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A Diverse Outlook on the Performance of Perovskite Solar Cells to Meet the Energy Demand

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Abstract: Population growth considerably expands the limits of residential regions and human living standards, resulting in a massive increase in energy consumption. Unlike non-renewable sources, solar energy is renewable and widely available around the planet. The remarkable development of organic-inorganic hybrid perovskite materials for transforming solar radiation into electricity has revolutionized third generation photovoltaic (PV) devices. In addition to development of various solar cells, the perovskite solar cells (PSCs) is an emerging solar cell technology whose efficiency has been reached up to 25.5% (in year 2020) in less than a decade of intense research and innovation. A collection of relevant literature papers is compiled to offer an outlook in the area of advancement in the development of PSCs. Distinct set of constraints are reported here that must be overcome concurrently to commercialize the perovskite technologies in order to meet specific technical objectives effectively.

Keywords: Perovskite solar cell, commercialization, energy demand, hole transport layer, efficiency, degradation and stability.

1. Introduction

The rapid use of non-renewable energy resources (fossil fuels) such as petroleum, coal and natural gas has radically increased in 21st century as compared to the rate of formation of fossil fuels, which leads to complete consumption of the fossil fuel reservoir. Hence, providing sustainable energy to humankind will be one of the major challenges to meet the future challenges for the energy demand.

The large fraction of increase in energy consumption comes from non-organization for economic cooperation & development (OECD) listed countries and this growth is mainly focused in regions where demand is driven by the strong economic growth, particularly in Asia [1].

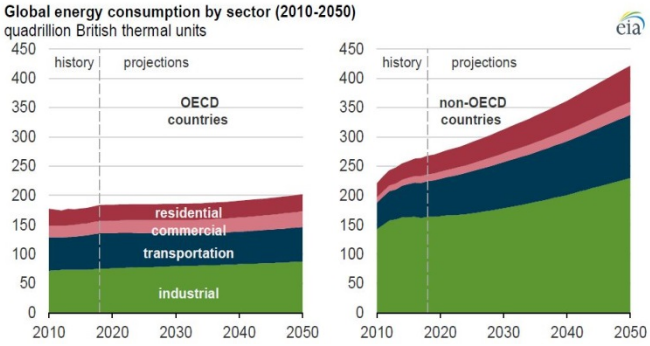


Figure 1. Global energy consumption by sector (2010-2050) (1QBTU ~ 293 TWh) [1]

World industrial sector energy (WISE) usage will get increased by more than 30% between 2018-2050 due to the increment in good's consumption as clearly seen from Figure 1. The industrial sector comprises of manufacturing, agriculture, construction, refining and mining, bags largest share of energy consumption throughout the projection period (2010-50).

It is clearly projected that consumption for WISE is predicted to get reached to 315 quadrillion British thermal units (Btu) by 2050. Increase of nearly 40% in transportation energy consumption (TEC) can be projected from the reports for 2018-2050. This significant increase in TEC is largely driven by non-OECD countries, where TEC will increase by nearly by 80% between 2018 and 2050 [1]. The growth in personal travel and freight movement can be considered as two major factors responsible for significant energy consumption in these countries as compared to OECD countries. Reports also suggested that energy consumption for residential and commercial of the sector will increase by 65% in the projected period, i.e. from 91 quadrillion to 139 quadrillion Btu. Moreover, factors like urbanization, rising income, and efficiently access to electricity will lead to rising demand for energy [1].

According to the Kyoto Protocol CO_2 emission has to be reduced and this should be done by utilizing less fossil fuel. Hence, the CO_2 problem is another reason why new and environment friendly renewable energy resources are required to be taken into account.

The United States Energy Information Administration (EIA) reported state that global annual energy consumption per year may increase by 3.1%, 0.6%, 0.4% and 1.1% in renewable, petroleum and other liquids, coal and gas consumption respectively between 2018 and 2050 [1]. This trend clearly indicates that human being will more rely on renewable energy resources to fulfill the energy needs.

Hence, Sustainable renewable energy development is considered one of the most critical scientific and technological problems facing humankind in the globe. Solar irradiance is directly falling on the surface of the earth which is clean and freely available that can be harness to produce electrical power for numerous applications. Solar cell technology is one the suitable approach to harness light to produce the power. The advancement in the light harvesting technology is improvising to boost up the efficiency and reduce the manufacturing cost etc. Few of the technologies are listed below.

This paper illustrated the performance trend of the perovskite solar cells (PSCs) along with the working principle. Recent development in the key components of the PSCs are also discussed which are responsible for efficiency modulation of the cell. Various challenges involved in the commercialization of the PSC are also presented in this paper.

2. Types of Solar Cell Technology

In Photovoltaic (PV), photo means light and volt means to measure the electricity. In 1983, Becquerel reports the PV effect by observing a system where a current was flowing across two metal electrodes (Ag) immersed in an electrolyte solution upon solar irradiation [2]. Based on the parameters; property of photosensitive material, components of PV system, optimum photo conversion efficiency available, and cost, Martin Green has classified PV solar cells and their technology into three major categories described below.

2.1 First Generation of PV systems (1G)

The 20% of the earth's crust contained Silicon (Si) in the form of silica sand (SiO_2). The abundant nature of silicon makes it an attractive material for semiconductor industry. In addition to this modeling and simulation of polycrystalline silicon photovoltaic cells investigated to analyze its performance [39]. The c-Si is a best candidate with band gap of 1.16 eV for solar cell application. The c-Si share of production was about 95% until 2019 as per HIS market. Based on silicon wafers manufacturing process [4], first generation solar cells are classified into two main types shown in Table 1.

