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Toward Commercial Viability: A Comprehensive Review of Organic Solar Cell Stability and Scalability

M. G. S. H. Sewmini, P. M. K. Alahakoon*

Department of Electrical, Electronic and Systems Engineering
Faculty of Engineering, NSBM Green University, Sri Lanka
Corresponding Author E-mail: mahinda.a@nsbm.ac.lk

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Abstract: This review paper provides a general overview of Organic Solar Cells (OSCs), more precisely their instability and commercialization challenges. The discussion begins by situating OSCs in the context of the global field of renewable energy, where their unique strengths of flexibility, low cost, and semi-transparency are brought out. Despite significant advances made, with power conversion efficiencies (PCEs) over 20% under laboratory conditions, the biggest challenge for wide-scale commercialization remains poor device stability and scalability. This report outlines the historical evolution of photovoltaic technologies, recent development of OSC efficiency and material advancement, specifically non-fullerene acceptors and ternary blends, and comparison with other generations of PV. Technical challenges are highlighted centrally, including intrinsic material instability, environmental degradation under oxygen, water, light, and heat, mechanical stress, and production bottlenecks. Solutions proposed and existing are presented, e.g., cutting-edge material engineering, optimization of device structure like inverted geometry, new processing ideas, and encapsulation technologies. Notably, the synergistic effect of optimizing the active layer thickness on stability and cost-effectiveness is discussed. Finally, the paper outlines critical directions for further study, such as the need for standardized test procedures, further material development, and an integrated methodology to accelerate the commercial readiness of OSC technology.

Index Terms: Cutting-edge material, Encapsulation technologies, Organic Solar Cells, Power Conversion Efficiencies, Stability

1 Introduction

The imperative need to transform to sustainable energy systems has never been more pressing with the world facing increasing energy demands, depleting fossil fuel resources, and the escalating threat of climate change. Among various renewable energy technologies, solar energy stands out due to its abundance, reliability, and environmental friendliness. As solar energy continues to expand its geographical footprint globally, advancements in photovoltaic (PV) technologies have become a key focus area for researchers, policymakers, and business people alike.

1.1 Global Energy Situation and the Role of Photovoltaic Technology

The 21st century is characterized by a skyrocketing energy demand and the compelling necessity to alleviate climate change, in large part instigated by anthropogenic carbon dioxide (CO2) emissions [1]. Amidst this critical scenario, the development and global deployment of renewable, clean energy technologies have emerged as the most significant agenda. Solar energy is an unlimited and environmentally friendly resource and has become a keystone in the world's movement to establish sustainable energy systems [1]. The enormous amount of solar radiation released from the sun, which by far surpasses the present global energy consumption, indicates the huge potential.

Photovoltaic (PV) technology is leading to this energy revolution in the sense that it directly transforms sunlight into electricity and hence makes a significant impact in reducing greenhouse gas emissions as well as climate change. It offers a path forward to a cleaner, more reliable, scalable, and cheaper electricity system. Over the past decade, the PV sector has made huge efficiency gains, propelling worldwide solar PV technology installations. These advances have translated into efficiencies of up to 30% and costs below $0.50/W, rendering PV a highly competitive energy source worldwide.

In 2017, worldwide solar cell production fluctuated between 18 GW and 27 GW. Total PV production has increased nearly two orders of magnitude, with annual growth rates ranging from 40% to 90% [2]. From 2001 to 2017, the solar price decreased by 40% [3]. Monocrystalline Silicon materials are superior by nearly 80% of the PV market, while thin film materials are gaining ground rapidly, as represent in Fig 1 [4].

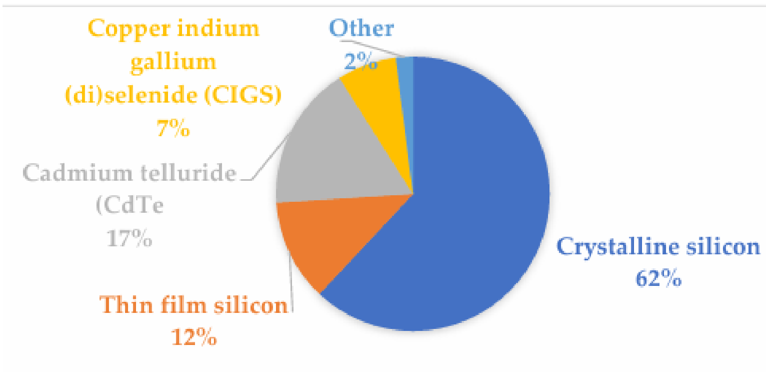

Fig.1. Solar cell materials market share in 2017 [4]

