ENERGY, ENVIRONMENT AND COST BENEFIT ANALYSIS OF SEMI-TRANSPARENT PV WINDOW-A REVIEW

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Abstract: The building integrated photovoltaic (BIPV) systems generate and save energy, counteracting transmission losses. In these systems, photovoltaic modules also serve as building envelopes in this kind of system. Thus, interdisciplinary concepts are required to realize the BIPV plants' functionality. BIPV economic decisions are complex; guidelines suggest NPV or LCC are best for design design consideration. When energy saving is considered, the EPBT of a STPV system is found to be 3-3.2 years. Also, the thermal performance enhances embodied energy payback time, leading to more economic viability.For example, STPV windows cut heat gain by 65%. Renewable energy, especially solar power, reduces harmful greenhouse gas emissions and hazardous particulate matters. In the case of photovoltaic systems, environmental factors are crucial in analysing the cost-benefit aspects.. Finally, the outcome of this paper will work as a platform for the renewable energy community in assessing the financial and environmental aspects of STPV window/façade systems.

Keywords: BIPV; cost payback, energy payback, environmental factors

Abbreviations

Notation	Description	Notation	Description
BIPV	Building Integrated Photovoltaic	LCC	Life Cycle Cost
CdTe	Cadmium Telluride	LCCE	Life Cycle Conversion Efficiency
EJ	Exa Joules	LCE	Levelised Cost of Energy
EPBT	Energy Payback Time	IEA	International Energy Agency
EU	European Union	NEB	Net Electricity Benefits
EPF	Electricity Production Factor	PBT	Payback Time
GHG	Greenhouse Gases	PV	Photovoltaic
HIT	Heterojunction with an Intrinsic Thin layer	STPV	Semi-Transparent Photovoltaic
HPVT	Hybrid Photovoltaic Thermal	WWR	Window to Wall Ratio

1. Introduction:

Recently the global primary energy consumption has reached 580.49EJ (1EJ=1018J) [1]. Fuel wise, oil stood at the top position with 33.63% of the total consumption. Coal had occupied the second position with 27.21%. The consumption of natural gas, nuclear, and hydro energies was 23.87%, 4.41%, and 6.84%, respectively. In total energy consumption, renewable sources of energy contributed the least (4.05%). However, some estimates show that in the renewable energy category, the solar radiation falling on the Earth's surface alone has the potential to meet the existing demand 10,000 times more [2]. By 2050, the world's primary energy demand is projected to be 1000EJ or more [3]. Moreover, as per the IEA, the photovoltaic sector will contribute around 11% of the expected world electricity supply by that time. In 2050, the expected installed capacity of the photovoltaic plant is estimated to be 3000 GW with 4500 TWh of electricity generation per annum [4].

Various photovoltaic technologies have been developed in recent times. The application of diverse manufacturing processes requires different amounts of energy to produce a unit area of the modules. Moreover, the dissimilar conversion efficiency among the technologies resulted in different energy per unit area. Each technology has its limitations and advantages. A broad classification of the available photovoltaic technologies is given in Fig. 1.