Table 1: Classification and performance of 1G solar cells

Type of c-Si solar cells	Silicon Wafer purity	Efficiency (η)
Mono-crystalline solar cells (Mono c-Si)	Highest-grade silicon	20-25%
Polycrystalline (Poly c-Si)	Lower silicon purity	13-16%

2.2 Second Generation of PV systems (2G)

Conventional technologies employed for manufacturing crystalline silicon for PV application deal with various complex processing steps and required great amount of energy. Due to advancement in thin film technology, a few micrometers thick multilayer of semiconductor materials are deposited on low cost substrates. As a result, in order to absorb the same amount of sunlight, they need less semiconducting material. Furthermore, it is possible to pack thin films into compact and lightweight flexible structures but using rare and toxic materials. Table 2 lists the commercially developed thin film solar cells [5-6].

Table 2: Classification and performance of 2nd generation solar cells

2G solar cells	Efficiency (η-%)
Copper-Indium-Gallium-Diselenide (CIGS)	20.3
Cadmium Telluride (Cd-Te)	15.8
Amorphous silicon (a-Si)	6-7
Copper-Indium-Selenide (CIS)	7-16

2.3 Third Generation of PV systems (3G)

In recent years, investigations of new solar cell materials have been going on to reduce the dependency on silicon, which extensively used for almost all semiconducting electronics. Cells of the 3G are less commercially sophisticated 'emerging ‘techniques. Organic Solar cells (OSCs), Copper Zinc tin sulphide (CZTS), Perovskite solar cells (PSCs), Dye-Sensitized Solar Cells (DSSCs), and Quantum Dot solar cells are all designed to combine the benefits of 1G and 2G PV systems. These technologies are expected to play a significant role in fast-growing PV areas due to low-cost materials and easy manufacturing. The classifications with the performance measuring parameters are listed in Table 3 [7]

Table 3: Classification and performance of 3G solar cells

3rd generation solar cells	**Material based**	**η**	**Charge Injection Process**
PV technology with concentrators	Silicon-based cells	20% - 25%	At the interface of Si semi-conductor junctions
	Multijunction solar cells using III-V	40%	At interface of multiple junctions
DSSCs	Dye adsorb on nano structured semicon-ductor material	5% - 15%	From the excited photosensitive dye
OSCs	Organic polymer materials for electron and trans-port layers	4% - 5% (com-mercially), 6% - 8% (laboratory)	Organic polymer materials

A rich variety of solar cells are developed from above mentioned 3G PV systems, such as Si solar cells, thin film solar cells, DSSCs, III–V solar cells and OSCs. However, practical, low-cost, and high-efficiency and better real time application and practical approach for 3G solar cells are yet to be established. Regardless of major market of Si solar cells, still under research for further improvements. Inspite of offering high performance for III–V solar cells, it suffers from application limiting factor of high manufacturing cost. Quantum dot solar cells also under current topic of research shows high efficiency and low cost, but it fabrication sometimes depends on the toxic materials such as of Cd or Pb [8-10].

Within such a short period of time, PSCs have risen to prominence in the PV family. It has emerged as one of the most promising photovoltaic technologies for the future, capable of meeting our energy requirements at a lower cost and with greater efficiency. Halide perovskites reported in the literature are considered as suitable material to produce efficient solar cells with low cost. A remarkable improvement in the efficiency of PSCs cells has reported rapidly, from ~14% in 2013 to 25% in 2020 [11] as listed in figure 2. This review paper examines the recent advancement of high-efficiency PSCs to provide an update on the topic. This paper begins with a brief history of PSCs before focusing on major advancements in high-efficiency PSCs. It will also be highlighted recent efforts on PSCs stability.

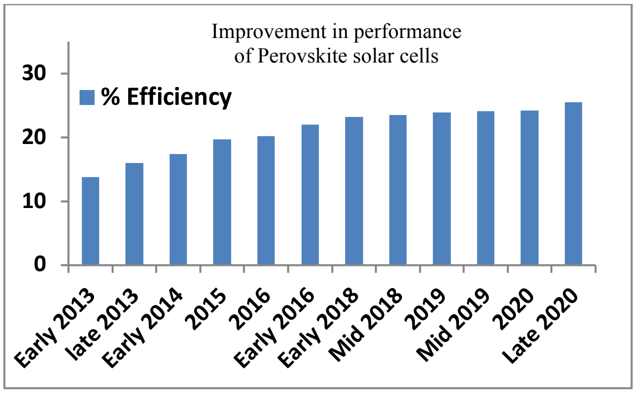
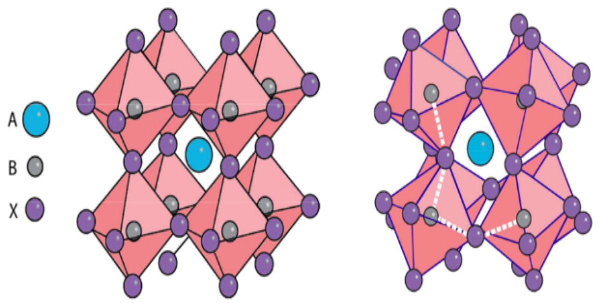


Figure 2. Improvement in performance of PSCs for 2013-2020.

3. Overview and Working Principle of PSCs

A perovskite is a substance with the same crystal structure as the first-discovered perovskite crystal, calcium titanium oxide. ABX3 is the chemical formula for perovskite compounds, where A and B (A= CH3NH3$^+$, B = Pb$^+$, X = I$^+$) are cations and X is an anion that bonds to both. Perovskite structures can be created by combining a variety of different components. Scientists can construct perovskite crystals with a wide range of physical, optical, and electrical properties using this compositional freedom. Ultrasound machines, memory chips, and now solar cells all use perovskite crystals.



