Photovoltaics Potential for Façade Renovations

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As urgent action is needed to tackle the climate crisis by lowering greenhouse gas emissions, façade renovations can improve the performance and reduce the environmental impact of the existing building stock. Integrating photovoltaics into the envelope can supply buildings with electrical energy generated from a renewable resource, limiting energy-related costs and reliance on fossil fuels. Embedding photovoltaics into façades can impact buildings' appearance and environmental performance differently depending on the solar technology used. From crystalline silicon to organic solar cells, first-, second-, and third-generation photovoltaics present varying characteristics such as energy conversion efficiency and visual qualities as well as embodied energy, durability, and recyclability. Additionally, methods ranging from solar concentration to cooling techniques may improve energy generation while reducing the amount of photovoltaic material needed. This study aims to identify the potential of photovoltaic-based technologies for integration into the building envelope, with a particular focus on facade renovation projects and improving the overall performance of existing buildings while considering the environmental impact of photovoltaics. It conducts a review of interdisciplinary literature, design examples, and products, by focusing on photovoltaics for building integration and façade renovation approaches, with attention to the whole lifecycle carbon as well as the experiential quality of solar façades. The paper proposes a framework of potential design strategies for holistically enhancing the performance of façades with integrated photovoltaics in building renovation projects, and highlights possible avenues for future research on the topic.

Keywords: Building-Integrated Photovoltaics, Solar Façades, Façade Design, Façade Renovation

1 Introduction

Recently the Glasgow Climate Pact (UNFCCC, 2021) confirmed the need for urgent action to reduce global greenhouse gas emissions and tackle the climate emergency. Given the large impact of the building sector on the world's energy use (International Energy Agency, 2013), solutions have been implemented to improve the energy efficiency of existing building stocks through façade renovations, and solar technologies have been deployed to supply built environments with energy generated from solar radiation which is a renewable resource. In particular, photovoltaic technologies can provide buildings with electrical energy generated from sunlight onsite, by reducing energy costs for building users as well as the reliance on electricity produced from fossil fuels. Photovoltaics can be deployed in different ways on the building envelope, which has been explored for decades. Already in the 1990s, Sick & Erge (1995) examined possibilities for photovoltaic installations on roofs and external walls and shading systems, noting the similarities in assembly methods between conventional envelopes and photovoltaic facades. They stressed the importance of suitable exposure to sunlight and buildings' energy efficiency to the effectiveness of photovoltaic energy generation. While considering the development stages of photovoltaic installations for building projects, they highlighted how the earlier design phase involves dealing with issues of size, orientation, form, and colour, while later stages focus more on functional, mechanical, electrical and operational issues (Sick & Erge, 1995). Although the vertical arrangement of photovoltaics may not be optimal for absorbing sunlight, Freitas & Brito (2019) highlighted the benefit of combined energy generation from both roof and façade surfaces in urban environments. When photovoltaic technologies are embedded in the building skin by replacing conventional materials, they are identified as BIPVs, or Building Integrated Photovoltaics (Shukla et al., 2016, p. 100), and their impact on the architectural image as well as on the environmental performance can vary according to the photovoltaic technology used.

With different visual and efficiency characteristics, photovoltaics are generally distinguished as first-, second- and third-generation solar cells. Crystalline silicon solar cells represent the most established technology, thus belonging to the first generation. The second generation refers to established thin-film solar cell materials like amorphous silicon, copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe). On the other hand, the third-generation group involves more recent technologies that are still being improved, such as organic solar cells (Sampaio & González, 2017). There may be also strategies that are worth exploring for enhancing the performance and appearance of BIPVs a, such as solar concentration, spectral conversion, the cooling of photovoltaic modules and employing high-efficiency photovoltaic cells as well as optimising and adapting geometries to local environmental conditions (Nicoletti, 2020, pp. 87-102). Photovoltaic technologies in development include dye-sensitised and perovskite solar cells among others, as well as systems using solar concentrators. While integrating photovoltaics into the building envelope appears overall advantageous for improving buildings' energy performance with aesthetically acceptable outcomes, more needs to be understood about the lifecycle environmental impacts of BIPVs (Zhang et al., 2018).

