Architecture and Planning Journal (APJ)

Volume 26 | Issue 1
ISSN: 2079-4096

Article 5

March 2020

TECHNO-ECONOMIC ANALYSIS OF USING PV CURTAIN WALLS IN HOT ARID ENVIRONMENTCASE STUDY; MIXED-USE BUILDING, JEDDAH, KSA

Abdelaziz Farouk A. Mohamed
Assistant Professor, Department of Architectural Engineering and Environmental Design, Arab Academy for Science, Technology & Maritime Transport, Egypt, drabdelaziz@aast.edu

Ahmed T. Elfakgarany
PhD Candidate, Department of Architecture, Faculty of Fine Arts, Alexandria University, Egypt, atelfakharany@gmail.com

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Abstract

Nowadays the world no longer has a choice to reduce the dependency of non-renewable energy resources, especially in buildings. This type of energy like fossil fuel is responsible for global warming and the climate change phenomenon. The construction industry has to depend on renewable energy to improve environmental impacts while operating the buildings. The most promising technologies for buildings are photovoltaic panels system which converts solar radiation into electricity without harming the environment. PV system is not only used as top-roof panels but also it can play an important role in the exterior building cladding and in curtain wall system as well. Building-integrated PV (BIPV) system has two functions the first is used as a façade cladding and the second is power generation for building operation. This research studies the PV curtain wall as a BIPV system and explains why this system is better than the traditional curtain wall through its environmental performance and initial, and operation costs. Based on the analysed tabulated feasibility study considering energy savings outcome and system cost, PV curtain walls proved technical, environmental and economic viability. The paper's case study in Jeddah-KSA provides a real example of how PV curtain wall application plays a fundamental role in achieving high energy performance standards as well as maximize the financial return of investment.

Keywords

Renewable Energy, Building Integrated PV, Curtain Walls, Hot Arid Climate, Life Cycle Costing

1. INTRODUCTION

Over the last decades, glass technologies for buildings have undergone radical changes and extended the functions and applications of glazing in modern architecture (O. Zogo, 2011)." Through the continuous improvement in thermal insulation performance, combined with new methods of modulating solar heat and light transmission, glazing has strengthened its position as an essential construction material for low energy buildings" (Glassforeurope, 2019). Despite the availability of these high-performance glass technologies, a preconceived idea that glass is the weak point in the building envelope is persist, which goes against existing evidence that demonstrates the positive role of glass in sustainable low energy buildings (U. D. O. Energy, 1999). The exterior wall of a building includes windows, cladding, and curtain walls which create the exterior building skin. The curtain wall system considers one of the facade technology components in the buildings. It usually integrated with the exterior of the buildings maintaining the aesthetic visual and façade cladding, for photovoltaic (PV) applications, facades have great potential. The photovoltaic system is used as top-roof panels, it can also play an important role in the exterior building cladding, shading devices, and in the curtain wall system as well (X. Zhang, 2018). PV could have a significant role in the integral energy strategy of a building as well as environmental aspects and they also can be opaque or transparent (E. P. a. Council, 2002).

1.1. Research Methodology

This paper aims at analyzing technical, environmental and economic viability of PV curtain walls. This has been accomplished through literature review, analytical tabulated and graphically represented data and simulation of case study, Mixed use Building, Jeddah, KSA, using Design Builder and Energy Plus software.

2. PV CURTAIN WALLS

Curtain walls are used to cover a very large surface with a transparent and a visually pleasing element. There is improvement process in curtain wall systems can be made by integrating with the photovoltaic panels. Adding PV system can enhance the existing design concepts of the conventional curtain wall systems in order to reduce the environmental impacts, enhance energy and human satisfaction. A facade could be created of a combination of glazed areas and opaque PV panels or it could have the combination of PV modules with opaque and transparent ones. PV system has a positive impact on environment due to the reduction of CO_2 emissions. (H. & M. Elnimeiri, 2002). At present, it is difficult to compare between CO_2 emission reduction and the high cost of PV system. On the other hand, the environmental pollution is a serious problem in the world. "Each square meter of PV panel will avoid approximately 1800 kg of C02 in 25 years period" (R. T., 2001). PV systems also represent a subject to environmental interest which encourages the buildings' owners to apply these systems in their buildings.