3 (a) 3(b)

Figure 3. Perovskite crystal structures. (a) Cubic phase. (b) less symmetrical orthorhombic phase [12].

Architecture of an organic-inorganic lead halide PSC is shown in figure 4. It is depicted from the figure that a sub-micron layer of semiconducting perovskite material is sandwiched between the low work function (WF) electron transport layer (ETL) and a high WF hole transport layer (HTL). The upper layer is indium tin oxide (ITO)/Fluorine doped tin oxide (FTO) coated glass to pass the sunlight into the device and the bottom region is an opaque metal, usually gold (although not an option commercially). Light illumination excites the electron from valance band (VB) of perovskite material into its conduction band (CB) leaving holes in the valance band. The differences in the WF of ETL and HTL layers promotes the photo generated electrons (e-) and holes (h+) to drift/diffuse in opposite directions as shown in figure 5, which further produce electric current in the load connected externally.

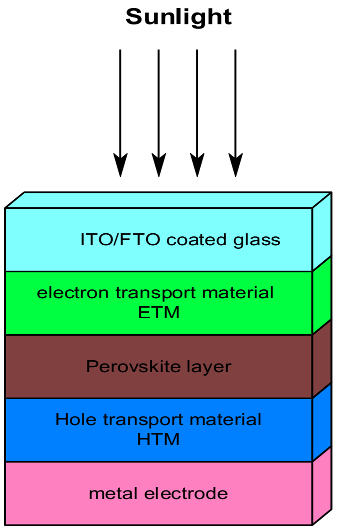


Figure 4. Architecture of Perovskite solar cell layer with different materials

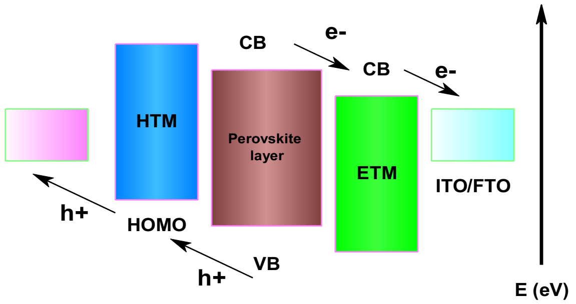


Figure 5. Energy band diagram of PSCs illustrating the e-h pair transportation across the layers

4. Recent Developments in PSCs

The effect of absorber thickness and scaling of HTM layer has been for solar cells based on $CH_3NH_3GeI_3$ (halide material) using SCAPS-1D tool. The effect of absorber thickness on device parameters indicates that for designing an efficient PSC, a thickness of 600–700 nm is optimal. In addition, a perovskite solar cell combining Cu_2O and D-PBTTT-14 as HTM layers has achieved the greatest performance, exceeding 20% [13] as listed in Table 4.

Table 4. Optimized performances with different HTM layers and absorber thickness [13]

M materials	J_{sc} $mAcm^{-2}$	V_{oc} (V)	FF (%)	PCE (%)	Absorber thickness (nm)	HTM thickness (nm)
Cu_2O	14.20	1.92	79.28	21.60	350	200
D-PBTTT-14	14.09	1.92	79.52	21.56	250	150
NiO	13.91	1.93	74.97	19.30	300	100
CuI	14.78	1.92	70.64	20.05	450	100
Spiro-OMeTAD	13.92	1.91	68.76	18.28	350	150
PEDOT-PSS	14.69	0.97	86.97	12.35	400	200

A one-step and two-step solution process is adopted to grew MAPbI3 perovskite layers to produce mesoscopic PSCs (Ag/Spiro- OMeTAD/$MAPbI_3$/SnO_2/FTO/glass). The enhanced fill factor (FF) from 48% - 77% is reported, which is attributed to the reduced recombination associated with non-radiative process due to improved crystalline property and larger grain size achieved in two step processed perovskite layer. The power conversion efficiency (PCE) is also improved by 56.86% as compared to one step process as shown in table 5 [14].

Table 5 Mesoscopic PSCs device PV performance

	J_{sc} $mAcm^{-2}$	**V_{oc} (V)**	**FF (%)**	**PCE (%)**	**R_s Ωcm^2**	**R_{sh} $k\Omega cm^2$**
One step	20.02	1.07	48	10.27	22.5	1.97
Two step	20.86	1.0	77	16.11	3.0	7.92

A number of devices were created to investigate the exact influence of graphite, and it was discovered that the 9 µm graphite-based carbon counter electrodes (CCEs) had a relatively greater PCE of over 11% (see table 6) characterized by larger average pore size and a smaller square resistance. CCE-based mesoscopic PSCs with fully printed hole-conductor-free mesoscopic PSCs have been observed for the futuristic potential for large-scale production. To summarize, graphite, as a main component, has a significant impact on the porosity and conductivity of CCEs. Changes in graphite size cause variances in the filling of PbI_2 and $CH_3NH_3PbI_3$ precursors, resulting in differences in device PCE [15]

Table 6. Performance of PSC devices based on CCEs for various thicknesses.

	V_{oc} (mV)	**J_{sc} $mAcm^{-2}$**	**FF (%)**	**PCE (%)**
5 µm	902	16.71	65	9.79
7 µm	883	17.13	66	10.02
9 µm	894	18.06	72	11.63
12 µm	873	17.41	71	10.56
15 µm	868	16.91	72	10.53

By altering the size of the TiO_2 nanoparticles (NPs) and the thickness of the mp-TiO_2 layer, the charge-injection and transport capabilities of mesoporous (mp)-TiO_2 layers in PSCs are studied. Surface area of perovskite CH_3NH_3PbI)/TiO_2 interface are directly connected to particle size and layer thickness, which might affect electron life time for mp-TiO_2 layers in PSCs. Samples of PSC of different layer thickness (150 nm - 400 nm) and NP diameter (25 nm and 41 nm) of TiO_2 are examined as shown in Table 7 [16].

