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Thin-Film Photovoltaic Building Façade: A High-Performance and Smartachitectural Solution

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***Abstract*.**
The energy crisis, and a demand for green building initiatives along with the concept of Net Zero Energy Buildings (NZEB's) have led to debates and discussions of replacement of conventional building materials with new, innovative, smart and efficient building materials. In achieving this task, the role of renewable energy system (RES) and opportunities created by them cannot be ignored. The solar energy systems and particularly the photovoltaic technology is an important aspect of the RES and plays a very critical role in designing built environment fostering values of energy efficiency and sustainability. The photovoltaic technology's potential in creating architecture, which is unique, smart, energy efficient has not been explored enough. This technology has enough potential for converting a passive building design into a smart and efficient system. The paper aims to understand the role of thin-film photovoltaic technology in creating a smart and efficient building façade. The concept of designing, assessing and analyzing photovoltaic façade has been investigated in this paper. The analysis to identify the feasibility was done through the identification of feasibility parameters.
***Keywords*:** *Thin-film photovoltaic, photovoltaic façade, smart façade, adaptive façade.*

INTRODUCTION:

The façade of a building is endowed with many roles. It acts as a barrier between the external and internal environment, provides thermal, optical, and visual comfort and lends an image to the building. These primary functions of the façade act as guidelines for selecting materials which could perform efficiently as building skin. An additional role of façade is its ability to adapt and respond to external and internal stimuli. This new role has also opened new avenues for identification and selection of innovative technologies and materials. The discussion of Net Zero Energy building (NZEB), sustainability of the built environment, inclusion of renewable energy system (RES), has led to the investigation of façade's potential in achieving these objectives. There is a need to identify a façade system, which can respond to the change in external environment, offset the building demand (energy requirements), and at the same time efficiently perform its function as a building envelope. This type of can be termed as a smart system, catering to the need of the occupants (thermal, visual, optical comfort) with a potential to provide support to the building to meet its energy demands.
The COST Action TU1403 Adaptive Facades Network has very clearly defined the concept of new and innovative façade systems. The term adaptive façade clearly highlights the ability of the building envelope (i.e., building façade) to process and respond to the changing external environment, with the ability to minimize the energy requirements of the building and enhance the harnessing of renewable resources (daylighting, natural ventilation) (Favoino, et al., 2020). Thus, smart façade can be defined as a system that adapts with the changing needs and responds to provide comfort to the occupants. Previous studies like (Favoino, et al., 2020), (Orhon, 2016) (Nagyn, et al., 2016), (Johnson & Winther, 2015) have established certain performance parameters, that a façade needs to achieve to qualify as smart, dynamic, adaptive façade. The façade's ability to minimise the transmission of heat, and generate energy to offset the building demand, is one of the performance parameters. This is a very important criterion, ensuring that the façade's performance as an envelope is not compromised while performing as an energy generator. The second criterion of determining the performance of façade, its ability to harness the available renewable energy, achievable through active and passive strategies. This also includes harnessing the daylighting, while optimizing the heat gain of the building. The economic feasibility, societal and environmental benefits of adoptability of the façade system is the third criteria to assess the adaptability, smartness, and responsiveness of the system. The achievement of three-performance criteria's i.e., minimizing heat gains while generating energy, harnessing renewable energy, economic, social, and environmental feasibility, would lead to the designing of smart façade.
The associated roles of façade and multifunctionality lead to a complexity in its design and material selection. The smart material when applied as a façade component should be able to perform its function (i.e.,

energy generation, adapting and responding to external environment) and subsequently provide comfort (thermal, visual and optical) while maintaining its mechanical and structural integrity. This sometimes causes conflict, which implies that the material compromises its function either as a smart material or as an envelope material. Smart material should be able to mitigate this conflict. Therefore, the selection of material or system should be done to avoid compromising any functions of the smart façade. In this regard, the concept of photovoltaic façade is a very promising system to create smart facades. It can achieve the benchmark performance parameters of a smart façade, and produce a sustainable and efficient system, which tries to achieve the realization of Net Zero Energy buildings.

I.I. Photovoltaic (PV) technology integrated as building façade:

Renewable energy system (RES) is a particularly important concept in the twenty first century, considering the energy crisis the world is facing. The increase in energy demand in India has been majorly triggered by the fast-paced development. The construction industry has an important role to play in this development. In this regard the use of photovoltaic systems is important, and relevant. This system has been adopted in buildings as an added component to produce energy. They have been installed on roofs, ground farming components, sunshades, vertical louvers, and now a days with advancements in the field of solar technologies, even as window glasses. This application is termed as building added photovoltaic (BAPV)systems. Despite this, the uptake of PV system in the building industry has been on a lower side. Largely, because PV products are additional components, leading to an increase in the cost, and not acting as an integral part of the building. The problems associated with the application of BAPV were resolved through BIPV. They have brought new concepts and different photovoltaic technologies apart from the monotonous crystalline silicone cell technology to the forefront. It has become possible to design a smart PV façade with the application of PV system as an integrated building component.