1.2 Defining Organic Solar Cells (OSCs): Strengths and Impacts

Organic Solar Cells (OSCs) are a novel form of photovoltaic technology that utilizes organic, carbon-based semiconductor materials, such as conjugated polymers and small molecules, to convert solar energy into electricity [5]. This novel material composition confers several peculiar strengths that set OSCs apart from conventional inorganic PV technologies. As of 2022, PV technology includes tandem solar cells for improved absorption cost cost-effective, and highly efficient perovskite solar cells.

The field of organic solar cells has observed a remarkable acceleration in power conversion efficiency over recent years. Among these technologies, OSCs emerge as promising candidates for building-integrated photovoltaic (BIPV)/automotive-integrated photovoltaic (AIPV) and indoor PV applications [6]. This potential is attributed to several advantages, such as their high power conversion efficiency (PCE ;>20% under incident light;>30% [7] under indoor light) the inherent average visible transmittances of their photoactive materials (AVTs; >60%) [8], their fine-tunable spectral absorbance/frontier energy levels [7], and their low-cost/energy production process [9]; hence, OSCs are regarded as potential renewable and sustainable energy resources for the near future.

Through 2022, photovoltaic (PV) technology has seen numerous advancements with the aim of enhancing efficiency, reducing costs, and expanding application versatility. Tandem solar cells, i.e., silicon–perovskite structures, represent one of the most groundbreaking developments since they significantly improve light absorption and conversion efficiency. Perovskite solar cells have also emerged as a low-cost option with high efficiency and low-cost manufacturing. Bifacial photovoltaic modules, able to capture light from both the front and rear surfaces, have also become an area of interest for higher energy generation. Transparent solar cells have even been integrated into windows and building façades, offering new fronts for building-integrated photovoltaics (BIPV).

Enhancements in light-harvesting devices, based on nanomaterials and optimal surface engineering architectures, have also boosted the efficiency of PV systems. Roll-to-roll processing and other scalable manufacturing technologies have assisted in reducing production costs and enabling massive deployment. Artificial intelligence (AI) and machine learning have been employed to optimize system design, detect faults, and predict performance. Moreover, flexible and light-weight thin-film solar panels have increased the opportunities for installation, e.g., on curved, mobile, or portable surfaces. When discussing the organic cell technology.

Organic solar cells (OSCs) have undergone significant progress in recent years, with the power conversion efficiencies reaching 18.3% up to the year 2020. The developments are largely due to the advent of novel donor–acceptor materials, enhanced molecular engineering, and device structure optimization. Current studies are even more focused on addressing the ever-burning issue of operational stability under real conditions like moisture, oxygen exposure, and long-term UV irradiation.

The scientific trend on OSCs has shown consistent escalation with a high Research Tendency index (RT5), reporting increased academic and industrial interest. Fig 2 represents that OSCs are transitioning from exploratory to applied research, based on both performance enhancement and scalability during manufacturing [10].

