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Design Strategies for Façade integrated Photovoltaic Technology (FiPV)

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Abstract
The rapid pace of urbanisation has caused a surge in the energy demand, thus emphasizing the need for Net Zero Energy buildings. A plethora of financial and non-financial incentives for promoting energy efficient and renewable energy buildings are being offered by several local governments in India. Policies have favoured the inclusion of photovoltaic technology within the buildings. Despite the efforts, adoption of the technology within the envelope is quite restrictive. The photovoltaic technology is either added onto the rooftops or provided as double façade. The concept of replacing the building skin with this technology has not been explored enough. This paper attempts to propose a framework, for designing a photovoltaic façade, replacing the conventional building skin. It has tried to address some of the barriers, and inhibitors in uptake of the technology. It explores provision of an assessment framework for envelope performance of photovoltaic facade.
Keywords: Photovoltaic Façade, Design Strategies, Building Skin, Framework Design.

1. Introduction

The dynamics of rapid urbanisation and the energy consumption is a leading cause of increased pressure on the existing fossil fuels. According to Khan, Abas, & Kalair, (2015) the increasing energy demand would lead to exhaustion of oil reserves by 2050, gas reserves by 2070, uranium ores by 2090 and coal reserves by 2150. Globalisation has led to higher rate of urbanisation in major cities, leading to extensive use of energy, swelling the demand of exhaustive fossil fuels. Buildings are a major source of energy consumption in cities, especially the commercial buildings, with central HVAC system, and other state of art technologies. There has been a change in the perspective and use of buildings. Apart from being major energy guzzlers, buildings provide great opportunities to save and generate energy at the same time. The change in perspective of buildings, has brought many technological innovations at the fore front of the building integration. Renewable energy system is a concept being incorporated into building to transform it into energy generator, leading to the realisation of Net Zero Energy buildings (Zhanga, et al., 2018). Highly feasible renewable energy system, with greatest viability of building integration is the photovoltaic system for incorporating the solar energy in the buildings.

Photovoltaic technology has been used in buildings for many years, though the incorporation of this technology is majorly limited to roof-tops, double façade or as add-on components. Nagyn, et al, (2016), had studied the concept of adaptive solar facades, where motorised solar panels were added on to the building façade. Saretta , Caputo, & Frontini, (2019) assessed the potential of façade retrofitting with photovoltaic panels, through analysis of geographical, building technical parameters. In studies like Gholami & Rostvik,(2020), Gholami, Rostovik, & Muller, (2019), the economical evaluation of adding the thin-film photovoltaic panels on a offcie building were evaluated. In studies like Nagyn, et al.,(2016), Saretta , Caputo, & Frontini, 2019, Gholami & Rostvik,(2020), Gholami, Rostovik, & Muller, (2019), the incorporation of photovoltaic technology on the building façade has only been explored as double façade or as a added on component on the existing façade. The idea of photovoltaic systems replacing the conventional materials and acting as building skin has not been explored enough. Adoption of the photovoltaic technology on the roof is fairly simple process, involving mounting of panels on flat horizontal surface, not affecting the functioning of the building or its envelope. When integration of photovoltaic system on façade is considered, the complexity of designing increases significantly. The process of designing photovoltaic panels to function as façade replacing the building skin, is quite complex. Inspite of the complexities, the integration of technology on the façade is quite efficient. The roof areas are places for installing services, or leisure activites or other leasable activites, creating greater economic benefits. Whereas the façade surfaces of multistoried commercial buildings are unused, unobstructed areas, presenting great opportunity for integration. Efficient designing of photovoltaic façade requires bridging the gap between the technology and the building façade. The framework design, proposed in this paper is an attempt to simplify the process of desinging a photovoltaic façade and allow it to fucntion optimally and effciently.

The complexity in the process of designing a photovoltaic façade is due to: (i) barriers in the adoption of the technology as a building skin and (ii) conflict in the functioning of photovoltaic panels as energy generators and building skin. The paper attempts to identify the barriers and their impact on the designing process. It also tries to identify and reduce the conflict of the photovoltaic façade to act as building skin and energy generator. The solution to mitigate the conflict and barriers in the adoption, are in the form of design strategies. The paper has been divided into four sections, section one dealing with the identification of barriers and their impact on the design process. Section two describes the design strategy for designing a photovoltaic façade. Section three is the methodology or the framework for designing a photovoltaic façade and achieve its architectural integration. Section four is the conclusion.