Facade integration of PV technology has not been explored enough. Its potential for increasing the uptake of the technology, has not been realized to full extent. The reason behind this slow-paced development, non-façade integration, was the existence of barriers. These barriers or inhibitors were challenges, issues, and concerns in integrating the technology within building façade. A few studies like (Prieto A. et al, 2017), (Shukla A.K., 2018), (Salem & Kinab, 2015), (Corti, Capannolo, Bonomo, Berrardinis, & Frontini, 2020) tried to establish some of the inhibitors which posed a challenge in adoption of the technology. These studies identified perceived barriers in the adoption of PV systems in the building façade. Study by (Ahmad & Zia, 2022) had classified barriers in the process of designing a photovoltaic façade (table 1). The barriers were classified into three categories, viz, barriers in the technology, in the design process and the barriers affecting different stakeholders. Majorly the inhibitors were economic non-feasibility, optical visual properties of the PV technology, climatic responsiveness of the PV technology, structural and mechanical integrity, non-suitable PV products for façade design, reduction in efficiency of the PV system at a tilt angle of 90°. Thin-film photovoltaic technology plays a very important role in mitigating or minimizing most of these barriers.

Table 1. Categorization of barriers. Source (Ahmad & Zia, 2022)

CATEGORY 1 (Barriers in the photovoltaic technology)	CATEGORY II (Barriers in the photovoltaic façade design)	CATEGORY III (Barriers affecting different stakeholders)
Type of photovoltaic technology (multi/mono-crystalline technology vs thin-film technology).	lack of knowledge of the architect/façade designer. Economic non-feasibility.	Economic non-feasibility.
Reduced efficiency with 90° tilt angle.	Non-availability of codes for integrating photovoltaic system with local byelaws.	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. Non-availability of proper tools for designing photovoltaic façade.	Photovoltaic façade's visual and optical properties.	Photovoltaic façade's visual and optical properties.
	Non-availability of proper tools for designing photovoltaic façade. Structural and mechanical integrity. Lack of skilled workforce. Climatic responsiveness of photovoltaic façade.	Lack of client's interest.

1.2. Thin-film PV technology as a smart envelope material:

The primary function of a façade is to act as a barrier between the uncontrollable external environment and the controlled internal environment. Hence, the applied smart facade material should ensure building's structural and mechanical integrity. The next concern when designing a PV façade is its optical properties which restrict the admittance of daylighting and acts as a visual barrier between inside and outside of the building. The third concern for integration of photovoltaic panel/glass in the façade of the building is the appearance of the PV panel/ glass. The mono/multi crystalline silicon technology photovoltaic panels have a granular appearance and are non-suited for façade application. The development of thin-film technologies like amorphous silicon technology (A-Si), cadmium telluride technology (CdTe), cadmium Indium gallium diselenide technology (CIGS), lead to the possibility to create façade performing the primary functions of providing comfort (thermal, visual, and optical) and having the ability to generate energy. In economic terms (Sharma A., 2017) had studied the application of thin film technology on the high-rise structures of Mumbai and demonstrated that thin film technology compared to crystalline silicon cell technology was more feasible for façade application. The A-Si PV glass can be produced in three levels of transparency (Visible transmittance = 10%, 20%, 30%). This allowed the admittance of daylight and maintained a visual connection between the internal and external environments. CdTe and CIGS had a planar, smooth appearance, with varied colors, providing an opportunity to be integrated as cladding material. CIGS PV glass/panel performed at an efficiency of 22.9%, when placed at a tilt angle of 90^0. The rising temperature had minimum effect on the thin-film performance criteria, therefore no ventilation was required (Nguyen, Sang, Vu, & Le, 2019). The climatic responsiveness of PV panels/glasses is a major inhibitor of the uptake of this technology. But with the advent of thin-film PV panels/ glasses, this concern has been resolved. Study by (Meng, Jinqing, Hongxing, & Yimo, 2018) established that thin-film PV technology is better adapted on the building façade not only in terms of energy generation potential but also with respect to energy saving potential. Thus, supporting the concept that thin-film PV glasses/ panels have higher adaptability as building façade.

2.1. Methodology:

The feasibility of adoption of thin-film photovoltaic technology as a building façade must be assessed, to establish it as a smart material. The assessment is based on performance parameters identified through previous studies and survey[1]. The photovoltaic façade has many prerequisites, which need to be fulfilled. The complexity of façade application, combined with the dual performance criteria, requires the adoption of thin-film PV technology to achieve PV facade (figure 1).

[1] A survey was conducted through google forms and administered in an online mode distributed amongst 100 photovoltaic consultants, architects (working with the photovoltaic system as well as simulation software's related to solar energy).