Table 7. PV performance of the perovskite (CH_3NH_3PbI) bases PSC for various thickness of TiO_2 nanoparticle paste. BET surface area (70.347**/39.99* m^2/g), total pore volume (0.20**/0.39* cm^3/g) Mean pore diameter (11.8**/39.8* nm). ** T25 sample/* T41 sample

Sample	**Thickness (nm)**	**V_{oc} (V)**	**J_{sc} $mAcm^{-2}$**	**FF (%)**	**PCE (%)**	T_{avg}
T25	150	1.060	23.64	72	18.03	79.32
	250	1.036	23.13	69	16.52	--
	400	1.030	21.43	65	14.34	74.76
T41	150	1.090	22.89	75	18.72	87.97
	250	1.066	23.18	74	18.38	--
	400	1.044	23.6	72	17.77	81.35

Lead is a toxic material and lead halides may also show toxicity and also possess almost all the characteristics of perfect solar cell materials. Germanium halide perovskites are an attractive alternative to lead perovskites because of their well-suited optical properties for photovoltaic applications. In order enhance the performance of germanium based PSCs, various research teams are following real time experiments.

1D-Solar Cell Capacitance Simulator (1D-SCAPS) is employed to investigate a Germanium-based PSC ($CH_3NH_3GeI_3$) whereby, evaluating the impact of ELT layer. When compared to previous proposed ETL materials, the significant improvement is observed in the performance of a Ge-based device via C60, TiO_2, and SnO_2 as ETL. As a result, when compared to the other ETL materials, the perovskite device with C60 has the greatest PCE of 13.5%. [17]. Results show that C60 is a good choice for improving Ge-based device performance as listed in Table 8. As a result, including C60 into the structure of a PSC could be deemed an unique design for future Ge-PSCs .

Table 8. Photovoltaic parameters of $CH_3NH_3GeI_3$-based solar cell with diversified ETLs and with "PEDOT": "PSS as HTL".

Various ETL materials	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	PCE (%)
PCBM	23.07	870	55.37	11.16
IGZO	23.04	810	54.36	10.16
C60	23.38	940	61.66	13.5

SnO_2	23.4	930	60.39	13.19
ZnO	20.82	880	60.64	11.05
TiO_2	23.44	930	60.75	13.30

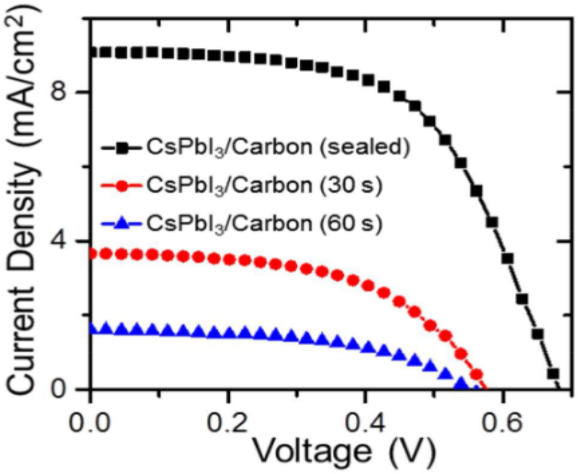


Figure 6. PV performances of $CsPbI_3$/carbon based inorganic PSCs; sealed $CsPbI_3$/carbon and after exposed in humid air without encapsulation for 30s and 60s, respectively [18].

PSCs are also studied with the impact of the encapsulation on their PV performance. The CsPbI3/carbon based inorganic PSCs are fabricated and tested under the humid air (90-95% RH, 25 °C) conditions for a short duration and compared its performance with the sealed PSCs. It is observed that PCE degraded up to 87.5% in 60s of humid air exposer as compared to sealed PSC as shown in figure 6 and table 9.

Table 9. PV parameters of PSC shown in figure 6.

Aging Time	Jsc ($mAcm^{-2}$)	V_{OC} (mV)	FF (%)	PCE (%)
$CsPbI_3$/carbon (sealed)	9.08	700	57	3.6
$CsPbI_3$/carbon (30s)	3.66	580	53	1.13
$CsPbI_3$/carbon (60s)	1.61	560	50	0.45

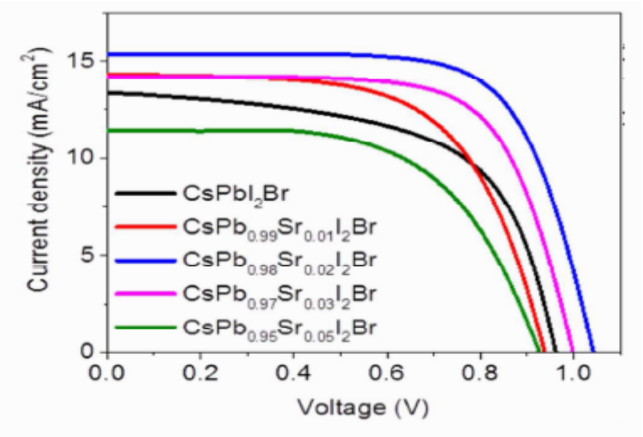


Figure. 7. J-V curves under reverse scan of FTO/c- TiO_2/mp-TiO_2/ $CsPb_{1-x}Sr_xI_2Br$ /P3HT/Au devices as a function of Sr^{2+} percentage [19].