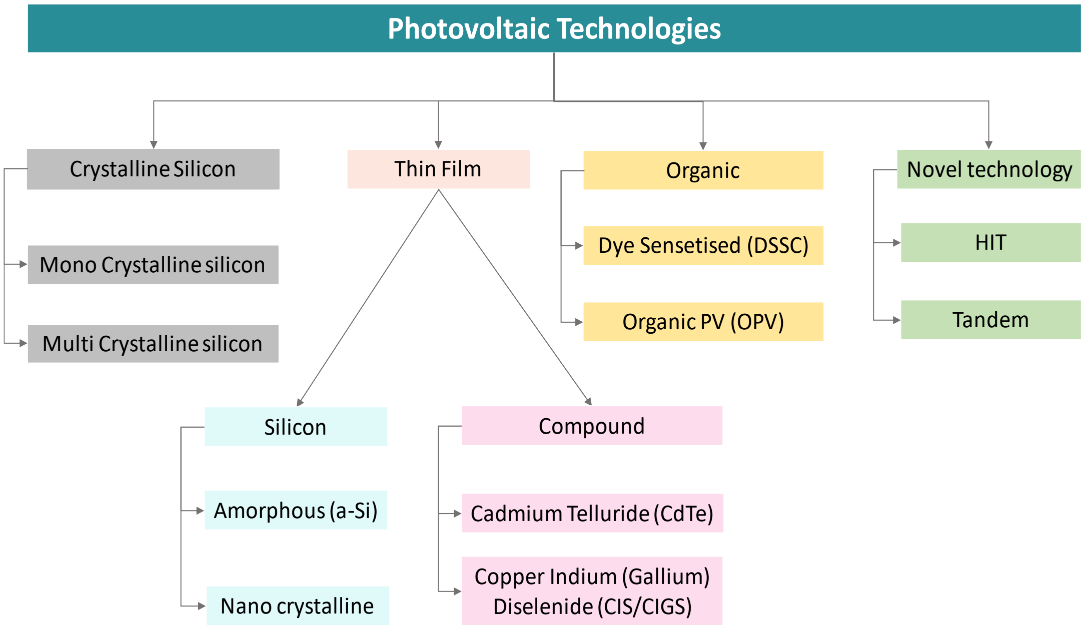

Fig. 1: Broad classification of solar photovoltaic technology

In the recent past, the PV incorporated window/façade technology has become popular among researchers [5]. Among different photovoltaic modules, the thin film STPVs are preferred for the window/façade of a building. The thin film modules are mainly preferred because of the better daylight performance and aesthetic appearance [6]. STPV integrated window systems considerably reduce direct solar heat gain [7]. In other words, the STPV modules used in the window/façade also work as a shading device in a building [8-9]. This feature further enhances the potential benefits of the STPV integrated window/façade system. The organic photovoltaic modules also possess good potential in building applications, but these are yet to be commercialized on a large scale. In this article, the techno-economic basics of BIPV technology have been critically analyzed and discussed. The focus of the analysis is the window/ façade system of a building.

2. Cost-benefit aspects of BIPV systems

Energy, economy and environmental issues are considered in the cost-benefit analysis of renewable source based energy systems [10]. Due to the involvement of several components such as material, installation, operation & maintenance, fluctuation, and so forth, the cost-benefit analysis is a challenging task. In this section, an attempt has been made to summarize the relevant information regarding the energy, economic, and environmental cost-aspects of BIPV systems. Different researchers have investigated the energy and economic aspects with respect to EPBT, LCCE, LCE, PBT, LCC, NPV. In the environmental head, calculation of the reduction in GHGs like CO2, NOx, and SOx are the prime focus points.

2.1 Energy-saving potential of BIPV systems

The generation of energy by the BIPV system at the consumption center nullifies the deficiencies suffered in the course of transmission and dissemination. Thus, the BIPV system saves some amount of energy besides generation. Further, the heat transmission across the STPV window system is less compared to conventional glazing [11]. Compared to clear glass, the STPV window can obstruct up to 65% of heat energy from entering the inhabitant region [12]. The reduction in heat gain can be increased by laminating the photovoltaic cell between two insulation glasses [13]. The lower heat gains further enhance the energy-saving potential by using the STPV window. Through numerical inquiry, Peng J. et al. [5] found 50 % less net electricity consumption with STPV windows than the commonly used glass windows in the cool climate of the Mediterranean. Miyazaki T. et al. [14] presented the energy functioning of an STPV integrated house in Japan. With the optimized system, they achieved 54% energy savings. Further, a low room air temperature can be maintained by using ventilated STPV window/facade systems [15,16,17]. The lower room air temperature helps in lessening the energy expenditure of a building in a cool-demand country. Chow T. T. et al. [6] got 28% save in electricity for cooling of a standard office building of Hong Kong in a tropical climate. The energy functioning of the STPV window is also superior to absorptive glass [18, 19].