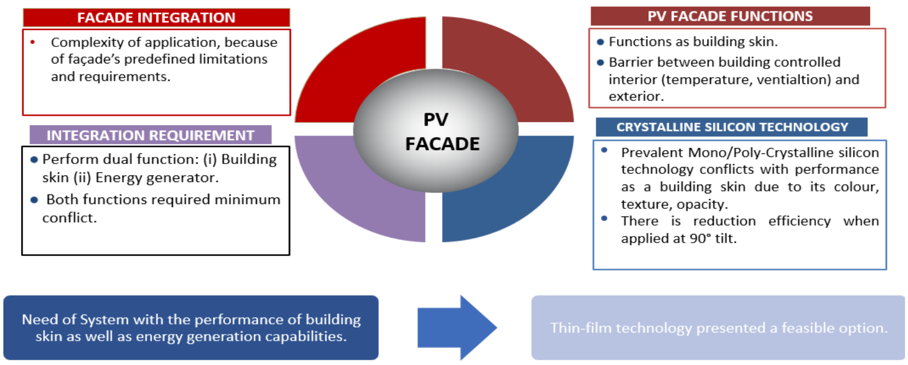

Fig. 1. Performance parameters of PV facade

The methodology adopted in the paper for identifying and assessing the feasibility of thin-film photovoltaic façade is elaborated below:

Step One: Establishing the parameters for performance analysis. The parameters were derived from literature as well as the survey (involving the photovoltaic consultants and professionals).

Step Two: Assessment of the ability of thin-film technology to perform as smart material. This step involved three processes.

I. Selection of thin-film technology.

II. Generation of building façade using the selected technology.

III. Analysis of the generated building with photovoltaic façade through simulation. The analysis would be based on the economic feasibility, energy generation parameters and visual analysis.

Step One: The first step in the process is establishing the performance parameters for the assessment of feasibility of thin-film photovoltaic façade. The first parameter is the assessment of PV façade's ability to function as a building skin. The assessment of its performance as an energy generator was the second parameter. The parameters of performance assessment have been elaborated in figure 2.

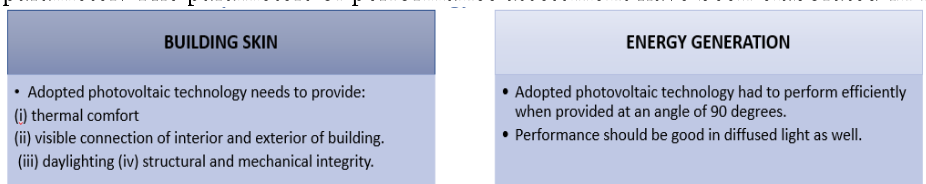

Figure 2: Performance parameters of the adopted PV technology

Step Two: This step involves three interconnected processes to designing a thin-film photovoltaic façade.

Process one: The first process in this step is the selection of thin-film technology. Thin-film photovoltaic technology selected included A-Si and CIGS. The detail of thermal, optical, and electrical properties of PV glasses are given in table 2, 3.

Table 2: Thermal, optical and electrical properties of the A-Si PV glass

Photovoltaic glass type (Model number)	Category 1	Category 2
Panel Dimensions (mm x mm)	2456 X 1245	2456 X1245
Transparency	L-Vision (10%)	L-Vision (0%)
Cell type	A-Si (amorphous silicon)	A-Si (amorphous silicon)
Power Output Wp	123	177
Thermal Transmittance-(U-Value) W/m2K	1.6	1.6
Solar Factor (g)	32%	32%
Visible Light Transmission	10.8%	0.2%

Panel Dimensions (mm x mm)	2456 X 1245	2456 X1245

Table 3: Thermal, optical and electrical properties of the CIGS PV glass

Photovoltaic glass type	CIGS SOLAR GLASS
Panel Dimensions (mm x mm)	1587 X 664
Transparency	0%
Cell type	CIGS
Nominal Power (PNom)Wp	130
Module Efficiency	12.3%
Total ouput power kwp	(0.130 x 1180) = 153.4
Glass Thickness	37mm

Process two: This process involves the generation of photovoltaic façade. The selection of commercial building typology housing the office spaces has been supported in studies by (Kosoric, et al., 2021), (Kosoric, et al., 2018), (Gindi, et al., 2017), (Atmaja, 2013). These studies have demonstrated the ability of commercial building typology to adopt and integrate photovoltaic systems. Hence, the base-case building was selected as a commercial office building. Studies by (Sandak, et al., 2019); (Singh, et al., 2018) have discussed the choice of building materials for commercial building façade to be very specific like glazed façade, aluminum composite paneling and R.C.C. structure with brick infill and exposed brickwork. Curtain glazed façade, with cladding panels (varied colors), was chosen as the façade type for the base-case building. The building with southern façade had curtain glazing, and on western, eastern, and northern façade ribbon windows with aluminum cladding panels (ACP) were provided. Figure 3 shows the plan of the base-case building and figure 4, depict the southern and western elevation respectively.

