A Review on Semitransparent Solar Cells for Real-Life Applications Based on Dye-Sensitized Technology

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***Abstract*—A dye-sensitized solar cell (DSSC) is one of the emerging photovoltaic technologies that shows promising prospects in the commercial applications because of its semitransparency, low manufacturing cost, facile fabrication procedures, and good performance under low-light conditions. Despite the aforementioned advantages of DSSC technology, the transition from laboratory to industrial applications is hindered by several major obstacles. This article aims to explore the potential of DSSC technology in real-life applications, namely, building-integrated photovoltaic, indoor energy harvesting, and smart farming, and the research challenges that must be overcome to pave the way for DSSC commercialization. The challenges can be categorized into the long-term stability issue and difficulty related to the scale-up processes. This article also presents insights into the potentials of DSSCs in smart farming and controlled-environment agriculture, which were never been reported before.**

***Index Terms*—Building-integrated photovoltaic (BIPV), dye-sensitized solar cell (DSSC), indoor energy harvesting, smart farming.**

I. Introduction

SINCE the pioneering work of O'Regan and Grätzel in 1991 [1], the dye-sensitized solar cells (DSSCs) have garnered substantial interest from the researchers worldwide owing to the various attractive features offered by DSSCs. DSSCs have the edge over the conventional silicon-based photovoltaic (PV) devices in terms of low cost, semitransparent, ease of fabrication, and operable under low-light condition [2], [3]. In particular, the semitransparency of DSSC makes it a promising candidate for fenestration in buildings [4], [5]. Generally, a conventional DSSC comprises four components, namely the semiconducting metal oxide as photoanode, dye or sensitizer, electrolyte, and the counterelectrode, as depicted in Fig. 1. When the DSSC is exposed to the sunlight, the photoexcited dye molecules inject the electrons into the conduction band of the photoanode. The electrons diffuse across the photoanode to the external load before reaching the counterelectrode. The oxidized dye molecule is reduced to the ground state by electron transfer from the redox couple (i.e., iodide/triiodide couple) present in the electrolyte. The oxidized mediator is in turn reduced at the counterelectrode [6]. The transparent conducting oxides (TCOs), such as fluorine-doped tin oxide and indium tin oxide (ITO), are used for the fabrication of both photoanode and counterelectrode. One of the DSSC electrodes has to be transparent to allow the sunlight to pass through, but the high transparency of a complete cell can be added value for the commercial application [7]. The thickness of the photoanode has a significant influence on the PV performance of DSSC, as the increased film thickness can improve the dye loading and light harvesting efficiency [8]. However, when the thickness exceeds the optimum value (typically in the range of 10–12 μm [9], [10]), the cell efficiency decreases because of the increased electron transport resistance that arises from the longer travel distance of photoexcited electrons [8], [11].

Envisaging the upscaling of DSSC technology, the assembly of individual cells into large modules is required to generate a high voltage that can meet the desired power requirements. Several architectures have been devised for DSSC modules, as shown in Fig. 2, including architectures with a series connection, namely *Z*-type [12], *W*-type [13], and monolithic [14] connections or parallel connection [15]. Generally, series-connected modules can deliver a high voltage but low-current output, while parallel-connected modules can generate a high current but low-voltage output [16]. Besides exhibiting a lower power conversion efficiency (PCE) than the laboratory-scale DSSC, the DSSC modules are prone to a long-term stability issue. The highest PCE reported for the DSSC module is 8.4%, which is much lower than that of the laboratory-scale DSSC ($>$14%) [17]. The comparatively lower performance of DSSC modules is mainly ascribed to the lack of investigation toward the device engineering of DSSC modules. While a significant amount of research has been undertaken to optimize the laboratory-scale DSSC, the amount of research on large area DSSC modules is merely $\sim$1% of that on DSSC [18]. Therefore, in Section II, we will be reviewing the real-life emerging potentials of DSSC technologies as well as the commercialization challenges posed by the DSSC technologies.