2. Identification of The Barriers and Their Impact on The Design Process

Designing a photovoltaic façade, requires understanding of the technology, process, issues and concerns of the integrating the technology and the apprehensions of the designers. According to Akinwale, Ilevbare, & Ogundari,(2015), the acceptance of technology is based on its usage, learning, and application. Therefore, for designing the façade with photovoltaic technology, we need to understand and identify the barriers in the adoption of the technology. Barriers are defined as inhibitors, issues and concerns with the product, process and the stakeholders involved in the design process. Inhibitors are the problems identified in the photovoltaic product, system and the designing process, which restrcit the realisation of the photovolataic building skin to its full potential. Issues and concerns are the apprehensions of the different stakeholders involved in designing process.

Ahmad & Zia, (2022), had identified different barriers and categorised them into three categories. Category I barrier was the identified problem in the photovoltaic product and system, category II was the barriers in the designing process and category III barriers were the barriers affecting different stakeholders. Table 1, depicts different categories of barriers identifed in the study by Ahmad & Zia, (2022).

Table 1: Categorisation of barriers. source: (Ahmad & Zia, 2022)

CATEGORY I (Barriers in the Photovoltaic product)	CATEGORY II (Barriers in the photovoltaic façade design)	CATEGORY III (Barriers affecting different stakeholders)
Type of photovoltaic technology (multi/mono-crystalline technology vs thinfilm technology).	lack of knowledge of the architect/façade designer.	Economic non-feasibility.
Reduced efficiency with 90° tilt angle.	Non-availability of codes for integrating photovoltaic system with local bye-laws.	Operating and managing the photovoltaic system.
Non-availability of suitable photovoltaic product	Non-availability of suitable photovoltaic product	Non-availability of suitable photovoltaic product
Photovoltaic façade's visual and optical properties.	Photovoltaic façade's visual and optical properties.	Photovoltaic façade's visual and optical properties.
Non-availability of proper tools for designing photovoltaic façade.	Non-availability of proper tools for designing photovoltaic façade.	Lack of client's interest.
	Structural and mechanical integrity.	
	Lack of skilled workforce.	
	Climatic responsiveness of photovoltaic façade	

Identifying solutions in the form of design strategy, was the next step in the process. To propose design solutions, it is important to understand and identify the barriers that had a direct impact on the design process. In the study Ahmad & Zia, (2022), the barriers were identified which had a direct impact on the design process. The type of photovoltaic technology and its selection affected the design process as it determined whether a translucent, opaque, or transparent façade could be designed. The insufficiency in architect's and façade designer's knowledge had a direct impact on the process of design, hence it required a proactive approach to solve the problem. Absence of uniform codes that provided a regulatory guideline for incorporating photovoltaic products and system within the building directly impacted the designing process. Non-availability of façade compatible photovoltaic products along with their optical and visual properties had a direct impact on the process. Climatic responsiveness of the photovoltaic façade, mechanical and structural integrity of the photovoltaic product also directly affected design process. The non-availability of skilled workforce was also a very critical barrier affecting the design process. Identification of the barriers with direct impact is a very critical step in planning of design strategies.

3. Strategy for Designing a Photovoltaic Façade

Identification of a design strategy for photovoltaic façade, required solution to the barriers with direct impact. The identified solution attempts to transform the barriers into enablers and drive the process to achieve a photovoltaic façade with minimum conflict between its role as energy generator and building skin. The aim of proposing the design strategy is to remove any hinderances in the process of design, enable the designer with a simplified and efficient process, and to minimise, if not remove the conflict between the photovoltaic roles as energy generator and building skin. The identification of barriers was the first step towards achieving a design strategy. Next step in the process is to understand the conflict between photovoltaic systems acting as energy generator and building skin.