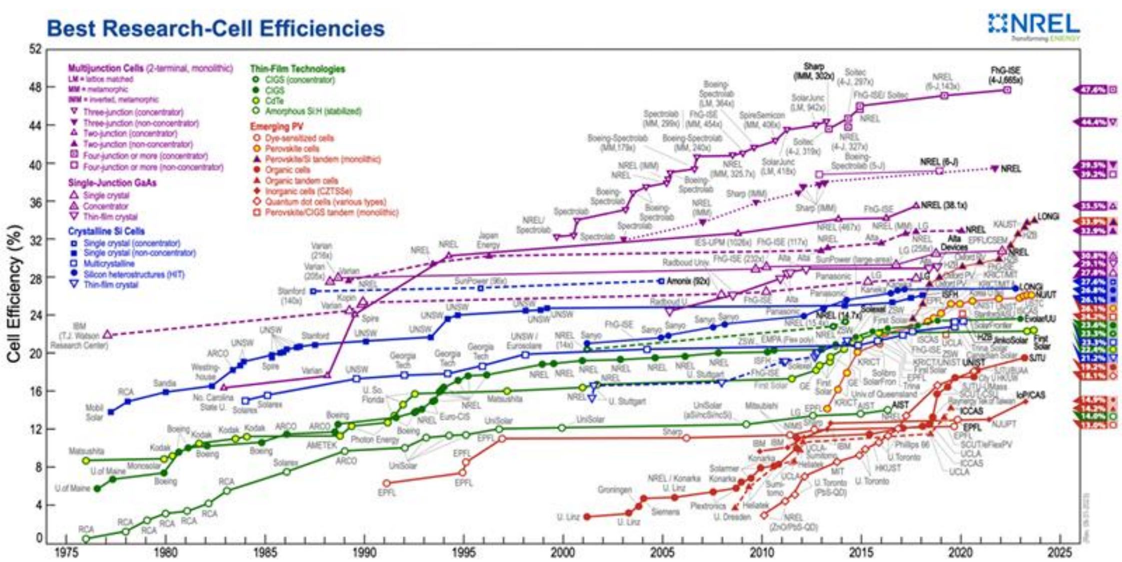

Fig.2. Best Research cell efficiency [11]

According to the National Renewable Energy Laboratory (NREL) maintains a chart, Figure 2, this figure represents the highest independently confirmed efficiency type of solar cell, as well as the graph represents the high efficiency solar cell chart update about the latest research findings [11].

2 HISTORICAL DEVELOPMENT TIMELINE AND RECENT ADVANCES

2.1 Evolution of photovoltaic Technology: A Generation overview

The history of PV cells can be traced back to the late 19th century, when French physicist Alexandre Edmond Becquerel invented the phenomenon of the PV effect [12] [13]. He observed that some materials exposed to light produce small electrical Current; this was a basic stage of the development of PV technology [14].

20th-century early researchers such as Albert Einstein and Charles Fritts continued to study the photovoltaic effect and improve upon the efficiency of PV cells. For example, Fritts created the first working PV cell layering selenium and gold onto glass, which had an efficiency of only 1% [14]. In the 1950s and 60s, the space race between the US and the Soviet Union led to significant evolution in PV technology [15] [16]. The US government invested and developed this because they wanted to use this PV technology in their space satellites. In the creation of more efficient and durable PV cells with around 14% [17].

As well as 1970 renewable energy source increase the demand and usage because the oil crisis. for that reason, in PV technology, manufacturing techniques and future improvement are developed [18]. In the 1980 and 90s, silicon-based PV cells became the dominant technology and various ways of application were used around the world. in that period, we saw the development of the thin film PV cells, which used less silicon and were more cost-effective to produce.

In the 21st century, photovoltaic (PV) technology was still evolving at a frantic rate with tremendous advances in efficiency and materials development. Modern PV cells have achieved efficiencies exceeding 25%, due in large part to the creation of new cell structures and the introduction of new materials such as perovskites and quantum dots. Perovskite materials, in particular, have garnered widespread attention owing to their excellent light absorption properties, high charge-carrier mobility, and ideal bandgap for solar energy collection [19], [20]. These attributes have pushed perovskite solar cells (PSCs) to the forefront, with their power conversion efficiency (PCE) now surpassing 25%, making them a promising low-cost alternative to traditional silicon-based cells.

Alongside the evolution of conventional PV technologies, organic photovoltaic (OPV) cells have taken an alternative route of advancement. The concept of utilizing organic materials for solar energy conversion is not new and was conceived at the start of the 20th century, when initial experiments demonstrated the photoconductivity of certain polymers when exposed to light [14]. This initial observation was the foundation upon which later research on organic semiconductors for photovoltaic applications would be established.

Considerable advancement in OPV technologies began to evolve during the latter half of the 20th century. Scientists began experimenting with polymers as active layers in solar cells during the 1970s and 1980s, although the devices realized tended to have low efficiencies, typically below 1%. Nonetheless, these early advances provided the fundamental understanding that led to the creation of more sophisticated OPV architecture.

The 1990s were the breakthrough decade with new conjugated polymers and small-molecule materials revolutionizing OPV performance. Efficiencies as high as 4% were recorded during the period, helped by advances in cheap processing methods such as solution processing [14]. The baton was passed into the 21st century, with newer materials and cell structures enabling OPV cells to approach 18% efficiencies [14]. The utilization of multilayer architectures also facilitated charge separation and light harvesting, resulting in this growth.