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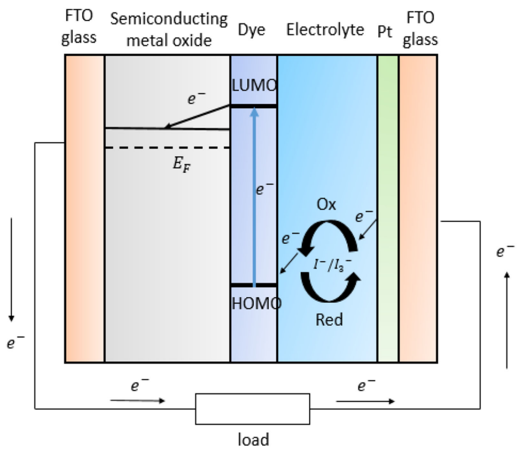

Fig. 1. Schematic view energy band diagram of a DSSC [6].

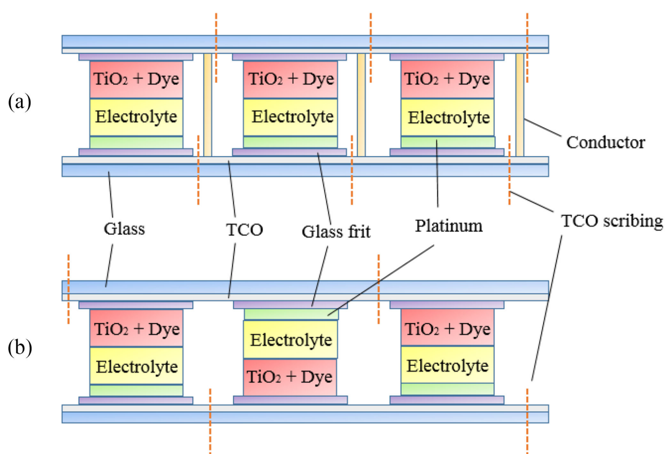

Fig. 2. DSSC module with (a) *Z*-configuration and (b) *W*-configuration [13].

II. Real-Life Applications

A. Building-Integrated Photovoltaic Applications (BIPV)

Because of the semitransparency and tunable color properties of the DSSC module, it is suitable to be utilized for the BIPV application. In definition, BIPVs are PV technologies that can substitute the conventional building structures as parts of the fenestrations, such as roof tiles, wall cladding, or skylight. Besides electricity generation, PV facade is cheaper to construct compared with the conventional building facade, while providing a modern and attractive appearance [19]. There are several conventional and emergent BIPV technologies that exist in the market, as shown in Fig. 3. The prototypes of DSSC modules in BIPV applications have been developed by several industrial entities, such as Dyesol, Dyepower, and CSIRO. The application of large-scale DSSCs in BIPV was also demonstrated in several prominent architectures, namely, the SwissTech Convention Centre in Lausanne, Switzerland, and Science Tower in Graz, Austria. It was reported that DSSC is less sensitive to the angle of incidence and temperature compared with the conventional PV cells [20] and can even achieve higher PCE when operating at an increased temperature [21].

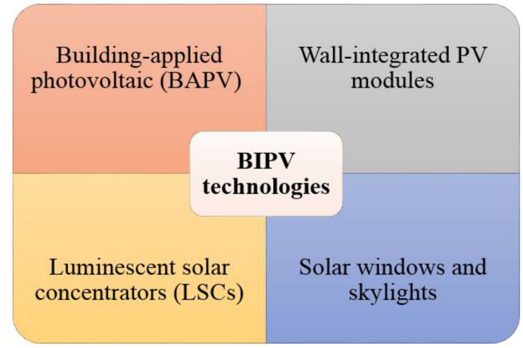

Fig. 3. Conventional and emergent BIPV technologies [22].