2.1 PV Visual Characteristics

The main component of the photovoltaic system is PV cells which produced in many colors such as blue, brown, range of black, etc. There are two layers of these cells one in the front which colored and the back layer which colored or not according to the system design (R. T., 2011). PV panels are produced in different sized rectangular spandrel units, top roof panels, or opening elements. They produce custom-made products to fit into various building design alternatives with additional cost. According to the PV system design the transparency can be achieved by using transparent cells or through the spaces between PV panels and the pinholes on the panels themselves with different values of transparency (R. T., 2001).

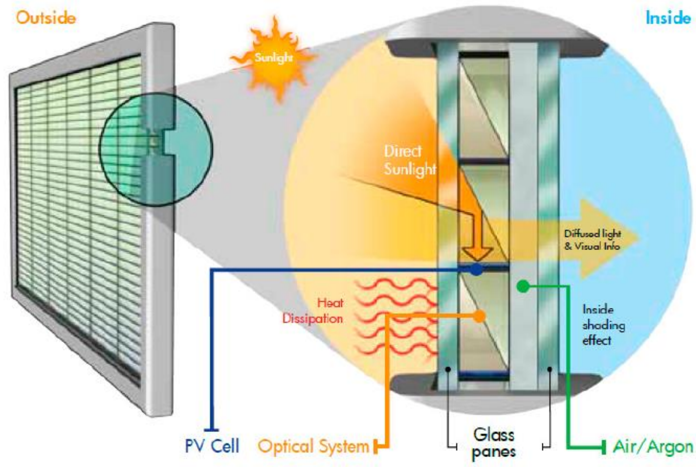


Fig. 1: Integration of photovoltaic (PV) systems into window design (Ugochukwu, 2017)

2.2 Building Integrated PV (BIPV)

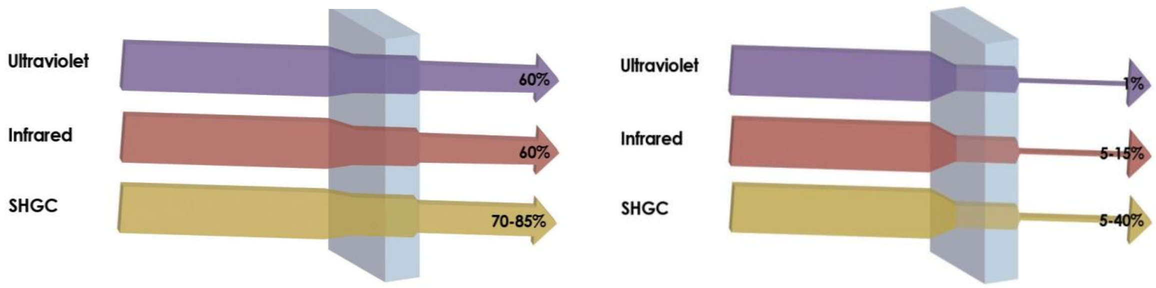
Photovoltaic panels can be integrated with a building called BIPV system. Mainly, BIPV refers to the integration of PV materials into building envelopes. Therefore, providing it with multiple functions such as acting as part of the building structures by replacing traditional building materials and producing electricity on-site (Mohamed, A., 2019). In fact, BIPV shows a high level of innovation and the potential to realize green or zero-energy buildings in the future (Z. Tiantian, 2018) As indicated in Fig. 1 PV cells generate electricity from solar radiation directly without fossil fuel burning which has a negative impact on the environment. There are no pollution, operation and maintenance costs when PV system generating the required electricity.

3. PROPOSED SYSTEM PHYSICAL CHARACTERISTICS

3.1 Proposed PV Thermal Properties

The proposed PV curtain wall has thermal properties that affect the efficiency of the main components of a building by influencing heat flow as indicated in fig. 2 & fig. 3: PV Thermal transmittance is the efficient amount of heat transferring (U Factor) from outside to inside the building (G. Arasteh D., 1994). The control of the solar heat gain of the building is called Solar Heat Gain Coefficient (SHGC), it is the ratio on the gained heat from sun through building openings (H. & M. Elnimeiri, 2002). Shading Coefficient (SC) is the ratio on the solar heat gain through building openings with or without building shading devices (G. Arasteh D., 1994). The thermal control requirements should be considered carefully. The thermal effects are different according to the building context and orientation so, they are also different in each side of the building. The thermal insulation of the building's wall system and interior thermal control should be balanced economically. This economic balancing depends on different parameters which are:

- The ratio of opaque to transparent areas, (H. & M. Elnimeiri, 2002).
- Glass type,
- Spandrel area,
- Shading devices (louvers),
- HVAC factors (Heating, Ventilating, and Air Conditioning)



Standard glass PV glass

Fig. 2: Comparison between standard glass and PV glass (www. Onyxgreenbuilding, 2014)

These parameters should be determined clearly during the design phase of the proposed PV curtain wall for the economically, aesthetically and functionally better solution (G. Richard, 1972). In addition, the Insulation of the proposed PV is considered due to its cost and efficiency which can reduce about 35 % of thermal radiation when PV added on the curtain wall design (IEA-PVPS, 2001). Thick and heavyweight materials are used in the conventional building walls as skin and barrier of thermal transition. On the other hand, curtain walls consist of thin and lightweight materials that transmit thermal effectively. There are several types of curtain walls through their materials and structure systems, they may be designed as structural glazing which covers all walls with glass, opaque and glass to opaque ratio. Curtain wall types have different thermal characteristics so, the structural glazing systems are the best to express the concept of the curtain wall system but the opaque types are more thermally efficient (C. Habitat, 1992).

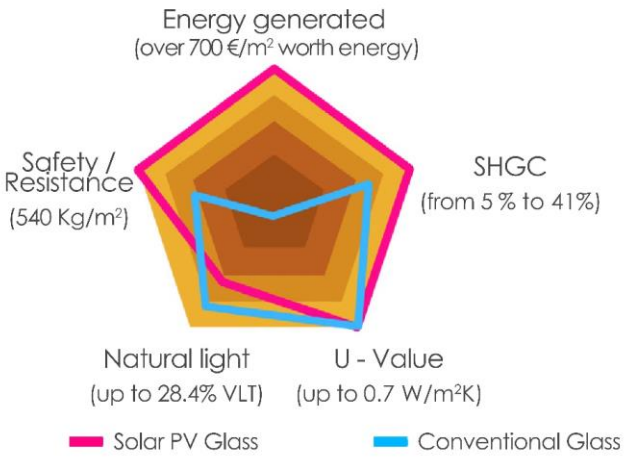


Fig. 3: Properties of conventional glass and solar PV glass (Onyx Solar, 2018)

Thermal insulation of the proposed system: The thermal insulation of a traditional window depends on orientation, the colour of the wall components that promote the system. In addition, climatic conditions of a building context have an important impact on the building's facade temperature (C. Habitat, 1992). The joints and different sealant materials like silicon within the facade should be able to adapt to these differences in temperature. In addition to adding glass panels inside the system can enhance its thermal properties.

3.2 Daylight

Building openings (Windows) are the essential part of the exterior wall systems to admit daylight, provide outside view and have a significant role of these openings in energy-efficient design. The designer should exploit the benefits of winter solar radiation and daylight through the windows (C. Habitat, 1992). They can create an attractive building facade and also provide the daylight inside the interior without the unwanted sun glare. The opaque PV cells maintain the PV curtain wall Transparency. This transparency is created by the distance-replaced cell and shade devices which created inside the building changes the different times of day (R. T., 2001). The cells can pack the façade and may create additional spaced out in order to change the transparent effect into semi-transparent which can be above the glass layers.

3.3 PV Curtain Wall Eco-system

The eco-system of the PV curtain wall gives high resistance against heat and sound insulation compared to the other systems. PV temperature should be kept low to get better performance. Ventilation gaps and spaces can be created between curtain wall and building structure to combine with building ventilation. This gap must be at least 100 mm and it can also provide for services.

Figure 4 shows the eco-system of the curtain wall which allows the hot air exhausted in the summer and kept in the winter and vice versa. This ventilation helps to reduce the PV own temperature, which increases the panels' efficiency (IEA-PVPS, 2001). This ventilation process should be included in the system design as an eco-system to mitigate the heat transferring from outside to inside the building. The air flow duct has an air gate which allows or not the air motion between inside and outside building according to the weather condition.