The last couple of years have seen remarkable advances in the efficiency, stability, and scalability of the production of OPV technologies. The state-of-the-art OPV cells now reach efficiencies close to 20% [14] due to progress in novel donor–acceptor materials, fullerene derivatives, and tandem architectures. Progress in roll-to-roll processing and print technologies has further enhanced the commercial appeal of OPV cells by enabling low-cost and large-area production.

While OPV devices still lag inorganic counterparts in terms of absolute efficiency, they have unique advantages like mechanical flexibility, lightness, semi-transparency, and compatibility with flexible substrates. As active research addresses remaining challenges, most significantly stability and long-term performance, OPV cells will play an increasingly important role in the diverse universe of renewable energy technologies.

2.2 Generation Overview

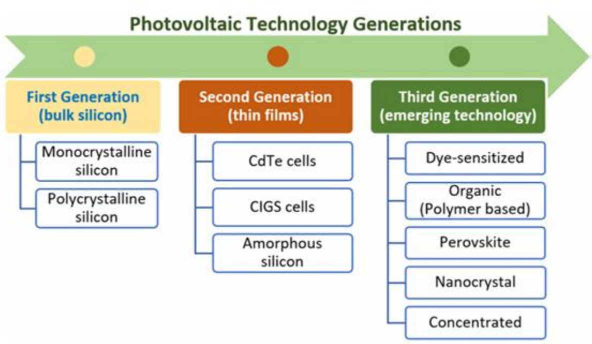

Fig.3. Three generations of PV [4]

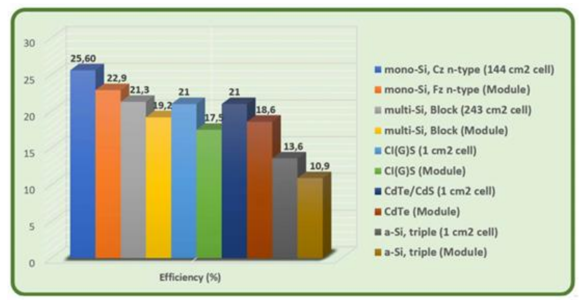

Fig.1. Efficiency of silicon-based technologies in laboratories [22]

As in the above section, photovoltaic (PV) manufacturing technologies have developed significantly over the years and thus, there are numerous technologies available in the market today. Policy-makers, investors, and customers ought to be informed of the categorization of these technologies in order to facilitate them making efficacious decisions on the installation of solar power systems. A general categorization of PV manufacturing technologies is presented in Fig. 3 [21].

First-generation solar cells, also referred to as conventional or traditional PV technologies, are predominantly crystalline silicon (c-Si) based. Initially discovered in the 1950s, these cells remain the most widely installed PV technology globally [13]. The original devices were in the range of 6–15% efficiency, but through continuous research and development, their efficiency has increased significantly. Modern silicon-based solar cells have an efficiency of more than 25% as evidenced are represented in Fig. 4 [22].

Despite their accomplishment in the market, the first-generation solar cells have several limitations. These include fairly high costs of production due to energy-consuming processes that are used in silicon purification and wafer production and performance loss at high-temperature conditions. High temperatures lead to a reduction in output power and hence thermal management is an issue to be considered in actual installations. Consequently, recent research has focused on overcoming these issues through optimizing the quality of materials, developing passivation techniques, and investigating other designs that enhance thermal and electrical performance.

To bypass the shortcomings of first-generation PV technologies, new semiconductor materials and processing techniques are being engineered to improve efficiency while keeping costs low.

Second-generation solar cells, or thin-film solar cells, employ novel semiconductor materials such as copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (a-Si [22]. They are far thinner compared to their crystalline silicon counterparts on top of offering improved tolerance to temperature variations. Thin-film technology efficiency ratings typically range from 10% to 15%, and the technologies draw less raw material, are more mechanically flexible, and weigh less overall. In addition, the technologies can be used for roll-to-roll production, which provides scalability and affordability. Due to these characteristics, thin-film solar cells are well applied in building-integrated photovoltaics (BIPV), mobility solar panels, and flexible electronic uses [23].

