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QUESTION EVERYTHING

The potential of solar paint to harvest solar energy

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Abstract

Solar energy represents a climate friendly, potential long-term sustainable solution for catering to increasing energy demands. Conventional photovoltaics are space consuming, rigid cumbersome devices that are difficult to install on some solar collecting surfaces. The availability of land for building solar farms hence represents a key challenge for the large-scale adoption of solar electricity generation because it competes with land that would otherwise be used for agriculture. Solar paints have been receiving much attention in recent years because of their portability, usability, and potential to replace conventional solar panels. Solar paints have the ability of transforming any surface into one which can absorb sunlight and convert it into electrical energy. These paints have the potential to be applied on the surfaces of houses, vehicles and roads, potentially turning any surface into an energy generator. Solar paint's advantage also originates from the tunable size characteristics of its ingredients, flexibility, and manufacturing ease. The main technologies powering these paintable devices are thin-films, perovskite solar cells and hydrogen producing cells. Among them, there is impressive literature available around thin-films and halide perovskite technologies. These may therefore be the potential candidates for use in solar paint. However, much work remains to be done in order to improve their power conversion efficiency and stability under real world conditions so that they can be made available commercially. This review paper, while covering some of the recent developments in solar paint techniques, emphasizes the need to address the last mile to commercialization. Solar paints have the potential to become a key contributor to meeting global energy demand without being a significant contributor to climate change.

Keywords

Solar paint, Photovoltaic, Perovskite, Nano-crystals, Solar cells, Hydrogen, Lead, Silica gel, Levelized cost of energy, Organic, Hysteresis.

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Introduction

Renewable energy is rapidly becoming a key contributor to global energy needs. As per United Nations research, around 85% of energy needs today are being met by fossil fuels. Renewable energy sources are helping mitigate the risks on account of climate change and contributing to the journey of reaching a net-zero target by 2050 (1, 2). As per estimates published by the International Renewable Energy Agency, out of the total global electric supply, around 90 percent can be derived from renewable energy by 2050 (3). Prices of renewable energy technologies have been dropping rapidly every year, concomittantly with advances in technology. Amongst the renewable energy sources, solar energy is emerging as the main contributor. Solar paint is the latest entrant in this space (4). This technology is based on the same working principle of photovoltaics; i.e., electron-hole splitting (5-7). More specifically, thin film technology and perovskite solar cells form the basis for this technology (8). This review paper, while covering the recent advances in solar paint technology by universities and private researchers, also stresses the need for more research funding, industry collaboration, and government support to assist in the commercialization of this technology. Solar paint can become a game changer in fulfilling energy needs and addressing some parts of climate change challenges in the long run (9).

Solar paints

Conventional photovoltaic panels (crystalline Si) have dominated the solar industry over the last few decades. However, the complication of setting up a roof-top panel installation that occupies a large space deters homeowners from switching to solar energy (10). Solar cells with thin film technology have the ability to replace conventional solar cells. Solar paint is simply a paint which, upon application, has the ability to transform a surface into a solar panel (8, 11, 12). Also known as photovoltaic paint, it can capture solar energy and convert it into electricity (11). The benefit of solar paint is that homeowners can paint their rooftops themselves without needing a full-fledged installation team to fix a solar panel on the roof, and start generating electricity. While the paint is akin to normal paint, it has particles of material, which is light sensitive in nature, suspended in it, which converts a typical paint into paint that can capture energy (11). Once coated with solar paints, any surface, such as a building, a road, railway carriages, or a vehicle can transform into a solar electricity generator on its way to becoming self-sufficient to satisfy its energy needs (13).

Principle of solar paints

The total solar energy harvested is minuscule compared to what the earth receives. It is also a relatively small percentage of the total energy consumed on earth. The potential for harvesting solar energy is immense. The most widely used solar cells are made of silicon, though they are characterized by high cost. On the other hand, use of organic solar cells has been slowly evolving, and they offer significant advantages over inorganic ones in terms of manufacturing ease (14), being relatively inexpensive, tailoring of molecular properties to fit applications, lightness, flexibility and possibility to apply on flexible & large surfaces. However, the main challenge in their commercialization has been their lower efficiency compared to inorganic cells.

Solar paints have seen multiple evolutions, such as nanocrystal Ink, nanocrystal photovoltaics, spray on thin film PV, and Quantum Dot Solar Paints. In simple terms, they all belong to the thin films category. This solution is sprayed or brushed on a plastic or glass material to make a solar cell.

A representative diagram of organic photovoltaics is presented in Figure 1 (15). Electrons gain energy when sunlight strikes the material, moving to a higher energy level. The flow of electrons is enabled when photons from the sunlight are absorbed, and this phenomenon is termed the photovoltaic effect (5, 16). In the photovoltaic cell, electrons are guided to flow in one direction, forming the current. This current is directly dependent on the number of photons absorbed during the process. If the excited electron has another energy band closer to its position, this gives the electron the possibility to lose some energy. The electrons fall to another energy band close to it so, generating electricity. When they jump, an electron vacancy is created in the material. These used electrons then migrate to the electrode. The circuit is thus completed (13). A summary scheme of this mechanism is presented in Figure 2. The excited electrons jump from the Highest Occupied Molecular (HOMO) energy band to the Lowest Unoccupied Molecular (LUMO) energy band of the donor material. Hence, the electrons flow into the LUMO of the Acceptor material and travel up to the cathode, where they are collected. Similarly, the holes left by the excited electrons are collected at the anode (15).

