Architectural integration of photovoltaics in the building façade: a framework for architects' design process

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Abstract: Building integrated photovoltaic (BIPV) system, is a method to create a functional, energy generating building skin. Though BIPV has the term 'building integrated', the complete architectural integration of the photovoltaic system is still missing. To achieve architectural integration, it is important to understand the connotations attached to a building material for functioning as façade. Aim of this paper is developing a framework for creating a systematic process, turning photovoltaic system into the building skin. A sequential five step process is developed to create an efficient, effective framework to achieve architectural integrability and turn photovoltaic system into optimally performing building skin. This is achieved by identifying the barriers in the process of architectural integration and their assessment of impact severity, thus suggesting possibilities for viable solutions. The solutions to the barriers lead to the formulation of design strategies.

Keywords: barriers; integrational framework; building integrated photovoltaic; BIPV; photovoltaic façade; architectural integration; thin film technology; façade integrated photovoltaic system; energetic building skin.

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1 Introduction

Dependence on fossil fuel has dangerous implications, one being that of exhausting them completely, creating global crisis. If non-judicious use is not stopped, then it would lead to exhausting the reserves of oil by 2050s, gas reserves by 2070s, uranium ores by 2090s and coal by 2150s (Khan et al., 2015). The world must look at the renewable energy systems for sustenance. In this context the building integrated photovoltaic (BIPV) system is one of the most rapidly developing technologies. BIPV acts as a means of integrating the photovoltaic system into the building envelope. Integration of the photovoltaic system makes them act as the skin of the building, thus responding to the needs of the building occupants. The occupant's basic requirement with regards to building envelope is quite elaborately defined. The prerequisite of any material to act as the skin of the building is to perform optimally in terms of thermal, optical, structural/mechanical, and visual performance. It is in this regard, that often the photovoltaic system does not correspond to the fulfilment of the prerequisite of the material to act as an envelope material. Photovoltaic system was initially not designed to become a material for building envelope, it was a renewable source of distributed energy. It was a system which was mounted on the rooftops or huge farmlands, harnessing the solar energy, in the most effective and efficient manner, to generate clean energy. There have been efforts at both governmental as well as non-governmental levels to increase the integration of solar energy within the building envelope. With agencies like International Energy Agency (IEA) working on specific projects to increase the incorporation of solar energy within buildings, still the pace of integration has been slow. With changes in the perception and functioning of the building, and the concept of green buildings using active or passive solar energy, there has been a lot of emphasis on incorporation of new envelope material, generating energy and making the building more sustainable (Mishra et al., 2013). Hence the concept of building integrated photovoltaic system was introduced. When the photovoltaic system must act as a building envelope material, there is a modification required in the material (photovoltaic panels/cells/modules), in the strategy of integrating it in the envelope, particularly facade. There is a need to develop a strategy for the functioning of the material as envelope without compromising its role of energy generation.

The resolution of conflict between the optimum functioning of the photovoltaic system as energy generator and functioning as the skin of the building is only possible through architectural integration. Architectural integration can be stated as the process of incorporating the photovoltaic panels, modules, glasses, tiles as the skin of the building. Implying, the primary function of the photovoltaic system is not only energy generation, but at the same time fulfilling all the prerequisites of a building envelope. Architectural integration can be achieved, by following a systematic process, which identifies, and defines strategies for the proper integration of photovoltaic system within the building, primarily focussing on building façade. The paper focuses on generating a systematic process of achieving architectural integrability of the photovoltaic system in the building façade.

2 Literature review

The first step in the process of achieving the architectural integrability, is to understand the issues and concerns in integration of photovoltaic system within the building façade. These issues/concerns highlight the reasons as to why the synchronisation of the photovoltaic system acting as energy generator and the building façade has not been achieved. For identifying these concerns, it is important to identify the inhibitors in the systematic process of architectural integration. When discussing about the inhibitors, the barriers in the uptake of the photovoltaic technology in the building envelope comes into action. Barriers metamorphosise as inhibitors, affecting the whole process of integration. Hence it becomes important to identify, understand and mitigate these barriers. Their understanding would lead to the evolution of a streamlined process of integrating the photovoltaic system into the façade of the building. For identifying the barriers, a literature review of previous research is done in this section. The barriers can be classified into three categories. Category 1 consists of barriers identified in the photovoltaic technology to be adopted as a facade building material. Category 2 is the barriers identified in the process of photovoltaic façade design. Category 3 is the classification of barriers which impacts different stakeholders, addressing their apprehensions, perceptions, and aspirations. One crucial aspect of BIPV is the technology acceptance, which should be based on technology acceptance model (TAM), highlighting the acceptance, acquiring, learning and usage of the technology (Akinwale et al., 2015). The barrier identification and its solution is an important step towards achieving technology acceptance.