However, despite their benefits, second-generation cells also have several shortcomings. They are less effective than crystalline silicon cells, and long-term stability and performance degradation are issues of concern, limiting their wide-scale use. Research is underway to improve these parameters to make thin-film technologies equivalent to conventional PV systems in terms of life span and overall cost-effectiveness [24]

Third-generation solar cells are a new class of PV technologies that aim to surpass the first three generations' performance and cost boundaries. They include a range of new devices such as dye-sensitized solar cells (DSSCs), organic photovoltaics (OPVs), quantum dot solar cells, and perovskite solar cells (PSCs) [14]. Third-generation technologies employ low-cost and abundant materials and low-temperature solution-based processes, which can potentially translate to high-cost reduction and low environmental footprint [24].

Of these, perovskite solar cells have attracted unprecedented attention based on their record-breaking efficiency improvement from its initial values of 3% to recent values well above 25% in just more than a decade [14]. Perovskite solar cells possess high absorption coefficients, adjustable bandgaps, and flexibility with respect to substrates, which makes them applicable to an entire range of applications ranging from tandem solar cells to wearable electronics [14]. In general, third-generation PV technologies are a good direction towards higher efficiencies and mass deployment of solar energy by resolving material limitations, cost of manufacture, and flexibility of integration. Current research is focusing on overcoming stability scalability, and environmental challenges to make these technologies commercially applicable. Fig 5 represent the PV cells timeline, and according to that, the organic cell was introduced in 1989.

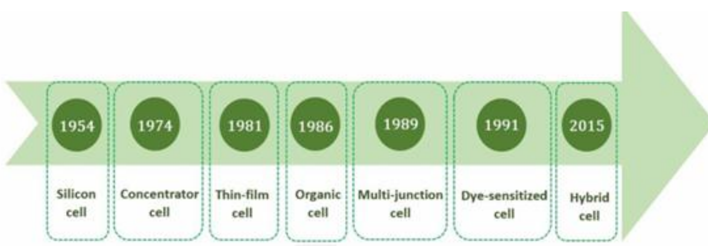

Fig. 5. Types of PV cells on a timeline [22]

2.3 Comparative analysis of First, Second, Third generation solar cells

While first-generation solar cells are a proven and tested commercial technology, second-generation devices are flexible and inexpensive. Third-generation solar cells, the newest and most sophisticated class of photovoltaic technologies, have a lot of promises for the future.

Table 1 represents a comparative summary of the salient features of first-, second-, and third-generation solar cells. As is clearly visible, first-generation cells are primarily crystalline silicon-based and possess efficiency levels of 6% to 25%. These cells are stable and widely used; however, they are associated with high raw material and manufacturing expenses, and their efficiency can decrease under hot weather conditions. Second-generation solar cells contain compounds such as copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (a-Si), whose efficiencies usually range between 10% to 15%. They are lighter, thinner, and more flexible than conventional silicon cells and can be produced at low-cost roll-to-roll processing techniques. Despite their advantages, they suffer from disadvantages related to lower efficiency, lesser long-term stability, and durability problems.

Third-generation solar cells utilize the next class of materials in the shape of perovskites, organic semiconductors, and quantum dots. Already, such technology has demonstrated efficiencies above 25% and the potential to achieve very low costs for solar electricity through low-temperature, scalable manufacturing processes. Further, they can produce more electricity per unit area due to the greater light-absorption efficiency in these cells. However, commercial introduction is still restricted due to ongoing challenges with environmental stability as well as scalability.

Table 1. Comparison between the first, the second, and the third-generation solar cells [14]

	First generation	Second generation	Third generation
Materials	Silicon	CIGS, CdTe, a-Si	Multi-junction cells, organic materials, perovskite materials, Flexible substrates >25%
Efficiency range Advantages	6–25%Proven technology, increasing efficiency	10–15% Flexible, lightweight, roll-to-roll production, cost-effective	Cheaper materials, potential to significantly reduce the cost of solar energy, higher efficiencies
Limitations	High raw material cost, performance drops in high temperatures	Lower efficiency, long-term stability and durability, not yet well understood	Still in the research and development phase
Manufacturing process	Wafer-based	Roll-to-roll	Various, depending on material and design
Applications	Residential, commercial, and utility-scale projects	Building-integrated photovoltaics, portable and lightweight solar panels, small-scale projects	Large-scale projects, consumer electronics, off-grid applications
Durability	Good	Moderate	Varies, depending on material and design
Stability	Good	Moderate	Varies, depending on material and design

2.4 Research trends in photovoltaic technology

Table 2 below compares the Research Tendency (RT) and RT5 indicators of various generations of solar cells. Research Tendency (RT) is a measure of the overall amount of research interest for a particular technology or material. It is typically computed on the basis of a bibliometric study of the volume of published papers, patents, and investment in a specific area over a prolonged duration [25], [26]. If applied to photovoltaic (PV) technologies, RT illuminates the historical development of scientific and commercial interest for the different generations of solar cells.