An experimental research is also studied to investigate the impact of strontium (Sr) atom doping at low temperature processed $CsPbI_2Br$ PSCs as shown in figure 7. It is observed that Defect trapping lifetime (τ_{trap}) is relatively remains same for all the films with a value of 2 ns. However, as Sr content increases from 1% to 2%, the recombination life time (τ_{rec}) increases from 11.1 ns to 17.1 ns, suggesting better effective recombination lifetime. This results the optimized PV performance at 15.3 mA/cm^2, 1.043 V, 69.9 and 11.2% of Jsc, Voc, FF and PCE respectively for Sr content = 2% as listed in table 10. In addition to this, a better passivation is provided by the Sr enriched surface [19].

For the first time, PSCs flexibly featured fiber structure were created via continuous running winding aligned multi-walled carbon nanotube sheet electrode onto a fiber electrode in addition to photoactive perovskite materials. The PCE of the fiber-shaped PSC is 3.3%, and it remains stable when bent [21].

Table 10. PV parameters of FTO/c-TiO_2/mp-TiO_2/ $CsPb_{1}\ {}_{x}Sr_xI_2Br$/P3HT/Au devices as a function of Sr^{2+} percentage [19]

Sr %	*Jsc* (mA/cm^2)	*Voc* (V)	FF (%)	PCE (%)	τ_{trap} ns	τ_{ec} ns
0%	13.4	0.962	59.8	7.7	2.2	11.1
1%	14.3	0.938	62.2	8.3	2	13.3
2%	15.3	1.043	69.9	11.2	2.1	17.1
3%	14.2	0.999	69.2	9.8	1.6	16.7
5%	11.2	0.927	61.3	6.4	2.3	9.3

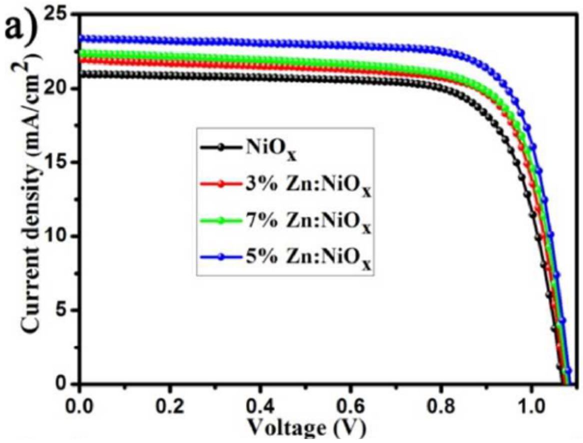


Figure 8. J-V characteristics of a multi layered P-i-N based PSC as a function of NiOx:Zn %. Reprinted (adapted) with permission from [20]. Copyright 2016 American Chemical Society.

An investigation related to doping impact of Zinc for NiOx based planar PSCs is also carried out. A Ag-glass/FTO/NiOx(NiOx:Zn)/MAPbI$_3$/PCBM/BCP/Ag multi layered P-i-N based PSC structures is considered for experimental process. PSCs with different Zn (3%, 5%, 7%) percentages are fabricated in order to increase the conductivity of hole transport layer known as NiOx:Zn inorganic layer as shown in figure 8. It is observed that PCE is maximized at 19.6% for Zn = 5% with Jsc = 22.8 mAcm-2, Voc = 1.1 V and FF = 78.14% [20].

Few of the research work are also carried to improve the performance and stability for Tin-based PSCs as shown in figure 9. By adopting the method to enhance the nucleation rate along with suppression of Sn2+ oxidized species [22] by introducing HPA (hypo-phosphorous acid) co additives. Reducing the trap density in the perovskite material by controlling the morphology of the film with PMMA (poly-methyl-methacrylate) co-additives [23]. The impact of suppression of p-doping decreasing conductivity of perovskite material is also studied with (piperazine) co- additive [24].

The impact of homogeneous dispersion of SnF$_2$ [25] with PZ (pyrazine) co-additive and suppression of Sn$_2^+$ oxidation is also discussed in the literature [26] with HZCl (hydrazinium chloride) co-additive. The role as oxygen scavenger and grain boundaries offering passivation is also investigated on PSCs performance [27] with HBAS (hydroxybenzene sulfonic acid) co-additive. In addition to regulating film morphology through formation of a complex with SnI$_2$ (or SnF$_2$) with TMA (trimethylamine) co additive [28], impact of orientation of crystal growth in quasi-2D structure is also studied with FASCN (formamidinium thiocyanate) co additive [29] The role of co additives is also analyzed such as NH$_4$Cl (ammonium chloride), EDAI2 (ethylene di ammonium di iodide) and NH$_4$SCN (ammonium thiocyanate) accountable for film morphology and crustal growth orientation, inducing defect passivation in surface and bulk states of the film and crystal growth and phase distribution in 2D/3D structure respectively regulating the PCE of PSCs [30-33]

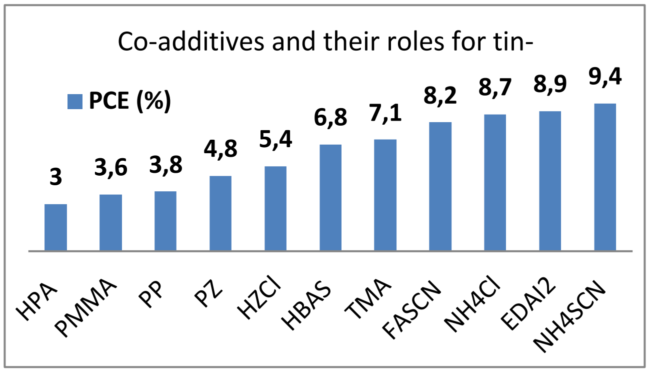


Figure 9. Impact of types of co-additives on the performance the performance Tin-based PSCs

A recent research also reported that an Inorganic cesium lead triiodide (CsPbI3) perovskite materials are now becoming the attractive due to its idle band gap of 1.7 eV. AnAg-PC71BM-CsPbI3-PEDOT: PSS-ITO structured based PSCs are investigated in order to determine the formation of cubic or black phase (α-CsPbI3) of CsPbI3 absorber by treating with various concentration of Hydroiodic Acid (HI). Results shows that that PV parameters are improved for various concentrations and get optimized at PCE$_{avg}$ = 6.30% for HI concentration of 36 μL/mL. It is also noticed that HI treatment also minimized the charge transport resistance RCT = 12.8 kΩ [33]. Impact of Al2O3 scaffold layers are also investigated [37].