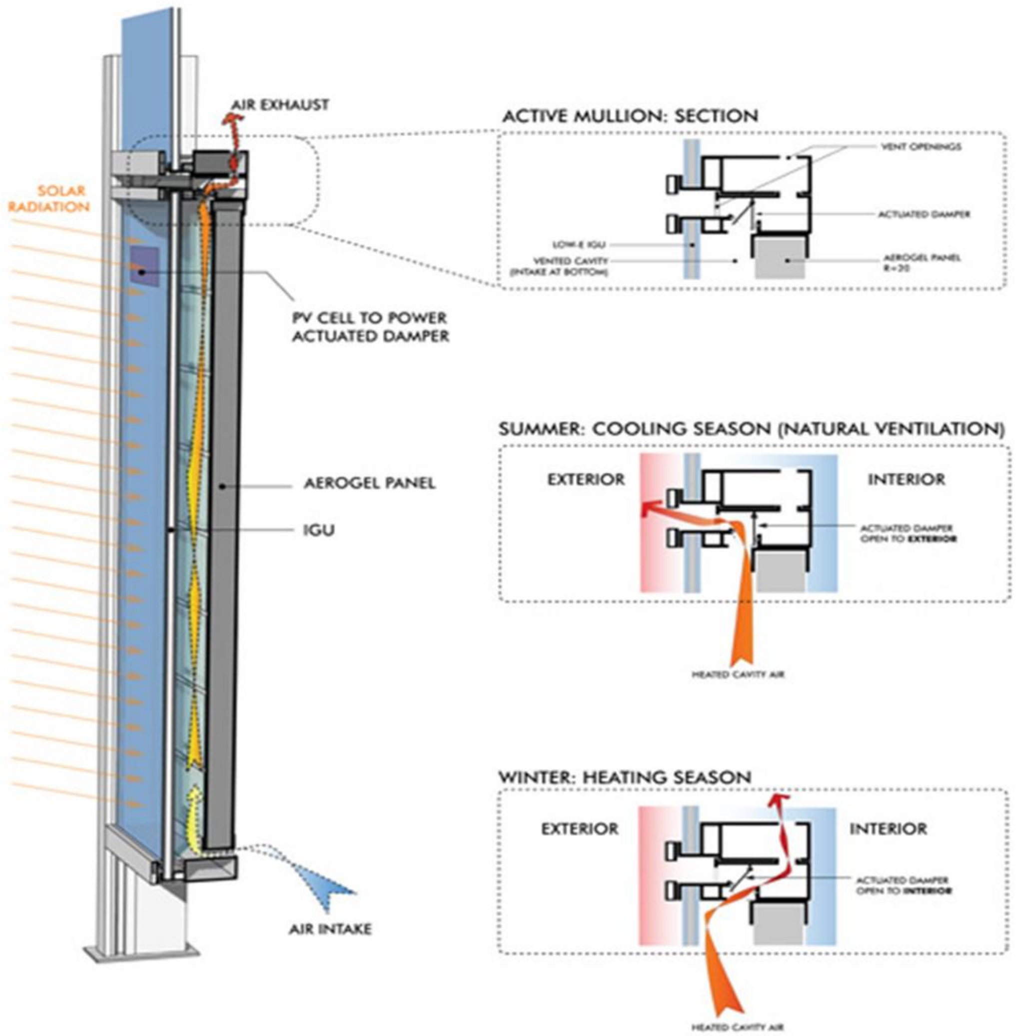


Fig. 4: Eco-system of curtain walls (Hyun Tak, 2017)

3.4 Acoustic Insulation

On the design phase of curtain wall system of any building, the acoustical features should be considered. There are acoustic sensitive sensors which work to control the noise problems. Using enclosure by solid material and double glazed systems are the most effective method to control the noise problems but the openings reduce the effectiveness of this enclosure. The acoustic insulation of the curtain wall system can be applied through the gap distance between glass layers and between the curtain wall itself and the building structure. This gap distance between building and curtain wall should be at least 90 - 100 mm to be effective. Furthermore, laminated glass and argon gas are more efficient for acoustical insulation (G. Richard, 1972).

4. PROJECT CASE STUDY

4.1 Project Location

The project is located in Prince Sultan road in Jeddah, Saudi Arabia, as per the following map, shown in figure 5.