Augmenting RT, the RT5 metric gives a more modern perspective by examining research activity in the recent five years. As a quantitative analysis, this examination is concerned with recent advances, new materials, and shifts in research focus. RT5 is particularly useful in identifying emerging trends and predicting potential breakthroughs by examining ongoing momentum in research and development.

As seen in Table 2, first-generation solar cells all exhibit strongly positive RT values, which bear witness to them being the most commercially mature and widely applied PV technology [27]. Despite the general opinion, constant efforts are made to enhance performance and reduce manufacturing costs.

On the other hand, second-generation solar cells have relatively lower RT values, reflecting declining long-term research interest with time. Nevertheless, their moderate RT5 values reflect renewed interest over the last few years, potentially caused by improvements in material quality, processing techniques, and applications in flexible photovoltaics [27].

Third-generation solar cells have displayed a large average RT, but a large RT5, which reflects a recent surge of research activity in the past five years [27]. This surge is mainly attributed to the arrival of perovskite solar cells, quantum dots, and tandem cell architectures, each of which holds potential for high-efficiency, low-cost solar energy conversion [27].

Finally, fourth-generation solar cells, in their early stages of development, have low RT values conventionally. High RT5 of theirs, however, indicates a rapidly emerging field with the opening of new ideas such as hybrid nanostructures, multi-functional materials, and integration of PV with energy storage or sensing technologies [27].

These RT and RT5 trends provide valuable insight into the evolving research landscape and can guide future funding priorities, policy decisions, and technology roadmaps for sustainable energy innovation.

Table 2. Research Tendency RT and RT5 metrics for the different generations of solar cells [27]

Solar Cell Generation	RT (1954–2021)	RT5 (2016–2021
1st Generation	High	Low
2 nd Generation	Low	Moderate
3rd Generation	Moderate	High
4th Generation	Low	High

3 Technical challenges & solutions

Organic solar cells (OSCs) have made great advancements in efficiency, yet stability remains one of the largest obstacles to commercialization. Several important technical problems limit OSC stability under real-world conditions, including metastable morphology, environmental exposure (oxygen and water), light irradiation, heat, and mechanical stress represented in Fig. 6 [1].

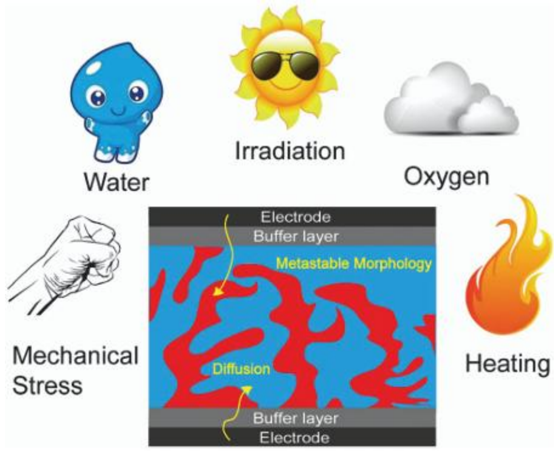

Fig. 6. Limitations of Organic Solar Cells [1]

Metastable Morphology: Active layers of OSCs are prone to phase separation of acceptor and donor materials, which is metastable and prone to morphological degradation. Additives with high-boiling-point solvents lead to better starting performance but enable higher morphological instability at the expense of long-term efficiency. Fig 7 represents the proposed model of morphological degradation. Simulated and measured short-circuit current. Black squares represent the relative short-circuit current as theoretically expected from the time-dependent morphology probed by mGISAXS (microbeam Grazing incidence small-angle x-ray scattering). The red line indicates the measured normalized short-circuit current density. Error bars are estimated from errors in the structure parameters. Visualization of the inner film morphology at the different times stated above, as generated during the Monte-Carlo simulation. The images represent an excerpt of 2.5 mm 2.5 mm. The red circles represent the domains of pure material. The green cylinder walls represent, together with the red core, the active area of the solar cell where absorbed photons contribute to charge carrier generation. Photons absorbed in the blue phase do not contribute. (d) Unit cell of a square lattice as assumed for predicting the theoretical values of the normalized short-circuit current density [28].