3 Severity of the barriers and their impact on the process of architectural integration of photovoltaic system within the building façade

Barriers impacting the incorporation of the photovoltaic technology within the building façade have been enlisted in Table 1. When analysing these barriers, it becomes important to assess their severity of impact. Severity of impact is the affect the individual barriers have on the process of designing the photovoltaic façade. The previous studies like Maria et al. (2012), Heinstein et al. (2013), Prieto et al. (2017), Attoye et al. (2017) and Shukla et al. (2018) have worked on identifying the barriers or defining the inhibitors. Most of the studies like Vesna et al. (2018) and Attoye et al. (2017) have targeted on identifying the barriers and proposing a solution. For the solutions to be effective for most categories of buildings, it is important to understand the severity of barriers impact. The aim of this paper is to understand the severity of barrier impact and then propose a systematic process of architectural integration of the photovoltaic façade.

Table 1 Barriers and their category

Description of the barrier	*CATEGORY 1 (barriers in the photovoltaic technology)*	*CATEGORY 2 (barrier in the process of photovoltaic façade design)*	*CATEGORY 3 (barriers affecting different stakeholders)*
Multi/mono-crystalline silicon (mono-C-Si) technology vs. thin film technology: Mono-C-Si technology photovoltaic modules are architecturally misappropriated to be used in building façade. Whereas the thin film technology is an apt technology for application on the building façade. But their efficiency is inversely proportional to the architectural suitability parameter (Heinstein et al., 2013; Shukla et al., 2018)	X		
Insufficiency in the architect's/façade designer's knowledge: There is still a lacuna in knowledge- base of the designers regarding the harmonious synchronisation of the photovoltaic system and the building façade design (Prieto et al., 2017; Maria et al., 2012; Kanters et al., 2013).		X	
Economic non-feasibility: The higher initial costs of photovoltaic products and their management and operation cost, balance of system cost, lead to an economic non-feasibility of integrating the technology in the building envelope (Prieto et al., 2017; Maria et al., 2012; Kanters et al., 2013; Mishra et al., 2013).			X
Reduction in efficiency, with change in tilt angle from 180° to 90°: When the tilt angle of the photovoltaic system is changed from 0° or 180°, to 90 degrees there is a reduction in efficiency from 20% to 5–7% (Orhon, 2016).	X		
Absence of uniform standardised codes related to photovoltaic system: The absence of regulatory authoritative code provision for the incorporation of photovoltaic system integration, makes it difficult to establish a framework (Prieto et al., 2017; Maria et al., 2012; Shukla et al., 2018)		X	
Operation and management (O&M) of the photovoltaic system: Considerably a tedious task when it comes to the O&M, of the photovoltaic system within the building envelope (Prieto et al., 2017; Mishra et al., 2013).			X

Table 1 Barriers and their category (continued)

Description of the barrier	*CATEGORY 1 (barriers in the photovoltaic technology)*	*CATEGORY 2 (barrier in the process of photovoltaic façade design)*	*CATEGORY 3 (barriers affecting different stakeholders)*
Non-availability of suitable photovoltaic products: The available photovoltaic products are not suited for application on the building façade. Primarily owning to their finish/appearance and their transparency (Maria et al., 2012; Heinstein et al., 2013; Jelle and Breivik, 2012; Kanters et al., 2013; Prieto et al., 2017).	X	X	
Lack of client's interest: Owners are least interested in creating photovoltaic façade, because of economic non-feasibility and the appearance of the building (Maria et al., 2012; Kanters et al., 2013)			X
Photovoltaic façade's visual and optical impact on the building and the stakeholders: The optical performance of the photovoltaic façade is limited if the efficiency needs to be maintained. A transparent façade yields less energy as compared to the opaque façade. The visual appeal changes with the cell technology used (mono-crystalline- granular, flat, dark blue in colour, opaque; thin film technology, colour choice available, translucency possible, matches the façade of the building) (Attoye et al., 2017).	X	X	X
Non-availability and usage of appropriate tools for designing building integrated photovoltaics: The digital tools for designing the photovoltaics in the building envelope, do not have user friendly interface. Also, their compatibility with the other building design software's is limited. Apart from this the architect's ability to learn and implement these tools is quite limited (Maria et al., 2012; Prieto et al., 2017).	X	X	
Structural and mechanical integrity of the photovoltaic façade: The mechanical and structural rigidity of the photovoltaic façade is questionable (SUPSI, 2019).		X	
Climatic responsiveness of the building façade with integrated photovoltaic system: A photovoltaic integrated building façade is climatically less responsive, especially in hot and dry, warm and humid, arid climates (Aaditya and Mani, 2013; Attoye et al., 2017)		X	X
Absence of skilled labour force: Manpower to handle building integrated photovoltaics system is not easily acquired. Hence creating in-confidence in the construction process (Maria et al., 2012)		X	X

