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To cite this article: Changying Xiang and Barbara Szybinska Matusiak 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **352** 012062

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Facade Integrated Photovoltaic, state of the art of Experimental Methodology

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Abstract. The concept of Building-integrated Photovoltaics (BIPV) is one of the most promising strategies to employ clean energy in the built environment. Up to now, the PVs have been applied mostly on roofs, but since the total roof area is insufficient, there is a need to integrate photovoltaics on building façades as well. This challenges not only the architectural design of a single building but also the visual image of urban environment, as photovoltaics have to harmonize with conventional building materials used on building facades as brick, concrete, wood, etc. Aiming to provide a foundation for research exploring facade-integration methods that will ensure successful architectural result, the paper presents a state of the art on façade integrated photovoltaics (FIPV) with focus on the experimental research methodology. It embraces both, theoretical research and PVs applications in building projects. As pure computer simulations are not recognized as an experimental methodology, papers conveying such generated results have not been included. In addition, the research that deals exclusively with energy aspects is omitted. The study is based on a comprehensive literature review. Advanced experimental methodologies from selected literature are described and categorized according to the scale (building or urban) and the transparency of the PVs (opaque or translucent). Then detailed features of PV experimental methods are demonstrated in structured tables for analysis and discussion. The study shows that even though solid scientific methods are used to evaluate single features of PVs, e.g. colour or reflectance, there is an obvious lack of methodology providing holistic assessment of Façade-integrated Photovoltaics, especially at the urban scale. The further research will lead toward developing of evaluation criteria framework (in interdisciplinary cooperation) and then provide a holistic methodology combining qualitative and quantitative methods for a successful FIPVs in urban context.

Keywords: BIPV, experimental methodology, urban context, architectural perspective, façade

1. Introduction

Building Integrated Photovoltaic (BIPV) is one of the most promising strategies to employ clean energy in building environment. Up to now, the PVs have been located mainly on roofs, since roof is the most efficient integration area from energy production perspective. Due to the limitation of the total available roof area, façade areas have to be utilized as well. Previous studies for façade integration mainly focus on energy aspects [1,2]. However, façade integrated photovoltaics (FIPV) require holistic architectural design other than mere consideration to maximize electricity productivity. This study demonstrates the state of art on experimental methodologies of façade integrated photovoltaic. From more than 160 literatures, 9 valuable experimental methods are selected and



discussed in two scales (building scale and urban scale), aiming to provide a foundation for further research exploring systematic FIPV methods.

2. Experimental methodology

“*The experimental method is the only method of research that can truly test hypotheses concerning cause-and-effect relationships.*” — as Gay described in his book ‘Educational Research: Competencies for Analysis and Application’ [3], experimental methodology is a powerful empirical evaluation approach that has been widely used by researchers in various disciplines.

Experimental research usually includes: a hypothesis; one or more variables that could be manipulated by researchers in a controlled environment; experimenters and participants[4,5]. The generated result data will be measured or calculated and analysed. Researchers use experiments to establish a cause-effect relationship and prove or reject the hypothesis. There are three types of experiments [6]: *lab-experiments* (well-controlled environment), *field experiments* (in everyday outdoor environment and cannot really control extraneous variables) and *natural/quasi-experiments* (no control of independent variable in everyday environment).

In this article, computer simulation is not viewed as a type of experiments: firstly, virtual simulations are usually done in very idealizing situations which differ from real environment; Secondly, most solar design tools for Daylighting and PV simulation are using simplified methods [7], which cannot truly represent the reality. Beisbart also argues that computer simulations and experiments are different from a theoretical perspective[8]. Therefore, this study will not include computer simulation methodologies.

3. Objectives and methodology

This study aims to provide extensive list of current advanced experimental methods and approaches of BIPV in façade, the main objectives of this study is to:

- Identify and describe the most advanced experimental methods used for façade integration of PV
- Categorize the methods according to scale (building vs urban scale).
- Demonstrate the detailed features of PV experimental methods in a structured way.
- Analyze the investigation aspects/aims of presented PV experimental methods.

This paper is based on comprehensive literature review. The review methodology of this paper has been inspired by methodology from Saretta et al. [9] and consists of the following 5 parts:

1) First round literature search of recent 10 years’ studies in BIPV field since elder studies rarely address aspects other than energy and economy. Data is collected from English-language literature through *ScienceDirect*, *ResearchGate* and *Google Scholar* databases. Combination of keywords that used for search are: “*building façade integrated photovoltaic*”, “*BIPV façade*”, “*BIPV façade experiment*”, “*BIPV urban context*”, “*experimental method building integrated photovoltaic*”, “*BIPV colour*”, “*BIPV visual*”.