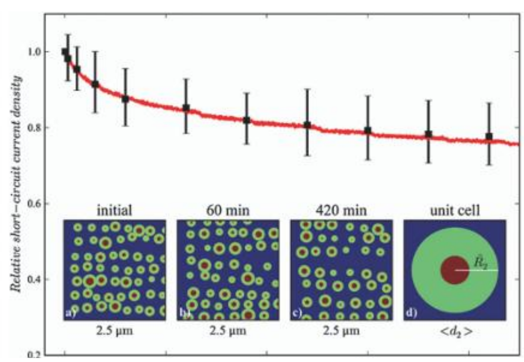

Fig. 7. Proposed model of morphological degradation. [1]

Electrode and Buffer Layer Diffusion: Fig 8 represents Aluminum (Al) and indium (from ITO) diffused into active, or buffer layers have been found to alter energy levels, degradation of device functionality by acting as recombination centers.

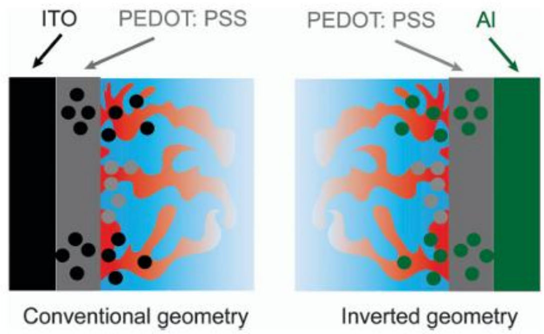

Fig. 8. Diffusion of electrode and buffer layer [1]

Environmental Exposure: Water and Oxygen: Infiltration of water and oxygen induces several degradation processes. Fig 9. represents metal electrode oxidation, which creates insulating films that reduce charge transport. Simultaneously, photo-oxidation in the donor and acceptor materials changes the structure and reduces the mobility of charge. Water may cause fullerene aggregation and result in morphological changes that reduce performance.

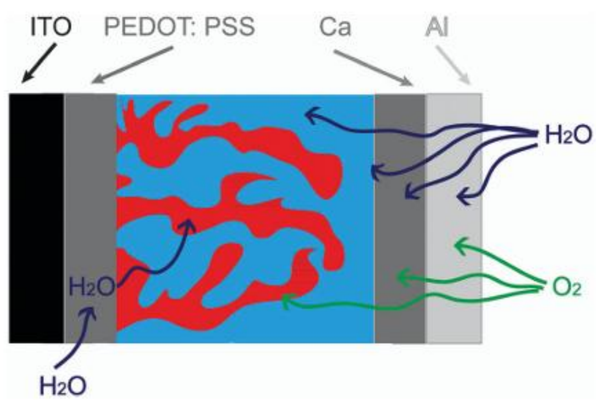

Fig. 9. Diffusion of oxygen and water [1]

Irradiation Effects: Exposure to light leads to photochemical and photophysical degradation. Photochemical reactions include oxidation reactions of the organic semiconductors, leading to trap states and energy level modification. Photophysical degradation includes photoinduced charge accumulation, decreasing open-circuit voltage (Voc).

Thermal Stress: Solar irradiation leading to high operating temperatures induces physical degradation. Polymer donors soften at temperatures above the glass transition temperature (Tg), inducing fullerene crystallization and phase separation. This will annihilate the donor/acceptor interface and its charge generation and extraction.

Mechanical Stress: Mechanical strain, which is typically encountered in flexible OSC devices, can induce cracks, delamination, and defects in the active or buffer layers, augmenting degradation by facilitating environmental ingress [1].