The paper assessed severity of impact by defining two factors. First factor is to identify whether the barrier has a direct, indirect or no impact on the architectural designing of the façade. Second factor is the assessment of the possibility of converting the barrier into a driver. Table 2 depicts the interplay of the two factors, and their effect on the severity of barriers impact.

Table 2 Assessment matrix of the barriers for defining the severity of impact

S. no.	*Barrier*	*Effect on the architectural designing process of photovoltaic facade*	*Possibility of converting the barrier into a driver*	*Severity of impact*
1	Barrier X	Direct impact	Possible	Major
2	Barrier X′	Direct impact	Not possible	Critical
3	Barrier X″	Indirect impact	Possible	Minor
4	Barrier X‴	Indirect impact	Not possible	Major
5	Barrier X″″	No impact	Possible/ Not possible	Minor

Table 2 helps in assessing the impact of severity for every barrier defined in Table 1. The severity of barrier impact is defined in table 3; the next logical step is to understand the process of converting them into drivers or enablers. For achieving the solution, a defined method of converting the barriers into drivers must be worked out. In previous study of Attoye et al. (2017), one important parameter of working out solutions to photovoltaic product related problems, was to understand the product itself. Similarly, in the study of Nagyn et al. (2016), the concept of adaptive prototype was worked out by working on the individual product. Thus, the method of creating a process to convert barriers into enablers is achieved by:

a reducing their impact, through modification/s in the product

b incorporating them in the building components, that do not hinder the optimum envelope function.

The systematic process would not only achieve the above-mentioned criteria, but would also lead to the creation of framework, that would in effect simplify and increase the efficiency of architectural integration of photovoltaic system, within the building façade.

4 Methodology

The framework formulation for developing a systematic process has a multi-fold approach. Multi-fold approach is defined as an approach where the solution of one variable in the problem leads to obtaining the solution for the second variable, in effect leading to the final solution. In this case first variable dealt is the minimisation/mitigation of the barriers in the architectural integration of photovoltaic system within the building façade. In conjunction, leading to the development of a harmoniously synchronised photovoltaic building façade. The framework creates an efficient and optimally functional photovoltaic building façade. And this framework simplifies the process of integrating photovoltaics system into the building façade through a sequential process of five interconnected steps.

4.1 Step 1

The first step of the process is the identification of the barriers or inhibitors, leading to non-integration of photovoltaics within the building façade. In this step the barriers are identified and assessed. The barriers have been identified in Section 2, Table 1. Barriers are assessed with respect to the barrier assessment matrix defined in Table 2, Section 3.

Following the assessment criteria (described in Table 2), Table 3 has been developed, defining the severity of impact of all the identified barriers. Once, the severity of impact is assigned for each barrier, the next step is the understanding of a process of converting them into drivers, and in turn developing a systematic sequential process of achieving architectural integration of the photovoltaic system in the building façade.

Table 3 Assessment of severity of impact of the barriers

S. no.	*Barrier (defined in Table 1)*	*Effect on the architectural designing process of photovoltaic facade*	*Possibility of converting the barrier into a driver*	*Severity of impact*
1	Choice of photovoltaic technology for façade integration	Direct impact	Possible	Minor
2	Insufficiency in designer's knowledge	Direct impact	Possible	Minor
3	Lack of client's interest	Direct impact	Possible	Minor
4	Economic non-feasibility	Indirect impact	To an extent possible	Minor
5	Reduction in efficiency with change in tilt angle	Indirect impact	Not possible	Major
6	Absence of uniform standardised codes	Direct impact	Possible	Minor
7	Complicated operation and management of the integrated photovoltaic system	No impact	To an extent possible	Minor
8	Non-availability of suitable photovoltaic products	Direct impact	Possible	Minor
9	Photovoltaic façade's visual and optical effect on stakeholders	Direct impact	To an extent possible	Minor
10	Climatic responsiveness of the photovoltaic building façade	Direct impact	To an extent possible	Minor
11	Structural and mechanical integrity of photovoltaic façade	Direct impact	Possible	Minor
12	Non-availability and usage appropriate design tools	Direct impact	Possible	Minor
13	Absence of skilled manpower	Indirect impact	Possible	Minor

4.2 Step 2

In this step, the parameters of envelope performance assessment are defined. It is important that before working on the solutions to the barriers, parameters of envelope performance should be defined. These parameters not only help in understanding of the barriers and their possible solutions, but also lead to the designing of strategies to achieve architectural integration. The parameters of envelope performance assessment are defined in Table 4, along with their descriptions.