By conducting an interdisciplinary review of relevant literature, including examples of façade designs and BIPV products, this study aims to shed light on the potential of photovoltaics for facade designs within envelope renovations directed at improving building performance, with attention to the environmental impact of photovoltaics.

2 Methodology

This study explores the integration of photovoltaics into facades with a focus on envelope renovation strategies, by conducting an interdisciplinary review on the topic in two stages, based on different key term searches on Google Scholar, Scopus, and Science Direct.

An initial broader review was directed at providing an overview of strategies for visually integrating photovoltaics into building envelopes, particularly in retrofit contexts. The key terms searched included "building-integrated photovoltaics" or "BIPV" or "solar facades" and "renovation" or "retrofit". Sources were selected among scholarly publications, as well as web sources where appropriate, that were found to have a focus on proposing approaches to solar façade design or exemplifying them through cases of buildings and products.

A later review concentrated on examining the environmental impact of photovoltaic technologies for façade integration, which was based on the search of the key terms including "photovoltaic" and "embodied carbon" or "embodied energy", "end-of-life", and "durability". To retrieve up-to-date information on the topic, the researcher selected scholarly sources published predominantly since 2018, with a primary focus on academic journal articles.

The following sections present and then discuss the findings of the reviews by relating reflections on solar façade design approaches in retrofit contexts to observations on the environmental impact of photovoltaic technologies for building integration, towards identifying potential strategies for sustainable façade renovations with photovoltaics.

3 Design and Lifecycle Considerations for Integrating Photovoltaics into the Building Envelope

3.1 Building Integrated Photovoltaics in Façade Renovations

The design of building-integrated photovoltaic systems is informed by multiple factors affecting the functioning and the appearance of solar architectural installations, including angles of PV modules and shading on them as well as their temperature, which can be simulated computationally (Biyik et al., 2017). Features of the PV system that impact its performance include the overall extent of the photovoltaic surface, the solar cell type and its efficiency, the geometry of the installation, shading and soiling on the PV modules, which can be exacerbated by unfavourable environmental conditions such as limited solar radiation and high temperatures. There may be a need for cleaning and maintenance of PV modules, with associated economic costs, while characteristics of other system components such as energy storage devices also need considering (Fouad et al., 2017). Given the complexity of the problem, there has been extensive research on designing solar facades, which has led to proposing a range of design principles that may be followed by architects.

Solar products for building integration include solutions for 'opaque' or 'transparent' and 'semi-transparent' facades, within a broad range of technologies including solar thermal and hybrid photovoltaic-thermal systems as well as adaptive 'smart windows' (Lai & Hokoi, 2015). Available solar skin products usually embed either crystalline (Fig. 1) or thin-film (Fig. 2), amorphous silicon cells. Photovoltaic cladding components can vary in weight and flexibility from 'foil' to 'tile' products or can replace conventional weather skin modules. On the other hand, photovoltaic glazing products can vary not only in colour but also in transparency level to fulfill daylighting, shading, and electricity generation functions (Shukla et al., 2016, p.105). To achieve semi-transparency, glazing products are characterised by lower solar cell coverage, which reduces the generated energy output (Robinson et al., 2008).

Fig. 1 Photovoltaic glass façade integrating crystalline silicon solar cells. *Note*. From *Balenciaga Miami Design District* [Photograph], by Phillip Pessar, 2018, Flickr, (https://www.flickr.com/photos/25955895@N03/46276576481). CC BY 2.0.

Fig. 2 Thin film photovoltaic modules. *Note*. From *Thin Film Flexible Solar PV Installation 2* [Photograph], by Ken Fields, 2008, Flickr, (https://www.flickr.com/photos/51925339@N05/4783039248). CC BY-SA 2.0.