According to the report from the World Energy Council, the buildings consume approximately 34% of the energy demand as well as being responsible for greenhouse gas (GHG) emissions. To alleviate the adverse effect of GHG emissions, the concept of energy-efficient buildings was introduced. In modern architecture, the building facade has a significant impact on reducing the building's energy consumption in terms of lighting requirement as well as heating and cooling loads by controlling the amount of light transmitted [23]. In the BIPV system, the increment in transmittance typically results in the decrement of lighting and heating loads but demonstrates an increase in cooling loads. Therefore, the degree of transparency of the PV window should be carefully chosen while evaluating their efficiency [24]. Compared with the opaque c-Si, glass DSSC technology has the distinct advantage of enabling the power-generating unit to be semitransparent. Furthermore, the transparency versus efficiency of the DSSC modules is tunable depending on the color and energy requirements [4]. The building glazing application of DSSC was studied by Selvaraj *et al.* [25], which demonstrated that the 37% transparent DSSC glazing can provide 21% more reduction in disturbing glare compared with double glazing. This result suggests the potential of DSSC glazing in building retrofit to improve the energy efficiency. Lee and Yoon [19] demonstrated that the sloped DSSC windows can generate 43.38% higher amount of power yield compared with the vertical DSSC windows, which showed that the installation angle has a significant influence on the power yield of the DSSC windows. The higher power yield of the sloped plane was because of its larger sky view factor and higher diffuse radiation than the vertical plane [19]. A study from Yuan *et al.* [26] showed that DSSC based on ruthenium dye Z991 achieved a higher efficiency than dye Z907. Besides, the DSSC BIPV can generate more electricity than the pc-Si cell, especially under high temperature and low irradiance. The results showed the potential of DSSCs in outdoor BIPV, particularly in the hot climate.

The DSSC modules integrated into buildings require challenging lifetimes exceeding 15–20 years [18]. Perfecting the encapsulation of DSSC modules is one of the main challenges that has to be overcome for the long-term operation in the BIPV application. Until present, the longest outdoor test of DSSCs for BIPV was merely four years [26]. Moreover, vertically mounted BIPV modules are subjected to a partial shading issue. The partial shadowing phenomena can be triggered by several conditions, such as the presence of neighboring buildings, different irradiance levels because of different orientations, or environmental factors, e.g., tree shadow and moving clouds [27]. From the MATLAB/Simulink simulation, a 30% reduction in the output power of a PV module was observed by the total shadowing of merely a single solar cell [28]. The power loss of PV modules was because of the variation of series and shunt resistance resulted from shadowing. To resolve the shading issue, the implementation of the current bypass feature is needed. However, the integration of bypass diodes in BIPV inevitably affects its aesthetic value, i.e., window's transparency [29].

B. Indoor Energy Harvesting Applications

The solar cell market can be divided into two sectors, one is the module installations for terrestrial power generation, and the other one is the portable electronics' applications by using smaller modules [30]. DSSCs are particularly attractive for the second category because of their outstanding performance under indoor conditions compared with other solar cell technologies [31]. The indoor lighting condition is vastly different from the outdoor lighting. The light intensity in the outdoor environment is standardized as AM 1.5G or corresponds to 100 mWcm^{-2}, which is defined as 1 Sun illumination. A significant portion of the solar spectrum is located in the red visible region and at the near-infrared wavelengths, which is more suitable for the crystalline silicon or gallium arsenide-based solar cells that have a string spectral response in this wavelength domain [32]. Conversely, the indoor lighting has a much lower light intensity (100–1000× lower) and diffuses easily [33]. The indoor lightings, including fluorescent light, light-emitting diodes (LEDs), and incandescent light, have wavelengths in the range of 400–700 nm, which mostly concentrate in the visible region [34]. Various portable small electronic devices can be powered by the indoor lighting, as shown in Fig. 4.

The performance of DSSCs under ambient or low-light condition has been investigated by several research groups [35]. Interestingly, most of the DSSCs can achieve higher PCE under the low-light condition compared with the standard AM 1.5G illumination. Freitag *et al.* [36] demonstrated that the DSSC based on D35:XY1 dye with copper-based redox system can achieve PCE of 28.9% under 1000 lx indoor illumination, which was much higher than 11.3% under AM 1.5G illumination. The PV performance of anthracene-based DSSCs under the T5 fluorescent illumination with the lux intensity from 300 to 6000 lx was studied by Tingare *et al.* [37]. A linear increase in PCE from 21.40% to 28.56% was observed when the lux intensity increased from 300 to 6000 lx. All above-mentioned results suggest the promising prospects of DSSCs in the energy harvesting application in buildings in which the ambient light sources are converted into electrical energy to operate low-power electronic devices [38]. The capability of DSSCs to work well under the low-light condition compared with the traditional silicon-based solar cells can be attributed to the favorable