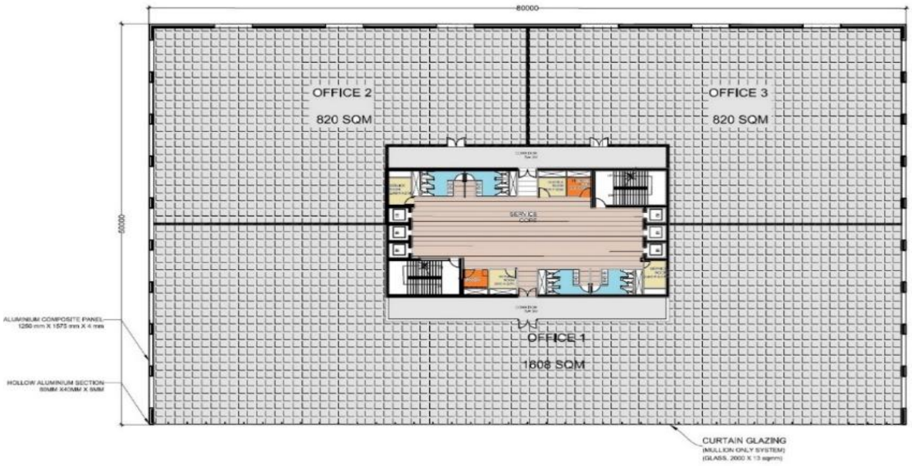

Figure 3: Plan of base-case building

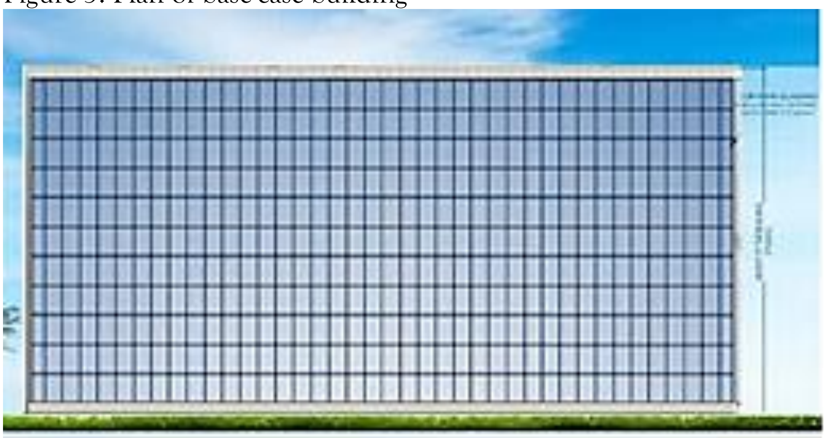

Figure 4: Southern elevation

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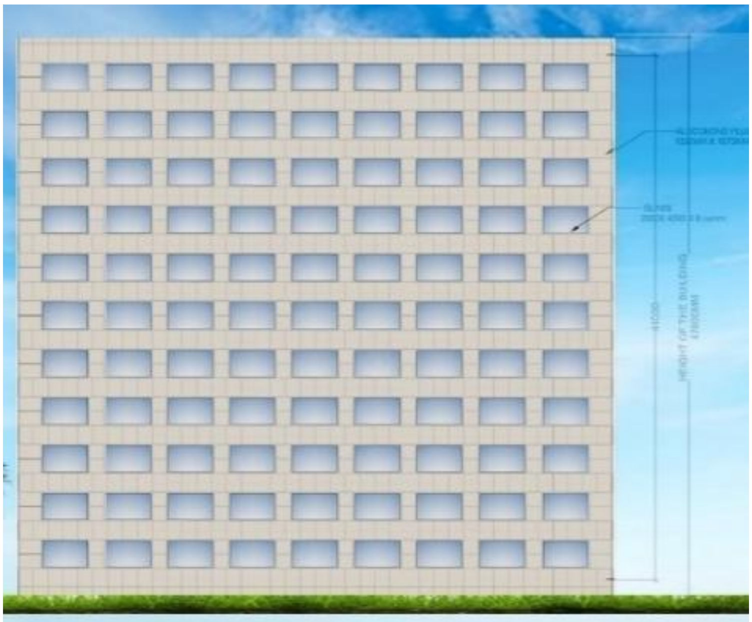

Figure 5: Eastern/western elevation

The photovoltaic façades were generated with two selected thin-film photovoltaic glasses. The building designed with A-Si photovoltaic façade was termed as variant 1. The building with CIGS photovoltaic façade was classified as variant 2. The selected facades for generating the variants 1 and 2 were the southern and western façade. In the studies by (Aaditya & Mani, 2013), (Cheng, Jimenez, & Chie, 2009) it has been stated that in northern hemisphere if the photovoltaic system would be designed it should have azimuth of south (0°)and tilt angle should be equal to the latitude of the place, for optimum performance. Figures 6, 7 and 8 show the planning, southern elevation, and western elevation of the variant 1. Similarly, the variant 2 building façade designed with CIGS PV glass were the southern and western façade. Figure 9,10,11 show the plan, southern elevation and western elevation of variant 2.