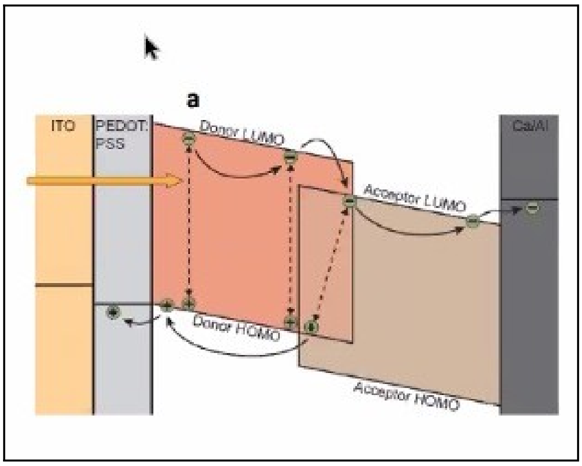

Figure 1: Schematic of an Organic Photovoltaic built over a Transparent ITO-Sputtered Glass (15).

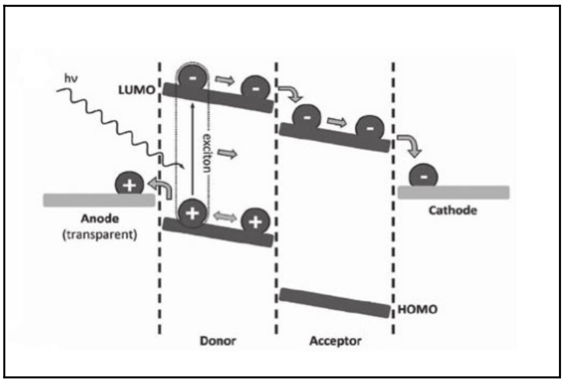

Figure 2: Simplified Mechanism of OPV Exciton Dissociation (17)

The power conversion efficiency (PCE) of solar cells is expressed by the following equation (13):

$$PCE = \frac{J_{sc} V_{oc} FF}{P_{polar}}$$

Where V_{oc} is open circuit voltage, J_{sc} is short circuit (photo) current, FF is the fill factor, and P_{polar} is the incident power. From the equation, it can be deduced that efficient solar cells are those which are able to effectively extract photo-generated electrons (13).

Figure 3 presents the JV curves of a solar cell under illumination conditions (red line) equivalent to 1 Sun (100 mW/cm^2). The figure also gives the JV curves under dark conditions (blue line). The figure also highlights the JSC, V_{oc}, J_{pmax}, V_{pmax}, and P_{max} points. The shunt-resistance and the series resistance of the equivalent circuit of the solar cell are represented by R_{sh} and R_s respectively (15). It can be observed that the photovoltaic effect produces a current of amplitude greater than 4 mA/cm^2 (red line) when the voltage is null, while in dark conditions for the exact value of voltage, no current is produced (blue curve).

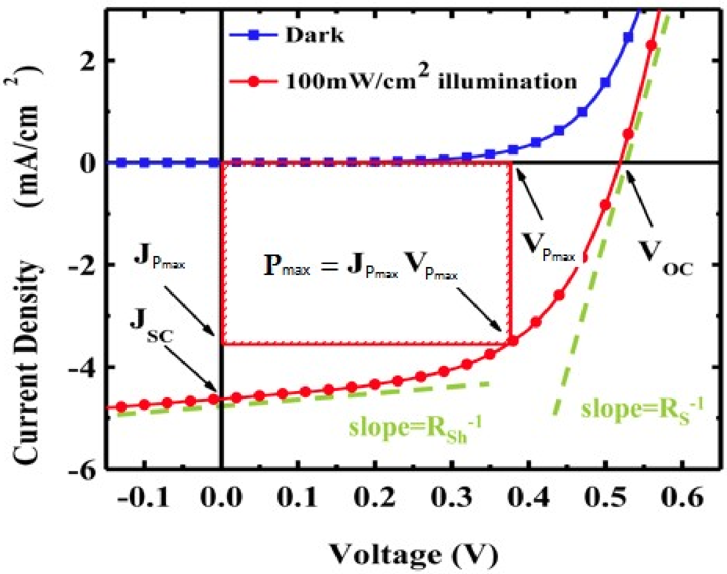

Figure 3: Solar Cell Parameters (15)

The squareness of the JV curve is measured by the Fill Factor (FF) parameter (15):

$$FF = P_{max} / V_{oc}{*}J_{sc} = V_{pmax}{*}J_{pmax} / V_{oc}{*}J_{sc}$$

An ideal cell should have an FF of 1 for maximum power. The value of FF usually ranges between 0 and 1 (18).

The solar paint based solar cells work on the principle similar to that described above, with the photoelectrode layer acting as the donor and the paint-like substance acting as the acceptor (Figure 4) (13). In these devices, there is a movement towards the surface of the paint like substance of the high energy electrons4. Electron vacancies are created in this process. The electrons move towards the cathode. The holes accumulate at the anode.

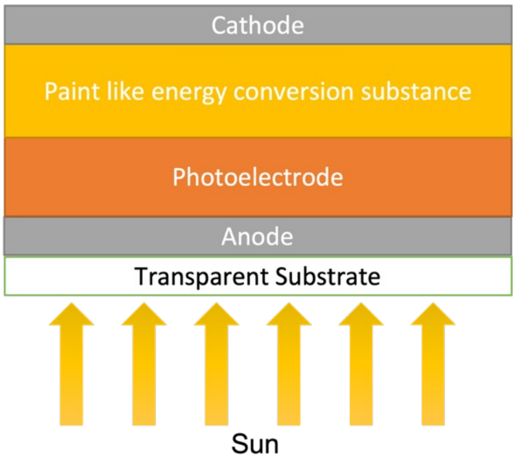

Figure 4: Solar Paint-Based Photovoltaics (13).

