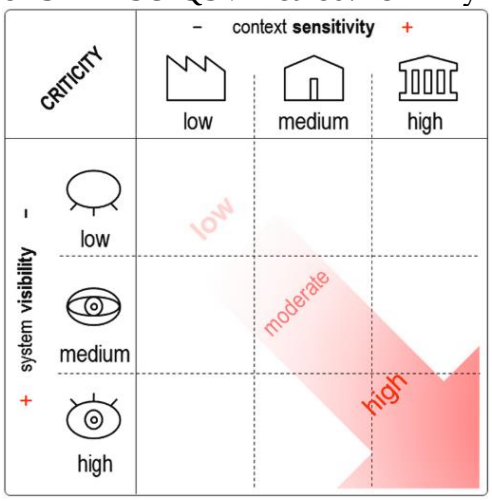
Figure 14 – LESO-QSV method: architectural integration quality evaluation.



Source: Munari Probst and Roecker (2019).

Furthermore, the "criticity" grid (Figure 15) combines the visibility level and the context sensitivity level of a city surface, in order to define a "criticity" level. Both the visibility and context sensitivity are classified into low, medium, and high levels. The higher these levels are, the higher is the "criticity" of a surface and the required architectural integration quality (FLORIO; ROECKER; MUNARI PROBST, 2015; MUNARI PROBST; ROECKER, 2015, 2019).

Figure 15 – LESO-QSV method: “criticity” grid.



Source: Munari Probst and Roecker (2019).

To establish the visibility percentage of the surface and its classification, both close and remote visibilities need to be considered, as the roof of a building on a plain terrain and surrounding will be far less visible than one of a building on a hillside (MUNARI PROBST; ROECKER, 2011, 2019). Visible percentages lower than 10% ($\beta < 6^{\circ}$) classify low-visibility surfaces; visible percentages of 40% ($\beta = 24^{\circ}$) or higher classify high-visibility surfaces; and results between these two values classify medium-visibility surfaces. A geometric calculation presented in Munari Probst and Roecker (2019) that relates the surface vision angle (β) with the viewer’s distance (d), building height (h), and roof tilting (α) can be used to estimate visibility (MUNARI PROBST; ROECKER, 2019). To automatize the procedure, Florio *et al.* (2018) proposed a visibility calculation tool which considers geometry-based parameters under a range of urban scales that goes from the strategic broad territorial to the district level, besides ranking the public visual interest between different points of view (FLORIO *et al.*, 2018).

Regarding context sensitivity, “contexts with poor urban/architectural qualities, and no specific identity, like many recent industrial/commercial urban developments” are classified as low-sensitivity cases; “contexts/buildings with no specific architectural/urban qualities, but with a meaningful identity for the community, like most post world war residential or tertiary urban developments” are classified as medium-sensitivity cases; and “heritage-protected or meaningful contexts/ buildings” are classified as high-sensitivity cases, according to city zoning and heritage-protected areas (MUNARI PROBST; ROECKER, 2011, 2015, 2019). Custódio, Zomer and Rüther (2020) applied the definitions of context sensitivity levels to two case studies and showed that they could lead to misunderstandings. Hence, they expanded the definitions of context sensitivity levels to make them more explicit and useful in the most variable, worldwide

urban and architectural contexts. These definitions are shown in Figure 16 (CUSTÓDIO; ZOMER; RÜTHER, 2020).

Figure 16 – Expanded definitions for the context sensitivity classification levels.

Context sensitivity	Low	Medium	High
Expanded definitions	- "Contexts with poor urban/architectural qualities, and no specific identity, like many recent industrial/commercial urban developments" (Munari Probst and Roecker, 2019) - Industrial, commercial, or residential buildings located at areas with high density, complexity, and mixture of architectural identities. - Residential constructions located at rural areas, which are intended for agricultural production.	- "Contexts/buildings with no specific architectural/ urban qualities, but with a meaningful identity for the community, like most post world war residential or tertiary urban developments" (Munari Probst and Roecker, 2019); - Buildings located at dense centralities, which are next to or surrounded by environmental preservation areas; - Residential buildings located at medium-density areas with few commercial buildings; - Residential buildings located at social interest housing areas.	- "Heritage protected or meaningful contexts/ buildings" (Munari Probst and Roecker, 2019); - Constructions located at environmental conservation areas, where any type of constructed element should take into consideration the preservation of the natural landscape; - Buildings located at areas with cultural/touristic attributes; - Institutional or community buildings, which guarantee the adequate performance of other urban uses and the well-being of the citizens; - Buildings with historical/cultural interest, which aim the preservation of either architectural, artistic, landscape, technological, or urban planning features, even if not protected by law; - Contexts of citizen interest, which aim the preservation of places where events of historical or renowned importance have occurred.

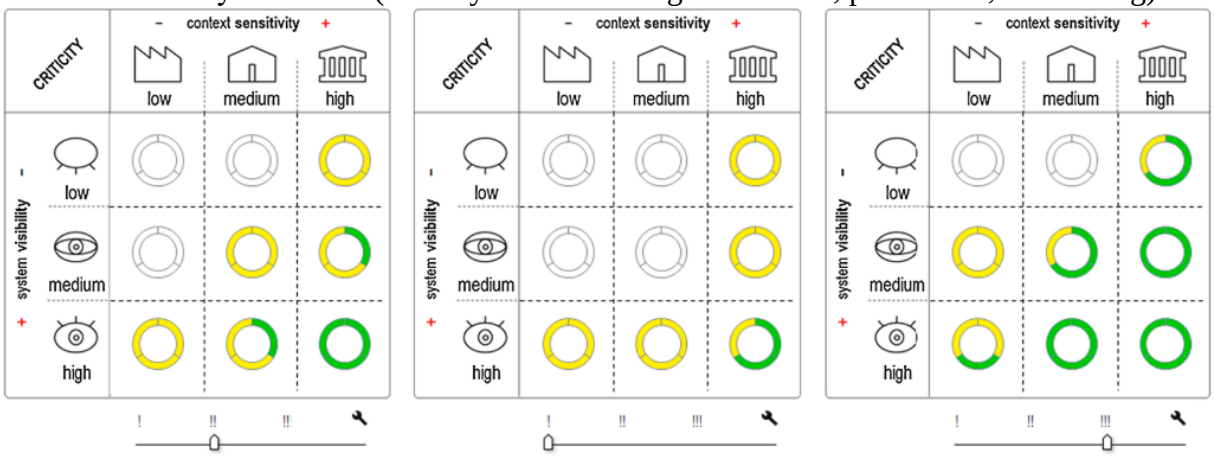
Source: Custódio, Zomer and Rüther (2020).

By crossing visibility and context sensitivity levels, the "criticity" level can be identified in the "criticity" grid as low, moderate, or high. Authorities can then relate the grid with the desired integration quality levels for each "criticity" situation, depending on socio-political context and energetic needs (Figure 17). Finally, to impulse the use of the method, two complementary tools were also created: the "LESO-QSV GRID software" and the "LESO-QSV Crossmapping" tool. The first one aims to support municipalities in establishing their own grid of local integration quality requirements, and the second one to be a strategy for energy policy planning, as it combines the "criticity" of city surfaces with Geographical Information System (GIS) solar irradiation maps (FLORIO; ROECKER; MUNARI PROBST, 2015; MUNARI PROBST; ROECKER, 2011, 2015, 2019).

Tablada *et al.* (2020) assessed the architectural quality of productive façades (PF), which are flexible and multi-functional structures integrating PV and vertical farming (VF) systems. The evaluation was done through a survey with architects, horticulturists, and VF and PV experts, and considered five characteristics: the visual impact of PFs on the exterior façade design; the impact of PFs and their main elements – PV modules and planters arrangements – on the view from the inside of a building; materialization (arrangement of PV modules – their size and position; material, texture and color of PV modules and planters; and the visual effect of the safety grill designs); the ease of operation and functionality of the designs; and the overall

architectural quality. Different design possibilities with variations on the aspects that impact the architectural quality (PV modules and VF systems integration, safety grill, and operation system) were shown in nine questions, and their characteristics had to be rated as “very poor”, “poor”, “fair”, “good”, or “very good”. The designs that were better evaluated were then used to create general design recommendations for PFs. Furthermore, the authors underline that the selection of PF elements should consider the entire building envelope composition, proportion, rhythm, transparency, scale, colors, and materials (TABLADA *et al.*, 2020).

Figure 17 - Example of possible grids with the desired architectural integration quality for each “criticity” situation (severity from left to right: standard, permissive, demanding).



Source: Munari Probst and Roecker (2019).

Celadyn and Filipek (2020) designed a systematized process for architects to improve their knowledge about PV in buildings. It is important that architects have a suitable knowledge before taking the project to PV specialists, who, in turn, are less familiar with spatial and aesthetical issues. The scope of the created process closely corresponds to the consecutive stages of architectural design: first, an analysis of a wide range of accessible PV products available in the market is carried out; then, the influences on the performance of the PV systems concerning zoning plans and the position of the building in the lot are explained; next, the effects of the spatial position on the performance of the systems are pointed out, considering especially shading and ventilation of the modules; the spatial relations between PV modules and the buildings is also discussed using the concepts of BAPV and BIPV; then, a discussion on the aesthetical issues of PV use in buildings is presented, which addresses the image of buildings as well as the coherency of the colors and textures of the PV modules with the other building materials; followed by the description of other functions of PV systems in buildings besides energy generation and how they can be integrated with other technologies such as green

roofs. If the architect acknowledges and incorporates all these steps, the integration of PV in buildings should reach higher aesthetical results (CELADYN; FILIPEK, 2020).

2.1.2 Research that describes the features of photovoltaic building integration

Hagemann (1996a) describes a successful architectural integration of PV for a day care center building (Figure 18 and Figure 19) in Frankfurt, Germany, in a holistic manner that includes the way the PV modules influence the perception of the building:

> "The building […] appears to be dynamic, playful, clearly defined, transparent and open. […]
>
> Openness and transparency are generated by means of a clearly defined building composition with only a few basic and easily recognizable shapes and by means of the protruding transparent and paramount glass prism integrated in the building.
>
> The building comprises single geometric bodies – a longish cuboid, a stout cuboid and a sloping prism make up this building. Basic geometric shapes such as the circle, the triangle, the rectangle and the square are repeated in different variations in and on the building […].
>
> A child becomes familiar with these geometric shapes quite early in life when playing with toys. This is why these shapes convey the feeling of a familiar environment. On the whole, the building's main characteristics – the playful elegance and light-heartiness – are immediately impressed upon the beholder.
>
> Photovoltaic modules are integrated in the play with geometric basic shapes. They comprise a longish blue rectangle which stretches across the entire width of the glass prism. A clip holds this rectangle to the glass house and marks its beginning and end. The contrast between the solid appearance of the PV bar and the bodyless, clean glass panes of the slanting glazing underscore this carefree, playful feeling.
>
> At the same time, the PV bar creates a horizontal countermovement to the vertical division of the slating glass prism. This is because, when the face widths of the horizontal and vertical profiles are the same length, the vertical glass profiles appear wider to the observer. This is because the viewing angle causes him to be subject to the optical illusion that the width of the horizontal profiles is shorter.
>
> The diagonal wood panels on the building exterior of the stout cuboid that intersects the glass house forms, in a somewhat subtle manner, a counter-movement to the slope of the glass. The diagonal wood panels that run in vertical form to the sloping glass surface provide a visual support and hold for the glass prism. The blue longish cuboid, which forms the north boundary of the building, is repeated as a two-dimensional figure in the rectangle of the PV system. Color, shape and dimensions are similar.
>
> The clearly defined, basic prism shape of the glass building is disturbed by an intersecting solid cuboid, which holds rooms for groups on two floors, but it is not completely unrecognizable as a prism. Order and disorder (disturbance) provide a tension-filled contrast.
>
> The south face of the building […] is made up of several layers that convey a three-dimensional effect. At the same time, the view from the building is both framed and directed in a special direction, establishing a particular reference to the surroundings. […]
>
> In order to take up this game with the various layers, the PV modules have not been set at the same level as the panes of the sloping glass, in keeping consistent

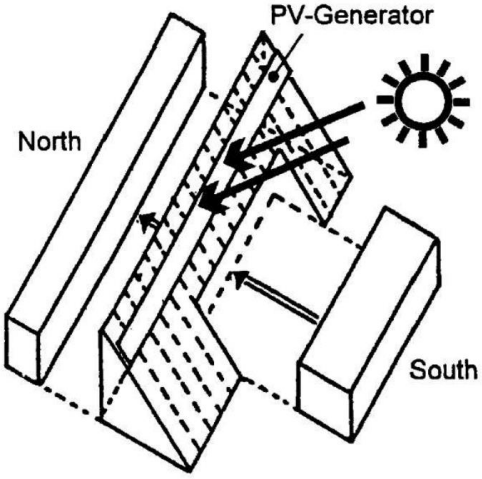
> with the concept of architectural design. The modules are mounted a small distance above the sloping glass. Through this arrangement, the profiles of the sloping glass, the modules frame and the individual PV cells cast silhouettes on the surface of the building interior. As a result, they create an intriguing play of light and shadows […].
>
> Photovoltaic modules are used in this case to achieve light and mood, as well as to generate electricity (HAGEMANN, 1996a)."

Figure 18 – South view of the kindergarten described by Hagemann (1996a).



Source: Hagemann (1996a).

Figure 19 – Schematic drawing of the kindergarten described by Hagemann (1996a).



Source: Hagemann (1996a).