Table 11. PV performance of a Ag-PC71BM-CsPbI3 PEDOT: PSS-ITO structured based PSCs on the treatment of various concentration of Hydroiodic Acid (HI).

HI conc.	Jsc_{avg} ($mAcm^{-2}$)	V_{OCcvg} (V)	FF_{avg} (%)	PCE_{avg} (%)	R_{CT} (kΩ)
30	10.84	0.846	56.33	5.17	39.1
33	12.78	0.866	53.91	5.96	13.9
36	12.83	0.875	56.21	6.30	12.8
39	13.29	0.806	54.05	5.79	19.1

42	11.14	0.770	50.25	4.33	37.7

5. Commercialization Challenges

On the basis of the few facts discussed in this paper, there are three major key challenges which representing a distinct set of constraints that must be overcome concurrently to commercialize the perovskite technologies in order to meet specific technical and commercial objectives effectively.

5.1. Efficiency of PSCs:

Perovskite devices have outperformed (almost-all) thin-film devices, excluding III-V technologies, especially w.r.t. power efficiency (η_{power}), with accelerated improvisation in the last 5 years. However, devices with efficiencies in upper range have not always been combined with reliable stability & manufacturing features. Sustaining such high PCE while establishing stability and scaling will be required for large scale commercial perovskite deployment. By modifying the properties of materials, perovskites can be tailored to respond to diversified wavelengths in the spectral region, and a range of compositions have exhibited outstanding performance. This energy band gap flexibility allows PSCs to be used in high-performance tandem device topologies, with theoretical PCE > 30%. To offer maximum power, perovskites are coupled with another, uniquely tailored absorber material in these arrangements [33].

5.2. Degradation and Stability

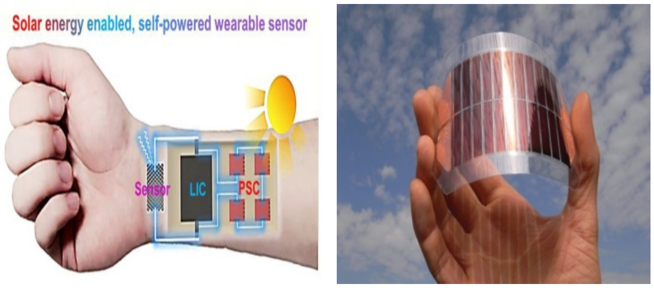
PCS have been testified with reasonable efficiencies further having the possibility for improvised performance, although their stability is rather constrained while observing against the leading Photo-voltaic technologies. They are not resistant to moisture, oxygen, prolonged light exposure, or high temperatures. Researchers are investigating deterioration in both the perovskite materials and the interfacial layers in order to improve stability. Moreover, lifespan of cell(s) under the scope of improvement is critical for the commercialization of PS devices. Absorber layers facilitated with improved surface passivation, ETL/HTL and electrodes; advanced encapsulation materials and approaches that help in mitigating the degradation sources during fabrication and operation are amongst the potential endeavors made to better comprehend and improvise the intrinsic and extrinsic stability and degradation as well [33].

5.3. Ability to manufacturing:

Perovskite manufacturing must be scaled up in order to produce PSCs. The cells are made up of layers of materials that have been printed, coated with liquid inks, or vacuum-deposited. Producing homogenous cum acceptable-performance perovskite material on a wide scale is not easy, because the performance of small-area cells versus large-area modules differs significantly. Solving this difficulty, which is still an active area of research in the PV field, will be essential to the growth of perovskite production. The potential environmental consequences of the lead-based perovskite absorber are also a hurdle to commercialization. As a result, alternative materials are being investigated in order to assess, alleviate, and maybe eliminate toxicity and environmental risks. Owing to the continually changing nature of material and device compositions of PSCs are, such standard validation is extremely difficult & necessary at the same time [33].

6. Applications

As PSCs is power generating PV devices which can be used for indoor and outdoor applications. The flexible property of the PSC makes it suitable for wearable devices as shown in figure 10 (a) to power electronic gadgets. It can be also employed on the windows of the buildings due to flexible and light weighted properties (see fig 10 (b)). Solar cells are also deployed for the space missions to power the spaceships etc. (see fig 10 (c)). The roll to roll manufacturing process can be adopted to produce large extent of printed PSCs as shown in fig 10 (d) [34-36]. In addition to this solar cell panels can be also applied to solar charging stations for electric vehicles and grids [38,40-41].



(a) (b)

(c) (d)

Figure 10. Area of applications for perovskite solar cells

7. Conclusion

To summarize, possible strategies for PSCs should include developing a better insight into the interaction between organic and inorganic components in order to exploit the properties of both core supporters, as well as forming a better perception of the impact of perovskite structure on its optoelectronic properties in order to realize optimal design. Meanwhile, a number of research teams from several countries have produced efficient PSCs. This suggests that, despite the difficulty in reproducibly producing high-quality perovskites, this is a problem that may be handled by careful adjustment of the material composition and deposition circumstances. Production of larger area cells and modules has progressed, which is important for commercialization of fabrication process. However, based on life cycle analyses, the main issue appears to be the device's lifespan. Multidisciplinary collaboration efforts are also expected to aid in further progress and the resolution of problems about reproducibility and stability.