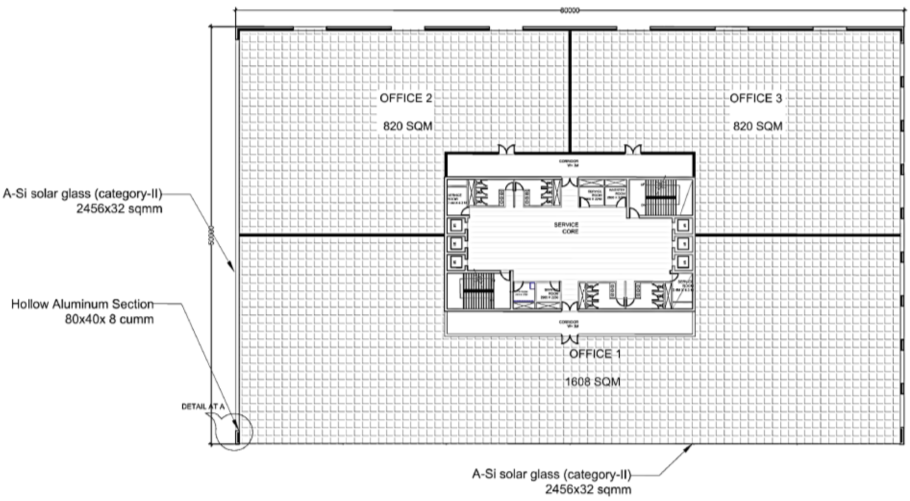

Figure 5: Eastern/western elevation

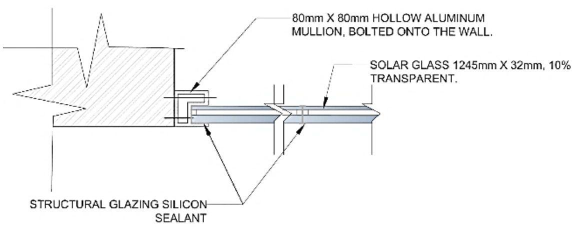

Figure 6: Detail at A

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Figure 7: Southern Elevation of variant 1

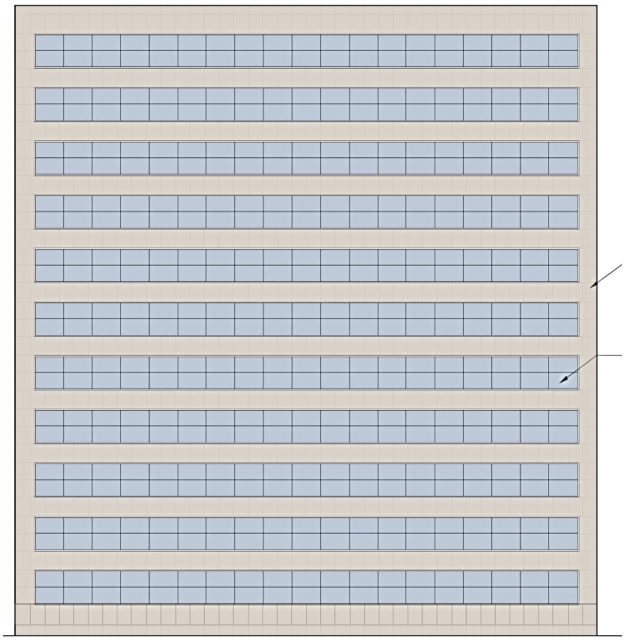
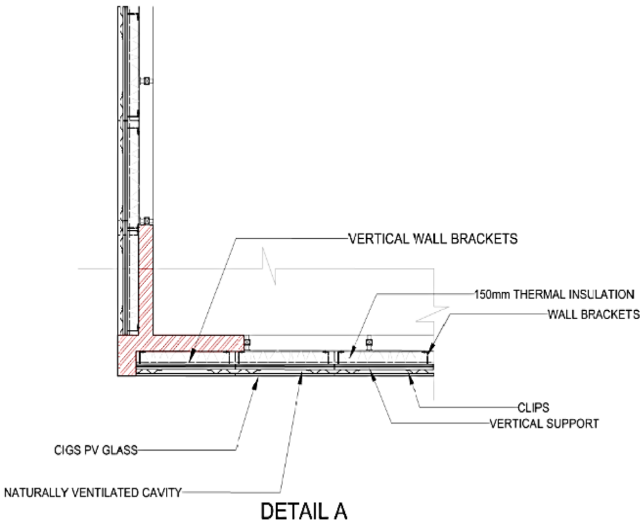