This holistic manner of describing the integration of PV systems in buildings can also be seen in Hagemann (2004), where successful projects of architectural integration of PV in Germany are presented. Likewise, Becker *et al.* (2018) defined the PV systems from the participants of the award for Building Integrated Solar Technology of the Bavarian Association for the Promotion of Solar Energy by describing their architectural aspects (conceptual design, type of PV integration, design quality, and functionality), innovativeness, energy yield/energy efficiency, and communicating of the system to the general public (BECKER *et al.*, 2018; HAGEMANN, 2004).

The IEA PVPS Task 7 (IEA PVPS, 1997) has also established PV design approaches, which are shown in Chart 2. The types of PV integration were classified in order of increasing value of architectural integration, but it does not mean that PV systems that are applied invisibly have the lowest quality, as they are appropriate in specific cases such as in historical buildings (KAAN; REIJENGA, 2004).

Chart 2 – Types of PV integration as defined by IEA PVPS Task 7.

PV is applied invisibly	The PV system is incorporated invisibly: it is not architecturally disturbing and harmonizes with the total project.
PV is added to the design	The PV system is added, not integrated, to the design. This does not mean that architectural quality is lacking.
The PV system adds to the architectural image	The PV system is integrated into the total design of the building, without changing its image.
The PV system determines the architectural image	The PV system is integrated into the design in a remarkable way and plays an important role in the total image of the building.
The PV system leads to new architectural concepts	The PV system leads to new architectural designs and its integration has been considered at the conceptual level.

Source: Kaan and Reijenga (2004).

Scognamiglio and Privato (2008) established “guide concepts” to emphasize the way architects use PV systems: uniqueness, discreetness, attractiveness, and self-sufficiency. “Uniqueness” is used to describe buildings that cannot be practically repeated, either because of their huge scale, distinctive shape, or material. The uniqueness depends on innovative designs, and not on the use of non-standard PV modules. “Discreetness” is used to describe buildings that correspond with the existing ambient, instead of imposing upon it. These buildings usually have easier public’s acceptance. Also, discreet buildings can provide repeatable solutions to envelope problems if building typologies, envelope technological details, and PV components are also standardized. “Attractiveness” is used to describe urban marks, which can draw the public’s attention either by its appearance or its function. PV urban

marks can be attractive because they are symbols of sustainability and/or for powering an activity of an urban mark. Lastly, “self-sufficiency” is used to describe small spatial elements that use a stand-alone PV system to supply all the electric energy needed for their operation. From design perspectives, the aesthetics of these elements are greatly influenced by PV, as the characteristics of the PV system (area, azimuth angle, tilt angle, technology) define its performance (SCOGNAMIGLIO; PRIVATO, 2008).

Peng, Huang and Wu (2011) used the conventional classification BAPV and BIPV to describe PV systems. The definition of BIPV and BAPV varies from place to place. According to the authors, BIPV are multifunctional systems that act as construction materials while generating electricity. They are integrated to the building’s design by replacing traditional envelope materials (shingles, tiles, slate, metal, brick, glass), enhancing the building’s appearance or just maintaining an architectural continuity. Curtain walls, canopies, windows, and skylights are also classified as BIPV, being composed either by semitransparent, opaque, or even tailor-made modules. Differently, BAPV are stand-off or rack-mounted systems whose only function is to generate electricity. Stand-off systems are mounted above the roof surface, parallel to its tilted surface, while rack-mounted systems are usually installed on flat roofs and positioned at an optimum orientation and tilt for energy generation. In practice, these two classifications sometimes are not that obvious. For example, BAPV becomes BIPV when PV modules are integrated tightly to buildings surfaces (PENG; HUANG; WU, 2011).

As mentioned, IEA SHC Task 41 A.2 defines “architectural integration quality”. It also defines six main categories of how PV can be used in the building envelope: added technical element, added elements with double function, free standing structure, part of surface composition, complete façade/roof surface, form optimized for solar energy, and other (if the integration does not belong to any of the previous categories) (IEA SHC, 2012).

The tool presented by Santos (2013) includes images of 325 reference projects, which were identified to verify common elements between their architectural composition. This analysis aimed to see which types of PV integration are mostly used by architects and designers, and considered the characteristics shown in Chart 3.

Chart 3 – Characterization features of reference projects of buildings with PV.

Characteristics	**Option**
Building use	Residential
	Commercial
	Industrial
	Services
	Institutional
Integration type	New building
	New structure
	Retrofit integration
	Integration applied to historical buildings
Architectural feature	Exponent architects
	Conventional buildings
Integration view	Invisible or non-noticeable integration in façades
	Integration in part of a visible surface
	Integration in an entire visible surface
Place of integration	Roof
	Façade
	Roof/Façade
	Brise-soleils and other elements
	More than one surface
Integration surface	Plan
	Curve
Seal	Opaque
	Translucent/Transparent
Substrate of the module	Rigid
	Flexible
Frame	Framed
	Frameless
PV technology	Crystalline
	Thin film
	HIT
	More than one technology
	Other
Relation with other construction materials	Exposed concrete
	Glass/ Polycarbonates
	Wood
	Metal
	Ceramics
	Stone

Source: Santos (2013).

Cronemberger *et al.* (2014) have classified the houses presented to the Solar Decathlon Europe competitions in Madrid 2010 and 2012 regarding their PV integration. According to the rules and regulations of the contest, the purpose of architectural evaluation was “To asses (…) the integration of the technologies in the architecture (…)”. In 2010 the purpose was specified as “Technological expression: architecture as an integration of the technology on which it is based. The means in which the solar elements and technological systems have been integrated

in the house will be evaluated", whereas in 2012 as "Systems' architectural integration: how naturally modules/systems are integrated in the house design concept and their coherence, and how they improve the perception of the house – which may consider aspects like form, color, texture, materials, light and transparency to create stimulating spaces". The PV systems integrated to the houses of the competitions have been classified according to their grade of integration, architectonic design approach, placement of modules, energy strategy, and technical characteristics. Chart 4 presents the topics used in the classification and their description (CRONEMBERGER *et al.*, 2014).

Chart 4 – Classification criteria used for evaluating the PV integration architecture of the houses from Solar Decathlon Europe competitions in Madrid 2010 and 2012.

Grade of integration	
BAPV – building applied Photovoltaics	"Modules are used solely for generating energy, even as part of the architectonical composition of the building, but do not replace or perform as a construction component. They may be assembled coplanar or not to the building envelope on roofs, façades, atria or shading devices."
BIPV – building integrated Photovoltaics	"PV construction elements are part of the building envelope, acting not only as an energy generator, but also performing as an envelope function, on roofs, façades, atria or shading elements."
Architectonic design approach	
Invisible application	"Modules are located out of the sight of the users, or are intentionally designed not to be distinguished from the rest of the building envelope."
Added application	"Modules are applied to perform a function in the building, added to the construction, as in shading devices over windows."
Highlighted application	"Modules are used to enhance the image of the building, without dominating it."
Leading application	"Modules are preponderant determining the image of the building."
Placement of modules	
Roofs	"Sloped roofs, flat roofs, atria."
Façades	"Cold façades, warm façades, window glazing."
Shading elements	"Canopies, louvers and brise-soleils."
Energy strategy	
"PV modules are used only to generate electricity, as part of the electrical energy balance."	

“PV modules are also used as part of the comfort strategy for the building, such as thermal, acoustic or lighting conditioning.”	
“PV modules are optimally tilted and oriented.”	
“PV modules use non-optimal tilts and/or orientations.”	
“PV modules are hybrid with thermal generation properties, with air or other fluids.”	
Technical characteristics	
PV technology	“Silicon based (a-Si, multi-Si, mono-Si), non-silicon based (cadmium telluride—CdTe, copper indium gallium or diselenide – CIS or CIGS) or new concepts (CPV etc.).”
PV systems use off-the-shelf modules	
PV systems use special custom-tailored modules	
PV systems include features for cleaning and maintenance	
Energy payback time	

Source: (CRONEMBERGER *et al.*, 2014).

Devetaković *et al.* (2020) investigated the PV application impact on the architectural value of ten landmark buildings, regarding their distinctive geometry and architectural features. The criteria for analyzing the architectural performance were: (1) PV system as an architectural and environmental value; (2) PV contribution in defining the fifth façade (the roof); (3) PV emphasizing the geometry of architectural building; (4) PV contribution to specific geometry of the architectural building; (5) PV as architectural accent; (6) PV integration in architectural visibility, sensitivity, and quality; and (7) PV as a peculiar element. The seven architectural performance parameters should be considered when designing buildings with PV systems. Figure 20 shows the landmark buildings presented in the study and the results of their architectural performance classification (DEVETAKOVIĆ *et al.*, 2020).

Regarding (1), the application of PV systems always relates to environmental responsibility and sustainability. On (2), the roof becomes “the fifth façade” when the geometry of a PV system is well articulated, and the roof is architecturally treated as the actual façades. (3) refers to situations where the geometry of an existing building object allows efficient and smooth application of PV systems. (4) represents PV systems that contribute positively to the geometry of the buildings. On (5), PV systems do not aim at generating significant amounts of energy, but to send a message of sustainability. (6) used the LESO-QSV method (MUNARI PROBST; ROECKER, 2019) to assess architectural visibility, sensitivity, and quality of the

systems. Finally, on (7) the PV systems represent dominant building elements (DEVETAKOVIĆ *et al.*, 2020).

Figure 20 - Architectural performance classification of the landmark buildings.

Landmark Buildings with PV	PV System as Architectural and Environmental Value	PV Contributing in Defining the Fifth Façade	PV Emphasizing the Geometry of the Arch. Building	PV Contributing to Specific Geometry of Architectural Building	PV as Architectural Accent	PV Integration in Architectural Visibility, Sensitivity and Quality	PV as Peculiar Element
Maracanã Stadium [BR]	✓	✓	✓			✓	
Apple Headquarters [USA]	✓	✓	✓			✓	✓
Shanghai Expo—Theme Pavilion [CN]	✓	✓		✓		✓	
Powerhouse Brattørkaia [NO]	✓	✓		✓		✓	✓
Paris Courthouse [FR]	✓			✓	✓	✓	
La Seine Musicale [FR]	✓		✓	✓	✓	✓	
Umwelt Arena [CH]	✓	✓		✓		✓	✓
Kaohsiung National Stadium [TW]	✓	✓		✓		✓	✓
Novartis Campus [CH]	✓	✓				✓	
Copenhagen International School [DK]	✓			✓		✓	✓

Source: Devetaković *et al.* (2020).

Finally, a recent study (SCOGNAMIGLIO, 2021) on the visual performance of BIPV proposed a vocabulary focused on the formal perception of the systems as part of the building envelope. It gathered formal and cognitive information in a hierarchical configuration that went from the coarse scale (the BIPV system as a whole) to the medium and fine scales (the PV module). The descriptive model integrated both perceptive aspects (subjective and qualitative) and technological ones (technical and quantitative), in order to translate the quality objectives which are set by architects into specific visual features for BIPV, to be obtained through the use of technological choices. In the course scale of description, the building envelope technology, the mosaic type, and the pattern and patch of the BIPV system are considered, whereas the medium and fine scales contemplate the shape, size, position, border, and the patch surface-texture of the modules. The justification of the method is that recognizability is not a visual feature of PV anymore, as the BIPV market has created modules with the most variable shapes, sizes, colors, and textures. Hence, the language of BIPV should be visual and the technology treated as any other material of the building envelope (SCOGNAMIGLIO, 2021).

2.1.3 Research that deals with the integration of photovoltaic generators in landscapes

Torres-Sibille *et al.* (2009) created an indicator to objectively determine the aesthetic impact of PV plants located in landscapes considering the variables of visibility (the area taken up by the PV generator with respect to the total landscape area), color (contrasts in hue, saturation and brightness), fractality (a measure of artificiality in the geometry of a pattern, so how "artificial" the rigid pattern of the system is in relation to the natural background), and concurrence (similarity in concentration of two types of solar panels within one solar plant; the contrast between concentrations due to concurrence of typologies will cause an impact). The variables were each given a weight of importance and combined in a formula that was applied to photographs of five PV generator case studies. Then, a social validation was made to ensure that the indicator results reflected public preferences. Photographs of the case studies were shown to 123 people, who were asked to order by how impacting they considered each solar generator to be. The results from the formula and from the social validation were very similar, proving that the indicator correctly represents perception of impact. Furthermore, the authors analyzed the behavior of human perception towards the aesthetic impact of the PV plants using the semantic differential method. This approach is used to investigate the affective meaning of things, so it is efficient to measure the overall impression of an environment. The semantic concepts used were "pleasantness", "complexity", "coherence", "openness", "affection", "originality", "naturalness", "liveliness", "stimulation", and "degree of protection", being their definition presented in Chart 5. Both the initial landscapes (without PV plants) and the landscapes with the PV plants were assessed by 35 individuals that evaluated the concepts from a grade of -3 to +3. Results showed that generally, a PV plant will not change the opinion of degree of protection of a landscape. However, it reduces its naturalness and pleasantness. Also, the PV plant increases complexity and reduces perceived affection. The objective study, then, gives the magnitude of the impact of the PV plants in the landscape, and the subjective study records emotions generated by the quantified impact. This combination can help control aesthetic impact in the design phase of PV plants. (TORRES-SIBILLE *et al.*, 2009).

Chart 5 – Definition of the semantic concepts used to describe the visual impact of PV plants.