Table 4 Parameters of envelope performance assessment

S. no.	*Envelope performance parameters*	*Description*
1	Climatic responsiveness	• Decides whether the photovoltaic façade can perform the basic function of envelope, to provide occupant thermal comfort
2	Optical performance	• It is as important as thermal comfort, photovoltaic façade to perform optimally as envelope, it must provide daylighting. • This performance criteria, compares whether the photovoltaic façade has impacted the daylighting provisions inside the building, by stating whether there has been an increase, reduction, or no impact on visual light transmittance.
3	Structural and mechanical integrity performance	• These performance criterions are dependent upon the architectural design of the façade. The structural installation of the photovoltaic system as the façade of the building would be based on the design. • The structural and mechanical integrity of the photovoltaic façade is the litmus test of its envelope performance.
4	Visual performance	• The visual performance is based on the colour, texture, transparency of the photovoltaic façade. The selection of the photovoltaic technology decides whether appearance of the façade is planar, granular, or smooth. • The transparency/ translucency of the façade is again a performance indicator, for the photovoltaic façade to have a mass appeal.
5.	(Architectural quality/aesthetic performance)	• This performance indicator is more of a qualitative analysis. Deciding the architectural image of the building, its vocabulary of expression. • It is important, as it would lead to the acceptance of the photovoltaic façade by the client, thus leading to its execution.

The performance indicators listed in Table 4 are not only assessment criterions, but also with their help efficient and effective design strategies can be formulated to provide photovoltaic façade performing optimally as a façade as well as an energy generator.

4.3 Step 3

Step 3 is the stage at which the solutions for identified barriers are worked out. There are two important sub steps in this stage. Stage one of step 3 is the identification of the possible solution of the inhibitor or barrier. It would provide a suggestive approach towards the possible solution for minimising the impact of the barrier. The suggestive approach would be concretised as a design strategy in stage 2 of step 3. This stage would convert the suggestive theory into practically applicable solutions. The solutions identified in stage 2 would eliminate or minimise the impact of the barrier. Table 5 discusses the two-stage approach, converting the barriers into enablers for architectural integration of the photovoltaic system in the building façade. In Table 5, the barriers with direct impact on the designing process have been discussed. As after understanding of the severity of impact, it can be stated that for the process of architectural integration to take place, it is quintessential to deal with barriers having direct impact on the architectural integration process through a design approach. So as per the Table 3, the barriers having direct impact are listed in Table 5, along with their suggestive solutions applicable on the building façade.

Table 5 Suggestive solutions to the barriers having direct impact on the architectural integration process

S. no.	*Barriers with direct impact on the designing (architectural integration) process*	*Converting barriers into enablers*	
		Stage 1 *Suggestive approach*	*Stage 2* *Solutions applicable on the building facade*
1	Choice of photovoltaic technology	1 Working with opaque, aesthetically low, planar, granular high efficiency, photovoltaic modules on the façade components that are not very prominent. (For example- stairwell wall, refuge areas). 2 Incorporating relatively lower efficiency, translucent, thin film technology photovoltaic modules on the main façade.	1 Integration of amorphous silicon technology in the transparent façade component. 2 Applying opaque Cadmium telluride (CdTe), cadmium indium gallium diselenide (CIS/CIGS) in the opaque components (Nguyen et al., 2019)
2	Absence of uniform standardised codes	1 Codes should combine the technical performance of the photovoltaic technology, with regional and local building norms. (SUPSI, 2019). 2 EN 50583, photovoltaics in buildings, (in two volumes), is a code given by International Energy Agency (IEA) in 2016, which provides with starting point of integration.	

