Solar Window as an Energy Source : A Patent Study

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***Abstract*—A study on the evolution of solar panels/cells within a window has been carried out within the patent database. This paper is a review of the study on solar window. The retrieved patent records were analysed and categorized into different technologies depending on the technical aspect. Several trends in this technology are studied. A timeline of the solar window technology has been presented based on this study. Block diagrams of solar window have been presented before and after significant technical advancements. Several methods of increasing transparency and ventilation of a solar window are discussed. The paper also examines different optical elements used for concentrating light on the solar cells as part of the light concentration technology. This study helps researchers in the field to be aware of the technology trends and develop further as an alternative to the rooftop panels.**

***Index Terms*—Solar panels, PV windows, Building Integrated Photovoltaic(BIPV)**

I. Introduction

Of late, generation of green electricity has become the first priority for the world countries [1] due to limited non renewable energy resources. Solar energy, being one of the renewable energy sources can be tapped easily to generate electricity.

Major generation of electricity from the sun is through light energy while heat energy is mostly used for heating purposes. One of the main reasons is that the electricity generated from sun light is more (recently achieved efficiency of 46% [2]) than that from the heat (5-8% [3]) till date. Photo-voltaic cells and Dye sensitised solar cells(DSSC) are the two different solar cells used to generate electricity from sunlight. Among these, PV cells are easier to install and maintain, that makes them the most preferred form of generating electricity from solar energy.

Solar rooftop panels are a well known form of tapping solar energy which amounts to 33.73GW of energy by the end of 2019 [4] in India. Rooftop panels is one of the earliest ways of capturing solar energy which is commercialized and installed massively across the world on the top of buildings and open fields. This has been very successful due to its robust deployment and less maintenance cost. However with the increase of high rise buildings, the area of rooftop has been reducing compared to the height of the buildings. Hence, installing solar panels in the windows and walls was thought of. Tapping solar energy from windows was a good idea but basic functions of window like transparency and ventilation posed certain challenges.

Hence, a study based on Solar window technology was carried out to understand the technical advancements in this field. A normal study requires the basic knowledge of all types of literature including patents, journals, conference papers and articles. Patent database is a major and free source of information about the innovations worldwide. A unique technology is first patented to protect from being copied or sold or imported. Later, it would be launched as a product by the patentee or a licensee. Hence, a patent landscape search has been conducted to get a clear picture of the advancements as well as commercialization of the technologies. This paper provides a detailed analysis of several aspects of solar window retrieved through the patents.

Section II gives an overview of the search details and patent trends of solar window. Section III gives an analysis of the timeline of a solar window plotted according to the study in this paper. Section IV gives an in-depth analysis of different approaches to improve efficiency of a solar window. Section V concludes the paper.

II. Search details and Patent trends

An exhaustive search was conducted considering all the relevant keywords and classification codes in appropriate databases like Derwent Innovation, Orbit, Google patents, Espacenet, USPTO, WIPO, KIPRIS, etc. The search has been conducted in December, 2019 and hence, all patent records published till this date have been retrieved. A total of 1019 relevant records were retrieved and analyzed. The type of patent records retrieved were Patent applications, granted patents and Utility model patents(China). (A utility model patent is granted to a product ready to be launched.). Patent documents have been studied thoroughly to understand the novelty of the invention and grouped into a broad technology cluster – Window Design, Shutter/ blind design, Light concentration, Tracking, BIPV(Building Integrated Photo-voltaics), Power usage/Charging. These were again divided into sub-technologies for a deeper analysis. This paper majorly highlights improvements made in Window/shutter design, light concentration, tracking and BIPV. These are the main advancements that escalate the efficiency of a solar window.

A number of patents published per year from the inception of the technology has been depicted in Figure 1. The graph gives an overview of patents filed from the year 2000. The idea of using solar cells in windows has been known since 1977.