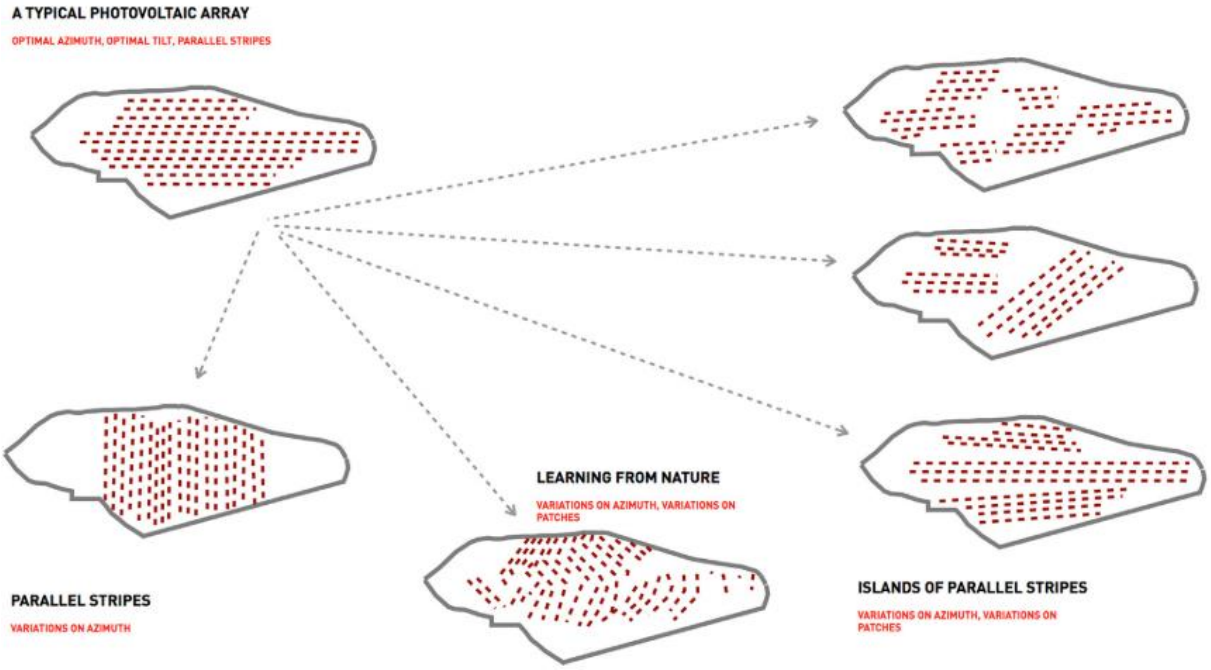
Concept	**Description**
Pleasantness	The degree of pleasantness, beauty, and security which the individual experiences in the environment.
Complexity	The environment's diversity.
Coherence	How well the various components in the environment seem to fit and function together.
Openness	The openness and degree of demarcation of the space.
Affection	An age as well as a feeling of the old and genuine.
Originality	The unusual and surprising in the environment.
Naturalness	The environment's authenticity, often connoted to elements of flora and fauna.
Liveliness	The degree of life-emanation of the environment.
Stimulation	The degree of stimulation, suggestion, and interest which the individual experiences in the environment.
Degree of protection	The degree of protection attributed to the environment.

Source: Torres-Sibille *et al.* (2009).

Scognamiglio and Røstvik (2012) introduced the concept of "Landscape-integrated PV (LIPV)", claiming about the necessity to investigate the use of PV in Zero Energy Buildings (ZEBs) from the architectural scale (one building) and from the urban and landscape scales (a cluster of buildings and even a whole landscape) as to increase PV area and generation, and to reduce aesthetical limitations. Since PV can in practice be the only energy provider of a ZEB, it can have a great influence on the aesthetics of the architectural design. In urban spaces, usually the existing area for PV is limited because of building characteristics, so the yield of the PV system must be maximized, influencing the shape of the building. Furthermore, "on-site" energy generation is the one where the PV system is located within the boundary of the building (inside the building's footprint) and "at-site" energy generation is when the PV system is located within the site's boundary but separated from the building. One can say that a detached system can be considered part of the building if its design has direct visual, formal or functional relationship with the building, as well as an appropriate scale of design, considering the building and the PV system as parts of a single composition. Also, this detached system, the building, and the public space should be considered as part of landscape. Then, the scale of design investigation for the use of PV should consider a cluster of buildings that belong to a landscape, or what can be called LIPV. In a technical point of view, the consideration of LIPV comes from the fact that many times the available area at a single building or site is not enough to achieve energy balance in ZEBs, what could be done if the system was designed considering other areas (SCOGNAMIGLIO; RØSTVIK, 2012).

Furthermore, Scognamiglio (2016) investigated “PV landscapes”, which are PV generators that have a “pattern” as their visual image. A PV landscape is composed by the “pore” space and the PV modules arranged in patterns. Usually, this pattern is designed as parallel stripes arranged at a regular distance from each other. The study, then, discussed the ecological impacts of these standard PV generators and advanced the idea that innovative patterns could ease the consequences and even improve land use and the perception (aesthetics) of the landscapes. The new patterns were studied regarding changes on the azimuth of the PV generators for non-ideal ones; on the arrangement of the parallel stripes pattern in different groups with different azimuths, shapes, and dimensions; and on the abandonment of the parallel stripes pattern in favor of a natural-agricultural pattern. Figure 21 illustrates the proposed new patterns.

Figure 21 - Landscape PV patterns.



Source: Scognamiglio (2016).

Finally, considering that PV systems have to extend to areas beyond the building envelope for achieving net zero energy balance, Scognamiglio and Garde (2016) stated that the design possibilities of PV for NZEBs should comprise the systems in terms of morphological and spatial related features. The morphological approach regards PV systems in/onto the envelope or into/onto external partitions, and the spatial approach considers PV systems located in the building footprint, on site, or off site. The usual categories used to describe the design

options for PV in connection with buildings – BAPV and BIPV – are, then, no longer sufficient to describe all the possibilities, as their definition could lead to ambiguity. Furthermore, depending on the size of the PV system and its proximity to the building, design should be addressed either in architectural or landscape scales. The architectural scale is suitable for PV in buildings' footprint or on site, and the landscape scale for cases of PV on site (if the site is big) or off-site. This leads to the fact that PV plants should also be thought in terms of design. The challenge is, then, projecting PV at the appropriate scale, establishing design relationships with the systems it belongs to (SCOGNAMIGLIO; GARDE, 2016).

2.1.4 Research that considers all the previous categories

Lobaccaro *et al.* (2019), framed in IEA SHC Task 51 C.3 (IEA SHC, 2018), analyzed 34 case studies regarding the perspective of solar energy in urban planning. Case studies in existing and new urban areas were examined according to their planning process; energy concept and simulation tools; architectural visibility, sensitivity, and quality; and environmental and social impact. Case studies of solar landscapes were investigated considering their planning process; solar landscapes site potential; and environmental, visual, economic, and social impact. The planning process is a description of the different spatial scales, stages of urban and landscape planning, and stakeholders involved. The category of energy concept and simulation tools presents the solar strategies (active, passive, or both), energy concept, technologies, approaches on the planning process, methods regarding solar energy in urban planning, and tools which were adopted. The assessment of architectural visibility, sensitivity, and quality used the LESO-QSV method presented by Munari Probst and Roecker (2019). The solar landscapes and site potential involved concepts presented by Scognamiglio (2016), such as the analysis of the formal functional features of the solar systems used (as the type of pattern or the presence of edges), and the specifications about energy production in the area. Finally, the environmental, visual, economic, and social impact included an evaluation of the impact of the solar systems in the surrounding environment, the creation of new business opportunities, the construction of new housing units, and the participation of the community/users as part of the planning process (LOBACCARO *et al.*, 2019).

2.1.5 Final considerations

The literature review on the aesthetics of PV in buildings showed that the existing investigations seek objective, functional, mechanical methods to understand the aesthetical aspects of PV architecture. They present practical criticism on the functionality, technique, plastic, and pictorial data of PV integrations. Even if important, they alone are ineffective in making the value of PV architecture understood, as its essence, the space, is neglected.

2.2 THE INTERPRETATIONS OF ARCHITECTURE

This section introduces an overview on the core of the architectural subject. The possible interpretations of architecture are presented and related to the existing investigations on the aesthetics of PV in buildings.

Architecture is an anonymous art: one usually does not care to know the authors of these buildings. This indifference probably comes from the lack of a clear and valid interpretation of architecture. If we really want people to see architecture, we need to propose a clarity of method. Historically, three-dimensional architecture seemed critically clear and technically achieved with the discovery of perspective and the invention of photography. However, the human mind discovered that to possess it fully, the piece would have to be represented by an infinite number of perspectives from infinite points of view. Consequently, three dimensions were not sufficient anymore, and time, or the consecutive displacement of the visual angle, was then established as the fourth dimension. Space itself, which is the essence of architecture, truly goes beyond the limits of four dimensions; it can have infinite dimensions. To our purposes, however, it is enough to assume that the space is a specific characteristic of architecture, which to be understood needs that men take time to experience it (ZEVI, 2009). Aesthetic experience needs openness, time, and space to tell us things (ALBERTON, 2021).

The main interpretations used in the architectural criticism are related to content, physiopsychological, and formalist categories, providing partial or incomplete histories of specific aspects of architecture. They are what we here call the “traditional” interpretations of architecture. However, it is the spatial interpretation the one that includes all the realities of a building. A well-established critique should increase the interest in architecture and arouse emotions in the public, making them understand that architecture can be found in monuments and historical churches, but also in the houses we live in and in the buildings that we pass by

every day. Learning how to see and recognize architectural and urban spaces will serve not only to understand aesthetic pleasure, but also to perceive the problems of the social environments in which we live (ZEVI, 2009). Comprehending architectural and urban spaces can also contribute to perceiving their environmental sustainability, which is essential in views of the current construction guidelines and demands.

2.2.1 Traditional interpretations of architecture

In this section, an overview of the traditional interpretations of architecture, or the ones related to content, physiopsychological, and formalist categories are presented.

2.2.1.1 Interpretations related to the content category

Interpretations related to content are the political, philosophical-religious, scientific, social-economic, materialist, and technical interpretations (ZEVI, 2009).

The political interpretation is very used in architectural history texts, which recapitulate the most important political facts of the different periods when describing a monument. However, sometimes the dependence established between architecture and political events is so memorable that it is like architecture only happened because of a determined political statement. An example to illustrate it is the fact that in 1933, when the Nazis took power in Germany and determined the end of Bauhaus (a school of modern design, architecture, and applied arts), the modern functional architects emigrated to England; that is why the movement evolved in the country (ZEVI, 2009).

The philosophical-religious interpretation declares that history only arises because of architecture, or that “architecture is the visual aspect of history”. This interpretation can be divided into philosophical-religious historical events involving architectural culture and symbolism. Examples are the Protestant Reformation in the 1500s and the Neoplatonic philosophy in the second century CE. The Protestant Reformation determined the end of the gothic architecture and the advent of Renaissance in England when many churches were remodeled into schools and castles. The Neoplatonism broke the individual view of human being and formulated the concept of infinite, which contributed to the replacement of the volumetric and plastic Greek temples by a more scenic and dramatic architecture (ZEVI, 2009).

The scientific interpretation attempts to relate mathematical and geometric conceptions with architecture. In the 17th century, the dome of the Royal Church of Saint Lawrence in Turin, for example, could only be created by Guarini because of the descriptive geometry methods and the discovery of integral calculus. Also, in Villa Savoie, which was completed in 1931, it was because of the fourth dimension of cubism and the denial of the perspective representation, which established a main point of view from which all the other elements were ordered, that Le Corbusier raised the construction on stilts and made all of its façades equally important (ZEVI, 2009).

The social-economic interpretation establishes a parallel between architecture and the economic systems and social institutions. It can also have symbolic applications. Examples are the medieval architecture and eclecticism. Medieval fiefs are based on the agricultural economy of the village, the system of co-participation and corporations, and the needs of defense. Differently, eclecticism is a combination of the past romanticism with the mechanism of the future, representing the architecture of industrial growth (ZEVI, 2009).

There are many sectors on the materialist interpretation. One of them states that the architectural form is founded on the geographic and geological conditions of the places where the monuments are built. For example, in Egypt (26° N, 30° E) rooftops are horizontal, in Italy (41° N, 12° E) they have little inclination and in Norway (60° N, 8°S), high inclination because of the existence of snow which must be drained off the roofs. Another sector of the interpretation is based on archaeological investigations, for example, Italian Renaissance (14th-17th centuries) only emerged because of the discovery of the texts of Vitruvius, which were written in the 1st century BC and established the conceptual principles of classic architecture. Other sectors such as the racial and the naturalist interpretations, which respectively declare that architecture pursues the morphology of humans and nature, also exist (ZEVI, 2009).

The technical interpretation evolved from a discourse against the “art for art’s sake” in favor of the art and technique together. However, architectural forms are not usually determined by construction techniques, as they usually repeat previous and antiquated practices. Taking notice of that, architectural manuals established a distinction between real construction and apparent construction, recommending that a building must present effective and apparent structural solidity. That is, the habit of traditional weighty relationships must be kept, since new techniques are not followed by new structural sensibilities. A great fact to illustrate this interpretation is the construction of the Fallingwater, a house designed by Frank Lloyd Wright in 1935. It is said that, because of a cantilever structured terrace, the workers refused to remove

the wood piles that were holding the huge terrace during construction and the architect himself had to do it (ZEVI, 2009).

Political, philosophical-religious, scientific, and social-economic interpretations are not used in the research from the literature review about PV. The studies mostly concern only the PV systems and their relation specifically to the building, and these interpretations regard the architectural construction as a whole. The materialist interpretation was used in four investigations that include the artificiality/naturality of the rigid pattern of the PV system in relation to the natural background of landscapes. Finally, the technical interpretation was used in 19 projects, including information of the mounting structures of the PV systems, as well as on PV performance and economic analysis. These projects and their respective interpretations can be seen in Appendix A.