Figure 8: Western Elevation of variant 1



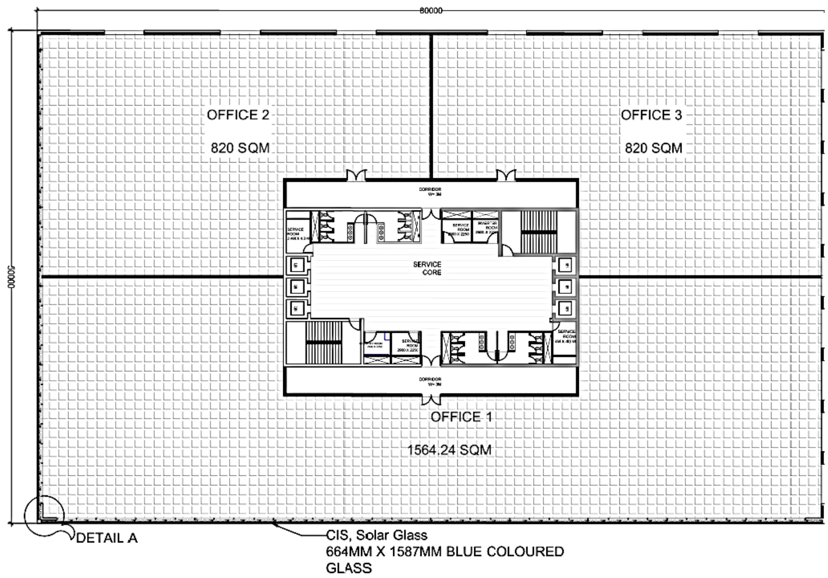


Figure 9: Plan of building with CIGS glass (variant 2)

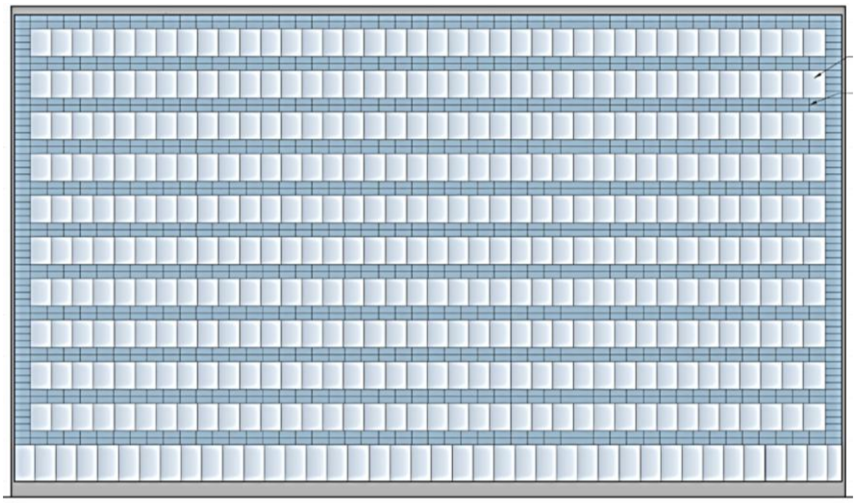


Figure 10: Southern elevation of variant 2

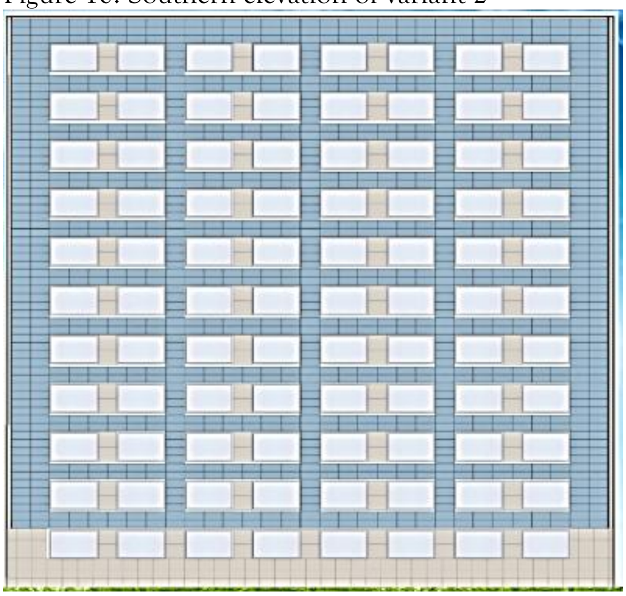
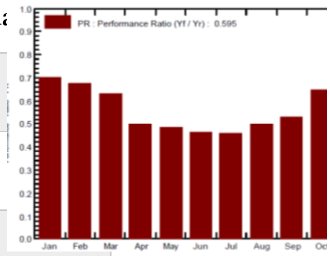


Figure 11: Western elevation of variant 2

Process three: The façade integrated system of photovoltaics was simulated using PVSyst V6.81 and RET-Screen Expert. The city selected for carrying out the simulation process was New Delhi belonging to the composite climatic zone. The feasibility of the designed building with photovoltaic façade was assessed on the basis of energy generation, visual analysis and economic analysis. The feasibility of photovoltaic product can establish if it efficiently performs its function of energy generation and building skin. Table 4 and 5 show the details of energy generation and saving potential achieved through the application of A-Si photovoltaic façade. The details of CIS photovoltaic façade's energy generation and saving have been shown in table 6,7.