The conflict management is very important to achieve efficiency and provide a sustainable solution for designing of photovoltaic façade. A building façade has its own set of limitation and perceptions, which a material should be able to fulfil. Therefore, photovoltaic technology adopted on façade should be able to provide: (i) connection between the interior and exterior of the building, (ii) daylighting, (iii) thermal comfort, (iv) structural and mechanical integrity. When acting as building skin the primary role of photovoltaic material i.e., energy generation should not be compromised. The main reason for having this apprehension is due to its tilt angle and place of application. When a photovoltaic panel is installed at a tilt angle of 90°, the efficiency of the panel reduces. When installed on the building façade, the sunlight available is not direct but diffused, again affecting the power output from the panel. Hence, it is important to identify a solution to this problem in the design strategy.

Architect's and façade designers involved in designing of photovoltaic façade are faced with the problem of understanding the technology and integrating it within the building envelope. They must reduce if not mitigate the conflict of the photovoltaic material to act as building skin and energy generator simultaneously. The proposed design strategy is an attempt to simplify the process, reduce the complexity of the application of technology and reduce the identified conflict. It is a streamlined sequential process of four identified steps: (figure 1)

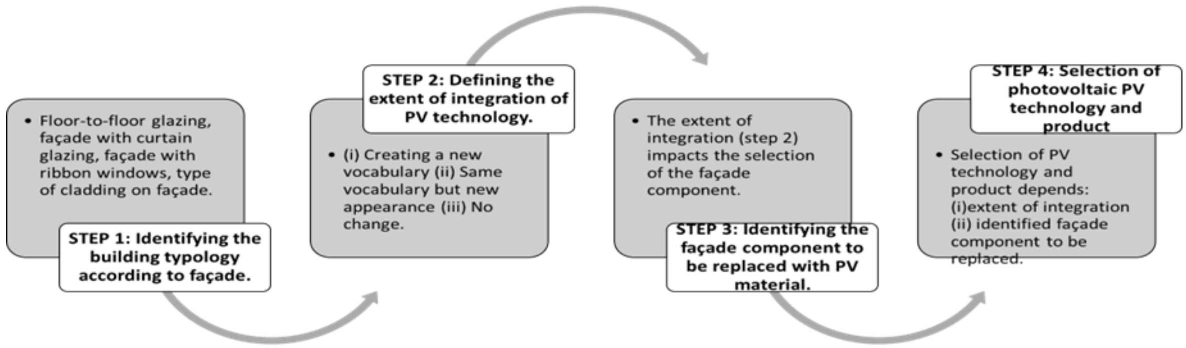

Figure 1. Steps of design strategy

STEP 1: Identifying the building typology, according to the façade type (façade with floor-to-floor glazing, façade with curtain glazing, façade with ribbon windows, type of cladding on façade).

STEP 2: Defining the extent of integration of photovoltaic technology within the building façade. Extent of integration would decide the type of architectural vocabulary. Three extents of integration have been identified: (i) Creating a new vocabulary (ii) Same vocabulary but new appearance (iii) No change.

STEP 3: Identifying the façade component to be replaced by the photovoltaic material. The extent of integration (step 2) impacts the selection of the façade component.

STEP 4: Selection of the photovoltaic technology and product depending upon the extent of integration and identified façade component to be replaced. **Table 2.** describes each of the steps in detail and delineates the design strategy to achieve a photovoltaic façade.

Table 2. Design strategy for generating photovoltaic facade.

DESIGN PARAMETERS		DESCRIPTION
STEP-1	**Façade typology of identified commercial building:**	a) Defining the architectural typology. Studies like Sandak, Sandak, Marcin, & Kutnar, (2019) Singh, Ravache, & Sartor, (2018), the prevalent commercial buildings are categorised into three typologies: (figure 2) 1. ***TYPOLOGY-I:*** Curtain wall system having aluminium composite panel cladding with ribbon windows. 2. ***TYPOLOGY-II***: Floor-to-floor glazing, with a façade of exposed brick work. 3. ***TYPOLOGY III:*** Aluminium composite panel clad facade with floor-to-floor glazing. b) The façade typology would be an important determinant of the possibility of the extent of architectural integration. c) According to the typology of the building the façade component to be replaced would be identified.