2.2.1.2 Interpretations related to the physiopsychological category

Among diverse physiopsychological interpretations, the theory of Einfühlung is one of great value. It established a relationship between architecture and humans by the concepts of symbolist sympathy, trying to reduce art to a science where architecture and its forms could transcribe the states of mind or human expressions. Also, through the method of identifying man with forms, it was deduced that the expression of architecture is descriptive, not static, as it changes with time (for the period of decades, years, different seasons, and even during a single day). Chart 6 presents examples of the responses of geometric shapes in the state of mind of humans, according to the theory of Einfühlung. Basically, this theory analyzes the extension of the behavior of architects and observers in the architectural elements of the whole building; it provides a physiopsychological interpretation of terms such as proportion, symmetry, contrast, and other qualities of architecture, very much used in the formalist interpretation (ZEVI, 2009).

Talking about pleasantness, impressiveness, motivational effect, degree of satisfaction, level of excitation, and feeling of familiarity means interpreting architecture in a physiopsychological way. As shown in Appendix A, nine examples from the literature review followed this approach.

Chart 6 – Examples of responses of geometric shapes in the state of mind of humans, according to the theory of Einfühlung.

Geometric shapes	Responses on the state of mind of humans
Horizontal line	It represents the immanent, the rational, the intellectual. It leaves no doubts about its length as there is always an obstacle limiting it when its trajectory is followed by men.
Vertical line	It is the symbol of infinity, ecstasy, and emotion. Seen by men, its trajectory breaks in the sky, gets lost in it and never finds obstacles and limits; it is a symbol of the sublime.
Straight lines	They indicate decision, rigidity, and strength.
Curved lines	They represent hesitation, flexibility, or decorative values.
Helicoidal	It is the symbol of rising, of detachment, of liberation from earthly matter.
Cube	It represents integrity, definitive and secure certainty, due to its comprehensive all-equal dimensions.
Circle	It gives the feeling of balance, of control over all the elements of life.
Sphere or hemispherical domes	They represent perfection, or the final and conclusive law.
Ellipse	It develops from two foci, so it never allows the eye to rest, making them unsteady and agitated.
Interpenetration of geometric shapes	It is the symbol of dynamism and continuous movement.

Source: Zevi (2009).

2.2.1.3 Interpretations related to the formalist category

The formalist interpretation of traditional aesthetics enumerates a series of principles to which architectural composition must respond. They are unity, symmetry, balance, emphasis, contrast, proportion, scale, expression or character, truth, property, urbanity, and style. A great contemporary contribution consisted in the maturing of the formalist criticism of the traditional aesthetics, by replacing the traditional terms with a modern critique of architecture that includes Wölfflin's scheme. The contrasting visual scheme is very much used in painting and sculpture assessment but is still little applied in architectural criticism even though it emerged from the contestation of Baroque architecture. The five symbols of pure visibility of Wölfflin (WÖLFFLIN, 2015) – linear or painterly, plane or recession, closed or open, multiplicity or unity, and absolute or relative – have a very evident application in architecture. From that, it is

possible to speak of “unlimited and prospective space”, “painterly qualification of surfaces”, “spatial infinity”, “chromatic values”, and “relationships between planes of color and light and shadow depths”. These specifications facilitate aesthetic emotion and avoid the common designation of styles (ZEVI, 2009).

Talking about a PV system’s geometry (field’s size, shape, and position), materiality (modules’ colors, textures and reflexivity), and modular pattern (PV modules plus mounting system) is interpreting architecture in a formalist way. Appendix A shows that 33 examples from the literature review on PV used this interpretation.

2.2.2 The spatial interpretation of architecture

As tradition, we interpret PV architecture mostly in technical and formalist ways. The movement of change to the spatial interpretation requires us to liberate from the tradition that is enforced on us. Therefore, an openness on the critic subject is necessary, as to allow something that is against it (GADAMER, 2015 apud ALBERTON, 2021). The spatial interpretation is not a specific interpretation like the others, as political, social, scientific, technical, physiopsychological, and formalist interpretations can be given of space. Therefore, spatial interpretation is a necessary element in any possible interpretation to give architecture a comprehensive meaning (ZEVI, 2009).

Architects use movement, time, or the consecutive displacement of the visual angle, to model space to arouse a certain state of mind in those who experience it. It is not coincidence that once space has suggested a move, everything that agrees with it seems to be pleasant while a movement in discordance seems inopportune (ZEVI, 2009). The spatial interpretation has to do with the movement of men who experience a given space. A passage from “The Architecture of Humanism: a Study in the History of Taste” by Scott (1914) illustrates how movement can be affected in the architectural space:

> “Space value in architecture is affected first and foremost, no doubt, by actual dimensions; but it is affected by a hundred considerations besides. It is affected by lighting and the position of shadows: the source of light attracts the eye and sets up an independent suggested movement of its own. It is affected by colour: a dark floor and a light roof give a totally different space sensation to that created by a dark roof and a light floor. It is affected by our own expectancy: by the space we have immediately left. It is affected by the character of the predominating lines: an emphasis on verticals, as is well known, gives an illusion of greater height; an emphasis on horizontals, gives a sense of greater breadth. It is affected by projections – both in elevation and in plan – which may cut the space and cause us to feel it, not as one, but several” (SCOTT, 1914).

The way men perceive contrasting effects, colors, scales and proportions, rhythm, textures, natural light, and sounds will also influence on the movement in the space and therefore on its interpretation (RASMUSSEN, 2015):

> "Understanding architecture, therefore, is not the same as being able to determine the style of a building by certain external features. It is not enough to see architecture; you must experience it. You must observe how it was designed for a special purpose and how it was attuned to the entire concept and rhythm of a specific era. You must dwell in the rooms, feel how they close about you, observe how you are naturally led from one to the other. You must be aware of the textural effects, discover why just those colours were used, how the choice depended on the orientation of the rooms in relation to windows and the sun" (RASMUSSEN, 2015)[2].

That said, to design buildings, architects must imagine the spatial values resulting from each individual case. There are no fixed features, categories, or relationships that must be considered. Architecture is not mechanics, but an art; therefore, the theories of architecture that provide texts already elaborated for the creation or criticism of design carry with them their own condemnation (SCOTT, 1914). Content, physiopsychological, and formalist interpretations have a meaning in architectural criticism, but they are not enough to make understandable the difference that exists between different works of architectural art. Only space can give us the specific value of architecture. To speak of architecture, content, physiopsychological, and formalist qualifications must be specified in spatial terms. Architectural criticism must include all aspects and interpretations with spatial values, as interpreting space means including all the realities of a building (ZEVI, 2009).

Understanding aesthetics takes a hermeneutic experience that belongs to the very encounter with the work of art. The truth of this experience can lead the subject to an encounter with himself and results from the work of art itself (GADAMER, 2015 apud ALBERTON, 2021). The imaginary is essential in this process, as it gives us the ability to see in a thing what it is not, or to see it differently from what it is (CASTORIADIS, 1982 apud ALBERTON, 2021). Characteristics of the architecture such as contrasting effects, colors, scales and proportions, rhythm, textures, natural light, and sounds (RASMUSSEN, 2015) provide a way to transcribe the imaginary as reality (CASTORIADIS, 1982 apud ALBERTON, 2021).

Furthermore, before perceiving anything, a person is already in the world, which is where comprehension and interpretation come from. Therefore, the impression that architecture

[2] Citation from the English version of the book: Experiencing Architecture.

causes in an observer depends on the work of art, but also on the observer's sensitivity, mentality, education, and environment. Also, it depends on the state of mind he is in at that moment. That is why it is interesting to recapitulate a work of art that we have seen before, in order to verify if we still react to them in the same way. Furthermore, it is easier to notice something when we already know it beforehand (RASMUSSEN, 2015). The BIPV system, for example, is considered a linguistic sign, but its significance (the form) and its meaning (the concept) are not the same for everyone (SCOGNAMIGLIO, 2021). That stated, the social imaginary is a set of images and ideas that we associate regarding some subject, that people share and have in common. It is molded and built over time, depending on experienced situations. It remains the same until a slow historical change or a new creation brings new social imaginary meanings (ALBERTON, 2021). The influence of the social imaginary can be noticed in Sánchez-Pantoja, Vidal and Pastor (2018), where the age of the participants influenced the aesthetic perception of the use of PV technology in the buildings of the Solar Decathlon Europe competition in Versailles 2014. Therefore, as every interpretation occurs in an existential and historical context (GADAMER, 2015 apud ALBERTON, 2021), spatial interpretation will depend directly on the critic subject, as his social imaginary will have a great influence on it.

Moreover, mobility and human senses are the basis of the activities, human behavior, and communication in urban and architectural spaces (GEHL, 2015). Since childhood, a person perceives that the forms and their surfaces can give impressions of being hard or soft, weight or light, smooth or rough, or even tense and loose. To feel architecture, it is necessary to have these senses, as each architectural element, form, surface, will lead to a particular effect over our minds. That said, the role of the architect to create buildings that will influence the experience of spaces becomes clear.

That is why seeing architecture is not enough, it has also to be experienced (RASMUSSEN, 2015). The existing research on the aesthetics of PV architecture helps us to see it (its functionality, technique, plastic, and pictorial data). However, they lack the comprehension of the experience of the spaces which are created from these architectures.

2.3 FINAL CONSIDERATIONS

This section provides a discussion on the gaps that exist in the literature on the aesthetics of PV architecture, outlining the theme of this thesis.

Appendix A presents the interpretation categories described by Zevi (2009) used in each of the studies on the state-of-the-art of PV architecture. It is possible to observe that the evaluation of PV architecture aesthetics is mostly **formalist (33 studies) and technical (19 studies)**. The materialist interpretation was used in only four studies that regard PV plants on landscapes. Also, nine studies conducted research on the physiopsychological category, regarding feelings/emotions that the PV integrations could give to the observers. However, none of the studies presented the influences of PV on the architectural spaces.

Moreover, the images of the studies from the literature review generally focus only on the PV systems. Some show the entire buildings, but the systems are always highlighted. Also, the pictures do not show people experiencing the spaces where the PV systems are at. This also confirms that PV architecture is not spatially interpreted.

Scognamiglio (2021) evidences the fact that most of the research in PV architecture differentiate "objective" and "subjective" aspects of perception. Additionally, usually these studies try to limit the complexity of the aesthetic perception by developing objective design assessment tools. The cognitive domain is the main feature of the aesthetic experience, being its response a combination of "sensory (initial impact of the senses), formal (compositional factors and understanding of patterns), expressive (pre- or post-perceptual knowledge and sensory information enter a critical discussion to come to terms with what is perceived), and symbolic (received cultural context and culturally conditioned meaning)" perceptions (SCOGNAMIGLIO, 2021).

Therefore, **even if the objective, functional, mechanical methods presented in the literature review are essential to understand the aesthetical aspects of PV, they alone are not enough to talk about PV architecture**. Being architecture a composition of art and science, it is also considered culture (the domain of the imaginary) and, therefore, concerns creativity. The functional (the science), on the other hand, is everything that is designed to be useful. Architecture is a functional art, that is, a combination of creativity and functionality. Both elements are essential and there is no way to define the boundaries between them (CASTORIADIS, 2004 apud ALBERTON, 2021). Furthermore, the aesthetic experience is a hermeneutic phenomenon achieved by the very confront of men with the artistic object, which in this case is the PV architecture. The truth of experience has nothing to do with the pragmatic conception that reduces it to utility; it regards an encounter of the subject with himself, which results from the work of art (GADAMER, 2015 apud ALBERTON, 2021). "Space" is the protagonist of the architectural subject (ZEVI, 2009), so it is what provides the aesthetic

experience of PV in buildings. Consequently, PV architecture spaces must be interpreted in order to understand the role of PV in their experience.

In the field of PV, Hagemann (1996a, 1996b) had already defined the importance to think about the concept of the architectural space that is being created with the use of PV modules as construction elements. The architectural design of a building must consider the creation of spaces which will be experienced by its users in shape and structural approaches. The consistency of the space is provided by the correlation and interrelationship between its individual elements and their multi-layered correlation to one another; individual parts arranged alone do not provide an experience of space. The significance of these characteristics of architectural planning and design is essential in the overall experience of space; thus it must be considered when using PV modules in buildings (HAGEMANN, 1996b, 1996a).

Unquestionably, PV architecture needs a critique that reveals it, and this critique should consider both what we call “traditional” interpretations (the methods of the research presented in the literature review) and spatial interpretations, since architecture is composed both by the solid matter and the void space (RASMUSSEN, 2015).

3 METHODOLOGY

The methodological procedure of this work is structured in four parts: first, 20 case studies of PV in buildings were defined; then, the traditional interpretation method was described; next, the spatial interpretation procedure was carried out; and, finally, the relationship analysis between traditional and spatial interpretations was described.

3.1 CASE STUDIES

This work contemplates the interpretation of PV in the built environment, considering buildings and urban infrastructures. The assessment of PV plants in landscapes was not considered, as these types of installation do not enclose a space for human activity, hence they were not interpreted as architectural spaces. This work considers the following definitions of “built environment” and “landscape”:

> “The term built environment refers to the human-made surroundings that provide the setting for human activity, ranging in scale from buildings and parks or green space to neighborhoods and cities that can often include their supporting infrastructure, such as water supply, or energy networks. The built environment is a material, spatial and cultural product of human labor that combines physical elements and energy in forms for living, working and playing. It has been defined as “the human-made space in which people live, work, and recreate on a day-to-day basis”. The “built environment encompasses places and spaces created or modified by people including buildings, parks, and transportation systems”. In recent years, public health research has expanded the definition of "built environment" to include healthy food access, community gardens, “walkabilty", and “bikability”” (DEFINITIONS, 2021a).

> “A portion of land or territory which the eye can comprehend in a single view, including all the objects it contains” (DEFINITIONS, 2021b).