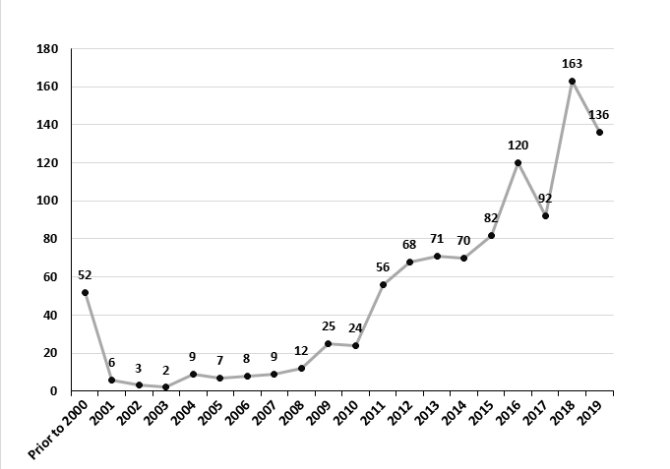


Fig. 1: Year wise Publication trend of Solar window

(In this paper solar cell is used to represent a PV cell for convenience.) The technology has evolved since then consistently, though the number of patent filings per year is less till 1987. From 1998, the patents being filed have been fluctuating from 1-10 in the successive years till 2007, except 2005 where 12 patents have been filed. There is only a maximum of 9 patents published in each year till 2008 as observed from Figure 1. In the year 2009, the government of China has announced a project called Golden Sun to fund several solar projects [5], which attracted many inventors to conduct research in the solar energy field and many investors to commercialize solar products. This might be a major reason for a tip rise in the number of patents being published since 2009, the main contributor to the technology being China. From then on, the published patents has increased significantly and continuously. Patents published in 2019 cannot be retrieved completely due to delay in website updates.

A study on geographic distribution of patent filings under this technology is done. Nearly half of the patent filings originated from China. Korea, US and Japan together contribute to 26% of total patent filings.An analysis on assignees(the owner of a patent) of patent documents has also been studied. The assignee trend revealed that nearly half the documents are filed by companies commercializing the technology and another 40% is shared equally among research universities and individuals.

The following section gives a picture of the timeline of the advancements in solar window.

III. Timeline of Solar Window Technology

The field of solar window technology has undergone significant developments since its beginning. Several milestones of the technology have been presented with respect to the priority years of the patent documents in Figure 2. The technology of solar window in 1977 [6] has started with solar cells embedded in shutter first, surprisingly not in a window. Four years later, the idea of concentrating light [7] on to solar cells has been patented. Immediately in the year 1983,