Previous studies outlined principles for the architectural integration of photovoltaics. Schoen et al. (2001) suggested a set of criteria ranging from a seamless integration of photovoltaics and ‘harmony’ with the local context to unconventional designs that stand out. Similarly, Kaan & Reijenga (2004) proposed that photovoltaics may be part of architectural designs in different ways, from ‘invisibly’ to installations that can enhance and produce the architectural appearance or even convey novel concepts.

The guidance provided by Farkas (2013) for developing building-integrated photovoltaic systems, which refers to commercially available solar technologies, distinguishes more technical issues of ‘functional’ and ‘constructive’ nature from aesthetic aspects that need considering. Besides fulfilling building envelope functions of security, views, sound and thermal insulation, comfort, ventilation, protection from the weather, and energy generation, building-integrated photovoltaic systems need to be designed with attention to their appearance, by considering the overall size of the solar installation as well as the shape, size, colour, texture, and the type of connections characterising the photovoltaic modules. Adaptability in the visual composition of the solar installation may be achieved by using non-active elements identified as ‘dummies' and coloured photovoltaic products (Farkas, 2013). Photovoltaic modules may also be integrated unnoticeably by seemingly ‘blending’ photovoltaic cells with the building skin, as highlighted by Corti et al. (2018, p. 93) through a case study located in Zurich, although this type of solution reduces the efficiency of photovoltaic modules. The cladding of the Copenhagen International School designed by C.F. Møller Architects (Corti et al., 2018, p. 68-69) also exemplifies the use of coloured photovoltaic façade modules with invisibly integrated solar cells (Fig. 3). As Scognamiglio (2021) pointed out, the ‘visual performance’ is not to be overlooked, as it determines people’s acceptance of solar installations. Kuhn et al. (2021) highlighted two alternative avenues for integrating photovoltaics into the visual design of facades: either to make the solar cells distinguishable within the façade design and use them as modular elements to compose patterns, or to make the solar cells invisible by applying front covers that produce a coloured effect but also reduce the energy generation efficiency (Kuhn et al., 2021, p. 14). As noted by Scognamiglio (2017), ‘preservation laws’ may pose obstacles to the integration of photovoltaics into buildings within certain settings (Scognamiglio, 2017, p. 192), where their visual contrast with the context might need to be minimised. Xu & Wittkopf (2014) pointed out that the visual impact of building-integrated photovoltaics may not be easily predictable if evaluated according to qualitative indicators and proposed the use of saliency maps for measuring the visual impact of photovoltaics integrated into the envelopes of historical buildings. Thus, the invisible integration of photovoltaics may be particularly suitable for renovations in historical contexts.

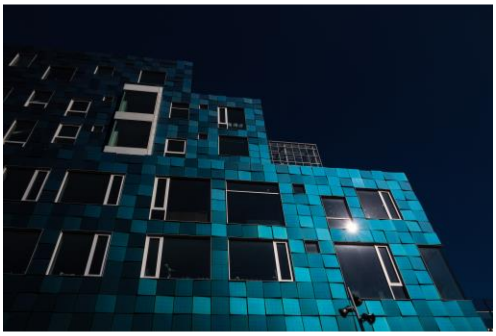

Fig. 3 Photovoltaic cladding of the Copenhagen International School designed by C.F. Møller Architects. *Note*. From *Copenhagen International School* [Photograph], by Stig Nygaard, 2019, Flickr, (https://www.flickr.com/photos/10259776@N00/48338691067). CC BY 2.0.

Polo López et al. (2021) explored the integration of photovoltaics into heritage buildings, noting that new interventions should be easy to distinguish and remove from the pre-existing artefacts without damaging them, and they should also be minimally invasive as well as compatible with the original buildings in terms of construction and aesthetics. Within their study, two Swiss case studies also exemplified the integration of photovoltaics into heritage buildings: a farmhouse from the 19th century, presenting roof-integrated, anti-reflective solar modules resembling traditional terracotta tiles, and a family villa from the late 1930s, where the roof was instead fully replaced by highly reflective solar panels of blue colour. It was shown that a design choice can be made between visually blending photovoltaic installations with the existing building and replacing entire parts of the envelope with new materials to prioritise energy performance enhancement (Polo López et al., 2021).