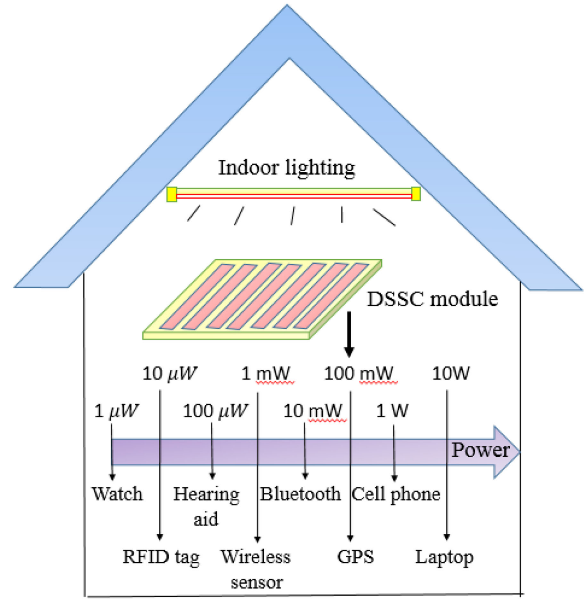

Fig. 4. Power requirements of various portable small electronic devices for indoor energy harvesting application [45].

"differential kinetics" present in the DSSCs [39]. In silicon-based solar cells, the electron is "promoted" within the original crystal upon the absorption of photons. When the light intensity is low, the recombination rate becomes higher because of the lower production rate of the high-energy electron, which results in a "cutoff" at a certain low level of illumination. On the contrary, the processes of light harvesting and charge carrier transport are separated in DSSCs [40], and hence, the recombination rate is low even under the low-light condition.

In 2009, G24 innovations created the world's first commercial products based on the DSSC technology, which were the backpacks and bags integrated with DSSC modules. The integrated DSSC modules can harvest energy even under indoor low-light conditions to recharge the mobile electronic devices [41]. Ricoh Company, Ltd., has developed a solid-state DSSC module that is integrated into the energy-generating desk to charge the mobile devices as a part of a sustainable office furniture range [42]. Buraidah *et al.* [43] from the University of Malaya reported the fabrication of DSSC modules in series connection with the PCE of 6.2%, which were used to power small decorative display items. The fabrication of flexible DSSC modules that use ITO/PEN film as a substrate has been reported by Wu *et al.* [44] and demonstrated for the cell phone charging application under ambient light.

C. Smart Farming

The agricultural production is dominated by the traditional open-field farming, despite its inconsistent yield because of the unpredictable weather patterns and geographical concerns [46]. In recent years, the issues of food security and agricultural productivity are further complicated by the climate change and

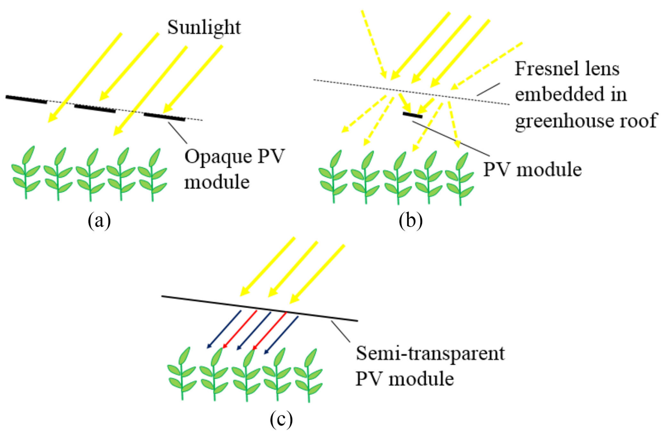

Fig. 5. Schematics of the various PV greenhouse concepts. (a) Partial shading with the opaque PV module. (b) Fresnel-lens greenhouse roofs to focus the direct light. (c) Semitransparent PV module [49].