2) Filter search result according to this study’s investigation scopes and investigation criteria.

3) Experimental methods from filtered literature are analysed and categorized.

4) Second round literature search of related studies in colour and daylight field is added. Data is collected from recent 10 years’ English-language literature through *ScienceDirect*, *ResearchGate database* and *NTNU University Library*. Combination of keywords that used for search are: “*façade daylight experiment*”, “*glazing color experiment*”, “*façade color experiment*”.

5) Comparison and synthetization of selected experimental methodologies.

Literatures without experimental methods are not included in this study scope. In addition, research that deals exclusively with energy aspects or only roof integration is also omitted. Investigation criteria are pre-set from architectural point of view, that is color and daylight performance, PV texture, pattern and dimension. More than 160 journal papers, conference proceedings, reports are searched in 2 rounds, among them only 36 papers are selected as deep review materials. 9 valuable methods from previous studies are summarized and discussed.

4. Experimental methods related with FIPV

Façade integrated photovoltaics function as normal façade materials beside the capability of producing electricity. Therefore, like conventional materials, façade integrated PVs will influence the perceived visual images from both single building and urban context levels. Previous valuable experimental studies are categorized according to **scale (building or urban)** and **transparency (translucent or opaque)** in the following paragraphs.

4.1. Methods on façade integrated translucent PV at building scale

Translucent PV products can produce electricity and at the same time be integrated into windows and façade glazing. Indoor daylight condition and visual perception is essential for integrated translucent PV products, however, most of current studies are carried out through computer simulation [10–17]. A limited number of studies have presented valuable experimental experience.

Vossen et al. studied the visual performance of a luminescent solar concentrator(LSC) windows at TU/e in Netherlands [18]. 54 participants aged 21-28 years were asked to evaluate visual experience of office environment with red LSC windows. A full-scale room with normal glazing and 3 physical models (1:6 scaled) equipped with sliding LSC covering were used for comparison study. Participants were first asked to experience the full-scale office room and filled one questionnaire. Then they observed the 2 physical models equipped with various LSC coverage percentages to get visual impression and fill another questionnaire. A third questionnaire was finished after all LSC coverage verification test. Simultaneously, interior horizontal illuminance and exterior illuminance are recorded by a lux-meter in the third scaled model and 2 Hagner SD 2 lux-meters outside the test room respectively. Five criteria are used in this test: visual comfort, naturalness, ambiance, precision and light level. The study results show that a warm color shifting is preferable and that participants prefer rooms with LSC coverage below 25%.

Aste et al. did a similar visual performance test[19]. Three types of LSCs (yellow, orange and red LSC) are tested in a 1:10 scaled physical model on a most cloudy day at the Politecnico di Milano. Experimental measurements were carried out for spectral power distribution, illuminance and correlated color temperature, which link the spatial feeling with surface colors of a real room. Results from different color LSC windows and neutral plate are compared and analysed. The study shows that yellow coloured LSC window is the most preferable due to its high luminous efficiency and the reduction of color temperature of incoming daylight.

Ghosh et al. tested the color properties and glazing factors of semi-transparent photovoltaics [20]. Firstly, the test objects are fabricated by one vacuum glazing layer and one single glazing with multi-crystalline solar cell on top. Two types of solar cells with different transparency are employed for comparison. An UV-VIS-NIR spectrophotometer was used to measure optical features of the combined PV-vacuum glazing. After that, UV transmittance, luminous transmittance, solar transmittance of PV-vacuum glazing is calculated and compared with values of vacuum and single glazing. This PV-vacuum glazing's correlated color temperature (CCT), color rendering index (CRI) were also calculated and compared with features of transparent suspended particle device (SPD). Only normal incident transmittance was measured. The study shows that semi-transparent photovoltaic-vacuum glazing can lower the daylight transmittance and provide preferable entering daylight quality and quantity (with high value of CCT and color CRI than 30% and 40% SPD).

4.2. Methods on façade integrated opaque PV at building scale

Opaque PV products are traditionally applied on building roofs. The glossy surfaces, dark-blue or black colors features and rigid shapes of typical opaque PVs make them difficult to be integrated in building façade as cladding or shading system. With the development of PV technology, new products able to tackle these barriers are emerging.