The case studies will be either private or public landmark buildings, as they have a bigger impact to society. A landmark is “a notable building or place with historical, cultural, or geographical significance” (DEFINITIONS, 2021c). They contribute to the dissemination the PV technology, sustainability, and environmental responsibility, sending a strong message to their surroundings (DEVETAKOVIĆ *et al.*, 2020). These buildings are frequently visited by the public, so results will be understood by a larger number of people, including the design and PV communities which will be inspired by the examples of traditional and spatial interpretations of the landmark buildings.

Twenty case studies have been selected and interpreted in traditional and spatial terms. For the doctoral qualification exam, one case study is presented to illustrate the methodology of the work. It is the building of the Solar Energy Research Laboratory at Universidade Federal de Santa Catarina (Fotovoltaica/UFSC Laboratory), in Brazil. Another ten of them are the landmark buildings with distinctive geometries investigated by Devetaković *et al.* (2020). For the last nine cases, buildings with traditional multi-crystalline silicon (m-Si) modules will be chosen in order to show that every PV integration, even ones that use traditional PV modules, can be interesting and arouse emotions in the public, as long as a well-established critique is employed. The list of the case studies is as follows:

1. Fotovoltaica/UFSC Laboratory, in Brazil
2. Maracanã Stadium, in Brazil
3. Apple Headquarter, in the United States of America
4. Shanghai Expo 2010 Theme Pavilion, in China
5. Powerhouse Brattørkaia, in Norway
6. Paris Courthouse, in France
7. La Seine Musicale, in France
8. Umwelt Arena, in Switzerland
9. Kaohsiung National Stadium, in Taiwan
10. Novartis Campus Building, in Switzerland
11. Copenhagen International School, in Denmark

12-20. To be defined

3.1.1 Limitation of the study

Literally experiencing a space is very different from interpreting it through images. When we experience a space, we see the constructions that stand in front of us, but we also have knowledge of the ones that are on our sides. Furthermore, we remember the ones we have just passed by. We feel the atmosphere around us, breath the air of the place, and hear its sounds. Everyone who has seen a picture of a place and visited it later, knows that reality is unique (RASMUSSEN, 2015).

The limitation of this study is, then, the fact that the interpretations of the case studies will mostly be made through the visualization of pictures from the Internet and scanning of the

locations on Google Earth Street View tool. In cases where the building is not constructed yet, 3D models or pictures generated from the models can be used, showing that the method can be applied also in the design stages, where the architect must imagine the results of spatial experience from 2D plans and 3D models. Even if these conditions do not provide an actual experience of reality, the results should be enough to reach the objective of this work, which is to inspire architects and designers, as well as give engineers and architects a better insight of how photovoltaic integration can be interpreted from theories of architectural perception, narrowing the gap that exists between the design and the PV communities.

3.2 TRADITIONAL INTERPRETATIONS OF PV ARCHITECTURE

All the possible traditional interpretations of architecture for each case study have been assessed, centered on the content, physiopsycological, and formalist categories.

3.2.1 Content interpretations of photovoltaic architecture

Political, philosophical-religious, scientific, social-economic, and materialist interpretations of the case studies will be described when they are available, as approaches to understand the purpose of the buildings and/or their PV systems.

The technical interpretation will include features that can influence the aesthetics of the buildings, that is, the technology, installed capacity, azimuthal deviation, tilt angle, and the energy strategy of the PV systems, when the information is available. Energy strategy will be evaluated according to Cronemberger *et al.* (2014), as presented in Chart 7.

Chart 7 – Characterization of the energy strategies for the technical interpretation of the case studies.

Energy strategy
“PV modules are used only to generate electricity, as part of the electrical energy balance.”
“PV modules are also used as part of the comfort strategy for the building, such as thermal, acoustic or lighting conditioning.”
“PV modules are optimally tilted and oriented.”
“PV modules use non-optimal tilts and/or orientations.”
“PV modules are hybrid with thermal generation properties, with air or other fluids.”

Source: Cronemberger *et al.* (2014).

3.2.2 Physiopsycological interpretation of photovoltaic architecture

The physiopsycological interpretation will use the Self-Assessment Manikin (SAM) method of perception, presented by Sánchez-Pantoja, Vidal and Pastor (2018). The dimensions of hedonic valence (pleasant-unpleasant) and arousal (level of excitation) will be evaluated by identifying the picture from Figure 13 that best represents the feeling that the PV integration experience provides (SÁNCHEZ-PANTOJA; VIDAL; PASTOR, 2018). Of course, this interpretation is highly influenced by the observer's sensitivity, mentality, education, environment, and state of mind.

3.2.3 Formalist interpretation of photovoltaic architecture

Finally, the formalist interpretation will consider the application of the LESO-QSV method by Munari Probst and Roecker (2019) with complements from Custódio, Zomer and Rüther (2020), in order to understand their “criticity” level and integration quality. Also, Cronemberger *et al.* (2014) and Santos (2013) presented the features that are mostly used on the research that describes the aesthetics of PV in buildings. Therefore, the case studies will be characterized using features from both works, as shown in Chart 8. The classification of the grade of integration (BAPV or BIPV) will not be used as they are no longer sufficient to describe all the integration possibilities and can lead to ambiguities.

Chart 8 – Characterization features for the formalist interpretation of the case studies.

Characteristics	**Option**
Building use	Residential
	Commercial
	Industrial
	Services
	Institutional
Integration type	New building
	New structure
	Retrofit integration
	Integration applied to historical buildings
Architectonic design approach	Invisible application
	Added application
	Highlighted application
	Leading application
Architectural feature	Exponent architects
	Conventional buildings
Integration view	Invisible or non-noticeable integration in façades
	Integration in part of a visible surface

	Integration in an entire visible surface
Place of integration	Roof
	Façade
	Roof/Façade
	Shading/other elements
	More than one surface
Integration surface	Flat
	Curve
Seal	Opaque
	Semitransparent
Substrate of the module	Rigid
	Flexible
Frame	Framed
	Frameless
Relation with other construction materials	Exposed concrete
	Glass/ Polycarbonates
	Wood
	Metal
	Ceramics
	Stone

Source: Adapted from Cronemberger *et al.* (2014) and Santos (2013).

3.3 THE SPATIAL INTERPRETATION OF PHOTOVOLTAIC ARCHITECTURE

As mentioned, the concrete matter and the void space of architecture depend on one another. Therefore, the traditional interpretations will be the base for the spatial interpretation; that is, content, physiopsychological, and formalist qualifications will be specified in spatial terms. The architectural space where the PV system is at will be evaluated as a whole, in order to understand how the system belongs to and what its role is in the space. There is not a fixed list of categories that will be assessed in the spaces, as each one of them has different evaluation needs. Spatial interpretation has to do with the people that experience the spaces and their paths, which are influenced by the concrete matter of architecture. This analysis will lead to the understanding of how the PV system influences these paths, that is, how they are perceived in the architectural space.

In urban spaces, there are spaces of movement (the streets) and spaces of experience (sidewalks, squares, and allotments). Distances of 100-25 m from the architecture we want to experience and interpret have little influence over the human senses. Distances of 25-7 m have more influence as details can be better identified. Finally, from 7-0 m all human senses can be used, and all details perceived. Furthermore, humans have facility to look down and to the sides, but the upper field of view is limited. That is why the upper floors of buildings can only be seen

from certain distances. Finally, we can perceive objects better when we walk at our normal speed of 4-5 km/h. Running or riding a bike (10-12 km/h) lower this perception and, driving a car (50-100 km/h) lowers it even more. Of course, there are architectures which are made to be observed from high speeds, but a walk on spaces like these provides uninteresting sensory experiences (GEHL, 2015). The spatial interpretations, then, will be done both from sidewalks, squares, and allotments, respecting the distance range of 25-7 m and from 7-0 m in relation to the building that will be analyzed. Since PV modules are used in rooftops frequently, in some case studies they will only have influences on the spatial experience from distances over 7 m. Lastly, interpretations will be carried out considering that the observer is either standing still or walking, as this will allow greater time opening for the assessment, improving the spatial perceptions.

The spatial interpretation will then be assessed from the characteristics gathered in the traditional interpretations, as political, social, scientific, technical, physiopsychological, and formalist interpretations can be given of space, as well as by imagining the experience of the spaces from specific points of view. These imaginations will be provided by pictures from the Internet and scanning the locations on Google Earth Street View tool. In cases where the building is not constructed yet, 3D models or pictures generated from the models will be utilized.

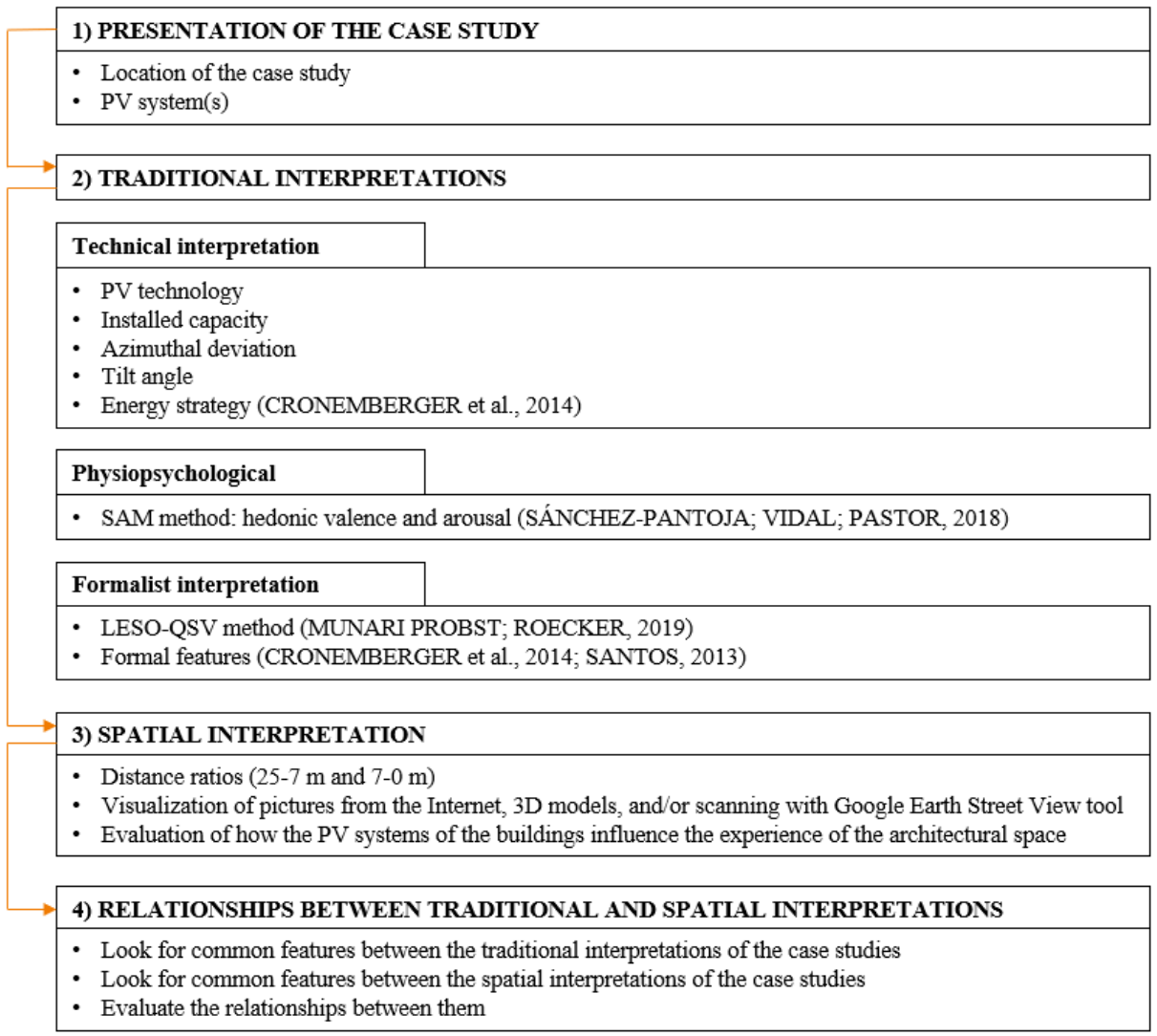
3.4 RELATIONSHIPS BETWEEN TRADITIONAL AND SPATIAL INTERPRETATIONS

A full comprehension of architecture will actually happen between the combination of the present and the past (GADAMER, 2015 apud ALBERTON, 2021), that is, among traditional and spatial interpretations. A relational analysis also means an appreciation of tradition, as the very historical condition of man does not allow a distance between history and man (ALBERTON, 2021). Understanding the relationship between traditional and spatial interpretations is creating a bridge over the gap that exists between design and PV communities, or architects and engineers. Therefore, common characteristics of both the traditional and spatial interpretations between the case studies will be verified, in order to evaluate the existence of relationships between tradition and spatial assessments.

3.5 OVERVIEW OF THE METHODOLOGY

Figure 22 presents a flowchart of the methodology, which is divided into four steps: presentation of the case studies, traditional interpretations, spatial interpretation, and the study on the relationships between traditional and spatial interpretations.

Figure 22 – Flowchart of the methodology.



4 RESULTS

4.1 CASE STUDY 01: FOTOVOLTAICA/UFSC LABORATORY

The Solar Energy Research Laboratory at Universidade Federal de Santa Catarina (Fotovoltaica/UFSC Laboratory, www.fotovoltaica.ufsc.br) is located at a technology park in the city of Florianópolis (27.59° S, 48.57° W), in Brazil. It is considered a landmark building because it is a public Positive Energy Building (PEB) (ZOMER *et al.*, 2020b, 2020a), a situation that is rare in the country. The Laboratory has two buildings (building A and building B), a third building that is under construction (building C), a solar carport, and an electric bus (eBus) charging station and bus stop. It also has ground-mounted PV systems, but they will not be included by this analysis. Figure 23 shows an aerial view of the buildings and their PV systems, and Figure 24 shows a 3D model that illustrates how building C will look like.