Fig. 5 Project location map (google maps)

4.2 Project Description

Project is a mixed use building project which includes retail, hotel apartments, and residential apartments with following details in fig. 6:

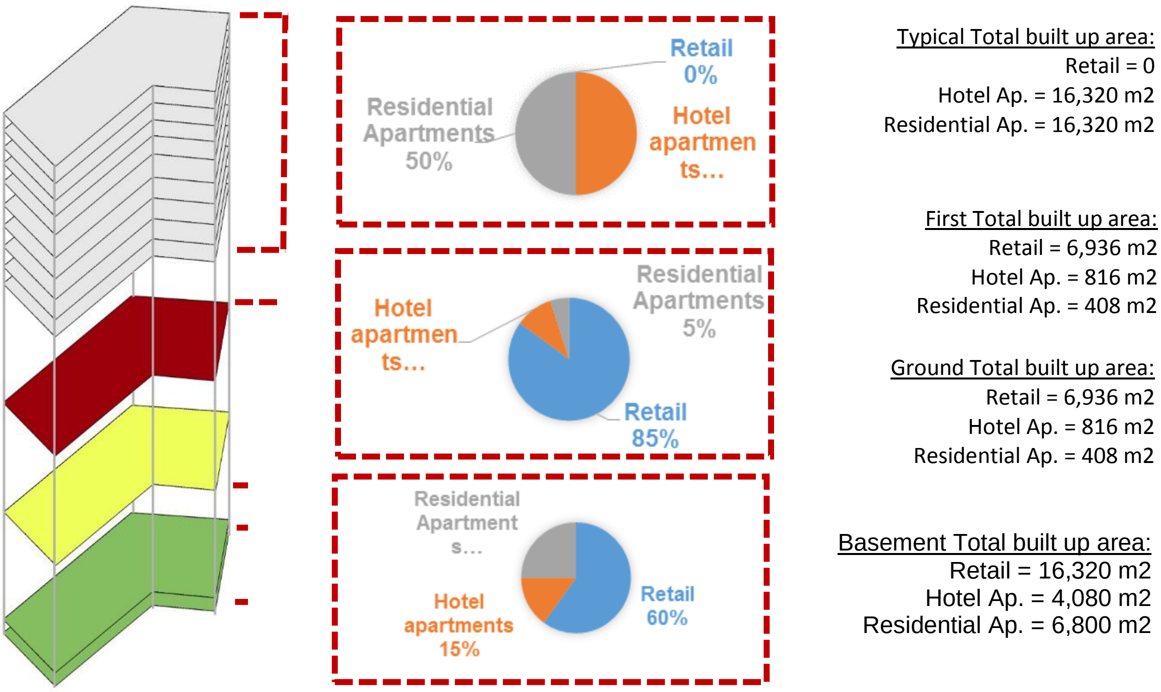
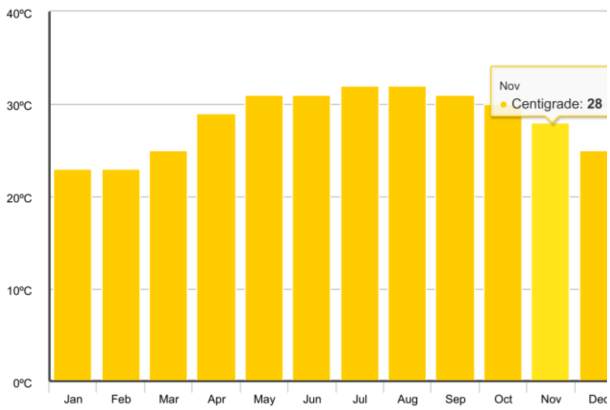


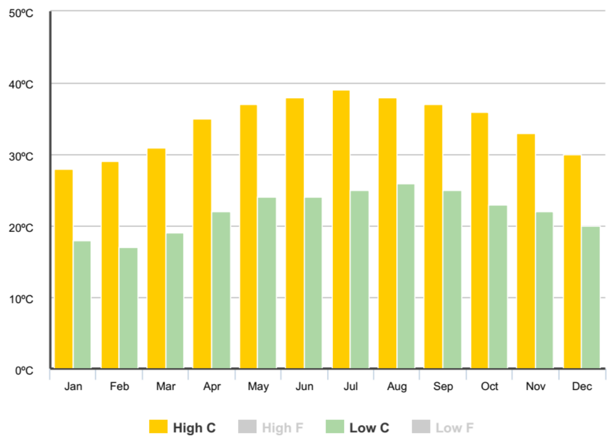
Fig. 6: Project components description (Researchers)