Table 5 Suggestive solutions to the barriers having direct impact on the architectural integration process (continued)

S. no.	*Barriers with direct impact on the designing (architectural integration) process*	*Converting barriers into enablers*	
		Stage 1 Suggestive approach	*Stage 2 Solutions applicable on the building facade*
3	Non-availability of suitable photovoltaic products	1 Customisation of the photovoltaic product. (Attoye et al.; SUPSI, 2019). 2 Important to understand customisation is required to make the photovoltaic technology suitable for façade integration. 3 Customisation may be needed in the solar cell technology, in the arrangement of technical aspects (junction box, wiring, diodes, optimisers) to make it adaptable for incorporation in the building façade (SUPSI, 2019)	1 Customisation of the size/dimension of photovoltaic panel. 2 Customisation in terms of visual, optical appearance of the photovoltaic panel. 3 Instead of customisation of the photovoltaic product, the design of the façade should be done keeping in mind the available photovoltaic panel with appropriate morphological properties.
4	Photovoltaic façade's visual and optical effect on stakeholders	1 With the usage of amorphous silicon (A-Si) technology, the transparency of the facade if required can be obtained with visible transmittance of daylighting in the range of 10–30% (Onyx Solar, n.d.). 2 CdTe technology, CIS/CIGS technology can be used, having photovoltaic panels with smooth texture in different colours.	1 A-Si technology photovoltaic panels can be integrated as curtain walls, windows on the façade. 2 Whereas panels appearing as cladding using CIS/CIGS, CdTe technology should be integrated as wall cladding.
5	Climatic responsiveness of the photovoltaic building façade	Climatic responsiveness of the photovoltaic panels can be improved by reducing the thermal conductivity of the photovoltaic glasses and photovoltaic cladding assembly.	1 In case of solar glass, the solution lies in the incorporation of the air gaps within the solar glass layer, thus reducing the thermal conductivity. 2 When using opaque panels as wall cladding, the introduction of thermal insulators between the panel and the structural wall is introduced to reduce the thermal conductivity of the façade assembly.

Table 5 Suggestive solutions to the barriers having direct impact on the architectural integration process (continued)

S. no.	*Barriers with direct impact on the designing (architectural integration) process*	*Converting barriers into enablers*	
		Stage 1 *Suggestive approach*	*Stage 2* *Solutions applicable on the building facade*
6	Insufficiency in designer's knowledge	Conducting training programmes, workshops for increasing the knowledge of designer with regards to the photovoltaic system and its application in the building façade (Maria, et al., 2012; Prieto et al., 2017; SUPSI, 2019)	
7	Lack of client's interest	1 Incentives in the form of societal and environmental benefits, through introduction of photovoltaic technology in the building façade. This is achieved through reduction in the green house gas emissions, and carbon footprint reduction. 2 With introduction of photovoltaic façade could help in achieving green building certification, thus recognition of the building as a sustainable building.	
8	Structural and mechanical integrity of photovoltaic façade.	With the possibility of combining the photovoltaic technology with building facade glass, the mounting system used for the façade glass can be used for the solar glass as well. Thus, ensuring the mechanical and structural integrity of the building façade.	1 For mounting the solar glass as curtain glazing system of mullion and transoms can used for mounting. 2 When applied as window, the solar glass can be mounted as windowpane using a system of top rail, bottom rail, and gasket sealant to seal the windows. 3 Photovoltaic panels when used as cladding materials, have a system of back rail, clamps, filler layer, mounted over the structural wall. Thus, ensuring the mechanical and structural integrity.

Table 5 Suggestive solutions to the barriers having direct impact on the architectural integration process (continued)

S. no.	*Barriers with direct impact on the designing (architectural integration) process*	*Converting barriers into enablers*	
		Stage 1 Suggestive approach	*Stage 2 Solutions applicable on the building facade*
9	Non-availability and usage of appropriate design tools.	Architect friendly solar energy digital tools have been identified in the international survey conducted by the IEA. PV Syst, PV*Sol, RetScreen have been identified as most architect friendly tools, along with others (Miljana et al., 2011)	