Solar paints versus conventional technologies – a broad comparative

While conventional photovoltaics are superior to thin film, it may be that the balance may soon tilt the other way, because of the intensity of research in the area of thin films (19, 20). Table 1 presents the major differences between Crystalline Si based photovoltaics and thin film based photovoltaics.

Table 1: Comparison between Crystalline Si and Thin Films

Parameter	Crystalline Si	Thin Films
Cost	Higher	Lower
Weight	Higher	Lighter
Durability	Greater	Lesser, more prone to cracks, breaks, and malfunctions from weather conditions like rain or snow.
Flexibility	Less	More
Efficiency	Higher	Lower
Strength	Greater	Lesser, Can decompose faster than PV panels. The tenure of warranties available for thin-film panel are of shorter durations.
Invasiveness	Bulky, Silicon Panels	Less invasive. More visually appealing than large photovoltaic arrays. Fits all shapes.
Large scale deployment and Operating Experience	Yes	No, Real-world deployment of thin-films very limited.
Shelf life	Long	Significantly shorter
Scaleable	No	Yes, larger areas can be covered
Aesthetics	Bulky	Simple, attractive compared to solar panels.
High-Temperature Tolerance	Yes	No
Environmental Issues	No	Yes, toxic heavy metal ingredients

Emergence of thin film technologies

Efficiency trends

Table 2 presents National Renewable Energy Laboratory (NREL) data on thin film technologies vis-à-vis conventional solar cells (21).

Table 2: Efficiency (%) trends of solar cells since its first stages (Source NREL) (21)

Year	Crystalline Si cells	Thin Film Technologies	Multijunction cells
1977	14	-	
1980	16	-	
1985	20	-	17
1990	23	-	30
1995	23	-	30
2000	21	-	32
2005	22	-	39
2010	24	10	42
2015	25	15	47
2020 / 2022	24 / 25	17/18/25	47

Thin film technologies are relatively young. While the lab efficiency of the thin film technologies may lag that of Crystalline Si technology, the pace of improvement in the last decade or so has been much higher. Reported efficiencies of Thin Film Technologies have almost doubled in the last decade. Lastly, multijunction thin film technology is a separate high cost, high efficiency category currently deployed only in satellite and aerospace applications. It is anticipated that technological advances may make this category usable in solar paints.

Capital cost comparative

Forbes Home gives an indicative statewise cost comparison of solar energy installations. It also gives an indicative comparison between costs of solar panels versus that of thin films. For a 6 KW system, while costs vary from region to region, the average cost for crystalline panels mentioned is around USD 16000 per panel. Compared to this, the cost of a thin film for a 6 MW capacity is anticipated to range between USD 6000 – 9000 per 6 MW facility (22). The cost of land for the solar panel installation may further increase the difference.

Levelised Cost Of Energy (LCOE)

The LCOE gives an assessment of the net present value of unit-cost of power for the full life of the power-generating asset, i.e. over the total power output. It helps compare the impact of technology advancements over the years. Factors that affect the LCOE include aspects such as efficiency, system reliability & performance, operating conditions or state incentives that help offset the project cost (23). In simple words, it is a measure of the cost of electricity generated. It is a straightforward analysis and can be understood easily which is why it is widely used. While LCOE is a good indicator, but it has some shortcomings. It may not consider all relevant aspects of costs required to be considered for a financial decision. It does not factor project risks & uncertainties. Aspects such as interest rates or costs of capital are not factored in their entirety (24). Despite all this, LCOE is a good tool to compare power assets and can give a fairly good comparison of power systems.

As per the report published by Lazard Financial in October 2021 (15th Edition), the continued improvements in technology of renewables has resulted in a reduction in their LCOE year-on-year. There is also a healthy competition in the sector which has lead to a reduction in capital costs. LCOE data published by Lazard is presented in Table 3 (25, 26).

Table 3: LCOE data (Source: Lazard (25))

LCOE	Type of power project	Lazard LCOE October 2021 (unsubsidized analysis) in $ / MWH	Lazard LCOE October 2021 (Capital Cost) in $ / KW
Conventional Energy	Coal	65 – 152	2950-6225
	Gas combined	45-74	700-1300
	Gas peaking	151-196	700-925
	Nuclear	131-204	7800-12800
Renewable energy	Solar PV rooftop C&I	67-180	1400-2850
	Solar PV rooftop residential	147-221	2475-2850
	Solar PV Community	59-91	1200-1450
	Solar PV crystalline utility scale	30-41	800-950
	Solar PV Thin Film Utility Scale	28-37	800-950
	Wind	26-50	1025-1350

Based on Table 3, the LCOE of solar pv thin film technology compares favorably to solar crystalline and gas, and hence is a strong motivator to develop this technology.

Emerging thin film technologies in solar paints

As part of solar paint technology research, three different technologies are being studied (27). With the solar industry experience exponential growth, newer innovations are being exhibited which may occupy center stage in the future. The following sections describe three leading technologies and analyse where they may stand from a commercialization standpoint.

Solar paint hydrogen

Hydrogen is the key component of this technology. The combustion of hydrogen is clean since the only product is water. As part of this concept, hydrogen gas is produced using solar power (28). There is a huge potential for hydrogen gas as a green fuel. Moisture is absorbed and solar energy used to decompose it into hydrogen and oxygen (29-31). The stored hydrogen is subsequently used to generate electricity. Synthetic molybdenum-sulphide contained in the paint absorbs moisture. Solar paint contains titanium oxide which helps in conversion of moisture into hydrogen and oxygen in the presence of solar energy (32, 33). Hydrogen, an environmentally friendly source of fuel, is generated, which produces clean energy. Clean water is not needed for this process. The key problem with the commercialization of this solar paint is designing a storage system for the released hydrogen gas (33). Hydrogen storage compact systems in cars are being researched, as is hydrogen-carrying pipeline infrastructure (33, 34). The process can be helpful for hydrogen-based vehicles in the future. It can also be applied in tall buildings if a suitable method is found to capture the hydrogen released.