8. References

[1] D. Kumar, “A short review on the advancement in the development of TiO2 and ZnO based photo-anodes for the application of Dye-Sensitized Solar Cells (DSSCs)”, Engineering Research Express. 2021; 3(4) 042004.

[2] K. Ranabhat, L. Patrikeev, A. Revina, K. Andrianov, V. Lapshinsky, and E. Sofronova, “An introduction to solar cell technology”, Journal of Applied Engineering Science. 2016; 14(4):481-491.

[3]. M. A. Green, “Third Generation Photovoltaics: Advanced Solar Energy Conversion”, Physics Today. 2004 Dec; 57(12):71-2.

[4]. A. Wang, J. Zhao, and MA. Green, “24% efficient silicon solar cells”, Applied physics letters. 1990 Aug 6;57(6):602-4.

[5] M. A. Green, Y. Hishikawa, ED. Dunlop, DH. Levi, J. H Ebinger, and AW. Ho-Baillie, “Solar cell efficiency tables (version 52)”, Progress in Photovoltaics: Research and Applications. 2018 Jul;26(7):427-36.)

[6] J. Britt and C. Ferekides, “Thin-film CdS/CdTe solar cell with 15.8% efficiency”, Applied physics letters. 1993 May 31;62(22):2851-2.

[7] H. Cotal, C. Fetzer, J. Boisvert, G. Kinsey, R. King, P. Hebert, H. Yoon, and N. Karam, “III-V multi junction solar cells for concentrating photovoltaics”, Energy and Environmental Science. 2009;2(2):174-92.

[8] B. O'regan, and M. Grätzel, “A low-cost, high-efficiency solar cell based on dye sensitized colloidal TiO2 films. Nature”, 1991 Oct;353 (6346):737-40.

[9] G. Smestad, C. Bignozzi, and R. Argazzi, “Testing of dye sensitized TiO2 solar cells I: Experimental photocurrent output and conversion efficiencies”, Solar energy materials and solar cells. 1994 Mar 1;32(3):259-72.

[10] J. Gong, K. Sumathy, Z. Zhou, and Q. Qiao, “Modeling of interfacial and bulk charge transfer in dye-sensitized solar cells”, Cogent Engineering. 2017 Jan 1;4(1):1287231.

[11]. P. Roy, NK. Sinha, S. Tiwari, and A. Khare, “A review on perovskite solar cells: Evolution of architecture, fabrication techniques, commercialization issues and status”, Solar Energy. 2020 Mar 1;198:665-88.

[12]. NG. Park, “Crystal growth engineering for high efficiency perovskite solar cells”, Cryst Eng Comm. 2016;18(32):5977-85.

[13]. AA. Kanoun, MB. Kanoun, AE. Merad, and S. Goumri-Said, “Toward development of high-performance perovskite solar cells based on CH3NH3GeI3 using computational approach”, Solar Energy. 2019 Apr 1;182:237-44.

[14]. M. Wang, Y. Feng, J. Bian, H. Liu, and Y. Shi, “A comparative study of one-step and two-step approaches for MAPbI3 perovskite layer and its influence on the performance of mesoscopic perovskite solar cell”, Chemical Physics Letters. 2018 Jan 16;692:44-9.

[15]. L. Zhang, T. Liu, L. Liu, M. Hu, Y. Yang, A. Mei, and H. Han, “The effect of carbon counter electrodes on fully printable mesoscopic perovskite solar cells”, Journal of Materials Chemistry A. 2015;3(17):9165-70.

[16]. DG. Lee, MC. Kim, BJ. Kim, DH. Kim, SM. Lee, M. Choi, S. Lee, and HS. Jung, “Effect of TiO2 particle size and layer thickness on mesoscopic perovskite solar

cells",Applied Surface Science. 2019 May 31;477:131-6.

[17]. N. Lakhdar, and A.Hima, "Electron transport material effect on performance of perovskite solar cells based on CH3NH3GeI3", Optical Materials. 2020 Jan 1;99:109517.

[18]. J. Liang, C. Wang, Y. Wang, Z. Xu, Z. Lu, Y. Ma, H. Zhu, Y. Hu, C. Xiao, X. Yi, and G. Zhu, "All-inorganic perovskite solar cells", Journal of the American Chemical Society. 2016 Dec 14;138(49):15829-32.

[19]. CF. Lau, M. Zhang, X. Deng, J. Zheng, J. Bing, Q. Ma, J. Kim, L. Hu, MA. Green, S. Huang, and A. Ho-Baillie, "Strontium-doped low-temperature-processed CsPbI2Br perovskite solar cells", ACS Energy Letters. 2017 Sep 11;2(10):2319-25.

[20]. X. Wan, Y. Jiang, Z. Qiu, H. Zhang, X. Zhu, I. Sikandar, X. Liu, X. Chen, and B. Cao, "Zinc as a new dopant for NiO x-based planar perovskite solar cells with stable efficiency near 20%", ACS Applied Energy Materials. 2018 Jul 9;1(8):3947-54.

[21]. L. Qiu, J. Deng, X. Lu, Z. Yang, and H. Peng, "Integrating perovskite solar cells into a flexible fiber", Angewandte Chemie International Edition. 2014 Sep 22;53(39):10425-8.