Table 6 Suggestive solutions to the barriers with indirect and no impact

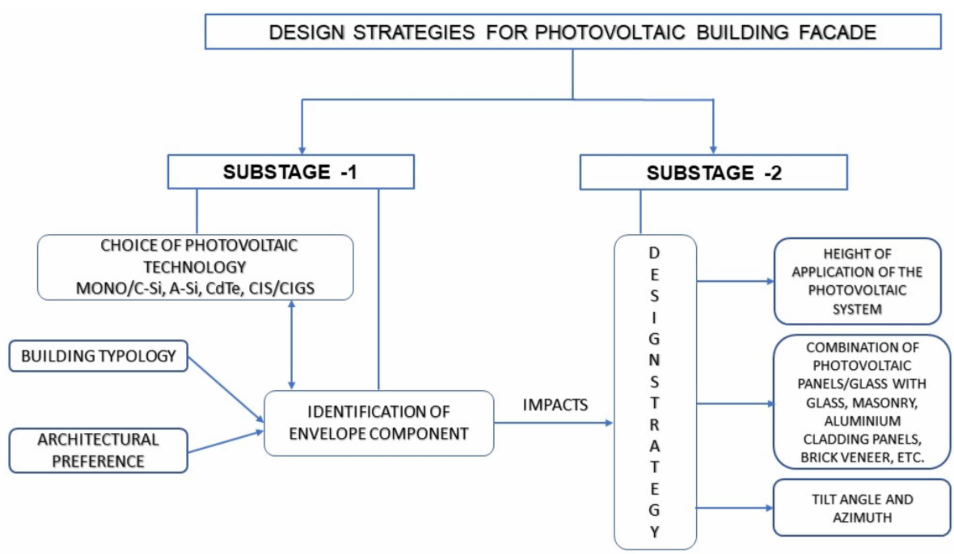
S. no.	*Barriers with indirect impact*	*Suggestive solution*
1	Economic non-feasibility	• Due to greater initial costs of the photovoltaic system, the payback period is quite large. (Source?) • Sometimes, the return on investments is also not high. • Still, the client can be convinced by arguing about the greater environmental and societal benefits when the system is applied.
2	Complicated operation and management of the integrated photovoltaic system	• Conducting workshops, training to make the managing personnel adept to the handling of the system.
3	Absence of skilled manpower	• Solution providers for façade photovoltaic system, have their own trained executing personnel to handle the installation process. • Hence the total dependence on finding skilled manpower locally is reduced.
4	Reduction in efficiency with change in tilt angle	• Prima facie, there is no solution to this barrier. • Use of thin-film technology, especially CIGS, CdTe, as they perform better in non-optimum tilt angles. • But with incorporation of certain design strategies like combination of glass and photovoltaic in different tilt angles, the reduction in efficiency can be compensated.

The barriers having indirect impact or no impact on the designing process do not necessarily need a design-based solution and hence have been dealt separately. They do not hinder the designing process of architectural integration, the solution to these barriers will be non-design-based strategies. The suggestive solutions to the barriers having indirect impact or no impact are discussed in Table 6. Though these barriers don not have a direct impact on the design process, but it is important to suggest a solution, as they do define the architectural integrability of the photovoltaic system within the building façade.

4.4 Step 4

In this step, the strategies for designing of the photovoltaic façade are formulated. This step is very distinctive and would vary with the typology of the building under discussion, and the region of application. Step 4 is further divided into two substages. Substage one is the stage at which decisions regarding the choice of photovoltaic technology to be applied are made. Substage 1 has two important determinants. The choice of the photovoltaic technology (Mono/C-Si, A-Si, CdTe, CIS/CIGS) to be implemented, is the first determinant. The second determinant is the identification of the envelope component for the integration to be achieved. This decision is based on building typology (building with curtain glazing, floor to floor glazing, with aluminium cladding panel, brick masonry, etc.) and architectural preference. Architectural preference dictates whether the selected component is defining, enhancing, or alternately creating a new architectural vocabulary. Substage 2 is the design strategy, which determines the exact method of integration. Figure 1 illustrates the substages of step 4. More than one alternative can be worked out using different design strategies, hence giving the opportunity of comparing and choosing the most beneficial alternative.

Figure 1 Description of step 4, with its sub-stages (see online version for colours)



4.5 Step 5

Final step is the assessment of the impact of the integration. Once the façade integration of the photovoltaic system has been achieved, it is important to assess its performance as a façade component. The parameters of envelope assessment performance have been defined in step 3, Table 4. The comparative matrix would help in understanding the envelope performance of different generated alternatives. The comparison would be based on assessing the performance indicators as shown in Table 7.

Table 7 Assessing the envelope performance indicators

S. no.	*Envelope performance indicators*	*Assessment parameters*
1	Climatic responsiveness	1 Thermal comfort, based on heating, cooling load: **x** Reduction **x** Increased **x** No impact. 2 Energy savings – dependent upon heating, cooling load: **x** Reduction **x** Increased **x** No impact
2	Optical performance	• The optical performance would be based on the visible light transmittance (VLT) percentage. **x** % VLT reduced **x** % VLT increased **x** No impact
3	Structural and mechanical integrity performance	• The performance indicator for this parameter is a system to assess: 1 Mounted photovoltaic façade is securely placed, by assessing the mounting system. 2 Performs the role of the façade, by shielding the occupants from the outside environment. Decided by the thermal comfort assessment. 3 Completely seals the inside environment from outsides. • Thus, the performance indicators for this parameter would be: 1 Compared to the traditional mounting system (mullions, transoms, clamping to substrate wall), is the new system: **x** Structurally enhanced **x** Structurally diminished **x** Structurally same 2 Performance of saving occupants from outside environment: **x** Thermal comfort enhanced **x** Thermal comfort reduced **x** No impact.
4	Visual performance	• Assessing the performance of this parameter, would be based on the transparency achieved and the texture, appearance of the façade. 1 The transparency of the photovoltaic façade is: **x** Increased **x** Decreased **x** No impact. 2 The appearance of the photovoltaic façade is: **x** Granular **x** Planar **x** Smooth
5	(Architectural quality/aesthetic performance)	• Aesthetic performance indicator is based on the architectural vocabulary being generated with the photovoltaic façade: The architectural vocabulary being generated is: **x** New vocabulary with new appearance. **x** Same vocabulary, but with new appearance. **x** No change