SwissINSO advertised a promising Kromatrix panels for building façade integration which can overcome traditional color and glossy hinders. The Kromatrix panels co-developed by SwissINSO and EPFL (Swiss Polytechnic Institute) use a special nano-deposition technology. Various colour choices

can be obtained through multi-layer interference effect (not by pigment based colouring) while nonglossy effect are achieved with outer surface etching[21]. Jolissant et al.[22] presented in their paper a series of experimental tests consist of gloss index test, electricity generation performance and color degradation as well as demonstration of real project applications. The gloss index of Kromatrix panel, c-Si PV panel and thin-film PV cells were measured by a Glossmeter at 60 °. Kromatrix panels demonstrate much lower gloss index (6 GU) than c-Si PV (90 GU) and thin-film (120 GU). Following flash test modules at SUPSI in Switzerland showed Kromatrix panels in blue and yellow have almost same electricity production efficiency as standard black panels. Kromatrix glass also passed color degradation test at EPFL-LMT laboratory and further TUV or SUPSI certificates are also obtained.

More interestingly, real façade applications at Kohlesilo in Switzerland and Copenhagen International School in Denmark show satisfying performance in energy harvesting and architecture integration at individual building scale. However, scientific experimental evaluation from indoor users and outdoor citizen's perception is lacking, and more exploration needs to be done to investigate methods and strategies of applying similar products in urban context.

Nagy et al. studied opaque PVs' application from dynamic façade shading system perspective: an advanced adaptive solar façade prototype is developed in lab and applied at the living lab at ETH[23]. The modular prototype equipped with thin-film PV is firstly tested in laboratory for its soft pneumatic actuators' functionality. Then real scale implement is carried out through ETH's house of nature source living lab. However, the lighting, shading performance is not tested in this research, potential data could be further collection from living lab study.

4.3. Methods on façade integrated PV at urban scale (mixing translucent and opaque)

Danks et al. [24] pointed out that there is a lacking of evaluation criteria and empirical study on visible and thermal impacts of reflected solar energy in urban environment. Sánchez-Pantoja et al. [25] proposed a series of aesthetic factors of solar system in urban context: color, glare, pattern-texture, fractality, visibility, integration degree etc..

Some researchers investigated BIPV/solar energy systems' visual perception in urban context with participants-involved qualitative methods. Sánchez-Pantoja et al. [25] presented a study of aesthetic perception of BIPV and BAPV prototypes in Solar Decathlon Europe 2014 Exhibition with non-verbal Self-Assessment Manikin (SAM) survey method. This SAM survey includes emotion assessment and excitation degrees. Firstly, the method of using prototype photos for assessment is validated by result comparison with data from participants' on-site visit. After that, only prototype photos are used for later SAM survey. Subjective opinion of citizens about 20 BIPV and BAPV design prototypes are collected and the result shows that BIPV systems are rated higher than BAPV systems.

Basing on the concept of 'architectural criticality' of building surfaces, Cristina Munari Probst and Roecker proposed a LESO-QSV method to support integration of solar energy system in pre-existing urban areas [26]. A building surfaces' criticality level is defined by combination of sensitivity level of the urban context and surface's visibility level from public domain. The higher the criticality level, the higher integration requirements for solar energy system integration. A LESO-QSV grid software tool[27] with qualitative assessment method is also developed to support the decision making for municipalities to install solar energy systems in urban context.

Based on the LESO-QSV method, Florio et al. present a scale-dependent methodology to assess the visibility of building surfaces with potential to harvest solar energy from territorial scale to urban neighbourhood scale. A cross-mapping application case study the city of Geneva (Switzerland) is also presented in their paper. Aims to combine solar radiation map and an estimate of the socio-cultural sensitivity for a multi-criteria decision making [28]. Multi-criteria decision-making framework for BIPV in urban context is urgently needed. The qualitative LESO-QSV method and tools could be helpful to combine quantitative experimental methods together for supporting FIPV in urban context.

4.4. Methods on façade integrated translucent PV at urban scale

Study by Lynn et al. shed light on investigation of translucent PV façade at urban scale[29]. Semi-transparent thin films (STPV) colour performance has been investigated through experimental comparison of indoor and outdoor CRI value, providing a reference of considering façade integrated PVs' colour property in outdoor urban context. A portable measurement system was designed to realize measurement at both interior and exterior environment. Firstly, the transmitted spectral irradiance of various STPV glazing with different visible range is tested in laboratory. Then respective color rendering index (CRI) values are calculated. Secondly, outdoor on-site measurement of STPV's CRI was conducted to compare with indoor lab test result, in order to investigate the applicability of indoor lab test result in exterior built environment. The comparison shows that although correlated color temperatures are significantly different for indoor and outdoor situations, the CRI result in both situations share similarity. Lynn et al. stated that CRI is an important integration parameter for BIPV.

5. Analysis and discussion

5.1. Building scale analysis and discussion

For BIPV application research, products and building level methods can be viewed as bottom-up approaches. Table 1 summarizes the above-selected 6 experimental methods applied in building scale.

Table 1. List of state of art of methods on façade integrated PV study at building scale.