Quantum Dot Solar Cells (QDSC) based solar paints

Quantum dot–sensitized solar cells (QDSCs) technology have the desirable optoelectronic properties of QD light absorbers. The main benefits of this technology are stability, tuneable light-harvesting range, cost effectiveness, availability, and high absorption coefficient (35). These semiconductor crystals are already used in solar panels and LEDs (27, 33, 36). Quantum dots have tuneable band gaps and changing their size can lead to the absorption of different amounts of sunlight (27, 36). These semiconductors capture light and convert it into electric current. One of the noticeable advantages of colloidal quantum dots is that they are cheaper than conventional silicon-based solar cells. This reduces the cost of electricity generation. The other benefit of QDSCs is that by changing the quantum dots size, the light-absorption spectrum can be changed (37). The QD's extremely small size facilitates the capture of the incident solar light (37). By incorporating nanoparticles into solar cells, quantum dot solar cells can possibly capture a wider spectrum of light; including infrared; than traditional solar panels. This can make solar energy systems much more efficient. The nanoparticles are very tiny. It is possible to mix the small QD nanoparticles into liquid paint and then apply it in layers (38).

Literature suggests that this technology could be more efficient than traditional solar panels. It may help substitute some bulk materials such as Silicon, Cadmium Telluride or Conventional Cu $(In_{1-x},Ga_x)Se_2$ (CIGS) solar cells (39). A challenge with QDSCs' is that their efficiency is still at around 18% (32), (35-37). Research is underway to increase the conversion efficiency to enable the widespread utilization of the Quantum Dots technology. This technology can be implemented on a massive scale provided there is an increase in its efficiency and a decrease in its price.

Perovskite solar paints

These are named after the Russian mineralogist Lev Perovski. They are derived from Calcium Titanium Oxide Minerals (33, 40). A perovskite has a similar structure as titanium oxide ($CaTiO_3$), ABX_3, where A and B are the cations and X is the anion. Lead is often the dominant metal used in perovskites (33, 40). While these materials were discovered a couple of centuries ago, the observation that they could be used to generate solar energy is recent. When light strikes a perovskite material, the various mineral compounds in the crystals conduct an electric charge. That is the reason why they find use in solar cells. These solar cells can exist in the liquid state of matter and at the same time conduct electricity. Spray liquid perovskite has been developed by researchers at the University of Sheffield (11, 40).

While researchers and technology leaders have been discussing about "Perovskite" technology for many years, it is only recently that the pace of events has quickened (27, 41). It may be possible to enhance the efficiency of solar manufacturing at a lesser cost through the use of new thin-film technology if laboratory results are promising. Perovskite technology can dominate the solar space, not least because it uses inexpensive materials which are widely and plentifully available (10, 14, 32, 33).

The efficiency of perovskite cells in research laboratories has increased substantially in the last few years. However, there is a decline in efficiency with an increase in the module size, which has been attributed to the non-uniformity of the coating of the cell chemicals on the substrate upon scale-up (11, 40).

Perovskite, is also capable of being incorporated into other thin film solar technologies. Perovskite layers have improved the ability of such hybrid solar cells to withstand UV, since their first utilisation within such solar cells. They have also shown the capability to efficiently absorb visible bands (42). The electrode layers in turn have the potential to capture the IR bands. Together, this leads to a synergy in energy capture. CIGS-perovskite hybrid cells have shown improvement in efficiencies from 17.8% in the late 2016 to > 21.5% currently (43). Researchers are trying various combinations. IMEC researchers feel that silicon-perovskite stacked cells may achieve efficiencies as high as 30% (44).

It is believed that perovskites will play a key role in indoor applications and indoor photovoltaics. Light here is from indoor sources such as LEDs. These sources are different from outdoor sources in terms of spectral range as well as light intensity. Therefore, halide perovskites find room also for indoor application, particularly as an energy supplier for the Internet of Things (IoT). It is estimated that by 2025, billions of items will link to IoT with most being inside homes or commercial establishments. The main challenge has been the want of a robust charging technique for these wireless devices. While these devices need little power, replaceable energy sources such as batteries cannot be used since they require frequent human intervention (changing) and on account of the complexity involved in installations. A solution is self-powered wireless sensors which can charge using the energy available in the rooms. Halide perovskites represent such a material with an efficiency of around 40% even with in-house lights.

Organic thin film solar paints

These solar cells comprise of organic semiconductors. They have been drawing attention, especially in the electronics domain in the last few years (5, 45-49). They are relatively cost effective in comparison to inorganic semiconductors. They are also relatively more flexible (49). An organic solar cell consists of an organic active layer (50). Fabrication of large area, cost-effective element, flexible and light-weight devices is possible by using simple techniques. These are also environment friendly. There are still shortcomings in research in terms of stability and power conversion efficiency. However, if these technological challenges are overcome, then organic thin film solar cells may prove a lucrative alternative to inorganic solar cells in the solar energy market.

Comparison of thin film technologies

Power conversion efficiencies

Researchers in all three technologies, Perovskite Cells (Thin Film), Quantum Dot and Organic Cells seem to be competing for improvement in efficiencies. While Perovskite leads the pack as of today in the efficiency chart (Table 4), others are not too far behind (21).