Dinode E. L. et al. [20] conducted a theoretical investigation using EnergyPlus on the energy-saving possibility of STPV window. In comparison to the simple glaze window, they observed an energy-saving of up to 43% with the STPV window. But it is to be noted that these energy-saving changes with WWR, orientation, and module transparency [21]. For example, when the WWR changes from 20% to 50% for a window system having an STPV module of visible light transmittance 32.7%, the energy-saving changes from 24.8% to 45.6% for the south orientation. For the similar set of the arrangement, the energy-saving changes from 33.7% to 4.9% with a change in orientation from south to north with WWR 30%. Ordenes M. et al. [22] conducted EnergyPlus simulation to investigate the effect of the BIPV plant on the energy demand of Brazillian multi-family dwellings. In the analysis, they found that in a year 30% time, the photovoltaic modules' energy generation suppressed the need for the considered building. The potential of STPV systems in the energy-saving of the building with considerable glazing has been studied by Bahaj A. S. et al. [23]. The investigation was carried out on the buildings of the Middle East, which experiences a harsh climate. Among different technologies, the thin film photovoltaic showed the most effective in energy saving. They also concluded that if very high-efficiency modules are used, the energy generation will exceed the building's cooling demand. Further, an estimate shows that the BIPV systems have the potential to meet up to 22% of the whole electricity utilization of the EU in 2030 [24].

The energy-saving possibility of the STPV window increases with WWR in the high-glazed buildings of the tropical climate [25]. The increase in energy-saving with WWR has also been observed by Olivieri L. et al. [26] in the Mediterranean environment. Compared to the reference glazing; they noticed an energy saving of 18% and 59% with WWR 30% and 88% respectively. In their simulated study, Li Z. et al. [27] also observed the change in energy-saving rate with orientation. The application of solar energy through a passive mechanism is another important area for energy saving in the building. In a case study, Lotfabadi P. et al. [28] observed up to 30% energy saving in the high-rise buildings of London by combining the passive and active mechanisms of solar energy utilization.

The above discussion shows that the energy-saving possibility of BIPV structure changes with many factors. It also changes with many passive/active effects and applied solar technology [29,30]. Therefore, before installing, the STPV systems need to be optimized properly. However, different optimization methods should be considered depending upon the climate of the location and application of the building [7,31]. A summary of the above discussion is given in **Error! Reference source not found.**.

Table 1:

Authors	Type of study	Aim of the study	Important findings	Ref.
Lu L. et. al	Theoretical work	To develop a methodology for overall performance investigation of STPV window	STPV window can block 65% more heat gain compared to clear glass	[12]
Dinode E. L. et al.	Simulation work using EnergyPlus	To study the energy-saving possibility of STPV window	Compared to clear glass, STPV window can save 43% of energy consumption depending upon the orientation and climatic conditions	[20]
Barman S. et. al	Simulation work using EnegyPlus	To examine the overall energy functioning of an STPV window	Energy-saving potential changes 24.8% to 45.6% with WWR, 20% and 50%	[21]
Olivieri L. et al.	Simulation work using EnergyPlus, PVsyst, and COMFEN	To study the energy-saving possibility of STPV windows	Energy-saving potential changes from 18% to 59% with WWR 30% and 88%	[26]
Lotfabadi P. et al.	Simulation work using Autodesk Green Building Studio	To study the influence of PV on the energy load of a building	Combinedly, the passive and active mechanisms of solar technology can save 30% of energy from high-rise buildings	[28]

2.2 Cost and energy payback time

The involvement of many interdependent parameters makes the economic decision of BIPV systems a little complex. Eiffert P. et al. [32] developed a guideline for the selection of the BIPV system under task 7-05:2002, of IEA. In the guideline, the methods for investment, design, and sizing of BIPV systems have been proposed.

According to the guideline, for investment decision-making in the BIPV sector, all conventional methods can be used. However, for designing and sizing a BIPV system, the NPV or LCC provided the more practical outputs. Ng P. K. et al. [33] developed a factor for ease of the design and architecture in selecting the STPV module for building applications. They proposed the concept of NEB. The NEB is the combination of electricity saving in lighting, electricity utilization for room heating and cooling, and energy production due to photovoltaic effects. They also observed that, under certain conditions, the cost of some photovoltaic modules could be less than the conventional double-pane window.