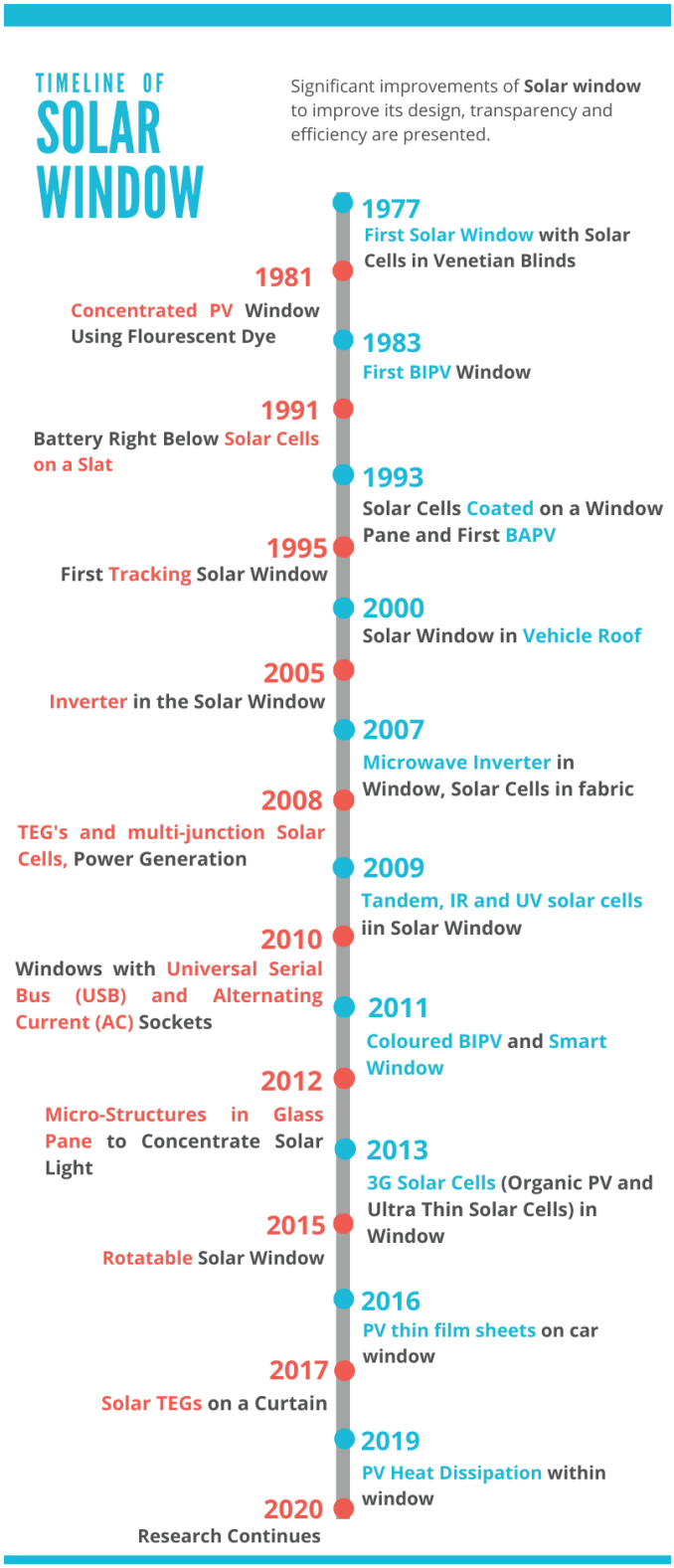


Fig. 2: Timeline of the solar window technology

solar cells were embedded in the window paving a way to the now popular BIPV technology [8], [9]. A battery is integrated within the slat below each solar cell to store the electrical

energy in 1991 [10]. Coatings were proposed to realize solar cells on a window in 1993 [11], while solar cells were till then separate entities attached or fixed to a window pane or shutter slats. Retrofitting of solar cells to a window also was first explored in 1993 [12], which has later evolved into a new technology called BAPV (Building Applied PV). BAPV is a technology where ready-made sheets/glasses with solar cells can be attached to a conventional window that converts it to a solar window.

The year 1995 has seen a major development where solar cells would track the sun to optimize electricity generation [13]. By the end of the millennium, the solar cells were also used in vehicle roofs of four wheeled vehicles [14]. It has been observed that major developmental areas like Tracking, Light concentration, BIPV and BAPV have been already pioneered by the beginning of this century. All the milestones in the later years were predominantly technical advancements in these fields.

The year 2005 has seen the inclusion of an inverter in to solar window field [15]. Two years later, a micro inverter was incorporated within the window frame [16] which had reduced the space requirement for an inverter and made solar window more operational. In 2008-09, second generation solar cells like Multi-junction or tandem solar cells [17], [18] helped in absorbing light of different wavelengths to generate electric power. Multi-junction solar cells consist of multiple p-n junctions, each absorbing photons of a specific band gap. Thus, photons of multiple wavelengths or multiple energies can be absorbed, providing better efficiency compared to a single junction solar cell [17]. Also, solar cells which utilize Infrared [19] and Ultraviolet [20] wavelengths to generate power have been integrated into a window in 2009. Charging outlets and a.c. power sockets has become common from the year 2010 [21], [22]. Solar cells were used as a source to power smart windows which include electrochromic layers and multimedia embedded in a window [23]. The technology of light concentration has seen a major development where micro structures were used to concentrate light [24]. Micro-structures are small pores made in the glass pane of a window which help in refracting light falling on them that guide the light to solar cells. This avoids other objects like prisms, dichroic mirrors being explicitly inserted in the glass panes. Using third generation solar cells like Organic PV [25], Quantum dot technology [26] is trending now in the field, as they offer several advantages like transparency, high absorption efficiency and power efficiency, etc. After 16 years of installing solar panel on vehicle roof, Mitsubishi has invented vehicle solar window with thin sheets of PV cells on the car window [27]. In 2017, solar TEGs were embedded in a foldable curtain [28] to generate electricity. Ventilation cavities, arranged to dissipate heat generated from the solar panels of a window, were claimed in a patent application [29] filed in 2019.