Table 4: Detail of energy generated, and losses incurred with A-Si PV glass (simulated through PVSyst 6.8.1.)

Table 5: Energy savings with the use of A-Si PV glass (simulated through RETScreen Expert)

Total energy production (MWh/yr)	System losses, array losses, useful power production		Performance ratio (%)
137.5		kWh/kWp/d	
	Array losses	1.26	
	System losses	0.15	
	Produced useful energy	2.08	

End-use base case	End-use Proposed case	Savings
Cooling =1,07,41,682KWh /yr Heating= 24,13,689 Kwh/yr Lighting =14,97,595KWh/yr Miscellaneous= 5,11,585KWh/yr	Cooling = 1,07,77,492KWh /yr Heating =23,38,163KWh/yr Lighting =14,97,595KWh/yr Miscellaneous= 5,22,662KWh/yr	

	HVAC load (kwh/yr)	Electrical energy consumption (kwh/yr)	Energy Produced (kwh/yr)
Base-case	1,31,55,371	20,09,180	-
Proposed case	1,31,15,655	20,09,180	1,37,500
Savings	39,716		

Table 6: Detail of energy generated, and losses incurred with CIS PV glass (simulated through PVSyst 6.8.1.)

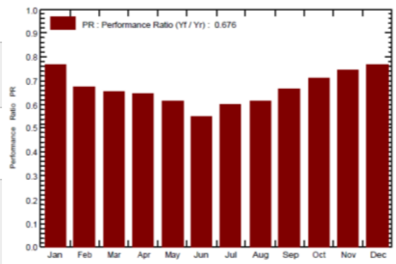
Total energy production (MWh/yr)	System losses, array losses, useful power production		Performance ratio (%)
232.73		kWh/kWp/day	
	Array losses	0.92	
	System losses	0.16	
	Produced useful energy	2.26	

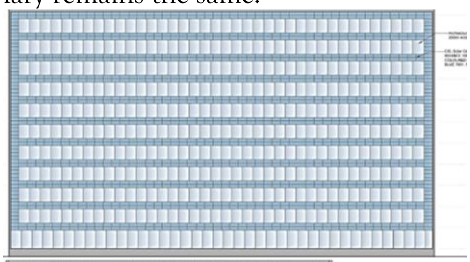
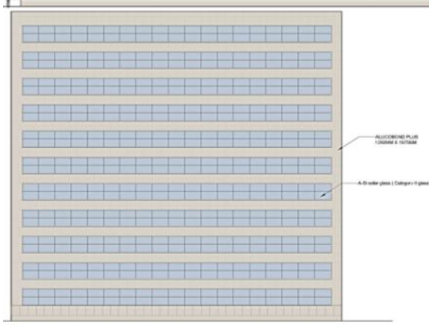
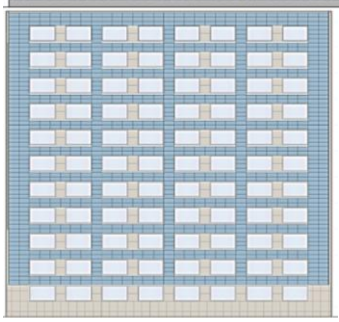
Table 7: Energy savings with the use of A-Si PV glass (simulated through RETScreen Expert)

End-use base case	End-use Proposed case	savings

Cooling = 1,01,38,559Kwh/yr Heating= 24,71,024Kwh/yr Lighting =14,97,595KWh/yr Miscellaneous= 5,11,585 KWh/yr	Cooling = 1,00,28,914 kWh/yr Heating = 24,63,558 KWh/yr Lighting=14,97,595KWh/yr Miscellaneous= 5,22,662KWh/yr

	HVAC load (kwh/yr)	Electrical energy consumption (kwh/yr)	Energy Produced (kwh/yr)
Base-case	1,31,55,371	20,09,180	-
Proposed case	1,31,15,655	20,09,180	1,37,500
Savings	39,716		

The visual analysis is the second assessment parameter for establishing the feasibility of photovoltaic façade. The visual analysis of variant 1 and 2 for has been done according to the visual parameters and is shown in table 8.