Building renovations do not always involve intervening in protected areas on artefacts with historical and cultural value. Evola & Margani (2014) showed that using photovoltaics in renovating the façade of a poorly energy-efficient block of flats built during the second half of the 20th century can improve its performance towards zero-energy standards, enhance its architectural image and increase its commercial value. Martín-Chivelet et al. (2018) showed how replacing an existing polymer concrete skin with a BIPV ventilated façade system can improve a building's energy efficiency and appearance while providing it with a source of electrical energy. Thus, it can be observed that there may be renovation cases in which the building energy upgrade becomes the priority, and more freedom may be given to the designer on how to transform the architectural image through façade integrated photovoltaics.

In a study on designing solar facades for visual engagement, Nicoletti (2020) proposed a framework for conceiving solar architectural skins that are capable of attracting attention and interest, which involved strategies inspired by media façades for producing motion impressions in various ways through static solar envelopes. The framework considered the architectural potential of photovoltaics that are still in development, highlighting strategies for increasing the efficiency of photovoltaics, such as improved geometries, spectral conversion, using optical devices with low-concentration ratios, and ventilated systems for cooling solar modules. These strategies may even be used to display contents like images or patterns and add visual qualities to the building envelope, such as colour, reflectivity, refractivity, or luminescence. Existing facade designs with similar visual properties may serve as references for developing innovative designs integrating more efficient photovoltaic-based technologies (Nicoletti, 2020). However, while new photovoltaic solutions for their building integration are being explored, the environmental impact of the technologies used needs to be taken into account.

3.2 Environmental Impact of Photovoltaics

Photovoltaic technologies continue to be developed. While silicon solar cells currently prevail among commercial products, other photovoltaics are being improved in terms of efficiency, stability, durability, material composition and costs (Ontiri & Amuhaya, 2022). While energy generation efficiency needs to increase and cost needs to be reduced, it is important to understand the environmental impact of photovoltaics in the long run (Zhang et al., 2018). The durability and operational performance of photovoltaics may be improved by superhydrophobic coatings facilitating the cleaning of solar modules and preventing the accumulation of dust or ice (Wu et al., 2021), potentially avoiding the breakage of glass covers or solar cells, that are known, according to Kim et al. (2021), among the causes of solar panel degradation, along with the penetration of moisture (Segbefia et al., 2021), which is likely to stimulate research on high-performance encapsulants for better protecting solar cells (Gaddam et al., 2021). However, more research is needed on how the whole life cycle of BIPVs affects the environment (Yan, 2019).

Bartie et al. (2022) suggested that the spread of photovoltaics contributes to depleting the planet's natural resources, as the technology involves the use of valuable materials such as precious metals. By analysing the lifecycle and cost of rooftop photovoltaic systems in the European context, Martinopoulos (2020) questioned their sustainability which may vary according to factors such as the geographic area and its climate, the local energy supply, the impact of transportation and cleaner energy generation systems that may be introduced in the future. According to Ludin et al. (2018), monocrystalline silicon products have the worst impact among photovoltaic technologies in terms of energy use, energy payback time and greenhouse gas emissions. Nonetheless, as highlighted by Muteri et al. (2020), the results of evaluations on the lifecycle of photovoltaics can vary depending on the scope and methods of each assessment.

As highlighted by Piasecka et al. (2020), the negative environmental impacts of photovoltaic systems are those of production and end-of-life processes that are energy- and material-intensive. The disposal of PV systems can be harmful due to the presence of materials such as lead and cadmium among others, thus it requires careful recycling (Piasecka et al., 2020). End-of-life processes in the lifecycle of photovoltaics can produce dangerous waste which may contaminate potable water if dispersed in the environment, so there is an urgent need for accelerated implementation of recycling solutions through rapid developments in technologies and policies (Chowdhury et al., 2020). The inadequate disposal of photovoltaic system elements can cause the leaching of carcinogenic materials including lead, cadmium, and arsenic (Nain & Kumar, 2020).