Year	Author	PV technology	Quantitative Methods	Qualitative Methods	Investigation aspects
2016	Vossen, Aarts and Debije	Translucent LSC	Full-scale room as reference; interior horizontal illuminance of scaled model recorded by Lux-meter; exterior vertical illuminance recorded by Lux-meter.	3 Questionnaires for 54 participants	Color (red color-indoor perception) CCT&CRI; Glare Daylight illuminance
2016	Aste et al.	Translucent LSC	Physical scale model with alternative LSC windows in 3 colors; Daylight condition measured by spectrophotometer	None	Color (multi-color) CCT Daylight illuminance; spectral power distribution
2018	Ghosh, Sundaram and Mallick	Translucent multi-crystalline PV	Glazing optical features measured by UV-VIS-NIR spectrophotometer; PV glazing from 2 transparencies are compared.	None	Daylight Glazing factor; Color CCT& CRI
2012	Lynn, Mohanty and Wittkopf	Translucent thin-film PV	A mobile daylight measurement system was configured to measure the transmitted spectral power distribution (SPD) through the PV; Indoor and outdoor measurements are carried out and results are compared.	None	Color CRI
2017	Jolissant et al.	Opaque Kromatix panels	gloss index measurement and compared with c-Si PV and thin-film PV; flash test of blue and yellow panels for electricity production efficiency and compared with standard black PV; color degradation test at lab; real project application	None	Color Color choices and outdoor stability Texture Glossy or nonglossy; outdoor glare risk Energy Electricity harvest efficiency
2016	Nagy et al.	Opaque thin-film PV	Lab test and living lab test	None	Mechanical function Dynamic adaptivity

For façade integrated PVs at building level, indoor daylight and color are current study focuses. However, no holistically investigation combining both qualitative and quantitative methods has been applied to cover all important indexes of daylight and color. Experiments under different climate conditions are also needed. For instance, study from Vossen et al. shows good combination of illuminance measurement and participants' perception survey, but multi-color aspect experiment is missing, test under more climate conditions could be desirable for further improvement. Research experience from related color science disciplines like color perception of advanced glazing [30], interaction impact between daylight and colors [31] could be good inspiration to help enrich the further BIPV experiment study. For PV integrated façade shading systems, valuable experimental approaches from architectural integration aspect is rare and similarly, knowledge and experience from related glare study and daylighting system investigations [32,33] could be valuable for reference.

5.2. Urban scale analysis and discussion

Urban scale assessment study can be viewed as top-down means, table 2 present the selected 3 façade integrated PV methods applied at urban scale.

Table 2. List of state of art of methods on façade integrated PV study at urban scale.

Year	Author	PV technology	Quantitative Methods	Qualitative Methods	Investigation aspects
2018	Sánchez-Pantoja et al.	No data	None	Self-Assessment Manikin survey through presented photos	Emotional perception pleasant-unpleasant; emotional intensity
2015	Florio, Roecker and Munari Probst	No data	None	3-steps quality evaluation software tool based on LESO-QSV method	Geometry Size/position Materiality Texture; Colors Details Module shape/size; joints
2012	Lynn, Mohanty and Wittkopf	Translucent thin-film PV	A mobile daylight measurement system was configured to measure the transmitted spectral power distribution (SPD) through the PV; Indoor and outdoor measurements are carried out and results are compared.	None	Color CRI

Compared with study at building scale, experimental methods are barely explored in urban scale, this could be due to the very lack of holistic design and assessment criteria for BIPV from architectural perspective. Current studies are mainly using qualitative survey, as IEA-SHC Task 41 "Solar Energy and Architecture" defined, the "architectural integration quality" is the result of a coherent integration from all points of view, including functional, constructive, and formal (aesthetic)[34]. Therefore, systematic experimental methodologies like mixed-methods combining both qualitative and quantitative methods are urgently needed to explore texture, dimension, outdoor color perception of BIPV products in urban context.

6. Conclusion

There is a growing demand to utilized building façade for PV integration, but there is very limited research in this field currently, especially from architectural point of view. This study shows that the current experimental methodologies on BIPV in urban context are still in its infancy. Although new PV technology create more freedom and possibility of integrating PVs on building façade, advanced research supporting BIPV for building facade is still lacking, especially in urban scale. Therefore,

future research focusing on building façade photovoltaic integration in the urban scale from architectural perspective is very essential. More advanced holistic study methodology combining quantitative and qualitative approaches, covering important architectural aspects like color, daylight, texture, dimension etc. is urgently needed.

The next research step could be establishing an evaluation criteria framework of BIPVs from the architectural point of view, supporting the holistic design and implementation of BIPVs in urban context. Interdisciplinary research activities should be carried out combining strength from PV, color and daylight science, architecture and urban design and PV industry partners to achieve the goals.

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