5 Analysis

The methodology for architectural integration of the photovoltaic façade has been explained in the previous sections (Section 4, 4.1, 4.2, 4.3, 4.4). Identification of barriers was first step towards the formulation of the framework. Analysis of the framework, leads to the following conclusion:

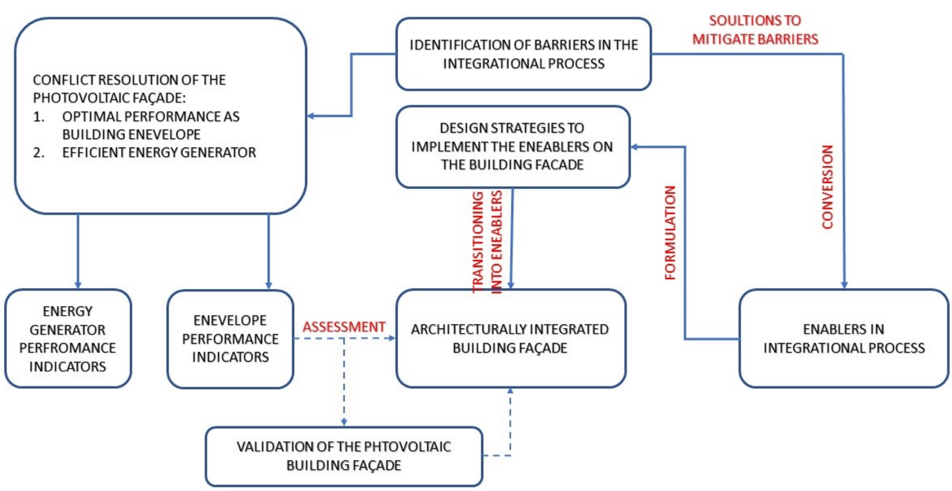
a the framework is based on the resolution of conflict between the optimal performance of the photovoltaic system as an energy generator, and façade

b the resolution of conflict is achieved by defining the performance indicators for the photovoltaic façade

c the performance indicator parameters are important as they lead to the formulation of design strategies to architecturally integrate the photovoltaic system in the building façade.

It can be stated that framework thus developed here is a systematic, sequential process of resolving the conflict of energy generation and envelope performance. This resolution itself is a multi-stage process. Beginning with the identification of barriers in the integrational process, to converting them into enablers, followed by the design strategies to implement the enablers, turning them into drivers of integrational process. And finally, an assessment of the design strategy based on defined envelope performance indicators (Figure 2).

Figure 2 Analysis of the framework (see online version for colours)



6 Discussion

Previous studies (Miljana et al., 2011; Maria et al., 2012; Aaditya and Mani, 2013; Heinstein et al., 2013; Prieto et al., 2017; Sharma, 2017; SUPSI, 2019) have identified the barriers in the integrational process. They have stated the importance of solving the barriers, to achieve a photovoltaic façade. But they have not taken severity of barriers impact into consideration. It is important to consider the severity of impact, until the impact is assessed, it cannot be dealt with. The framework proposed in this study has not only considered the severity of impact but has suggested design-oriented solutions. The framework proposed here not only deals with the integration of the photovoltaic system, but also tries to enhance its applicability to a wider building industry. The novelty of the proposed framework is that it not only proposes a design approach for efficient and optimal performance of the photovoltaic system as building façade, but also emphasises its primary function of energy generation. Also, the proposed framework would help in achieving the technology acceptance model, which allows the user to acquire, learn, use and accept the BIPV technology (Akinwale et al., 2015)

7 Limitation and future research

The integrational framework has been developed, limiting the process to the solutions based on design strategies. Though, limiting the development of solutions for barriers that had a direct impact on the design process, still a suggestive solution has been proposed to the barriers having indirect impact or no impact on the design process. The policy level intervention or solutions have not been defined. Also, a further research is required in the design strategies to implement the enablers and convert them into drivers. This stage of design strategy development is a critical stage for achieving the concept of architectural integration.