Lamnatou & Chemisana (2019) conducted a review on different photovoltaic technologies with a focus on their life cycle assessment, noting that existing studies on the topic are predominantly on crystalline silicon photovoltaics, and more is to be researched about less established solar cell types. While it was suggested that the environmental impact of façade-integrated photovoltaics is comparable to that of optimally oriented solar panels installed on roofs, the benefits depend on local conditions. Instead, known negative impacts of thin-film photovoltaic technologies include the human and environmental toxicity of some of the materials used, e.g., cadmium in CdTe solar cells or lead in the otherwise very promising perovskite solar cells. Third-generation photovoltaics such as organic solar cells are much less durable and efficient in generating electricity but may offer potentially lower environmental impacts including a reduction in lifecycle greenhouse gas emissions, in comparison to conventional silicon photovoltaics. On the other hand, concentrating photovoltaics can replace large amounts of solar cell material with optical devices that direct sunlight onto smaller photovoltaic areas, with potential economic and environmental benefits that could be investigated further. Negative environmental impacts of photovoltaic systems are also associated with energy storage devices, their manufacturing and their relatively short life span. While recycling photovoltaics may be advantageous, it is evident that there is a need for more research on end-of-life processes and their environmental impacts (Lamnatou & Chemisana, 2019). Recycling photovoltaic modules can be less energy-intensive than producing new products. Recycling thin-film photovoltaics can be economically advantageous, and chemical recycling may be preferable to mechanical and thermal processes in terms of environmental impact (Padoan et al., 2019). Lamnatou et al. (2020) also highlighted the environmental problems associated with storage elements of solar energy systems, with notes on embodied energy as well as the toxicity, fire hazard, and recycling issues of batteries in the context of BIPV and hybrid photovoltaic and thermal systems. End-of-life processes should be further improved with attention to the toxicity of the involved substances and the environmental impact of transportation (Lunardi et al., 2018), which was also noted by Seo et al. (2021) and Celik et al. (2020).

Lisperguer et al. (2020) emphasised the importance of reducing the environmental impacts of current PV recycling methods relying on thermochemical processes, which suggests the need for more careful design from the onset of the lifecycle of photovoltaics. According to Deng et al. (2019), photovoltaic products should be easier to disassemble and recycle, without involving harmful substances, and manufacturers could be responsible for the end-of-life stages. There need to be developments not just in the technologies for effective end-of-life processes, but also in the socio-economic and policy aspects impacting them, which requires engaging the relevant stakeholders (Salim et al., 2019), techno-economic evaluations (Heath et al., 2020), and potentially, economic incentives for recycling practices (Sica et al., 2018). According to Lamnatou et al. (2019), who examined the environmental and human toxicity of photovoltaics, the system elements with the highest negative impact are the PV cells. Freier et al. (2018) noted that employing static non-imaging solar PV concentrators may lead to reducing the use of photovoltaic material as well as the environmental impact of photovoltaic systems. Ziemińska-Stolarska et al. (2021) highlighted that systems with concentrators achieve higher performance than those without and suggested an approach for assessing their lifecycle environmental impact. Freier Raine et al. (2021) compared the embodied energy and the cost of a static concentrating photovoltaic module to that of a conventional flat module of equal electrical output, concluding that the concentrating photovoltaic solution involves lower embodied carbon but higher costs, thus requiring a trade-off to reach commercial viability. On the other hand, using solar concentrators may have a positive impact on the overall durability of photovoltaics, as breakage in the optical device can have a small detrimental effect on the system performance (Alzahrani et al., 2020). Thus, concentrating photovoltaics may potentially reduce the negative environmental impacts of photovoltaic technologies.