4.3 Climate

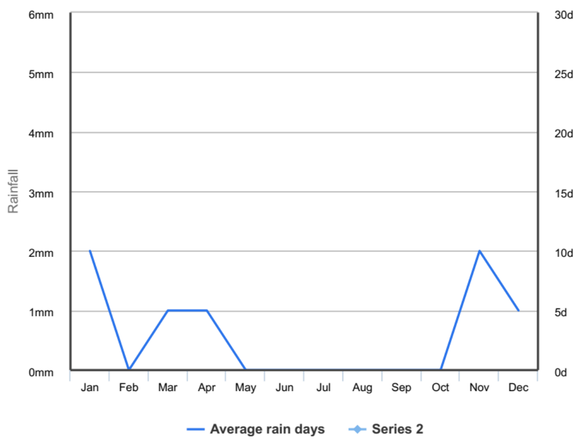
July is the hottest month in Jeddah with an average temperature of 32°C and the coldest is January at 23°C with the most daily sunshine hours at 13 in May. (S. e. Company, 2012). Fig 7 summarize the climate indicators.



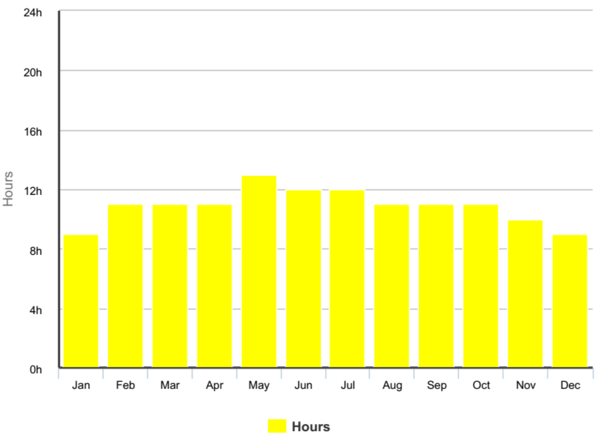
Average Temperature



Average High/Low Temperature



Average Rainfall



Average Daily Sunshine Hours

Fig. 7: Project climate indicators (Researchers)

4.4 Hypothesis and Assumptions

Table 1: Hypothesis and assumptions of case study (Researchers)

Location	**Jeddah, Saudi Arabia**
Typical floors Construction Area (M^2)	32,640
WWR	70%
Glass Area (M^2)	22,848
Local Electricity Cost	0.075 USD
Variation in Electricity Cost	0.00%

- Electricity price was taken from K.S.A Company. (https://www.se.com.sa/enus/Pages/ChangingTariffForCommercialAndIndustrialSectors.aspx
- The increasing of electricity price is ignored.
- Design Builder and Energy Plus are used as simulation programs and database to calculate the Saving of Energy.
- The shadows and losses from the system are ignored in energy calculation
- The reduction of PV power output in 30 years is estimated in 19.9%.
- Useful life of the system assumed 30 years.
- The case study building used as a guide and designed under the (ASHRAE 90.1-2010 Standards for Buildings.)

- Curtain wall: The composition of an insulating glazing unit (IGU) 6T.6T/12 Air/4.4mm. The estimated cost is 83 USD/SQM.
- Air conditioning is connected to the electricity grid.
- The additional saving of energy in the air conditioning and reduction of electricity load due to any improvement in thermal insulation are ignored from this simulation study.
- Balance of the system cost has been extracted from the Solar Market Insight Report 2015 Q1 elaborated by the Solar Energy Industries Association of USA (SEIA) where inverter cost is 0.2 US$/WP., electrical BOS is 0.15 US$/WP. & electrical related labour, engineering and PII is 0.06 US$/WP.
- The total additional cost of the balance of system (compared with the installation of the regular clear glass studied along this Feasibility Study) has been estimated in 0.37 US$/WP for SAUDI ARABIA.
- Feed in Tariff system or any incentives are not existed in this study, and the exchange rate is assumed that 1US$=0.9 EUR when the installation of PV calculated.