References

Aaditya, G. and Mani, M. (2013) 'Climate responsive-integrability of building integrated photovoltaics', *International Journal of Low Carbon Technologies*, pp.271–281.

Akinwale, Y.O., Ilevbare, O.E. and Ogundari, I.O. (2015) 'Utilising renewable energy technologies for electricity', *International Journal of Renewable Energy Technology*, Vol. 6, No. 3, doi:10.1504/IJRET.2015.070149.

Attoye, D.E., Aoul, K.A. and Hassan, A. (2017) 'A review on building integrated photovoltaic facade customization potentials', *Sustainability*, Vol. 9, No. 12, p.2287 (Climate Change Mitigation and Adaptation – ZEMCH 2016), doi:10.3390.

Heinstein, P., Ballif, C. and Aebi, L.E-P. (2013) 'Building integrated photovoltaics (BIPV): review, barriers, potential and myths', *Green*, Vol. 3, No. 2, pp.125–156.

https://www.solar.gwu.edu.

Jelle, P.B. and Breivik, C. (2012) 'State of the art building integrated photovoltaics', *Technoport RERC Research 2012, Energy Procedia*, Vol. 20, pp.68–77.

Kanters, J., Dubois, M.C. and Wall, M. (2013) 'Architects' design process in solar-integrated architecture in Sweden', *Architectural Science Review*, Vol. 56, No. 2, pp.141–151.

Khan, N., Abas, N. and Kalair, A. (2015) 'Earthy, solaris and atmospheric energy sources', *International Journal of Renewable Energy Technology*, Vol. 6, No. 1, doi:10.1504/IJRET.2015.067515

Maria, W., Probst, M.C., Roecker, C., Dubois, M.C., Horvart, M., Jorgensen, O.B. and Kappel, K. (2012) 'Achieving solar energy in architecture – IEA SHC Task 41', *Energy Proceedia*, Vol. 30, pp.1250–1260.

Miljana, H., Dubois, M. C., Wall, M. and Snow, M. (2011) *International Survey about Digital Tools Used by Architects for Solar Design,* International Energy Agency, Energy and Building Design, Department of Architecture and Built Environment, IEA SHC.

Mishra, S.P., Ali, S.M., Pradhan, A., Mohapatra, P. and Singh, V. (2013) 'Increasing energy efficiency in India by the use of green building', *International Journal of Renewable Energy Technology*, Vol. 4, No. 4, doi:10.1504/IJRET.2013.058140.

Nagyn, Z., Svatozarevic, B., Jayathissa, P., Begle, M., Hofer, J., Lydon, G., …, Schlueter, A. (2016) 'Adaptive solar facades: from concepts to prototypes', *Frontiers of Architectural Research*, Vol. 5, No. 2, pp.143–156.

Nguyen, L.D., Sang, N.D., Vu, N.H. and Le, N.L. (2019) 'Facade integrated photovoltaic systems: potential application for commercial building in Vietnam', *International Conference on System Science and Engineering (ICSSE) 2019*, Dong Hoi City, Quang Binh Province, Vietnam.

Onyx Solar (n.d.) *Onyx Solar: Technical Guide* [online] https://www.onyxsolar.com/product-services/technical-specifications.

Orhon, A.V. (2016) *A Review on Adaptive Photovoltaic Facades*, Solar TR 2016, Istanbul, pp.463–470.

Prieto, A., Knaack, U., Auer, T. and Klein, T. (2017) 'Solar facades – main barriers for widespread facade integration of solar technologies', *Journal of Facade Design and Engineering*, Vol. 5, No. 1, pp.51–62, doi: 10.7480/jfde.2017.1.1398.

Sharma, A.K. (2017) 'Solar PV facade for high-rise buildings in Mumbai', *International Journal of Civil Engineering Research*, Vol. 8, No. 1, pp.15–32.

Shukla, A.K., Sudhakar, K., Baredar, P. and Mamat, R. (2018) 'Solar PV and BIPV system: barrier, challenges and policy recommendations in India', *Renewable and Sustainable Energy Reviews*, February, Vol. 82, Part 3, pp.3314–3322.

SUPSI (2019) *Standardization, Performance Risks and Identification of Related Gaps for a Performance-Based Qualification in BIPV*, BIPVBOOST Consortium [online] http://www.bipvboost.eu.

Vesna, K., Siu-Kit, L., Abel, T. and Stephen, L.S. (2018) 'General model of PV integration into existing public high-rise residential buildings in Singapore – challenges and benefits', *Renewable and Sustainable Energy Reviews*, pp.70–89.