STEP -2	**Extent of application of the photovoltaic panel/glass on the building façade:** Defining the extent of transforming the architectural vocabulary of the new generated variant.	Step one acting as reference point for identifying the extent of integration possible. Step two will determine the architectural vocabulary of the designed building façade. Three levels of integration are possible, depending upon intent of designing the façade: a) **New architectural vocabulary**: 1. The designed building façade has a different architectural vocabulary, achieved by the application of photovoltaic panels/glass with different granularity (colour and texture). **2.** Integration of the photovoltaic glass/panel are at different angles or using a combination of solar glass/panel with conventional building material. b) **New appearance maintaining the overall vocabulary**: 1. Designed façade will have the same architectural vocabulary. Hence the photovoltaic glass/panel integrated will be having the similar granularity (colour and texture). 2. Achieved by using a combination of solar glass/panel with façade glass, aluminium composite panel, or exposed brick masonry. c) **Minimum intervention, same vocabulary**: 1. The façade designed will be using photovoltaic panel/glass of same granularity, size, and modularity. 2. It can be done by replacing the glass of fenestrations with solar glass or replacing the cladding material with solar panels of same granularity.
STEP-3	**Identification of façade component for photovoltaic integration:**	a) Feasible façade components as identified, will be the components with highest feasibility of achieving architectural integration and allowing photovoltaic panel/glass to efficiently act as an envelope material without compromising its energy generation potential. b) The integrational façade components are decided based on façade typology: 1. Façade with curtain glazing, provide an opportunity to design with a translucent/transparent photovoltaic curtain walling. 2. Façade with panelling of aluminium composite panels, provides an opportunity to create a vocabulary with high efficiency opaque photovoltaic panels. 3. Windows on the south side can be provided with translucent solar pv glass. 4. Combining glass and photovoltaic glass, where possible, allowing the integration of high efficiency opaque glasses. c) Components with highest feasibility of application/integration of photovoltaic component are: - *Window glass, Curtain glazing, Floor to floor glazing, Sunshades, Panels between glass on the façade, Railings (panels between balustrade), walls (covering the fire exits and lift wells), Spandrel areas or areas between floor-to-floor glazing's.*
	Selection of façade component with respect to selected thin film photovoltaic technology and vice-versa.	a) Amorphous Silicon (A-Si) thin film photovoltaic panels are produced as transparent panels, efficiently and optimally integrated as curtain glazing, window glass. 1. The transparency achieved with A-Si technology varies (Visible transparency =30%, 20%, 10%, 0%). Panels with visible transparency of 20%-30% could be integrated as or in combination with window glass and curtain glazing. 2. Panels with visible transparency of 0% and 10% could be integrated as cladding materials, spandrel glass, panels between windows, staircase, and lift walls (in case of end cores). b) Cadmium Indium Gallium diselenide (CIGS/CIS) are produced as opaque panels, but in varied colours, can be integrated as cladding materials replacing the conventional ones. They can be provided in combination with curtain glazing.
STEP-4	**Heat dissipation method for façade application:**	a) The preferred method of heat dissipation is Naturally ventilated cavity (NVC). b) With the application of NVC, daylight admission within building interior would be possible, if transparent photovoltaic panels/glass are used.
	Choice of photovoltaics thin film technology:	a) Amorphous silicon, CIS (cadmium indium diselenide)/CIGS (cadmium indium gallium diselenide) thin film technology has been favoured over Mono/poly-Crystalline silicon, because of higher potential of customization, transparency without affecting efficiency. (Nguyen, Sang, Vu, & Le, 2019). b) CIGS/CIS, A-Si, and Cadmium Telluride (CdTe) photovoltaic panels and glass can be produced in different colours and sizes. At the same time the thin film technology with the amorphous silicon pv cells, have far efficient performance in diffused light as well as at a tilt of 90° as compared with crystalline silicon technology. (Nguyen, Sang, Vu, & Le, 2019).
		a) Use of thin-film CIGS, frameless glass-glass module, for curtain-walling technique. b) Use of Amorphous silicon PV glass which are available in 2456 x 1245 sqmm, also