[22] S.J. Lee, S.S. Shin, Y.C. Kim, D. Kim, T. K Ahn, J.H. Noh, J. Seo, and S. Seok, "Fabrication of Efficient Formamidinium Tin Iodide Perovskite Solar Cells through SnF 2 – Pyrazine Complex", J. Am. Chem. Soc. 2016, 138, 3974–3977

[23] Z. Zhu, C.C. Chueh, N. Li, C. Mao, and AKY Jen, "Realizing Efficient Lead-Free Formamidinium Tin Triiodide Perovskite Solar Cells via a Sequential Deposition Route", Adv. Mater. 2018, 30, 1703800.

[24] E. Jokar, C.H. Chien, A. Fathi, M. Rameez, Y.H. Chang, E.W.G. Diau, and E, "Slow Surface Passivation and Crystal Relaxation with Additives to Improve Device Performance and Durability for Tin-Based Perovskite Solar Cells", Energy Environ. Sci. 2018, 11, 2353–2362.

[25] H. Xu, Y. Jiang, T. He, S. Li, H. Wang, Y. Chen, M. Yuan, and J. Chen, "Orientation Regulation of Tin-Based Reduced-Dimensional Perovskites for Highly Efficient and Stable Photovoltaics", Adv. Funct. Mater. 2019, 1807696.

[26] F. Wang, X. Jiang, H. Chen, Y. Shang, H. Liu, J. Wei, W. Zhou, H. He, W. Liu, and Z. Ning, "2D-Quasi-2D-3D Hierarchy Structure for Tin Perovskite Solar Cells with Enhanced Efficiency and Stability", Joule 2018, 2, 2732–2743.

[27] Q. Tai, X. Guo, G. Tang, P. You, TW. Ng, D. Shen, J. Cao, CK. Liu, N. Wang, Y. Zhu, and CS, "Lee. Antioxidant grain passivation for air-stable tin-based perovskite solar cells", Angewandte Chemie International Edition. 2019 Jan 14;58(3):806-10.

[28] W. Li, J. Li, J. Li, J. Fan, Y. Mai, and L. Wang, " Addictive-assisted construction of all-inorganic CsSnIBr 2 mesoscopic perovskite solar cells with superior thermal stability up to 473 K", Journal of Materials Chemistry A. 2016;4(43):17104-10.

[29] L. Deng, K. Wang, H. Yang, H. Yu, and B. Hu, "Polymer assist crystallization and passivation for enhancements of open-circuit voltage and stability in tin-halide perovskite solar cells", Journal of Physics D: Applied Physics. 2018 Oct 8;51(47):475102.

[30] TB. Song, T. Yokoyama, J. Logsdon, MR. Wasielewski MR, S. Aramaki, and MG. Kanatzidis, "Piperazine suppresses self-doping in CsSnI3 perovskite solar cells", ACS Applied Energy Materials. 2018 Aug 1;1(8):4221-6.

[31] ME. Kayesh, TH. Chowdhury, K. Matsuishi, R. Kaneko, S. Kazaoui, JJ. Lee, T. Noda, and A. Islam, "Enhanced photovoltaic performance of FASnI3-based perovskite solar cells with hydrazinium chloride coadditive", ACS Energy Letters. 2018 Jun 11;3(7):1584-9.

[32] H. Kim, YH. Lee, T. Lyu, JH. Yoo, T. Park, and JH. Oh, "Boosting the performance and stability of quasi-two-dimensional tin-based perovskite solar cells using the formamidinium thiocyanate additive", Journal of Materials Chemistry A. 2018;6(37):18173-82.

[33]. NREL, Best research-cell efficiency chart, https://www.nrel.gov/pv/cell-efficiency.html (accessed: May 2020).

[34]. C. Li, S.Cong, Z. Tian, Y. Song, L. Yu, C. Lu, Y. Shao, J. Li, G. Zou, MH. Rümmeli, and S. Dou, "Flexible perovskite solar cell-driven photo-rechargeable lithium-ion capacitor for self-powered wearable strain sensors", Nano Energy. 2019 Jun 1;60:247-56.

[35] https://statnano.com/news/67695/Flexible Solar-Cells-Far-fetched-Then-But-Possible-Now. June 2020.

[36] O. Malinkiewicz, M. Imaizumi, SB. Sapkota, T. Ohshima, and S.Öz, "Radiation effects on the performance of flexible perovskite solar cells for space applications", Emergent Materials. 2020 Feb;3(1):9-14.

[37] H. Sun, S. Lin, R. Zhang, K. Yang, M. Xia, W. Li, and W. Guo, "Perovskite solar cells employing Al2O3 scaffold layers", 2014 International Conference on Renewable Energy Research and Application (ICRERA), Milwaukee, WI, pp. 442-444, 2014.

[38]. T. Sakagami, Y. Shimizu, and H. Kitano, "Exchangeable batteries for micro EVs and renewable energy", In2017 IEEE 6th International Conference on Renewable

Energy Research and Applications (ICRERA) 2017 Nov 5 (pp. 701-705). IEEE.

[39]. A. Belkaid, I. Colak, K. Kayisli, M. Sara, and R. Bayindir, “Modeling and simulation of polycrystalline silicon photovoltaic cells”, In2019 7th International Conference on Smart Grid (icSmartGrid) 2019 Dec 9 (pp. 155-158). IEEE.

[40]. F. Ayadi, I. Colak, I. Garip, and HI. Bulbul, “Impacts of Renewable Energy Resources in Smart Grid”, In2020 8th International Conference on Smart Grid (icSmartGrid) 2020 Jun 17 (pp. 183-188). IEEE.

[41] M. Yesilbudak, M. Colak, R. Bayindir, and HI. Bulbul, “Very short term modeling of global solar radiation and air temperature data using curve fitting methods”, In2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA) 2017 Nov 5 (pp. 1144-1148). IEEE