Table 4: Percent efficiency comparison of thin film solar cells (Source NREL Database (21))

Year	Organic Cells	Perovskite Cells	Quantum Dot
2010			2.9
2011	10		5.1
2012	11		7.0
2013	11	14.1	8.6
2014	11	19.0	9.2
2015	11.5	15.6	9.9
2016		22.1	11.3
2017	12.1	22.7	13.4
2018	15.6	23.5	16.5
2019	16.4	25.2	
2020	17.4		18.1

Hydrogen technology is still in its early phase and there are no reported efficiencies till now in the NREL database (21). Nonetheless, Li et.al. Have reported an effiiciency of 10% (51).

Perovskite Thin Film, Quantum Dot Thin Film, Organic Cells Thin Film and Hydrogen based paint technologies are yet to reach a full commercialisation phase. Field data regarding commercial power generation by these three technologies is still lacking.

Commercialization of solar paints - points for consideration

Solar paint efficiency and economics

Solar paints are still at the research stage. Till 2019, solar paint was struggling to break the double digit barrier of efficiency levels of solar energy capture (13). In contrast, traditional solar silicon panels have been surpassing the 20% capture barrier of solar energy. Solar paint has to convincingly break the efficiency capture barrier for a successful commercial rollout (13) – even slightly lesser efficiency may still be cost-effective as solar paints are cheaper to produce than conventional panels. Cell configuration, material, and substrate are some of the factors which affect efficiency.

In this quest for higher efficiency, Zhanhua et. al. designed a carbon-based composite cathode that was suitable for waterproof and HTM-free perovskite solar cells (40, 52). Their experiments demonstrated reasonable waterproof performance and a better efficiency of around 11% (40, 52). The utilization of a hole-transporter-free PSC based on a C+ epoxy electrode further enhanced the efficiency. Besides serving as a hole-selective extractor, the electrode also acted as a water-rejecting barrier. A silver paint coating further increased the efficiency levels (40, 52). No performance deteriorations were observed for the first 80 minutes when immersed in water. Furthermore, no deteriorations were observed in other harsher environments, such as high humidity and 50°C thermal stressing, in the same time span (40). The authors concluded that C+epoxy/Ag paint-based perovskite solar cells were efficient as well as water resistant (40).

Lead pollution

A lead-based absorber is used in perovskite based solar paint cells. Lead doubles the efficiency of these cells (53). In case of device failure, the lead may leak into the environment, may get washed into the soil and can also enter the food chain (53-56). One of the solutions is to create boundaries to stop lead leakage. The solution which is available today to prevent leakages if solar cells break or malfunction is not fail proof. The threat of lead contamination in the case of widespread usage of these cells remains, thus becoming a constraint for commercialization.

The lead pollution emitted by solar paint can be recycled in the manufacturing of lead-acid batteries (55). The lead is found primarily in the soldering paste and the ribbon coating. Various existing methods like Phytoremediation, Bioremediation, Gravity Setting Chambers, and Electronic Precipitators can be applied to trap the small quantity of lead and cadmium emitted by solar paints (57).

A newer method is being researched by Horvath et. al. They are using phosphate salts to prevent lead leakage to the surroundings (58). Phosphate salts react with lead to form a highly insoluble compound. Moreover, phosphate salts do not alter the advantageous optoelectronic properties of the device itself. The insoluble compound formed cannot contaminate the environment, therefore such technology can help in reaching a safe level of environmental risk category, thus helping achieve commercialization (38, 59, 60).

Quantum dots – detrimental optoelectronic features

Quantum dots solar cells have certain shortcomings which lead to undesirable re-combinations. This limits the conversion efficiency to around 19% (61). Hassan et. al. Have designed a new type of solar paint based on exfoliated MoS_2 (Molybdenum Disulphide) in a TiO_2-PbS nanocomposite (NC). The charge carrier generation and transfer characteristics of the NC were found to increase with the addition of MoS_2. The efficacy of MoS_2 addition was detected by using differential scanning calorimetry, while the thermal compatibility with TiO_2-PbS NC was also demonstrated, a crucial aspect of solar paint. It was concluded that the addition of exfoliated MoS_2 in TiO_2-PbS NC improved the performance of solar paints by lowering the charge transfer resistance (61).

Organic photovoltaic paints

As mentioned above, organic photovoltaic (OPVs) are lightweight and cost effective (62). However, more work is needed to improve the efficiency of cells so that commercialization can be achieved. The mobility of OPV carriers is relatively lesser which leads to reduced internal quantum efficiency. There have been various research papers published recently on how to increase the optical absorption (62). Research groups have reported improvements in efficiency by deploying metal nanoparticles as an optical engineering tool in organic photovoltaic paints (62).

Engineering design challenges

One more aspect which needs to be addressed by solar technology engineers is the engineering design of how to apply solar paints over large installations like buildings, roads, and vehicles. The question which needs to be addressed here is how the flow of electricity will take place on the walls of the buildings, roads, and vehicles without harming individuals staying in the building or walking on the streets, where will cathodes and anodes be constructed, and how electricity can move across the walls without people getting exposed to the current, how risks associated with electrical safety will be addressed. Innovative electrode engineering may be able to answer some of these aspects. These are some of the questions which will need to be addressed as one moves towards large scale commercialization of solar paints technology.

Challenges in hydrogen technology

Storing hydrogen safely will be a prime consideration in the commercial rollout of this technology. Hydrogen capture and storage is challenging, because it forms an explosive mixture with air or oxygen (63, 64). The technology for hydrogen storage in smaller installations is still under development. Successful engineering and materials science solutions may also facilitate the development of vehicles that use hydrogen as fuel.

Titanium dioxide and synthetic molybdenum disulphide is used in solar paints. The hydrogen produced is used to generate clean energy (28). Titanium dioxide resources have been decreasing over time and it is anticipated that the material may beccome scarce if solar paint use goes mainstream (65). Alternatives may have to be found to maintain continuity.