	Selection of pv panel:	available in other non-standard sizes, for curtain glazing and cladding material. c) Amorphous Silicon PV glass is manufactured in different sizes, and all the different sizes are available in varied transparency levels (V_{Trans}=0%,10%, 20%, 30).
	Pv panel customization: • **Panel shape and size** • **Granularity: transparency** • **Position and inclination**	a) The shape and size of the photovoltaic panel/glass will be rectangular, as it would be efficient and easily adaptable to majority of façades, and easier to expedite in case customization is required in terms of size. b) Granularity as expressed in terms of texture, colour, and transparency, will be like conventional building envelope materials, so it becomes easier to adapt. The texture will be smooth and planar, and transparency will depend on the application component. c) The amorphous silicon modules are available in four transparencies: No Transparency, Low Transparency, Medium Transparency and High Transparency. The efficiency or the energy output changes (reduces), with increasing transparency. d) Mounting of panels will be parallel to the façade in most of the cases. If the façade geometry works out then may be a combination of opaque photovoltaic panel, inclined to the sky and glass inclined to the ground can be designed.
	Mounting of pv panels on the façade	a. There are different solutions available for the mounting of pv panels on the façade. For example, seamless glass to glass module joining is available. b. Availability of cladding with Aluminium profile (Mullion, transom), with the help of screws and fastener. c. Mounting of solar glass/panel as louvers/sunshades and cladding material is possible with the help of fasteners, aluminium clips, and screws/brackets.
	Pv panel cross section/ cross-section of the facade	a. The pv panels cross-section chosen should be like the cross-section of the façade component it is replacing, to have least impact on the building footprint. b. Also, the structural system and mounting system will be simple, durable, and efficient, to have maximum possible integrability.

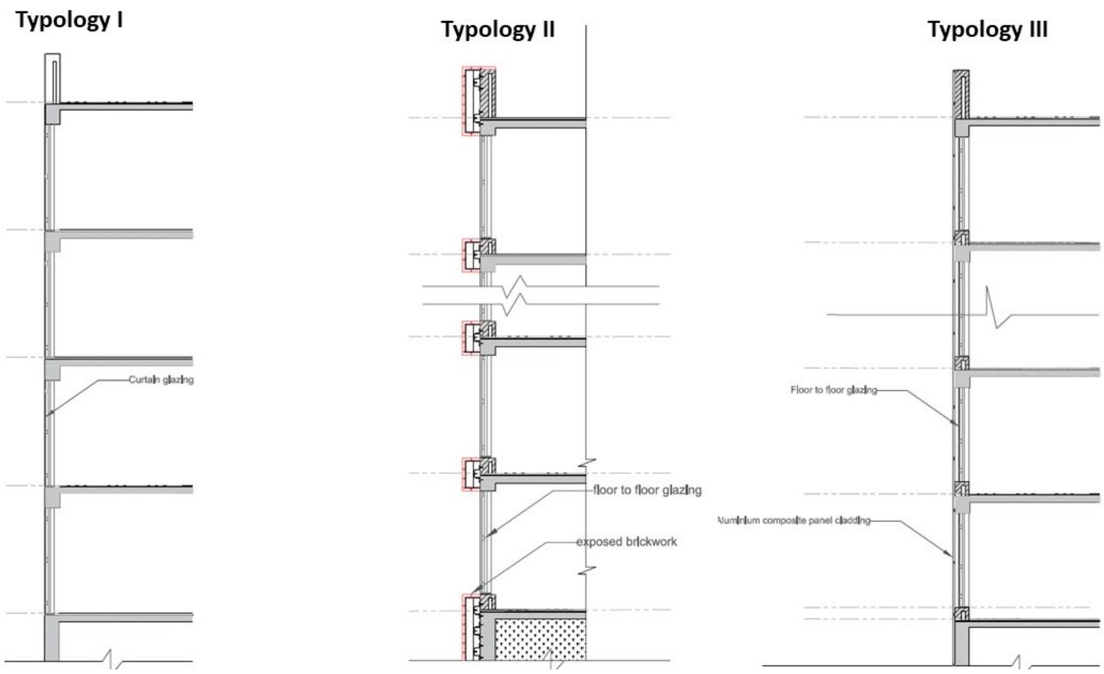

Figure 2. Sections of three building typologies

4. Methodology/ Framework for designing A Photovoltaic Façade and Achieving Architectural Integration

The framework is a methodology for designing a photovoltaic façade and achieving architectural integration. It is a process, comprising of three interconnected and sequential processes (figure 3).