4 Future Research Directions

The path to commercialization on the grand scale of Organic Solar Cells (OSCs) hinges on the solution to some interlinked efficiency, stability, scalability, and cost challenges. To realize their full potential, focused research efforts must be applied to the following key areas:

4.1 Understanding degradation mechanism

Although significant strides have been made in discovering limiting factors for OSC stability, detailed knowledge of degradation processes on both chemical and morphological scales is still crucial. All the stress factors associated with the environment, including oxygen, humidity, UV, heat, and mechanical stress, are responsible for long-term degradation of the performance. In the future, the research should clarify the synergy of these factors, especially under operating conditions similar to those encountered in practical applications, and the root causes of "burn-in" degradation using sophisticated spectroscopic, microscopic, and electrochemical methods.

4.2 Development of Standard Stability Standards

Instability in the test leads to obstacles in significant study-to-study comparisons. It requires increased adoption of International Summit on OPV Stability (ISOS) protocols for developing standardized testing methods. Additionally, development of standardized methods of determining mechanical durability and lifetime parameters such as T80 and T50 will facilitate generation of reproducible and industry-portfolio-pertinent stability standards, especially for flexible and wearable devices.

4.3 Next generation materials for best performance and cost

Holistic material design strategies have to be in a position to optimize power conversion efficiency (PCE), operation stability, and cost at the same time. Exploration of multi-functional polymer donors with tailor-made crystalline and flexibility can counteract several degradation modes. The future NFAs should possess high intrinsic stability and scalable, cost-effective synthesis. Furthermore, the attempt should be made to push high absorption coefficients, low synthetic complexity, and thickness-independent operation to enable large-area fabrication

4.4 Scalable and green processing techniques

Industrial scalability of OSCs necessitates cost-effective and eco-friendly processing pathways. Continuing development of aqueous and halogen-free processing pathways is required, particularly to mitigate surfactant-related constraint. Scale-up from batch to continuous flow synthesis and developing high-throughput coating techniques for ultra-thin films will enhance manufacturing yield and reduce costs. Chemical and thermal stability of formulations under conditions of processing remains an imperative.

4.5 Economic viability and cost-reducing measures

Reducing the cost of OSC manufacturing is essential for competitive markets. Technoeconomic modeling with advanced technologies can assist in identifying cost-efficient pathways through material usage, process efficiency, and scalability analysis. Priorities should include simplifying synthetic complexity, material yield maximization, and recycling approaches evaluation for active layers to minimize environmental impact and production costs.

4.6 Niche application focus and expansion markets

Although OSCs have the goal of achieving parity with conventional photovoltaics, initial commercial traction can be achieved by targeting niche markets. OSCs' flexibility, lightness, and semitransparency lend themselves well to application in building-integrated photovoltaics (BIPV), wearables, and Internet of Things (IoT) devices. OSCs have the potential for portable and off-grid power needs and emerging uses in agriculture and transport. Maximization of OSC performance for indoor lighting and mechanical robustness will be critical to success in these applications.

5 CONCLUSION

Organic Solar Cells (OSCs) are one of the most innovative and promising third-generation photovoltaic technologies, offering the unique benefits of mechanical flexibility, processability at low temperature, semi-transparency, and light weight. All these positions, OSCs, as potential candidates for the next-generation applications of building-integrated photovoltaics (BIPV), portable electronics, and the Internet of Things (IoT). Despite the impressive progress in power conversion efficiency (PCE) over 20% under laboratory conditions, their path to large-scale commercialization remains hindered by fundamental issues of device stability, environmental degradation, and scalability of fabrication.

The project sought to comprehensively review the stability issues and commercialization challenges of OSCs, their historical evolution, current status, and prospects. The study identified the key degradation mechanisms, such as morphological instability, electrode diffusion, and the detrimental effects of oxygen, water, heat, and UV exposure. The corresponding solutions were explored, including the use of new donor–acceptor materials, device architecture, and encapsulation methods. The article also mentioned the rising trend in research activity, particularly for third-generation technologies, with a high RT5 index reflecting the growing worldwide interest.

The expected outcome of the project is a coherent snapshot of OSCs' current limitations and prospects, which will serve as a valuable guide for researchers, manufacturers, and policymakers. The study reaffirms the potential of OSCs as a future-generation solar technology, given that ongoing research would effectively address the current technical and economic problems.

Lastly, this study contributes to the global energy transition narrative by outlining the need for targeted investment in OSC development. The study supports the contention that, with targeted research into materials, testing protocols, and scalable, eco-friendly fabrication techniques, OSCs can quickly move from lab-scale development to real-world application, where they can assume a key position in future sustainable energy systems.

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