The cost of energy or PBT of STPV systems is a function of many factors. For example, various photovoltaic modules like mono, ribbon silicon, multi silicon, and CdTe are accessible in the market. Each module uses diverse raw resources. The manufacturing processes are different. The energy yields are also different among the modules. Among various modules, the CdTe shows the least LCE [34]. It occurs mainly due to low energy requirements in the production of CdTe photovoltaic module. The EPBT is also observed to be minimum for the CdTe module in another research [35]. However, the EPBT of any technology may vary due to the operating conditions such as shading [36]. Similarly, in the case of PBT calculation, parameters like electricity tariff, energy-saving, trading of CO2 have importance. With CO2 trading, the PBT of BIPV systems could be 10 years [37]. In some other works, the PBT of STPV systems is found to be 15 years or at least less than the life of the technology [38-39].

Kamthania D. et al. studied the functioning of semi-transparent HPVT-DPF in different configurations [40]. They investigated the exergy and energy performance in four different weather settings of Srinagar. The consideration of thermal outputs has been found to be helpful in lessening the embodied energy payback time of the arrangements. Also, among various photovoltaic technology, the HIT has been found to be advantageous with respect to EPF, LCCE, and CO2 mitigation.

Further, the STPV system saves significant building energy consumption. The energy savings can be as large as three times of generation (1:3). Therefore, when energy-saving is considered, the PBT is reduced substantially. In a case study, Radhi H. et al. [41]. found that the EPBT drops from 12-13 to 3- 3.2 years with the consideration of energy saving by the STPV systems in the buildings of UAE. The useful application of the heat generated by the photovoltaic module also improves the economic viability of a BIPV system. Buker M. S. et al. [42] performed a techno-economic evaluation of the roof-integrated photovoltaic system embedded with the polyethylene heat exchanger coil. The polyethylene exchanger for heat observed to be effective in saving the waste heat from the arrangement. In the study, the cost of power generation has been calculated to €0.0778 per kWh using the LCC method.

3. Environmental aspect

Environmental concerns are one of the prime motivational causes for the development of energy technologies using renewable sources . With the increase in energy production from the sources of renewable energy like solar radiation, the emission of harm full GHG is expected to be reduced significantly [35]. Another significant contribution of the photovoltaic system is the reduction of hazardous particulate matters [38]. Therefore, the environmental impact is an essential part of the cost-benefit analysis of STPV systems.

A considerable amount of energy is involved in the manufacturing of photovoltaic modules. For this reason, the energy mix of the PV manufacturing country has a substantial role in the environmental impact assessment of STPV systems [33]. Environmental issues and related development also play a significant role in the STPV system's PBT [39]. An extensive investigation of the environmental influence of the most commonly used solar modules has been performed by Peng J. et al. [15]. The considered solar modules were Mono & multi-Si, amorphous Si, CdTe, and CIS. They obtained the smallest GHG discharge for the CdTe module. In the case of the CdTe module, the GHG emission has been calculated to 10.5–50 gCO_2 equivalents per unit energy production.

4. Conclusions

The study shows that the buildings integrated with STPV window/façade systems have got the immense interest of research towards achieving a low or net-zero energy building. Various researchers have investigated the photovoltaic vertical systems from different points of view. In summary, some of the key findings of the study are as follows.

As far as the cost is concerned, the initial cost of the STPV window/façade is a little high. However, the PBT is less than the device's life. Further, with the advancement of technology, the payback period can be expected to be lower with the passing of time.

Building an integrated STPV system generates electricity at the point of consumption. Thus, it bypasses the loss incurred in transmission and distribution. Further, in the working life, no environmental hazards such as greenhouse gases and particulate matters is contributed by STPV systems.

5. Future research prospects

The application of the STPV module as a part of the building envelope has many advantages in terms of the building's energy and comfort of inhabitants. It also improves the aesthetic appearance of a building. However, there is always an opportunity for the betterment of technology. Some recommendations for further study include:
Application of the bi-facial solar cell with the proper optical arrangement can be an important area of research.
Research on the development of an STPV module using more environmentally friendly materials like organic material with high photovoltaic conversion efficiency is very important.
A vertical BIPV system having control over the intensity, color, and glare of day-lighting can be a key area of research.
Research on real-time data acquisition, analysis, and the action should be endorsed for low-energy-intensive comfort building.

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