4.5 PV Glass Application Configuration

The proposed PV system has the following features:

- Clear Glass with mono-crystalline silicon photovoltaic cells with a 15% +12 mm transparent material degree, argon chamber low-e glass.
- PV unit includes the junction boxes, each one at the edge of the laminated glass.
- PV glass layer is manufactured with its own junction box. The junction box is mono-polar.
- The mono-polar junction box requires two units per module.
- PV glass panels are without framing system which different from the traditional glass. This allows the adaptability and multi-functionality as to where and how the PV glass is utilized.

4.6 Architectural Alternatives

A part of the tests done in the case study model, the following architectural characteristics had been tested to get extra reduction on energy consumption; those alternatives are subject to the final architectural decision:

a. Window to wall ratio:

The window-to-wall ratio (WWR) ratio is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area as shown in Fig. 8. This opening area has impacts on the heating, cooling, and lighting, of buildings relating to their context in terms of access to daylight, ventilation, and views. Facades can be designed using a higher percentage than the code prescriptive maximum by using high-performance glazing systems that may be used in combination with interior and exterior shading strategies. These designs can avoid the unwanted solar gain and glare through the large window area, while still allowing for daylight to enter spaces which results in reduced electric lighting use (H. & M. Elnimeiri, 2002).

Fig. 8: Window-to-wall ratio (H. Sozer, 2002)

b. Building rotation towards sunlight

Orientation is the positioning of a building in relation to seasonal variations in the sun’s path as well as prevailing wind patterns. Good orientation can increase the energy efficiency of building, making it more comfortable (Yourhome, 2020). With rising energy costs, it’s becoming increasingly important for architects and owners to orient buildings to capitalize on the Sun’s passive energy.

For architects, orienting a building to take advantage of the warmth of the Sun will increase the building's appeal and marketability. For users, it will increase their indoor comfort and reduce their energy running cost. Thus, building orientation, along with daylighting and thermal mass are crucial considerations of passive solar construction that can be incorporated into virtually any building design as shown in fig. 9 (H., M. Elnimeiri, 2002).

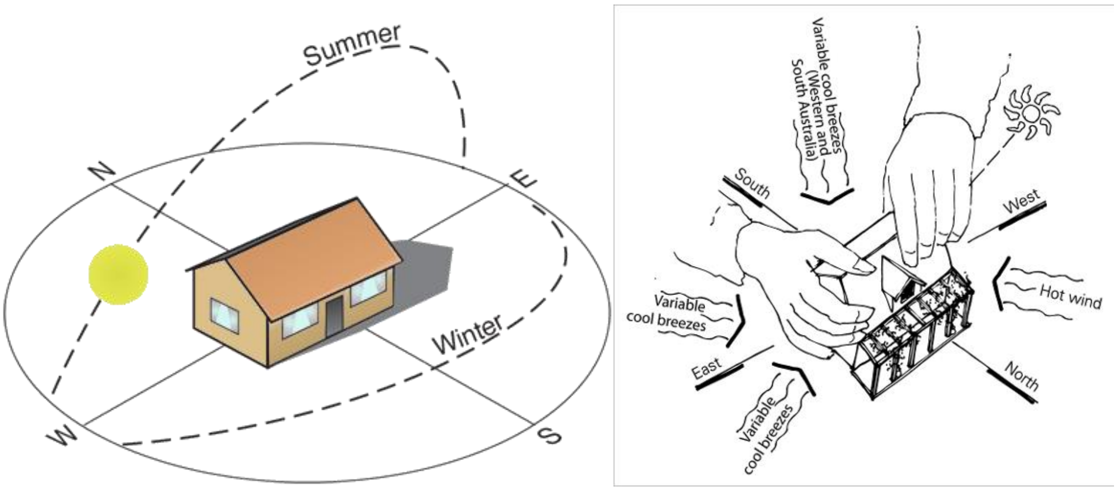


Fig. 9: Building rotation impact (H. Sozer, 2002)

5. STUDY RESULTS

The financial study had been carried out with respect to U.S. Guidelines for the Economic Analysis of Building-Integrated Photovoltaic Power Systems (T. A. Eiffert P., 2000).