human-induced environmental destruction, such as urbanization, deforestation, desertification, and salinization [47]. One of the solutions lies in the emerging greenhouse cultivation that allows the optimal growth for crops even in harsh circumstances. Typically, the greenhouse environmental control elements involve light, humidity, temperature, nutrients, and carbon dioxide, which entails the consumption of large amounts of energy [48]. A majority of the modern greenhouses depend on the burning of fossil fuels for electricity generation, which raise concerns about the GHG emission and associated global warming issue [46]. Consequently, it is highly desirable to look for a renewable energy source to sustain the development of the modern greenhouse. Several PV greenhouse concepts have been implemented, as shown in Fig. 5 [49]. The partial shading methodology [see Fig. 5(a)] has been applied to both crystalline silicon and thin-film PV modules. However, there is a limitation to the coverage of the PV module in order not to negatively impact the plant growth because of the decreased exposure to sunlight [50]. In the second approach [see Fig. 5(b)], a Fresnel lens is used to focus the direct light for PV generation, while the diffuse light can pass through and reach the plants [51]. The use of semitransparent PV modules, as shown in the third approach [see Fig. 5(c)], can optimize the light usage for the photosynthesis process, while the unused wavelengths can be harnessed for PV generation.

The semitransparent and color-tunable DSSCs are ideal for the greenhouse application [52]. The colors of DSSCs are tunable by the types of the dyes used, and hence, the DSSCs can serve as photoselective coverings or plant growth regulators by manipulating the light spectrum that can enter the greenhouse, which allows optimized plant growth [53]. The adjustable transparency of DSSCs can also minimize the negative impacts on crop growth compared with the opaque silicon-based PV. The permanent shadow zones projected by opaque PV roofs result in a poorly lit environment, which is detrimental for heliophiles' growth [46]. On the other hand, the semitransparent DSSCs can shade just a portion of incident sunlight while maintaining a uniform light distribution in the greenhouse [53]. Besides serving as shading for the greenhouse, the DSSC modules can also harvest the sunlight to generate electricity for greenhouse operations or can be integrated into smart farming in the rural area [54]. Smart farming involves the integration of advanced information and communication technology, such as the Internet of things (IoT) and cloud computing, in existing farming practices to improve the agricultural product quality and production efficiency [55]. The automated farm systems, for instance, can monitor the environmental condition and control the wireless sensors and actuators by collecting the data through wireless access networks [56]. The electricity generated from the DSSC modules can be utilized to energize various sensors (soil moisture sensor, temperature sensor, humidity sensor, etc.) as well as IoT setup (Wi-Fi modules and long-range devices), which require a low-power consumption. Besides reducing the reliance on fossil fuels for electricity generation, the DSSC modules also allow local electricity generation, in particular, in the area where the energy access is lacking, such as the rural and decentralized territories. The off-grid PV modules can eliminate the trouble of having to install the electrical grid in the rural farming area for the realization of smart farming. Sygkridou and Stathatos [57] demonstrated the implementation of DSSC panels in the 100 m^2 greenhouse prototype with hydroponic tomato cultivation. The results showed that the DSSC panels reduced the energy operating costs of the greenhouse up to 25% and enabled better crop growth because of its high optical transmittance compared with other PV technologies. Besides, the UV-blocking property of DSSC panels also led to reduced fungal diseases and insect populations, and hence reducing the use of pesticide.

DSSC modules can also be used to power up the LED grow lights for indoor vertical farming or controlled-environment agriculture (CEA) to improve the farming production. In the past decade, CEA has rapidly evolved because of the advent of high efficiency and spectrum-specific LED grow lights as well as computer-assisted control systems for monitoring the growth of the crop through the adjustment of the temperature, pH, and oxygen content of the nutrient solution [58]. The high performance of DSSC modules in indoor energy harvesting compared with other PV technologies makes it a promising candidate for powering the LED grow lights used for indoor farming. Ramadoss *et al.* [59] designed a self-powered system comprised of DSSCs, LED, and fiber supercapacitor. In this system, the electrical energy generated from DSSCs is stored in the fiber supercapacitor, which allows the continuous operation of LED without disruption. Lee *et al.* [60] developed an auxiliary power system to ship the LED lights by using DSSCs as the charging system, and the obtained environmental test results were promising.