Section IV discusses the architecture of a conventional solar window and an advanced version of the same. Also, the section throws some light on major advancements that helped in improving efficiencies such as Window/shutter design, Light concentration and tracking.

IV. Solar window technology

This section provides an in depth analysis of different parts or methods of achieving efficiency from the window. Improvements made in the solar window are studied over the years and some major observations were made depending on the overall technology. An effort of representing a solar window as a block diagram is made for a better understanding of further analysis. During the inception, the block diagram of a typical solar window was as shown in Figure 3. However, from the study of the retrieved patents, it was observed that the technology has gone through significant changes to improve the efficiency and also cater to the power needs of the changing world. Thus, the block diagram of a typical solar window at present can be represented as shown in Figure 4.

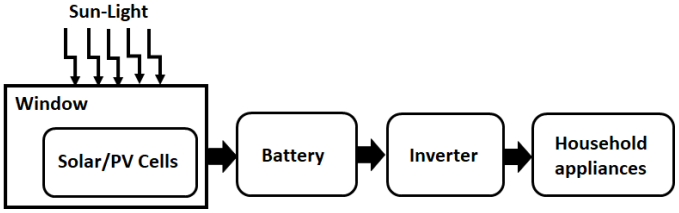


Fig. 3: Block diagram of a Traditional Solar Window

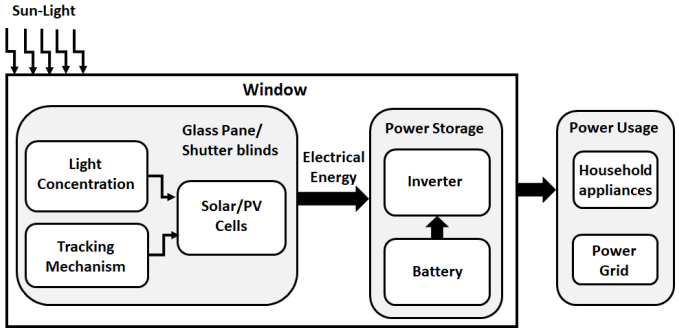


Fig. 4: Block diagram of an Advanced Solar Window

Earlier, the sunlight was incident on solar cells disposed on a window pane or a shutter blind, which would generate electricity and is used for household purposes to obtain partial independence from the power grid. But, capturing 100% of light energy incident on a solar cell into electrical energy is difficult, since the efficiency of a typical solar cell is only 46% [2]. Also, installing solar cells all over the window would interfere with the visibility through the window. Thus, Optical elements or layers are used to improve efficiency and also to provide better transparency, leading to a new advancement called Light concentration. These layers or optical elements are used to collect the light incident on them and direct it onto solar cells placed at selected locations on a window. Also, as the sun's inclination angle changes in a day, the electricity generation also is changed. The well known tracking mechanism improved the efficiency of the solar window in

this perspective. Thus, Light concentration and Tracking are two primary technologies helping in improving the efficiency of a solar cell in a window. The energy from the solar cells is converted to a.c. power and provided to the power grid in the recent years. Apart from these two advancements, the patent records are also categorized into window/shutter design. Such records made significant changes in the design of a window or a shutter to generate electricity. Subsection IV-A gives an overview of Window/Shutter design patent documents. Subsection IV-B gives a detailed analysis of light concentration and tracking.

A. Window/ Shutter design

Transparency and ventilation are two vital functions of a window. Traditional windows used crystalline Silicon solar cells installed on them, which made the windows opaque. Inventors concerning about the transparency of a window have evolved with different methods of achieving it.

Translucency (semi-transparency) is achieved using Dichroic mirrors [30] and parabolic lenses [31], which let in some part of the light and trap the other part of light on to solar cells placed within the window panes. Complete transparency was achieved earlier by placing solar cells in the parts other than glass panes of a window since the solar cells were of opaque nature being made of crystalline Silicon [32], [33] and [34]. Second generation solar cells made up of materials like amorphous Silicon, CdTe (Cadmium Telluride) and multi-junction would be deposited on glass substrates to make the glass look transparent. [35], [36] and [37] have proposed installing transparent solar cells in windows. Another way of making the solar window transparent is to use Infra-red [38] or Ultra-violet [39] light to generate electricity and pass the visible light into the insides of the building.