STEP ONE: Identifying and selecting three building typologies for commercial buildings was the first step. Studies like Sandak, Sandak, Marcin, & Kutnar, (2019), Singh, Ravache, & Sartor, (2018) have described the choice of materials for commercial building façade are: glazed façade, aluminium composite panelling and R.C.C. structure with brick infill and exposed brickwork. Hence the three commercial building typologies, are defined as: (i) Typology I: facades with curtain wall and cladding of aluminium composite panel with ribbon windows, (ii) Typology II: exposed brickwork facades having floor to floor glazing, (iii) Typology III: façade with cladding of aluminium composite panels (ACP) having floor-to-floor glazing.

STEP TWO: In this step design-oriented strategies are developed. This step has two very critical aspects: (i) identification and assessment of the barriers (ii) Selection of solar glass/panel.

Identification of the barriers: It comprises of inhibitors, issues, and concerns (section 2.2). Analysis of barriers and their impact forms the guidelines for development of design-oriented parameters. Design-oriented parameters are proactive strategies of eliminating or minimising the barriers, leading to the formulation of design strategies. For eliminating major barriers, design strategies are developed according to the identified building typologies.

Selection of type of solar glass/ panel (thin-film photovoltaic technology): Impacts the development of design strategy. Solar glass/panels selected for integration on the building façade have been described in table 2. Adopted photovoltaic technology must perform two functions: (i) Act as building skin (ii) Generate Energy, simultaneously, efficiently without compromising the other. Thus, the selection criteria for the photovoltaic technology are based upon the two parameters afore mentioned. The prevalent solar panels used were of Mono/Multi-Crystalline technology, which were quite efficient, but their performance as building skin was very low. The weight of the panel, transparency, granularity (colour and texture) were the factors limiting its performance as building façade. When applied at 90° tilt angle, the efficiency of these panels reduced (because of the diffused insolation), thus rendering it ineffective as energy generator. Whereas the thin-film technology is efficient and performs dual functions of acting as building skin and energy generation, without any conflicts. The thin-film technology allows manufacture of translucent panels (A-Si panels), panels with smooth, planar finish in different colours (CIGS panels), thus making the process of adoption as building façade more feasible. The ability of thin-film technology to perform at an efficiency of 20%-22.9% (CIGS panels), even in diffused lighting, renders its application on building façade quite feasible. Also, the rise in temperature did not affect its performance and efficiency, thus eliminating the need for ventilation (Nguyen, Sang, Vu, & Le, 2019). The lightweight of thin-film technology permits its integration within the building façade, by mullion transom system, screws and fasteners and other conventional methods.

STEP THREE: It is the process of generating façade integrated photovoltaic system for the three building typologies using the design strategies developed in step two. The design variants are simulated in selected cities. Depending upon the skill set and the time available, simulation software can be selected. Some of the simulation software used for photovoltaic system simulation are PV*Sol, PVSyst, RETScreen Expert. Photovoltaic system simulation is used to assess the energy generation potential of the designed photovoltaic façade. The parameters of assessment identified are energy available at the end of the grid and performance ratio of the designed system. Simulation analysis leads to the identification of efficiently performing system, with respect to the azimuth, tilt, and city of analysis. Simulation is also required to identify the performance of new building skin through comparative analysis with the base-case building. It tries to establish the performance of the new building skin as efficient or non-efficient. Achieved by comparing the energy consumption of the base-case building with the new photovoltaic integrated building. It also helps in working out the economic feasibility of the generated variants.