Hysteresis behaviour in perovskites

A critial challenge affecting perovskites solar cells is their hysteresis behaviour. This is an indication of the consistency of electrical output, which in turn decides whether they are suitable as sources of electric power. In case of halide perovskite cells, hysteresis is the condition in which the J-V curves obtained from the forward voltage scan and reverse voltage scan vary significantly. This results in varying values of efficiency of power conversion depending upon the direction of the scan (66). Addressing this issue has been an important research challenge and an important milestone in development of perovskite solar technology (67).

Device architecture (p-i-n versus n-i-p) influences the J–V hysteresis in halide perovskite solar cells. In addition, the J-V hysteresis is also influenced by aspects such as the selection of interface charge-transporting layers, the composition of the perovskite layer and the measurement conditions (68, 69). It is generally believed that hysteresis in PSCs is a result of mobile ions and their impact on charge carriers. Electrical bias and light also affect these aspects (70). Research indicates that p-i-n $MAPbI_3$ devices using all-organic transport layers can be a good alternative for indoor light harvesting with good efficiency (over 30%) and little hysteresis (70). However, the corresponding $MAPbI_3$ devices based on n-i-p architecture present larger efficiency deviations and noticeable hystereses (70).

Two aspects are important for halide perovskite indoor PVs. One of these is the choice of p-i-n architecture with organic charge transport layers. The other aspect is the choice of photoactive layers to subdue the ion movement (70, 71). In outdoor devices, the hysteresis effect becomes more pronounced (72). Despite these findings, there still exists a knowledge gap in the understanding of the hysteresis behaviour of PVs. This needs to be addressed before these cells can be widely used.

Stability in perovskites

Perovskites have ideal characteristics for solar applications. As stated above, some of these properties include the presence of a direct band gap, a wide spectrum capture capability, defect tolerance and optimum charge carrier diffusion lengths. Researchers continue to work on improving the stability of Perovskites in solar cells, making structural modifications, developing new materials and newer fabrication techniques (69). While power conversion efficiencies have improved substantially thus competing with conventional solar technologies, poor stability continues to be a major challenge hindering commercialization. Their stability and operating life under normal environmental conditions (68, 73) continue to pose hurdles for commercialization.

The soft nature of perovskite materials is an impedement to long term stability. There are unstable species in perovskite materials due to weak Van der Waal forces and weak hydrogen bonds (71). Stability of perovskite technology is also affected by environmental factors such as humidity, oxygen ingress, UV light, thermal treatment, and illumination; all of which accelerate decomposition (68). Even under normal conditions, degradation mechanisms accelerate and contribute to instability. According to Bass et. al., it may be possible to regulate perovskite crystallization by the control of humidity (74, 75). Exposure to UV frequencies is also known to cause degradation, despite the efficiency improvement obtained. This is a big obstacle for outdoor applications since sun light is composed of a significant UV frequency component (76). The most severe level of degradation takes place at the interface between the perovskite and the TiO_2-based electron transport layer (ETL) but this degradation is reduced significantly when an Al_2O_3 ETL is used instead (68). Pure oxygen is another concern as it has a strong preference for stripping hydrogen atoms from the perovskite organic components. This reaction rate increases at higher temperatures which becomes a problem for solar cells, requiring a complete encapsulation of the device from the local environment to prevent it from degradation. In paint form, such encapsulation is very difficult to achieve, especially when applied over large curved surfaces.

Continuing research on PSCs has led to improvement in stability from a few minutes to several thousand hours. However, that is still far from a concensus commercialization shelf-life of 10 years. Several aspects are being targeted by researchers in this connection. These include improving the structural design, use of various materials and films, changes in the electrode materials and encapsulation procedures (68, 77, 78). Damage from UV exposure can be partially mitigated by the heat from standard sunlight. Since perovskite's components are fairly mobile, adding energy in the form of heat pushes the efficiency back up but not quite to photonic absorption original levels (79, 80).

Oxygen is not entirely detrimental. When there are no organic components to react with, oxygen is a useful additive that fills in defects in the perovskite crystal through a process called passivation. Oxygen could be used in inorganic perovskites to passivate the crystal. This helps not only to increase the performance of the cell but also prevents some types of degradation. Passivation is the same process that keeps stainless steel or aluminium from rusting (68), (81-83).

Atmospheric moisture can be detrimental in multiple ways, one is it delivers reactive oxygen species to a perovskite or it can result in detrimental reactions of its own. Lead halide perovskites are slightly soluble in water, therefore too much exposure can lead to the perovskite layer dissolving from between the hole and electron transport layers (74). However, not all contact with water is harmful; especially when encountered during the manufacturing and fabrication process. In the proper concentration, moisture exposure of perovskites during the fabrication process can prevent pinholes in the perovskite films, increase crystal density and reduce locations where non-radiative recombination can occur. Denser crystals with fewer defects not only have better performance but also show a longer lifespan in testing, so there is a definite potential for the deliberate calculated use of water in the production process before the final encapsulation of the finished product (68, 71, 75).

Fabrication processes in perovskites

Manufacturing high-efficiency perovskite solar cells on a commercial scale is still fraught with challenges; not all of them trivial. The fabrication needs to take place in a controlled manner and under inert conditions since the ingredients are unstable in the presence of both oxygen and moisture (69). A novel fabrication approach exploiting machine learning is currently being explored in order to solve some of these problems (84).

Significant efficiency decreases under normal atmospheric conditions restrict the use of PSCs externally. Brown discoloration occurs in the presence of air and UV radiation, which Zhao and his team attributed to Iodine (72, 85, 86). High temperatures lead to degradation of perovskite cells. This research challenge needs to be addressed as solar panels may be subjected to high temperatures, even up to 100°C.