III. Challenges in the Commercialization of DSSC

There are several challenges faced by DSSC that have to be addressed in order to become an economically viable technology and, thus, realizing the commercialization of DSSC. In spite of the substantial research over the past 30 years, the slow progress on improving the long-term stability of DSSC and the difficulty related to the scale-up processes hinder the commercial production of DSSC [61], which are discussed in detail in Section III-A.

A. Degradation of DSSC

While a significant amount of research efforts have been dedicated to the improvement of DSSC performance through the optimization of DSSC components, the long-term stability issue of the DSSC is generally neglected [62]. In order to prolong the DSSC lifetime to be competitive with the silicon technology, understanding of the degradation mechanisms in DSSC is essential. The DSSC degradation can be attributed to several factors, which include the leakage issue of the electrolyte, decreasing I_3^- concentration, the instability of Pt in the electrolyte, and issues related to the improper sealing [63].

The stability of the DSSC is compromised by the usage of liquid electrolyte, which is a crucial DSSC component that governs the charge transport between two electrodes and regenerates the sensitizer. The most commonly employed electrolyte in DSSC is the iodide/triiodide (I^-/I_3^-) redox couple in an organic solvent (i.e., acetonitrile). However, the low-viscosity liquid electrolyte is prone to leakage and bleaching issues [61]. The bleaching phenomenon is caused by the decrease in the I_3^- concentration, which results in color change from yellow to colorless liquid [61]. Kontos *et al.* [64] showed that the loss of I_3^- was the main factor that resulted in a significant deterioration of DSSC performance under thermal aging. Moving from volatile liquid electrolyte to solid-state electrolyte is required to avoid the instability issues. The solid-state DSSC was first demonstrated by Bach *et al.* [65] by using 2,2',7,7'-tetrakis-(N,N-di-p-methoxyphenylamine)9,9'-spirobifluorene (spiro-OMeTAD) as a hole transport material (HTM). Since then, spiro-OMeTAD becomes the standard HTM for various solid-state technologies, including the perovskite solar cell with η that exceeds 25% [66]. Because of its high-cost concern, several alternatives to spiro-OMeTAD were investigated, such as CuSCN [67], CuI [68], and Cs_2SnI_6 [69]. Nevertheless, most of the solid-state DSSCs based on organic HTMs have lower PCE because of the high charge recombination rate from TiO_2 to HTMs, low intrinsic conductivities of HTMs, and poor electronic contact between HTMs and dye molecules because of the incomplete penetration of solid HTMs into the TiO_2 matrix [70]. Quasi-solid-state DSSCs based on gel electrolytes can also overcome the leaking and sealing issues resulted from liquid electrolytes. In addition, gel electrolytes can provide a good electronic contact as they have excellent TiO_2 pore filling properties [71]. The high viscosity of gel electrolytes also makes them compatible with roll-to-roll processing [72], which is important for the manufacturing of DSSC modules.

The degradation of the counterelectrode is one of the major issues for the DSSC integration. Typically, Pt is the most common catalyst material for electrode coating because of its excellent electrocatalytic performance and high electrical conductivity for the I^-/I_3^- redox reaction [73]. Nevertheless, it was found that the Pt coatings are not chemically stable in the iodide/triiodide-based electrolyte, which can corrode Pt and lead to the formation of PtI_4 [74]. Besides, as a noble precious metal, Pt is expensive and rare [75]. Several alternatives have been investigated as replacement for Pt in DSSC, which include Ag sulfides [76]–[78], iron diselenide ($FeSe_2$) [79], [80], polyaniline (PANI) [81], [82], graphene [83], poly(34-ethylenedioxythiophene) (PEDOT) [84], and carbonyl sulfide (CoS) [85]. Among these materials, only the spray-coated graphene has been demonstrated for the large-scale DSSC module application [86]. Nonetheless, the η of the DSSC modules based on graphene counterelectrode is generally lower than the Pt counterelectrode, and further optimization is required to realize Pt-free DSSC modules. In order to improve the transparency of the counterelectrode based on metal sulfides, one of the possible solutions is to utilize the semiconductor heterojunction to enhance the catalytic activity of single active sites to reduce its dosage [87], [88].