Figure 23 – Aerial view of the Fotovoltaica/UFSC Laboratory.

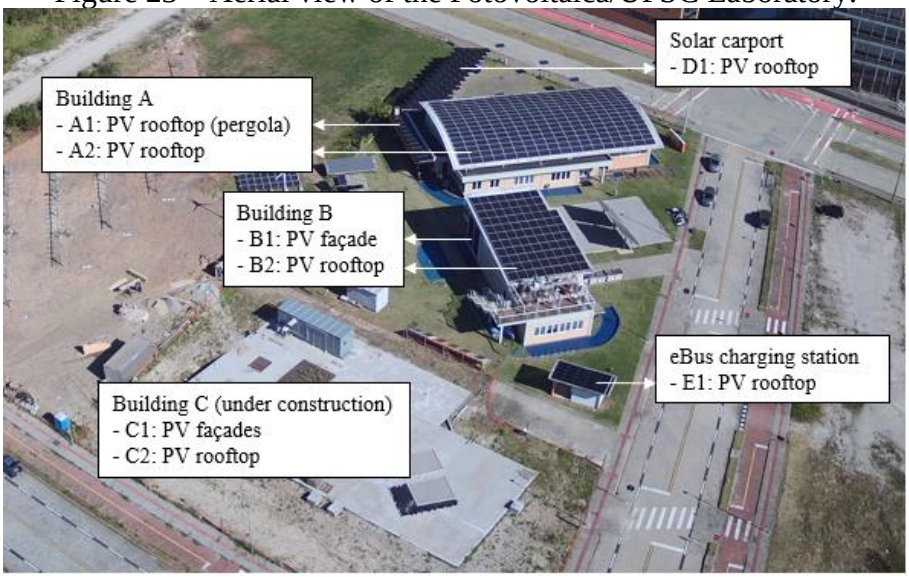


Figure 24 – 3D model of the Fotovoltaica/UFSC Laboratory, including the building C expansion which is under construction.



4.1.1 Case study 01: traditional interpretations

4.1.1.1 Content interpretations

Political, philosophical-religious, scientific, social-economic, and materialist interpretations can be assessed in this case study by the history of its construction. The new buildings of the Fotovoltaica/UFSC Laboratory opened in 2015, with building A, building B, and the solar carport. The eBus charging station and bus stop was built in 2017 and, currently, building C is under construction. The first buildings were made possible mainly through funding from the Ministério da Ciência e Tecnologia (currently the MCTIC) and ANEEL's R&D Project PE-0403-0027/2011, also counting on donations and technical support from several other institutions and companies. Building C will house a large bank of electrochemical batteries for the storage of PV energy, which is the object of study of ANEEL's R&D Project PD 0403-0042/2016. The PV systems of the laboratory can fully attend the energy consumption of the buildings, in addition to recharging the eBus after each of its five daily trips (round trips) to the main campus of the university. In months when there is a surplus of PV energy, it is injected into the electricity grid. In this case, the energy credit is consumed by the main campus. This makes the laboratory not just a Zero Energy Building (ZEB), but a Positive Energy Building (PEB). The laboratory aims to disseminate knowledge about the application of the PV technology in urban areas, through the development of research and continuing education to

the scientific community and society in general. It is linked to CTC/UFSC, and its team holds professors and undergraduate/graduate students from various areas: architecture, civil engineering, electrical engineering, and mechanical engineering. The researchers work for the innovation and expansion of renewable energies in the country, making the laboratory a reference center in Brazil.

The architectural project of the buildings was based on the shape and orientation of the PV rooftops. Furthermore, it was centered on the sustainability of the materials, the applications of bioclimatic strategies, and energy efficiency measures. The materials used in the buildings are exposed brick walls, pillars and beams in metallic structure, PV modules used either as rooftop shading, sealing materials, or façade shading devices, as well as PVC frames and adequate shading in the openings and roofs, favoring the internal thermal comfort. The strategies of sustainability used in the projects of buildings A and B are shown in Figure 25, and in building C are shown in Figure 26.

Figure 25 - Strategies of sustainability used in the projects of buildings A and B.

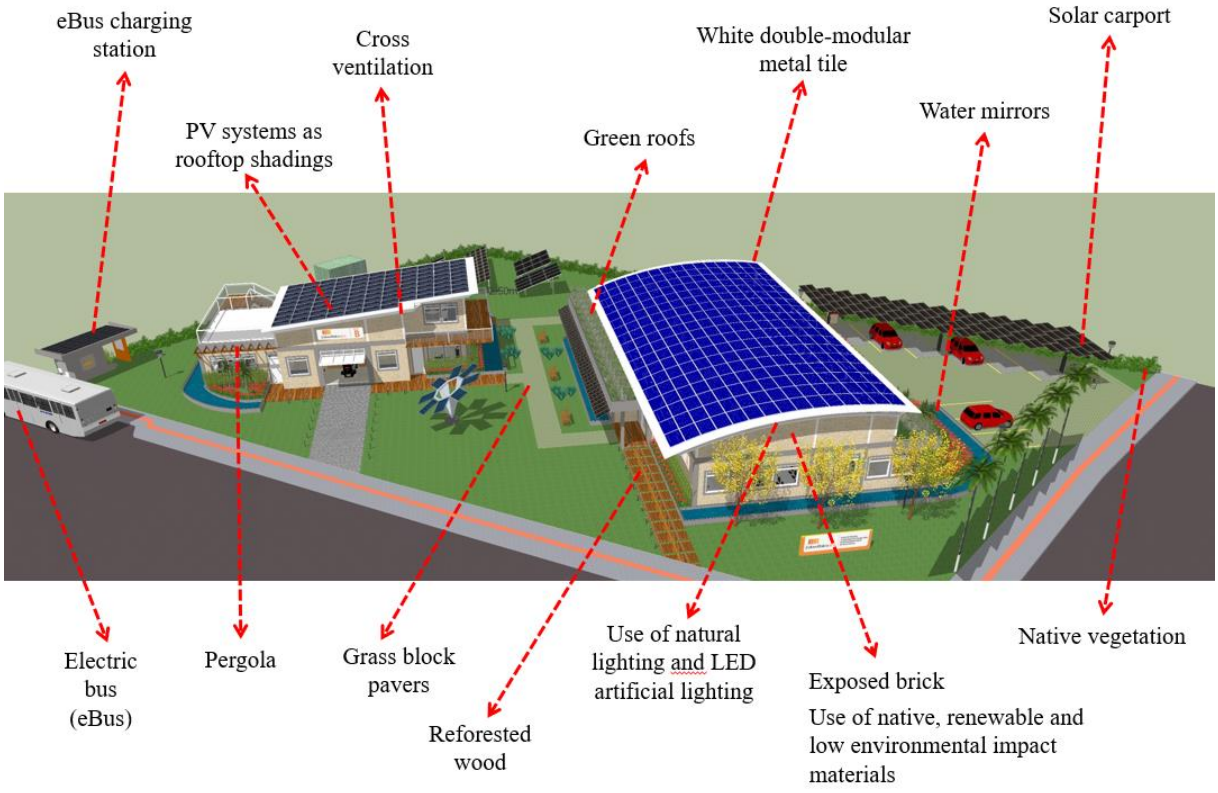
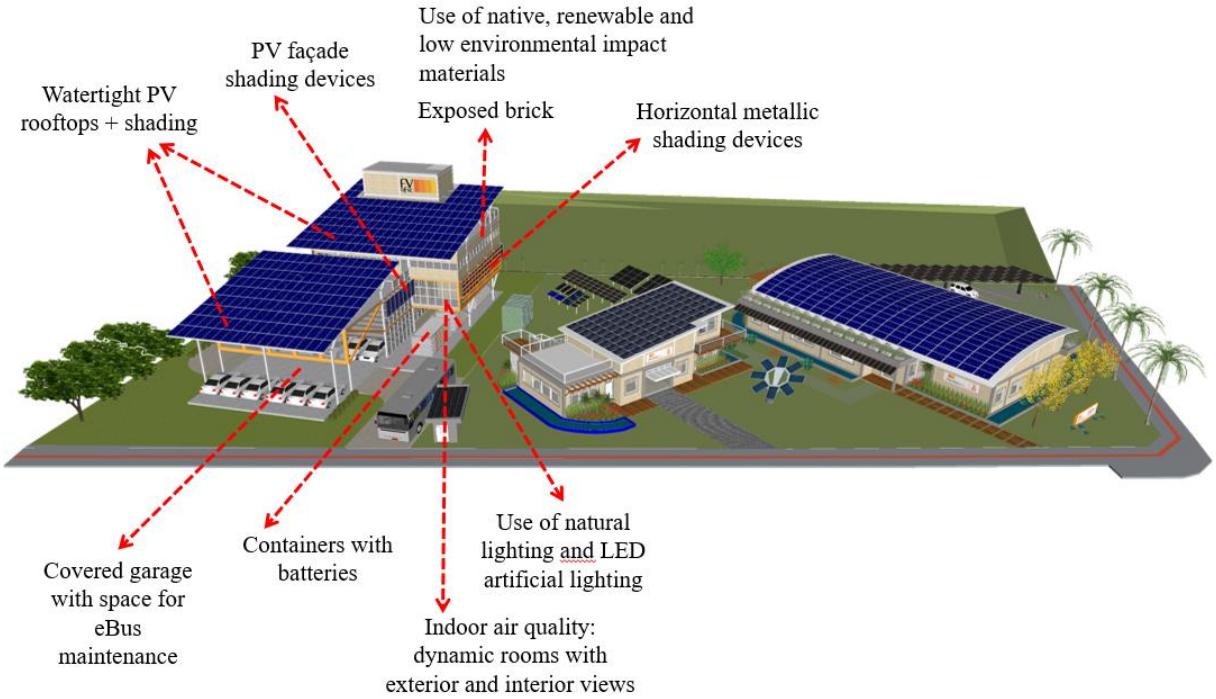


Figure 26 - Strategies of sustainability used in the project of building C.



Furthermore, Chart 9 presents the technical interpretation of the PV systems from case study 01. The technology, the installed capacity, azimuthal deviation, tilt angle, and the energy strategy of the systems were specified. The systems include a variety of PV technologies: thin-film cadmium-telluride (CdTe), multi-crystalline silicon (m-Si), thin-film microcrystalline-silicon (µc-Si), mono-crystalline silicon (c-Si), and thin-film copper-indium-gallium-diselenide (CIGS). Currently, m-Si represents the one with the highest total installed capacity (68.65 kWp), but the installed capacity on the rooftops of building C will add about 100 kWp of c-Si. Furthermore, systems A2, B1, B2, and E1 are installed above the building surfaces and follow their tilt and orientation, acting as shading elements that reduce the thermal load of the buildings; systems A1, C1, C2, and D1 are also used as comfort strategy, since they act as sealing materials of the buildings; all systems have non-optimal tilts and/or orientations; and none of the systems are hybrid.

Chart 9 – Technical interpretation of the PV systems of case study 01.

PV system	A1	A2	B1	B2	C1	C2	D1	E1
Technology	CdTe	m-Si	m-Si	µc-Si	c-Si	c-Si	CIGS	CdTe
Installed capacity (kWp)	4.41	66.15	2.50	13.50	To be installed ± 50 kWp	To be installed ± 50 kWp	13.44	2.44
Azimuthal deviation (°)	90	0	90	0	49/229	319	270	36
Tilt angle (°)	0	17/5/4	90	6	90	10	5	3
Energy strategy (CRONEMBERGER *et al.*, 2014)								
"PV modules are used only to generate electricity, as part of the electrical energy balance."								
PV system	A1	A2	B1	B2	C1	C2	D1	E1
		x	x	x				x
"PV modules are also used as part of the comfort strategy for the building, such as thermal, acoustic or lighting conditioning."								
PV system	A1	A2	B1	B2	C1	C2	D1	E1
	x				x	x	x	
"PV modules are optimally tilted and oriented."								
PV system	A1	A2	B1	B2	C1	C2	D1	E1
"PV modules use non-optimal tilts and/or orientations."								
PV system	A1	A2	B1	B2	C1	C2	D1	E1
	x	x	x	x	x	x	x	x
"PV modules are hybrid with thermal generation properties, with air or other fluids."								
PV system	A1	A2	B1	B2	C1	C2	D1	E1

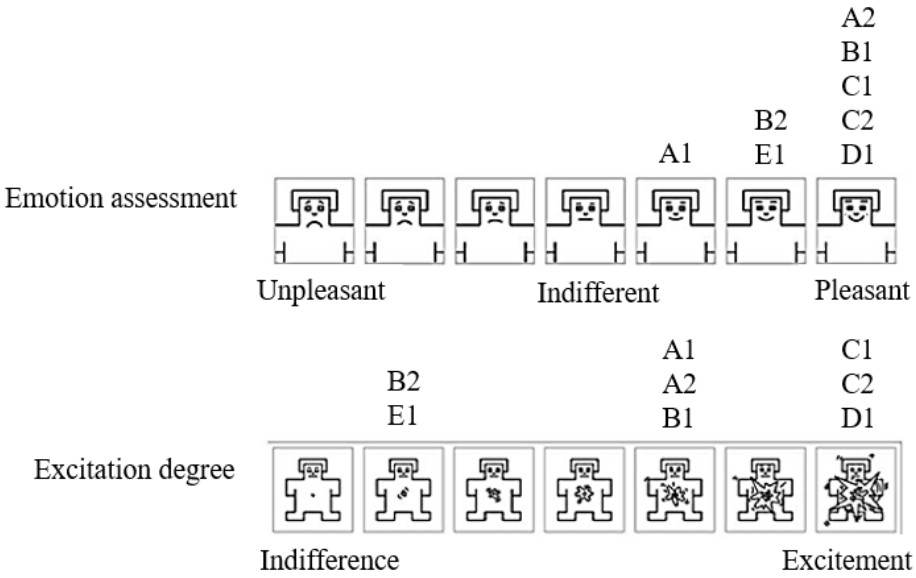
Source: Zomer *et al.* (2020b, 2020a) and Fotovoltaica/UFSC Laboratory (2020).