5.1 Results Due to Technical Characteristics of Glazing

Table 2: Technical Characteristics of PV glass vs standard glass

Technical Characteristics	Standard Double glass	Solar PV glass
U Value (W/m2K)	2.69	1.2
SHGC (%)	69.50%	15%
Visible Light Transmission (%)	78.6%	15%
Peak Power (WP/SQM)	0	152

5.2 Reduction in Energy Demand and Building Cost Saving

Table 3: Reduction in energy demand, and cost saving in 30 years (Researchers)

Item	Energy in KWH	Cost in EUR
Energy demand of the building with standard double glass	140,777,473	10,558,310
Energy savings induced by thermal envelope using solar PV glass	48,070,736	3,605,305
PV energy production solar PV glass	6,787,821	509,087
Total reduction of energy demand PV glass	54,858,557	4,114,392
% of total energy reduction		39%

5.3 Financial Results

Table 4: Financial performance indicators (Researchers)

Average reduction of required energy (euro/m2)	394
Amount to invest (euro/m2)	133
Return on Investment ROI (%)	196%
Payback period (years)	11 years
Internal Rate of Return IRR (%) in 30 years	9%
Accumulated benefit after 20 years	1,370,835
Accumulated benefit after 30 years	2,726,942

5.4 Extra Reduction in Energy Demand Due to Architectural Design

Table 5: Extra reduction in energy demand due to Architectural Design (Researchers)

Building orientation	Window to wall %						
	30%	40%	50%	60%	70%	80%	90%
0 degree	5.3%	4.3%	3.0%	1.6%	0.0%	-1.4%	-3.0%
45 degree	6.2%	5.5%	4.6%	3.9%	2.7%	1.6%	0.3%
90 degree	7.4%	6.7%	5.7%	4.9%	4.0%	3.2%	2.4%
135 degree	6.2%	5.3%	4.3%	3.2%	2.0%	1.2%	0.0%

Base case: window to wall % = 70%, rotation = 0%

5.5 Case Study Outcomes

This study proves that the proposed PV curtain wall system is more economical and eco-friendly than the traditional curtain wall system. In addition, the proposed PV curtain wall system has many benefits which made it an economical ecological system through the following:

- Aesthetic visual (Structural glazing curtain wall)
- Saving energy (PV generates electricity from solar radiation directly)
- Thermal & Acoustic insulation (The space gap between glass panels and building structure and the argon gas filled the gap between the glass layers)
- Transparency (The glass type and color)
- Saving money (Initial cost is high but the running cost is reasonable)
- Eco-friendly (PV cells powers the building without harming the environment)
- Users comfort (Providing the users with sunlight without its unwanted heat gain & glare, reducing the interior artificial lighting)
- Healthy (PV curtain wall feeds the interior spaces with vitamin D from the sun radiation)

6. CONCLUSION

The building’s facade provides the aesthetic and architectural style of the buildings, and it can also play an important role in the building’s structural systems. It includes windows, cladding, and curtain walls which create the exterior building skin.

The curtain wall system considers one of the facade technology components in the buildings. It usually integrated with the exterior of the buildings maintaining the aesthetic visual and façade cladding. Photovoltaic system is used as top-roof panels it can also play an important role in the exterior building cladding, and in the curtain wall system as well.

PV curtain wall system is one of BIPV technology; it may have a significant role in the required building energy and mitigates the environmental impacts. However, PV technology is still a developing technology and the initial cost of the system is still high but the operation costs are reasonable. PV curtain wall system characteristics are not known by architects and owners. But PV production and usage are growing quickly, improving its efficiency and reducing cost in order to make it a promising technology for the construction industry.

PV panels have additional benefits that may occur which could directly affect building environmental performance, acoustic and thermal properties, and budgets. PV can have a multi-functional role, on the building façade, not just a cladding material. When the building integration PV (BIPV) has been applied at the building it is not only used as a finishing element but also it is generating electricity that covers the required energy and used as environmental treatment as well.

The case study mixed-use building in KSA proves that the PV curtain wall is more efficient when compared with the traditional curtain wall through the life cycle cost and environmental aspects.

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