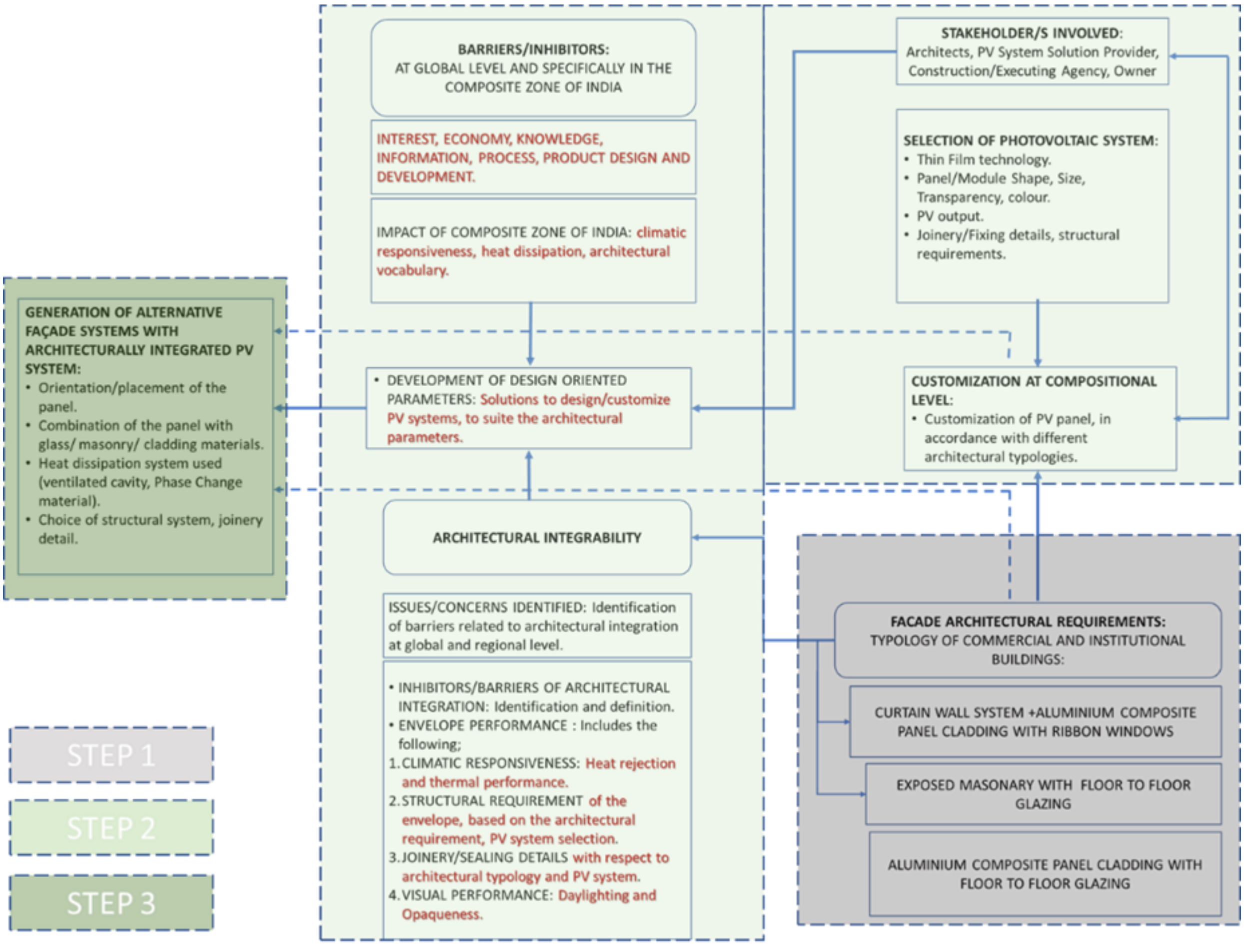

Figure 3. Framework for designing of photovoltaic facade and achieving architectural integration.

5. Conclusion

Previous studies Nagyn, et al., (2016), Nguyen, Sang, Vu, & Le, (2019) Saretta , Caputo, & Frontini, (2019), Zhanga, et al., (2018) have worked on the renovation of existing buildings with photovoltaic panels or have provided it as add-on components. The need to understand the integration of photovoltaic materials into the architecture of the building is important to achieve a photovoltaic façade functioning optimally and efficiently. It is important to understand the process of designing and achieving architectural integration. The study attempts to systematically identify the barriers and their impacts on design process, followed by the development of a framework to enable adoption of FiPV on commercial building. It has tried to propose a simplified, sequential process of designing a photovoltaic façade, and efficiently achieving architectural integration of the photovoltaic material on the building façade. The developed framework can be used to simulate several design options using PVSyst, RETScreen Expert, PV*Sol depending upon the available skill set. This simulation would enable the designer to take decisions based on parameters like energy generation, visual aspects, aesthetics, and economic implications. The impact of this framework and design strategy can be assessed from the fact that it will enable the architects and façade designers to incorporate renewable energy system within the building envelope and create an energy efficient, sustainable building system. The proposed framework holds the potential to fulfil the world's move towards having more of net zero energy buildings.

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