4.1.1.2 Physiopsychological interpretation

Figure 27 presents the physiopsychological interpretation (determined by the author of this thesis) of the PV systems' architecture using the SAM method. The emotion assessment had less variation than the excitation degree, because just the idea of using PV systems in buildings is pleasant, especially if they are in accordance with the architectural forms of the building. However, not all types of integration cause excitement. PV integrations over inclined

roof tiles are more common and less appealing, so they are not as exciting as the ones on façades or the ones used as sealing materials, for example.

Figure 27 – Physiopsychological interpretation of case study 01 using the SAM method.



Source: Adapted from Sánchez-Pantoja, Vidal and Pastor (2018).

4.1.1.3 Formalist interpretation

For the formalist interpretation, the LESO-QSV method (MUNARI PROBST; ROECKER, 2019) was applied to the PV systems, as shown in Chart 10, and their characteristics (CRONEMBERGER *et al.*, 2014; SANTOS, 2013) were defined in Chart 11.

Regarding the geometry integration quality, systems C2 and D1 are coherent as they were projected from the design stage of the buildings and perform also as sealing materials, therefore the buildings features respect their forms; system A1 is partly coherent because it has the same length, orientation, and tilt as the pergola that it covers, but not the same width; systems A2 and B2 are partly coherent as they do not embody the entire rooftops but are offset from the surfaces' limits in equal distances; system C1 is partly coherent as it follows the orientation and tilt of the wall where it is applied, involving its entire width, but not its entire height; system B1 is not coherent because even if it respects orientation and tilt, it does not follow the building's dimensions at all; and system E1 is also not coherent as it does not have the same dimensions of the rooftop neither the same tilt angle. The materiality integration quality of systems C2 and D1 are coherent as they are the sealing material of the structures;

system C1 is partly coherent because, even if the system is highlighted from the wall, its glass material matches the windows that it covers; and systems A1, A2, B1, B2, and E1 are not coherent because they do not have the same colors or textures of the surfaces over which they are installed. Finally, the modular pattern integration quality of systems C2 and D1 are coherent as they are the buildings' seal; hence the structure follows their modularity; system A2 is partly coherent as the modules of this system actually create a modularity for the curved rooftop where they are installed; system C1 is also partly coherent because the rectangle shape of the modules match the shape of the windows which they are covering; and systems A1, B1, B2, and E1 are not coherent as their modularity does not match the surfaces where they are installed.

Concerning "criticity", the context sensitivity was classified as "medium" because even if the buildings have a technological value, their context has no specific architectural/urban qualities. The visibility of systems A1, C2, and D1 is high because they are visible both from the outside and the inside since they are sealing materials; the visibility of systems B1 and C1 is also high because they are installed on façades; the visibility of systems A2 and B2 is medium because they are partly visible from the ground level; and the visibility of system E1 is low because it is not visible from ground level at all. Therefore, the "criticity" of systems A1, B1, C1, C2, and D1 is high, of systems A2 and B2 is moderate, and of system E1 is low.

Chart 10 – Formalist interpretation of case study 01: integration quality and "criticity" of PV systems.

	PV system							
	A1	**A2**	**B1**	**B2**	**C1**	**C2**	**D1**	**E1**
Integration quality								
- System geometry	 partly coherent	 partly coherent	 not coherent	 partly coherent	 partly coherent	 fully coherent	 fully coherent	 not coherent
- System materiality	 not coherent	 not coherent	 not coherent	 not coherent	 partly coherent	 fully coherent	 fully coherent	 not coherent
- Modular pattern	 not coherent	 partly coherent	 not coherent	 not coherent	 partly coherent	 fully coherent	 fully coherent	 not coherent
"Criticity"	**High**	**Moderate**	**High**	**Moderate**	**High**	**High**	**High**	**Low**
- Context sensitivity	 medium	 medium	 medium	 medium	 medium	 medium	 medium	 medium
- System visibility	high	medium	high	medium	high	high	high	low

Chart 11 – Formalist interpretation of case study 01: characteristics of the PV systems.

PV system	**A1**	**A2**	**B1**	**B2**
Building use	Institutional			
Integration type	Retrofit integration	New building	Retrofit integration	New building
Architectonic design approach	Added	Leading	Highlighted	Leading
Architectural feature	Conventional buildings			
Integration view	Integration in part of a visible surface			
Place of integration	Roof		Façade	Roof
Integration surface	Flat	Curve	Flat	
Seal	Opaque			
Substrate of the module	Rigid			
Frame	Frameless	Framed		
Relation with other construction materials	Wood	Metal	Ceramics	Metal
PV system	**C1**	**C2**	**D1**	**E1**
Building use	Institutional			
Integration type	New building			
Architectonic design approach	Highlighted	Leading	Leading	Invisible
Architectural feature	Conventional buildings			
Integration view	Integration in part of a visible surface	Integration in an entire visible surface		Integration in part of a visible surface
Place of integration	Façade/ Shading element	Roof		
Integration surface	Plan			
Seal	Semitransparent	Opaque		
Substrate of the module	Rigid			
Frame	Frameless		Framed	Frameless
Relation with other construction materials	Glass	Metal		Exposed concrete

All the systems are located at the Fotovoltaica/UFSC Laboratory, which is a public building and a research laboratory, and its architectural feature is conventional. Furthermore, system A1 is an added retrofit integration that seals a pergola. It is integrated in a part of a wooded, visible, flat roof structure. Lastly, its PV modules are opaque, rigid, and frameless. System A2 is a leading integration to a new building. It is installed on part of a metallic, visible, curved roof. Its PV modules are opaque, rigid, and framed. System B1 is a highlighted retrofit integration. It is integrated to part of a flat, visible façade, which is made of ceramic bricks. Its PV modules are opaque, rigid, and framed. System B2 is a leading integration to a new building. It is installed on part of a metallic, visible, flat roof. Finally, its PV modules are also opaque, rigid, and framed. System C1 is a highlighted integration to a new building. It is integrated to part of a visible glass façade, as a shading element. Its PV modules are semitransparent, rigid, and frameless. System C2 is a leading integration to a new building, which acts as the building's sealing material. It is installed in an entire visible, flat rooftop, over metallic structures. Its PV modules are opaque, rigid, and frameless. System D1 is a leading integration to a new building; it is a carport's sealing material. It is integrated in an entire visible, flat rooftop, over metallic structures. Its PV modules are opaque, rigid, and framed. Finally, system E1 is an invisible integration to a new building, as it cannot be seen from ground level. It is installed in part of a visible, exposed concrete, flat rooftop. Its PV modules are opaque, rigid, and frameless.

4.1.2 Case study 01: spatial interpretation

For this case study, pictures and the 3D model of building C were used, as the Google Earth Street View Tool does not provide the scanning inside the technology park where the laboratory is located.

The related spatial interpretation concerns people that experience the space by themselves. The laboratory provides guided visitations that involve some specific visualization points of the PV systems, but the actual experience does not concern this guided path. Also, this interpretation was done by someone who worked there for many years, so PV modules and systems have a meaning that is different from someone who goes there for the first time and, therefore, could have a different spatial experience.

Figure 28 presents the area affected by the distances of 25-7 m (in blue) and 7-0 m (in orange) from the Fotovoltaica/UFSC Laboratory. Therefore, the first analysis will consider the adjacent streets and a neighboring building (Softplan, which is a software company).

Figure 28 - Area affected by the distance ranges of 25-7 m and 7-0 m from the Fotovoltaica/UFSC Laboratory.

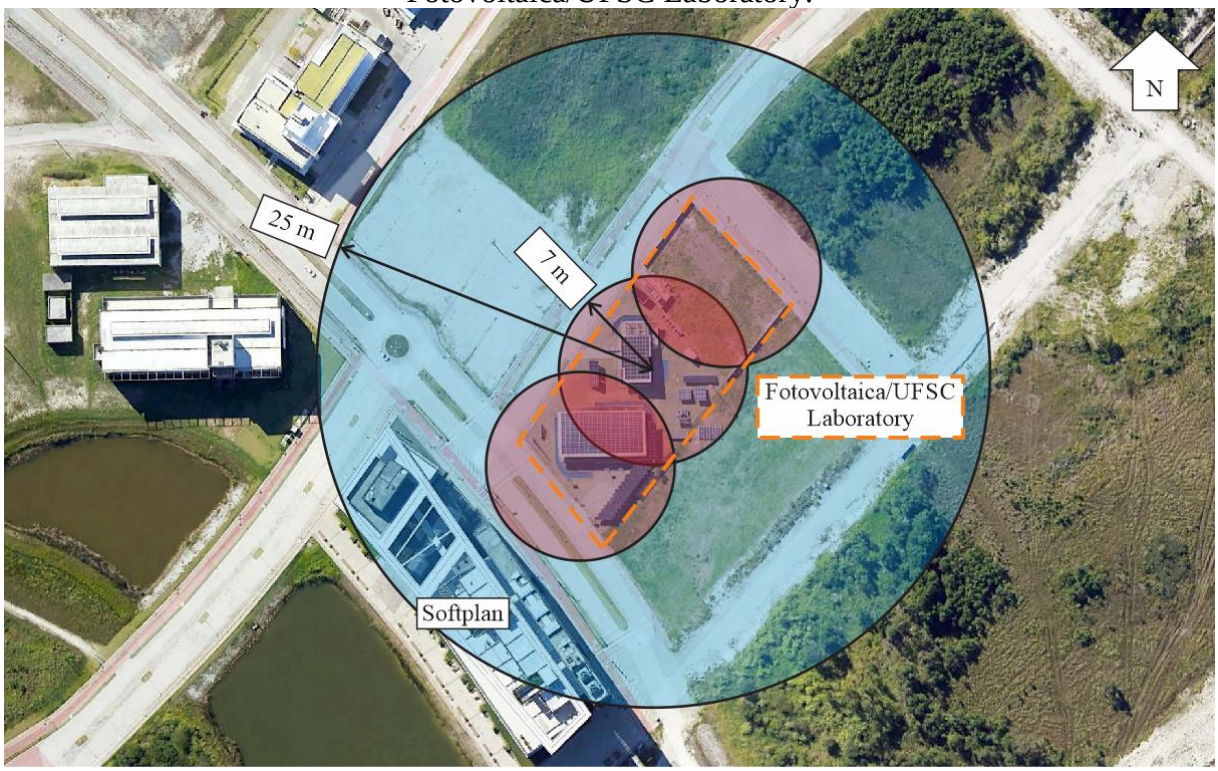


Figure 29 presents the spatial interpretation for a pedestrian in the blue area (25-7 m). Someone that walks by the technology park's main street (dashed black arrow) sees both the laboratory's building and its neighbor, Softplan. However, while Softplan is a huge building and is elevated from the street level, the laboratory's dimensions are more in line with men's scale and the building is at street level. Softplan has a square that highlights the building's entrance; however, it is also elevated from the street level. Moreover, this is a very windy place and the laboratory has ceramic brick walls and its terrain is covered by grass, which are very familiar and cozy materials, while Softplan's entrance has mainly cold materials such as concrete, metal, and glass. These characteristics make the laboratory's buildings more tempting and cooperate for a pedestrian to go in the direction of the main entrance of the laboratory (red arrow), instead of to the Softplan building. Besides this entrance, there is also going to be a pedestrian's entrance in building C (blue arrow), which is an open area with a PV rooftop. The concave shape of this entrance feels tempting and, as PV system C2 is the rooftop's sealing material, a person can appreciate it both from the inside and the outside of the building, especially since it is oriented to the entrance. The vehicles entrance (green arrow) is also located

at a strategic place, from where people can see PV system D1, which is highlighted by its orientation. These four views are illustrated in Chart 12.

Figure 29 – Spatial interpretation of case study 01 from the distance range of 25-7 m.