4 Towards Strategies for Façade Renovations with Building-Integrated Photovoltaics

The previous sections showed that various photovoltaic technologies are available for building integration, and while some are commercially established, others continue to be developed to achieve better performance levels. It was found that different approaches for embedding photovoltaics into the building envelope have been proposed so far that suggest ways of visually integrating energy-generating components into facades. Those approaches are based predominantly on the use of crystalline silicon photovoltaics as well as some thin-film technologies. Common ways of adapting the appearance of photovoltaic installations for building integration involve colour alterations that can make solar modules resemble conventional building components or, instead, compose innovative designs. However, such solutions tend to reduce energy generation efficiency. As this depends on the extent of the active photovoltaic area, integrating solar cells into glazed elements to achieve semi-transparency involves reducing the photovoltaic cell coverage and therefore the generated energy output. Developing technologies such as concentrating photovoltaics may expand the possibilities for the visual integration of solar cells into facades with qualities such as reflectivity, refractivity and luminescence while increasing the energy generation efficiency with reduced amounts of photovoltaic materials. In façade renovation projects, photovoltaics may be integrated into the envelope invisibly or in a distinctive way. The latter option may be less suitable for heritage contexts but in other cases, it can offer possibilities for exploring the visual communication potential of photovoltaics. With or without an innovative design that stands out, solar cells may be clearly distinguishable or not.

On the other hand, it was found that the environmental impact of photovoltaics throughout their whole life cycle is not negligible. Not only do the greenhouse gas emissions of production stages need more careful consideration, but also the durability of photovoltaic technologies needs to be improved to prevent breakages and degradation, for instance, due to moisture penetration. There are serious concerns about the end-of-life management of photovoltaic systems waste, which needs to be improved to reduce environmental and human health risks as well as the depletion of natural resources such as precious metals. More effective recycling processes need to be implemented with attention to minimising carbon emissions and pollution also due to transportation. Solutions must be found to problems such as the toxicity of certain materials used in photovoltaics and the possible contamination of drinking water. A greater effort is required to design photovoltaic installations for building facades, that can be easily disassembled and recycled.

Given the continuing development of solar cell materials and the relative uncertainty around the environmental impact of certain stages of their lifecycle, it can be suggested that a cautious approach to integrating photovoltaics into building facades would be appropriate. Reducing the amount of solar cell materials used and replacing them with materials with known, low environmental impact could improve the overall sustainability of solar facades. Adopting strategies for improving the performance of photovoltaics, such as solar concentration with low-concentration optical devices, spectral conversion, or cooling, may increase the energy generation efficiency of photovoltaic installations with reduced solar cell coverage, and improve their environmental impact. However, more research is needed to develop such systems for façade integration, and the environmental impact of materials that would replace solar cells also needs to be investigated in depth.

5 Conclusions

In conclusion, this research has identified a range of possible strategies that may be pursued and further investigated towards enhancing the performance of photovoltaics integrated into facades in renovation projects, with attention to the facades' appearance and energy generation efficiency as well as the environmental impacts of solar technologies.

In architectural renovations, photovoltaic installations may be integrated into existing buildings to improve their energy performance as well as their appearance. They may visually blend with the rest of the building envelope and be in harmony with the surrounding context, or they may stand out with an unconventional design that can be composed through the arrangement of photovoltaic modules, with the solar cells being clearly distinguishable or not.

Reducing the solar cell coverage with conventional technologies could lower the life cycle environmental impacts of photovoltaic façades but would also decrease the generated energy output. Developing solutions for increasing the efficiency of photovoltaics with smaller amounts of solar cell materials could improve the sustainability of solar facades. Strategies to be explored include the façade integration of low-concentration optical devices, spectral converters, and structures facilitating natural ventilation for the cooling of solar modules. These approaches could visually enrich photovoltaic façade designs for building renovations with qualities such as colours, light reflections and refractions. However, more research is needed on their materials and associated environmental impacts.

Acknowledgements

This research was funded by the Faculty of Environment and Technology at the University of the West of England and builds on the author's PhD thesis *Design of Effective Solar Architectural Skins for Visual Engagement*, completed with the University of Brighton / University for the Creative Arts.

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Submission of contributions

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