Solar cells in blinds have been used by embedding them within the slats in 1977 [6] or placing them on the glass blinds in [40] till 2000. In 2000, solar cells have been used on the rooftop of a vehicle [14]. MEMS (Micro Electro Mechanical Systems) have been used to design shutter blinds in [41] in 2005. The first generation solar cells which are made up of crystalline Silicon were hard enough to be used on foldable curtains and roll screens. With the invention of flexible thin film solar cells, [42], [43] have proposed using them in roll screens form 2009.

Building Integrated Photovoltaic (BIPV) has also been evolving since 1983, where glasses installed with solar cells can replace existing glass windows. Also, solar cells can be retrofitted on the existing windows, shutters or curtains. Tom Van Cauwenberghe [44] had filed a patent application of deploying solar cells within the mesh holes of a fabric that can be used as a shutter or sunshade. Tandem solar cells which help in absorbing different wavelengths of sunlight (unlike the normal solar cells which can make use of only one wavelength to produce electricity) were also placed between two glass panes to make the best use of visible spectrum in the patent document [18]. Inventors of [45] have patented a BIPV window which reflects colours for visual appeal, a technology called Colored BIPV.

TABLE I: Optical components used for Light concentration

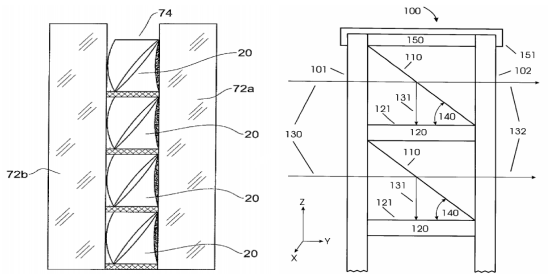
Optical element	Type of optical element
Prisms	1. Standard prisms [47] 2. Prism pairs- Triangular [48] and Curved [49] 3. Hexagonal prisms [50] 4. Brewster's Tetrahedrons [51]
Lenses	1. Parabolic lenses [31] 2. Liquid lenses [52]
Mirrors	Dichroic mirrors [30]
Structural elements	1. Slits [53] 2. Photonic crystals [54] 3. V-grooves [55] and V-grooves with cylindrical lenses [56] 4. Micro structures [24] 5. Angle selective reflectors [57] 6. Optical elements with Bifacial solar cells [33] 7.Quantum dots [26]

B. Light concentration and Tracking

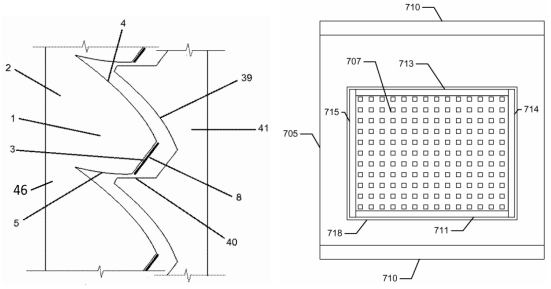
Installing solar cells in windows poses issues like overheating of solar panels arise [46] that reduce efficiency. To address such issues, incorporating solar cells all through the area of a window pane is avoided by Light concentration. It is a method of concentrating and guiding light falling on the window pane towards the solar cells.

Table I and Figure 5 show different types of optical elements used in Light concentration technology. Four different deployments of prisms were proposed in windows. [47] proposes a solution of using an array of prisms installed on the window pane. These elements concentrate the light falling on them to a solar cell attached to each prism. The prisms helped in trapping light which does not fall on the solar cells. The angle of this array can be controlled to let in light for transparency. [48] proposes the use of an array of a pair of triangular prisms arranged upside down. Such an arrangement helps in capturing light rays which may escape through one prism by the other. [49], as shown in Fig.5(a), further improvised this arrangement by changing the sides of the prism to concave and/or convex. This further supports the capture of light rays incident in other angles compared to a plain surface. The curved pair of prisms, one with a convex side and the other with a concave side, help in converging light on the solar cell. Dichroic mirror is another optical element that splits the light beam into two perpendicular components. In the invention protected in [30], Dichroic mirrors are arranged at an acute angle as shown in Fig.5(b), which allows some part of light to incident on solar cell arranged below the mirror horizontally and the other part of light to enter the inside of the building. The use here achieves light concentration as well as color appeal to the window. [51] proposed the use of Brewster's tetrahedrons arranged one over the other (upside down). Solar cells are placed at the bottom of this arrangement for capturing the rays from the Tetrahedrons. [31] discusses an arrangement of Parabolic lenses as shown in Fig.5(c). A solar cell is arranged