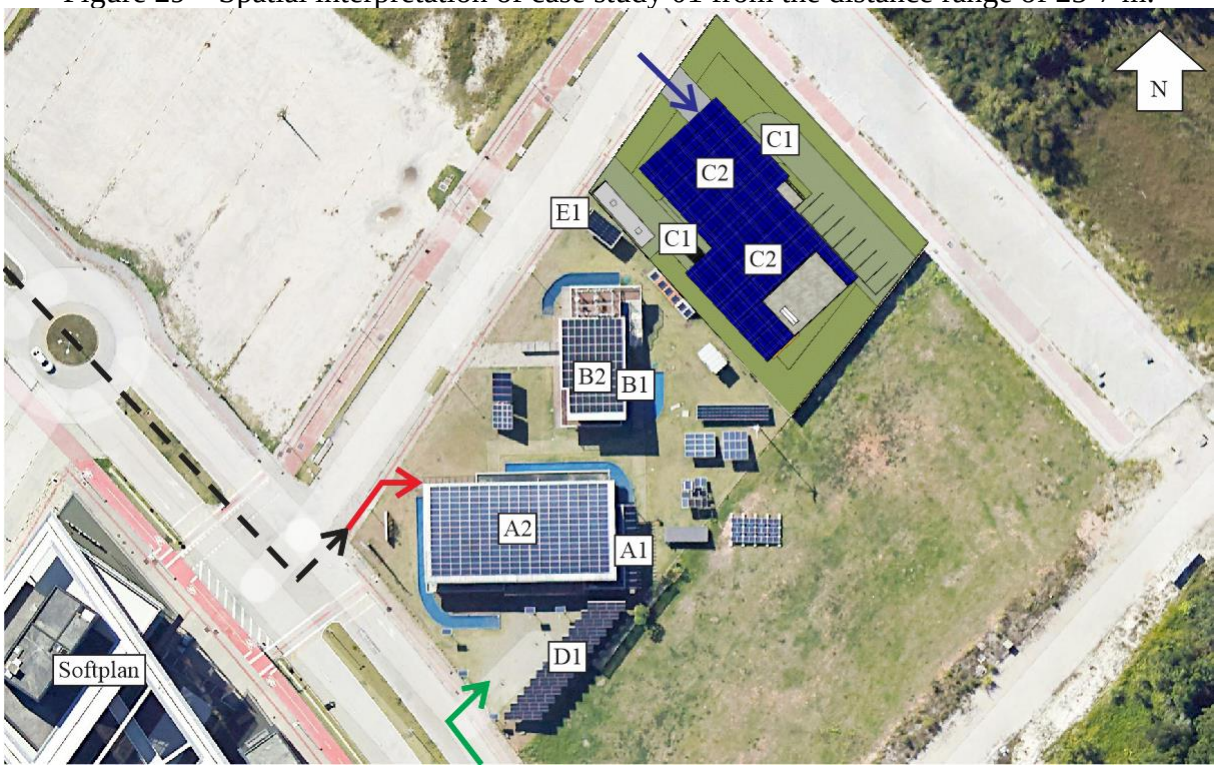


Chart 12 – Illustration of the spatial interpretation of case study 01 from the distance range of 25-7 m.

View angle	**Picture/Image**
Black arrow	

Red arrow	
Blue arrow	
Green arrow	

Figure 30 presents the spatial interpretation for a pedestrian in the red area (7-0 m). In the laboratory's plot of land, it is possible to see four curve shaped water mirrors that embrace buildings A and B. While concave shapes are welcoming, convex shapes such as the ones in the water mirrors lead to repulsive movements. These repulsive movements (red arrows) take people away from the buildings to the spots named P1, P2, and P3, from where the PV systems can again be perceived. Figure 31 shows that from P1 it is possible to have a better look at PV systems A2, C1, and C2, which is emphasized by the systems' orientations. From P2 it is possible to see the PV systems A1, A2, and B1, also having the orientation contribution to facilitate the visualization. From P3 it is possible to see PV system D1, which is oriented towards that point of view.

Also, as shown in Figure 32, there is a water fountain next to PV system B1. This is an element that draws people's attention, and, from that point of view, it is possible to better visualize systems B1 and A2.

Figure 30 - Spatial interpretation of case study 01 from the distance of 7-0 m, considering the water mirrors.



Figure 31 – Visualization of the PV systems from strategic points of view.



Figure 32 – Spatial interpretation of case study 01 from the distance of 7-0 m, considering the water fountain.

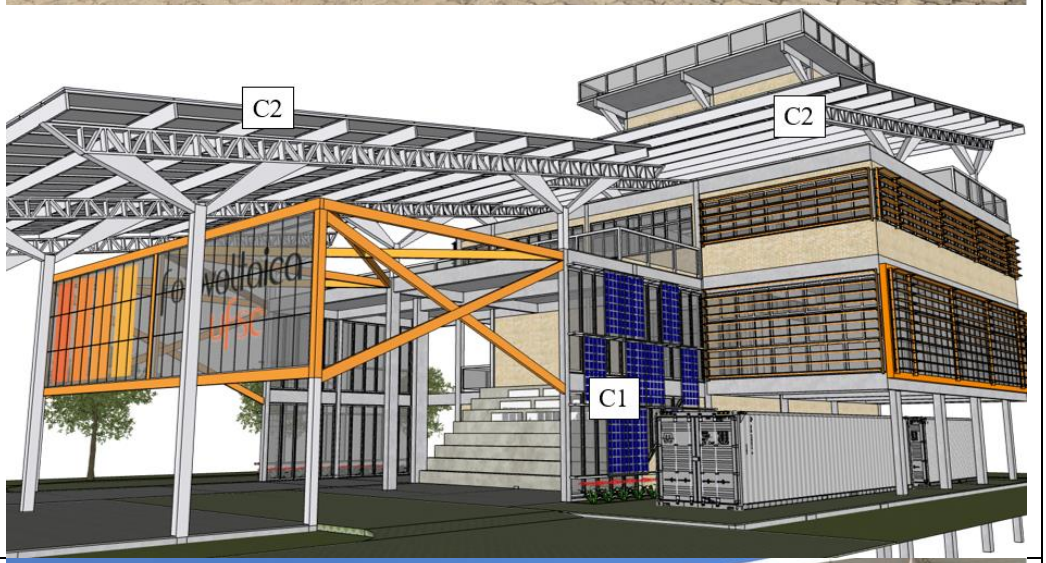


Furthermore, people tend to follow marked paths as to discover the places where they lead to. The marked paths in the terrain of the laboratory take us to the inside of the buildings and to two terraces (terrace 1 and terrace 2). From the terraces, which are in building B, the visualization of the PV systems is facilitated, as presented in Figure 33. From terrace 1 one can see better the PV systems A1 and A2, and from terrace 2, the PV systems A1, B1, B2, C1, C2, and E1. Chart 13 illustrates the views from P1, P2, P3, the water fountain, terrace 1, and terrace 2.

Figure 33 - Spatial interpretation of case study 01 from the distance of 7-0 m, considering the terraces.

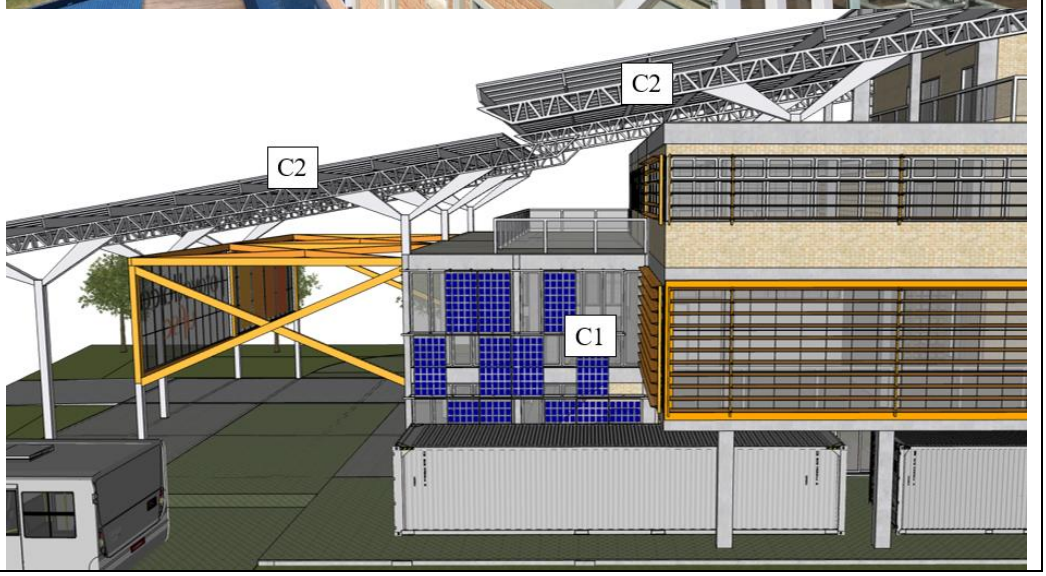


Chart 13 - Illustration of the spatial interpretation of case study 01 from the distance of 7-0 m.

View angle	Picture/Image
P1	 
P2	

	 
P3	

Water fountain	 
Terrace 1	

	
Terrace 2	 



Case study 01 is a solar energy research laboratory whose main objective is being a showcase for the dissemination of the PV technology. Therefore, the PV systems are the protagonists of the architecture, and all the spatial experience, or the movement provided by the architectural features, lead us to places from where they are more visible by pedestrians. The moment of invitation to enter the laboratory's buildings is provided by its surroundings, because as we arrive, we are invited to go away so our upper view limitation is not an obstacle to watch the PV systems. The convex water mirrors push us away from the buildings, from where we can see the PV systems; the water fountain catches our attention to a strategic point of view, and the demarked paths on the plot lead us to the elevated terraces, from where PV systems can also be better seen. Also, building C's concavity invites one to enter the building and to appreciate its rooftop PV system, which is also the building's sealing material. Therefore, the PV systems control the fluxes of men in the architectural space.

Furthermore, it is possible to state that, since the building is a landmark to the country and to the city of Florianópolis, people who know it can even experience its space in their minds when passing by the laboratory's electric bus during one of its trips. This refers to the concept of social imaginary.

4.2 RELATIONSHIPS BETWEEN TRADITIONAL E SPATIAL INTERPRETATIONS

More case studies need to be interpreted to enable the analysis of the relationship between the traditional and the spatial interpretations. Common characteristics between traditional and spatial interpretations of the case studies will lead this analysis.

The findings should give engineers and architects a better insight of how photovoltaic integration can be interpreted from theories of architectural perception, and the spatial interpretations will serve as inspiration and increase the acceptance of architects on the use of PV in buildings. This should bring together design and PV communities, resulting in the improvement of the architectural integration quality of PV in the built environment.

5 CONCLUSIONS

Building envelopes have become complex and multifunctional due to the need of implementing active and passive strategies for harvesting solar energy. The use of PV modules in buildings developed from this context, to produce energy and compose the architectural envelope as construction materials. With the declining costs and progressive uptake in the use of PV in buildings, modules are becoming more visible and changing the forms of our built environments and landscapes. Studies on the PV architectural integration quality, involving different stakeholders, are essential in order to preserve the quality of these contexts. To explore the technology's full potential, architects and designers need to improve their knowledge on PV, and engineers need to get a better insight of how architects and designers interpret PV architecture. Furthermore, besides concentrating on the development of the PV technology and its market, non-technical problems should also be considered to extract the highest benefits and potential of PV in buildings.

The tradition of PV architectural criticism is objective and practical; it is fixed on the concrete matter, which are the shapes and materials that we can see. However, the essence of architecture is the space, which is a void, or a denial of what is solid. Even though it is what gives us the pleasure we get from architecture, it is ignored. The architectural space and the construction itself depend on one another to exist, therefore, architects should work both of them. **The general objective of this work is, thus, to study how the integration of PV systems in buildings influences the experience of architectural spaces, and evaluate if the spatial interpretation has any relation with the traditional interpretations.** While it presents a somewhat disruptive investigation on the aesthetics of PV architecture, this work does not mean to invalidate all the investigations that were carried out so far, which are essential to the dissemination of the technology, but to go beyond this tradition and relate it to the core of architecture.

To do so, first, existing research on the aesthetics of PV architecture was presented; then, the concept of the architectural subject was delineated on its essence; the notion of the traditional interpretations of architecture was clarified, and related to the researches on the aesthetics of PV architecture presented in the literature review; the concept of the spatial interpretation of architecture was explained; and a general methodology for both traditional and spatial interpretations of PV architecture was presented. In the final version of this work, 20 worldwide case studies of PV integrated in buildings will have been evaluated by the adoption

of both traditional and spatial interpretations, to show the relationships between the traditional and spatial interpretations of PV architecture. The results of these relationships should give engineers and architects a better insight of how photovoltaic integration can be interpreted from theories of architectural perception, and the spatial interpretations will serve as inspiration and expand the acceptance of architects on the use of PV in buildings. This should narrow the gap between the design and PV communities, improving the architectural integration quality of PV in the built environment, and demonstrating the art and science of integrating photovoltaics in the built environment.

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APPENDIX A – Interpretation categories in the studies of the literature review on photovoltaic architecture.

References	Interpretation categories								
	A	B	C	D	E	F	G	H	I
IEA PVPS (1997)							x	x	
Kaan and Reijenga (2004)							x	x	
Schoen *et al.* (2000)							x	x	
Bahaj, James and Jentsch (2007)								x	
Kosoric, Wittkopf, Huang (2011)						x	x	x	
IEA SHC (2012)						x		x	
De Berardinis and Bonomo (2012)						x	x	x	
Bonomo, De Berardinis and Frontini (2013)						x	x	x	
Santos (2013)						x		x	
Polo Lopez *et al.* (2014)						x		x	
Xu and Wittkopf (2015)								x	
Xu, Wittkopf and Roeske (2017)								x	
Sánchez-Pantoja, Vidal and Pastor (2018)							x		
Florio, Roecker and Munari Probst (2015)								x	
Munari Probst and Roecker (2011)								x	
Munari Probst and Roecker (2015)								x	
Munari Probst and Roecker (2019)								x	
Custódio, Zomer and Rüther (2020)								x	
Tablada *et al.* (2020)						x		x	
Celadyn and Filipek (2020)						x		x	
Hagemann (1996a)						x	x	x	
Hagemann (2004)						x		x	
Becker *et al.* (2018)						x		x	
Scognamiglio and Privato (2008)						x		x	
Peng, Huang and Wu (2011)						x		x	
Cronemberger *et al.* (2014)						x		x	
Devetaković *et al.* (2020)								x	
Scognamiglio (2021)						x		x	
Torres-Sibille *et al.* (2009)					x		x	x	
Scognamiglio and Røstvik (2012)						x		x	
Scognamiglio and Garde (2016)								x	
Scognamiglio (2016)					x	x		x	
IEA SHC (2018)					x	x		x	
Lobaccaro *et al.* (2019)					x	x		x	

Interpretation categories:

- A – Political interpretation
- B – Philosophical-religious interpretation
- C – Scientific interpretation
- D – Social-economic interpretation
- E – Materialist interpretation

- F – Technical interpretation
- G – Physiopsychological interpretation
- H – Formalist interpretation
- I – Spatial interpretation