The DSSC stability depends heavily upon the sealing and encapsulation to avoid the electrolyte leakage and moisture ingress [63]. The sealing material is also important to protect the conductor grid from the highly reactive electrolyte [89]. Ideally, a good sealing material must be chemically inert against the electrolyte and able to maintain its chemical and mechanical stability under various test conditions. Glass frit is one of the common sealing materials used for the glass-based DSSC modules to confine the electrolyte and to avoid ion transport between cells [12]. It has stable thermal, chemical, and mechanical properties and can be conveniently deposited on the photoanode via screen printing [90]. Sastrawan *et al.* [12] reported the fabrication of glass-frit sealed DSSC modules (30×30 cm^2) with good thermal stability by undergoing the thermal cycling test from −40 °C to 80 °C. Nevertheless, it requires a high processing temperature (>600 °C) and, thus, it cannot be applied for the low-temperature roll-to-roll process [61]. Besides, the high processing temperature would degrade the dye, and hence, the sealing process has to be performed before the dye loading by injection through fill holes [91]. A typical low-temperature solution is the Surlyn thermoplastic film, which can be easily cured with a hotplate or hot iron at 170 °C [91]. However, the Surlyn film is not suitable for outdoor application as it has a low softening temperature and cannot withstand the temperature of more than 60 °C [61].

B. Upscaling of DSSC

The upscaling of module dimensions to meet the power requirements is another main challenge faced by the DSSC technology. [44]. In order to commercialize the DSSC technology, scalability and durability are the two primary aspects that need to be addressed. Generally, the fabrication of the DSSC module involves additional processing steps that are not factored in the fabrication of the laboratory-scale cell, which includes the following:

1) interconnection (series or parallel) and external electrical connections;
2) extensive sealing to prevent electrolyte leakage and moisture ingress;
3) coating of large-scale metal oxide on TCOs;
4) electrolyte filling; and
5) most importantly, anticipated device lifetime that is comparable with the conventional silicon-based PV technologies [18].

Therefore, there is a challenge to maintain the cell efficiency as the DSSC module is constructed with a large amount of interconnected cells in the series or parallel architecture. Several research groups have attempted to address the challenges related to the upscaling of DSSC, such as the fabrication of DSSC module with efficiency up to 8.2% by adopting the *W*-type interconnection [13], the development of solid-state DSSC module to prolong device lifetimes [92], [93], and the emergence of a flexible DSSC module that is more suitable for mass production [44], [94]. Nevertheless, there is still a gap in between the reported performance and the application requirement.

IV. Conclusion and Future Prospects

The semitransparency and tunable color properties of DSSC modules make it an ideal candidate for various applications that are difficult to be achieved through the use of the conventional opaque silicon-based solar modules. In the BIPV application, the DSSC modules can be used to replace the building envelope while generating electricity for the operation of the whole building. The same concept can be applied to the smart farming in which the DSSC modules act as the photoselective coverings for the greenhouse, while the electricity generated can be utilized to energize various sensors and IoT setup. The DSSC modules can also be utilized in the indoor energy harvesting application to power up various portable electronic devices because of their ability to operate under the low-light condition.

Apart from the three main applications as discussed in this review, there are several interesting prospects of DSSCs that are worth further investigation. First is the combination of DSSC with the electrochromic device (ECD) to form the photo-ECD (PECD) as a new design paradigm for smart windows [95], [96]. The PECD architecture comprises of dye-anchored TiO_2 nanostructured film deposited onto the WO_3 layer as the working electrode, Pt film as the counterelectrode, and an electrolyte in between both electrodes. In this architecture, the DSSC provides the electrical energy to power the ECD, which realizes a self-powered operation. Another potential application of DSSC is its integration with absorption refrigerator to thermally harness the high wavelength sunlight for power and cooling cogeneration [97]. In addition, DSSC can also be used in autonomous wireless sensing applications to power a wide range of building management system sensors by harvesting the artificial lighting [98]. Nevertheless, in order to realize the widespread commercialization of the DSSC modules in real-life applications, it is essential to further improve the PCE and stability of the DSSC modules as well as resolving the up-scaling issues. In addition, the understanding of the DSSC operation mechanisms through the electrical modeling is crucial to accelerate the development process. The deployment of DSSC modules in smart portable electronics can demonstrate its applicability and cultivate the emergence of DSSC technology.

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