Jiang et. al. reported that a gentle gas-quench fabrication method could be used to reduce the high temperature catalyzed degradation of perovskite cells. This method resulted in a bromine-rich surface layer and reduced the defect density. Solar cells manufactured using this process were able to maintain 90% efficiency at 65°C for more than 2200 hours (87).

The development of highly stable and efficient wide-band gap (WBG) perovskite solar cells based on bromine-iodine mixed-halide perovskite is important for creation of tandem solar cells. Tandem perovskite solar cells require stable, efficient wide-band gap perovskites with mixed bromide and iodide anions. It was however noted that these anions were prone to Br – I phase segregation during crystallization and during operation. This segregation limited the device voltage and operational stability. Alloying cations into the perovskite matrix, growing the grains on a non wetting matrix, controlling the grain size and other process modifications have allowed the preparation of stable wide-band gap perovskite solar cells (6, 75 87).

Sandwiching ferroelectric material between paraelectric superlattice structures

Several studies have been published to analyse this effect. The developments in thin-film fabrication opened up opportunities to improve material properties using superlattice structures. Yun et. al. presented an approach where sandwiching a ferroelectric $BaTiO_3$ in between paraelectric $SrTiO_3$ and $CaTiO_3$ in a superlattice form resulted in an improvement in photocurrent. Upon comparing with $BaTiO_3$ of similar thickness, the authors reported that the current was 103 times higher despite the reduction in the volume of $BaTiO_3$. Further research attributed this effect to the role of large dielectric permittivity and a lowered band gap (88).

A sandwiched electrode buffer (SEB) was also reported to bridge the perovskite absorber – to - metal contact. Not only does this SEB adjust the alignment of the band, but it also passivates multiple defects which increase the efficiency of carrier extraction as well as transport. The SEB also blocks mass loss and ion movement in the perovskite. Furthermore, it protects the material from humidity. The SEB design hence improves various factors related to efficiency and stability and brings PSCs closer to commercialization (88).

Zai et. al. developed sandwiched electrode buffer (SEB) with respect to the hole-transport layer (HTL). As part of their work, dual back surface fields were implemented at two interfaces (77). The SEB stabilized the perovskite, HTL and metal electrodes. Accordingly, planar n-i-p PSCs with SEB achieved an efficiency of 23.9%. They also exhibited improved operational stability with only a marginal decline in efficiency (77).

High-performance PSCs typically include a perovskite active layer sandwiched between an ETL and HTL. This technology still has some limitations (71). The process leads to cost escalation in case of additional layer fabrication, high energy consumption, possible moisture contact and contamination with harmful organic solvents (68). Researchers are trying to design better processes which address these limitations (73).

Tandem silicon-perovskite cells

Silicon and perovskite can be stacked to yield higher efficiencies with a smaller footprint. Cells are stacked with appropriate band gaps to give higher efficiency. The process of fabrication of a tandem cell involves several additional processing steps. There is therefore an expectation for improved efficiency and stability (6, 75). In early 2013, Heliatek manufactured organic polymeric tandem solar cells with a power conversion efficiency of 12%. Research continues on improving the fabrication process and pushing up efficiencies (68). Zheng et. al. reported a PCE of 27.6% in November 2022 using inverted perovskite / silicon V-shaped tandem solar cells (89). Al-Ashouri et. al. reported a PCE of 29.15% in December 2020 for monolithic PSC/Silicon tandem solar cells (90). However, the equivalent outcomes still continue to lag that of high-performing single junction c-Si cells. As a result, research still continues in the field of tandem solar cells (68).

Tandem photovoltaics represents a realistic approach for reducing thermal losses in solar energy conversion. This is accomplished by integrating two absorber layers into a single device. Optimizing the junction between the two the interconnecting layers leads to higher efficiencies. Other than c-Si as the bottom cell, CIGS and CZTS bottom cells, as well as a full perovskite tandem (SnPb/Pb) have also been constructed and studied. However, for competing with the SI technology, the efficiency of the device needs to be > 30% and the lifespan > 16 years (68, 75). Tandem photovoltaics have recently achieved efficiencies of 32%, approaching the theoretical Shockley-Queisser solar conversion energy limit.

Non-radiative recombination in perovskites

Non-radiative recombination is a major source of open circuit voltage losses in perovskite cells (91). Zhang et. al. Were successful in suppressing non-radiative recombination in Lead–Tin Perovskite Solar Cells. This was achieved through bulk and surface passivation. Lead–Tin perovskite solar cells (Pb/Sn PSCs) have limitations due to their intrinsic oxidizability of Sn (II), leading to formation of Sn vacancies in perovskite films. A Lewis base β-guanidinopropionic acid and hydrazinium iodide was introduced to passivate the perovskite (91). This resulted in power conversion efficiency of 20.5%, in part due to significantly reduced non-radiative recombination and voltage losses. Additionally, Zhang et. al. Also demonstrated that it was possible to improve the stability of PSCs by enhancing the chemical robustness of the perovskite layer. This highlights the importance of bulk and surface passivation in the development of efficient PSCs (91).

Interfacial engineering and modulators to prevent ion migration (and hysteresis)

Interface engineering is widely applied in the one-step anti-solvent deposition process to increase the efficiency of perovskite solar cells. Wang et. al. Inserted an alcohol-soluble small molecule, 2-mercaptoimidazole (MI) between the hole transport layer and perovskite layer to form a cross-linking bridge that increased hole transmission and decreased interfacial recombination (92). Hysteresis-free devices with a higher power conversion efficiency of 20.68% were thus obtained. Furthermore, these devices exhibited longer stability under normal environmental operating conditions. Interface engineering thus offers another avenue to increase cell efficiency and stability.