Visual assessment parameters	Variant 1	Variant 2
PV Type	A-Si	CIS
Application Of PV Glass On Façade	Curtain glazing and window glass	Combined with curtain glazing and ACP cladding
Visible Transmittance	10%	0%
Granularity (Colour and Texture)	Smooth and blue black	Planar and dark blue
Modularity	On the southern façade module was formed by 15 panels. The ribbon window appearance transformed into floor-to-floor glazing appearance.	664 x 1587 sqmm, forming modules of 232 panels on each floor on the southern façade and 148 panels on western façade
Appearance	The variant designed has a new vocabulary.	The appearance is new, but the vocabulary remains the same.
Southern façade		
Western façade		
Application Of PV Glass On Façade	Curtain glazing and window glass	Combined with curtain glazing and ACP cladding

Visible Transmittance	10%	0%
Granularity (Colour and Texture)	Smooth and blue black	Planar and dark blue

Table 8: Visual Assessment of Variant 1 and 2

The economic feasibility of the PV façade was assessed through life cycle cost analysis (LCCA). Previous studies by (Gholami & Rostvik, 2020) (Gholami, Rostovik, & Muller, 2019) (Gholami, Rostvik, Kumar, & Chopra, 2020) have discussed LCCA as a method to calculate the costs incurred and the benefits reaped throughout the life of the PV system. This analysis was the most reliable method of identifying whether, the system had any projected benefits over its lifecycle. The tools used to calculate the LCCA were Net Present Value (NPV), Discounted Payback Period (DPP), Internal rate of return (IRR), Return of Investment (ROI), shown in table 9.

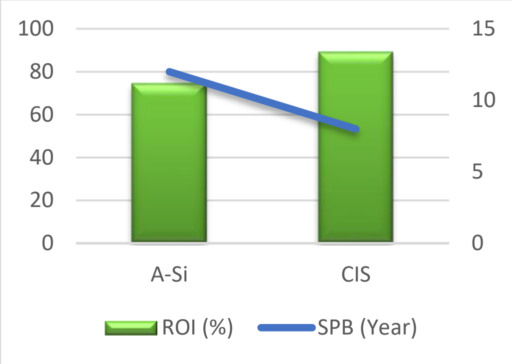
Table 9: Economic feasibility of Variant 1 and 2

Parameter	New Delhi Variant 1	New Delhi Variant 2
Thin Film Technology	A-Si	CIS
Facade Component replaced	Curtain Glazing, window glass	Curtain glazing, ACP Cladding
Facade Area (Sqm)	4507.00	2436.31
Electricity Tariff (INR/KWh)	8.50	8.50
Initial Cost of Investment	INR 2,15,26,073.3	INR 2,71,57,679.4
Cost of Projected Benefits for 30 years	INR 8,09,44,067.1	INR 11,08,53,681.5
Total Cash Outflows for 30 years	INR 4,64,34,815.2	INR 5,85,82,994.1
Discount Rate (%)	4.56	4.56
Net present value NPV	INR 3,65,47,342.50	INR 6,53,28,640.44
Return On Investment ROI (%)	74.3	89.2
Simple Payback Period (Yrs)	12	8

3.1. RESULT AND ANALYSIS:

Two alternative facades were designed for the building in New Delhi. The first alternative was designed with A-Si photovoltaic panel/glass and the other variant had CIGS glass panels. The facades chosen were south and west oriented. The designed buildings were analysed for visual parameters, energy parameters (generation and consumption), and economical parameters.

The simulation results provided a set of data's requiring collation to arrive at a conclusion. Data sets were collated in the form of graphs representing the economic feasibility through ROI and SPB. The return-on-investment parameter was simple to collate as higher value indicated a more profitable venture, whereas a negative value was indicative of the non-profitable nature. It was an indication that the project would be running in loss if it were undertaken. The graphs for a simple payback period, were used to identify the buildings and technology along with the city of implementation, where it was possible to recover the initial investment faster and incur profits. Simple payback period was inversely proportional to the feasibility of the project, implying that lower the SPB higher is the feasibility of project.



Graph 1: Comparative analysis of the A-Si and CIS variants for building façade

The results as seen in table 4,5,6,7,8,9 clearly indicate the achievement of feasibility parameter of functioning efficiently and simultaneously as a building envelope as well as an energy generator. Thermal performance of the building designed with thin-film photovoltaic façade (shown in table 5,7) supports its efficient functioning. The ability to provide visual comfort and generate energy to offset building demand further supports the efficient functioning of the thin-film photovoltaic façade. Therefore, it can be stated that a thin-film photovoltaic façade is efficient, smart and a sustainable option for contemporary needs.

4.1 Discussion:

The aim of this paper was to design a smart façade using thin-film PV technology and to assess its Energy generation and savings potential, visual performance and economic feasibility. The methodology defined are restricted to designing for a commercial building housing office space. Thus, a modification of the strategies could be done to include residential buildings (particularly housing towers), which form a large portion of the (new and upcoming) urban building stock. This would increase the chances of adoption of the technology and would help in creating a sustainable architecture with due consideration for future energy requirements. Another limitation of this research was the adoption of only two types of selected thin-film photovoltaic technology. With the on-going research in the field of building integrated photovoltaic technology (BIPV), new and efficient technologies have been developed. The design process could be further enhanced to adopt the newer, more efficient technologies.

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