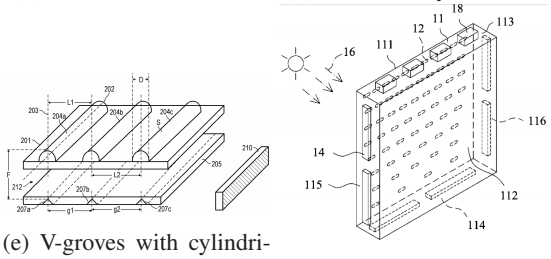
at the base of each parabolic lens to concentrate light. When the light beam is incident on the parabolic lens, a part of it is refracted on to the solar cells and the remaining part is transmitted through the window. [52] explores a way of collecting the light through liquid lenses.



(a) Curved prism pairs [49] (b) Dichroic mirrors [30]



(c) Parabolic lenses [31] (d) Photonic crystals [54]



(e) V-groves with cylindrical lenses [56] (f) Microstructures [24]

Fig. 5: Different optical elements used for Light concentration

[53] proposes a simple concept of making slits within the glass pane. These slits help in refracting the light rays onto the solar cells. [54] and [26] propose the use of photonic crystals and the well-known quantum dots used in TV screens in recent times. Photonic crystals are nano-particles that forbid propagation of certain frequencies of light. Fig.5(d) depicts a window including photonic crystals [54] where, the light with forbidden frequencies is used to generate electricity, while the other part of the light is passed through for transparency of the window. Quantum dots are also nano-particles which emit different colors when UV rays are incident on them. [55] and [24] solve this problem by embossing v-grooves within the glass pane, which help in refracting and reflecting light falling on them onto solar cells. [55] improvises this method by placing cylindrical lenses at the top of V-grooves which further reduces escape of light rays. The cylindrical lenses collect the light and direct it on to the v-groves. The v-groves, act as light guiding layer, further refract/reflect the light on to solar cells at the edge of the window. Light concentration mechanism of [57] consists of two arrays of reflectors arranged opposite to each other in a double glazing window pane. The two reflector planes guide the incident light by reflecting onto each other and finally redirecting it to the solar cell placed at the bottom of the window. [33] proposes an array of reflectors placed on 2/3rds of the window pane. The bottom 1/3rd of the window pane is arranged with Bifacial solar cells. These solar cells can capture light rays from both sides of the cell, while a normal solar cell only captures one side of light. Fig.5(f) displays several micro-structures made in a glass pane [24]. The micro-structures made in the glass pane act as light guide layer by refracting a portion of light on the solar cells and the other portion of light inside the window.

One more way of increasing the efficiency of a solar window is to place the solar cells in the optimum angle of reception by tracking the sun. Solar cells embedded in the window change the angle depending on the incident angle of the sun's rays to increase the amount of energy absorbed. It has been observed that a tracking solar window was filed in 1995 for the first time [13]. Different ways of calculating angle of the sun by the intensity of light [58], geographical location [59], temperature [60] and solar altitude [61] for tracking. The following section concludes the paper.

V. Conclusion

A patent study is carried out for solar window technology as an energy source. China, Republic of Korea, United States and Japan are found to be the major countries to contribute the research and development in this technology. Most of the research is carried out in the shutter/ blind design and window design technologies that use PV cell for electricity generation. Transparency of a solar window is improved using specific types of solar cells and other optical elements. Light concentration technology helped in reducing the number of solar cells in a window, thereby improving transparency. This is achieved by using elements like prisms and lenses or spray-on coatings or layers on the glass pane. Advanced technologies like quantum dot and photonic crystals are also incorporated and patented. A few patents on electrochromic windows reveal the application of solar windows for advertising in recent years. Flexible solar cells improved the deployment in rolling shutters. Solar windows have become more concise with the advent of VLSI and nanotechnology. Retrofitting has reduced installation cost by converting conventional window into a solar window.

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