Uses of solar paints

Lightweight, flexible, efficient thin film solar cells could unlock novel applications for solar power generation. Some applications are listed below:

Light films and the vehicles they will enable

With the reduced weight and higher flexibility of thin film perovskite construction, opportunities for integrated solar power in vehicular platforms seem increasingly possible and within the economic reach of the mass market.

Drone integrated photovoltaics

For some possible specialty applications, such as climate monitoring or long-duration observation of remote locations for ecological or national-interest purposes, the idea of a solar-powered drone, something not considered viable with traditional silicon solar cells, is very attractive (93). The NASA prototype solar powered long duration drone Helios® represents one such use (94). Weight savings are very important for aerial electric vehicles. Integration of lightweight flexible perovskite solar technology is of great interest to such projects.

The use of perovskites as a method of range extension for less specialized battery electric vehicles (BEVs), called Vehicle Integrated PVs (VIPV) ranging in size from e-bikes and cars to private planes, is also under consideration. With the ability to apply thin films to curved surfaces without the weight of thicker silicon panels, the amount of surface that can be covered by these devices is maximized while minimizing the amount of energy spent moving that weight (95, 96).

A fully solar-powered vehicle with “infinite range” for consumers is likely to be a niche application and may have to wait for improvements in energy storage technology.

Energy on the go and the Internet Of Things

The drive for smaller and more integrated computer components has resulted in the utilization of connected devices and sensors in more and more aspects of our lives. The Internet of Things (IoT), is an exciting field full of possibilities. Figuring out how to power all those devices, especially the ones that are not able to be connected directly to the grid, is difficult. Perovskite solar cells may make this possible (97).

Researchers have begun incorporating solar technology into clothing as well, so obtaining so called Fabric Integrated PV (FIPV). This would work as a kind of power hub source to supply extra energy to some of the many commonly-used devices such as headphones, smart watches, or fitness trackers (98).

Solar paints can save lives

Disaster sites, refugee camps, and other locations where threats to people’s well-being exist are always in dire need of energy to run devices. This energy is needed both to improve conditions for residents/victims and support emergency workers during whatever operations they might find themselves undertaking in their aid.

Integration into existing commercial infrastructure

Building Integrated Photovoltaics (BIPV): There is also potential for solar paints to be integrated more directly into residential and commercial building construction. Efforts may focus on harvesting the non-visible portions of the spectrum (UV and IR) (99).

The reflective nature of solar paints can be used to reduce heat absorption by the underlying surface. Air conditioning represents around one-fifth of the electricity utilization in the United States. Paints made with “Passive Radiative Cooling” properties can block sunlight. They thus reduce the temperatures on surfaces of roofs and walls, which, in turn, reduce cooling costs. The resultant lesser fossil fuel power consumption by air conditioning systems makes the paint an important contributor to lowering carbon emissions (100, 101). Researchers at Purdue University have developed a new ultra-white paint that reflects 98.1 percent of sunlight and can keep surfaces up to 19 ºF cooler than their ambient surroundings. This new paint could help combat global warming and reduce reliance on air conditioners, thus decreasing the use of fossil fuels (102).

If a solar paint can be manufactured that combined the properties of “Passive Radiative Cooling” with solar energy harvesting, a significant energy synergy could be obtained. At the time of publication of this article, the author did not find any reference to such a technology in the scientific literature. A solar paint with these properties may be the best solution to reducing power consumption.

Conclusion

Solar paint still needs considerable improvement in efficiency and stability before stand-alone commercialization. Multiple research teams are working on addressing the following research gaps in solar paints:

1. Capturing the generated energy flow into a current efficiently and safely and the safe storage of generated hydrogen.
2. Increasing durability, weather (UV, moisture and oxygen) resistivity, stability and shelf life to match that of solar panels.
3. Safer and cheaper substitutes for Pb and Ti respectively in cell ingredients.

Solar paint is a disruptive innovation with wide ranging applications, from being used to paint electronic devices, windows, vehicles and roofs. It is a new technology taking over an untapped new market. If progress in the pace of research is maintained, commercialization of solar paint may be achieavable in the near future. The solar industry is continuously progressing through technological advancements, increasing and decreasing energy harvesting efficiency and cost respectively. The industry has always been agile, fast to change, adopting newer ingredients, quicker processes, and new financial models. The development of solar paint seems to be following a trajectory that many other advances in solar technology has followed since the 1970s (38, 59, 60, 103, 104).

It is important that solar paints technology is supported during its evolution phase. There is a need for this work to be supported through industry collaborations and governmental funding until such time as the technology becomes self-supporting. Venture capital and ESG (Environmental, Social, and Governance) portfolio directed investment vehicles can fund solar paint technology start-ups. Many non-profit organizations can subsidize relevant areas of research and development.

Conventional solar photovoltaic cell installations need a large amount of dedicated land. Estimates range from 3-10 acres of land depending on the region, to produce one megawatt (MW) of electricity. This direct competition for agricultural land means sacrificing energy for food production, or vice versa, in the future (105). Thin film technologies, especially solar paints, do not require dedicated space to generate energy because every paintable surface can be potentially turned into a solar device.

Notwithstanding their stand-alone advantages, thin film photovoltaics may first achieve commercialization due to efficiency synergies; such as when they are integrated into existing silicon cells or used for radiative passive cooling so as to reduce air-conditioning power consumption. Furthermore, thin film photovoltaics have properties that will enable them to dominate the indoor IOT niche, where their environmental stability disadvantages may be rendered irrelevant. These properties are also well suited for range extenders, point of use energy generation for personal devices and in emergency shelters. If thin film photovoltaics can be manufactured without toxic heavy metals, it may be that they may succeed as consumables in other applications, where their relatively short shelf life may not be a deterrent for use.

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