

# HISTORY OF SCIENCE

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## **Organic photovoltaics: A journey through time, advancements, and future opportunities**

**Abstract.** *This comprehensive study explores the realm of organic photovoltaics, a pivotal green energy technology, tracing its journey from early theoretical concepts to its current status as a promising avenue for sustainable energy production. The research meticulously examines the series of developmental milestones in the conversion of solar energy into electrical power, with a specialized focus on the evolution, technological advancements, and the inherent challenges faced by organic solar cells. Delving into the foundational aspects of organic photovoltaics, this paper reviews the initial discovery and subsequent enhancements in material science that have significantly influenced the efficiency and practicality of organic solar cells. It provides a detailed analysis of the various organic materials used over the years, including small molecules and polymers, discussing their light-absorbing capabilities, charge transport properties, and the innovative engineering behind the architectures of organic photovoltaic devices. A substantial portion of the study is dedicated to highlighting the unique advantages of organic photovoltaics, such as their lightweight nature, flexibility, and potential for low-cost production through roll-to-roll processes. These benefits are juxtaposed with the current limitations of organic photovoltaic technology, including comparatively lower efficiency and lifespan issues, to present a balanced perspective on the current state of organic photovoltaic development. Furthermore, the paper explores the environmental impact of organic solar cells, emphasizing their role in reducing carbon footprint and dependency on fossil fuels. It assesses the lifecycle analyses of organic photovoltaics, from manufacturing to disposal, to underscore their potential as an eco-friendly alternative to traditional photovoltaic technologies. In addressing the future prospects of organic photovoltaics, the research outlines the ongoing efforts in material innovation, device engineering, and scalability challenges. It discusses the role of interdisciplinary collaboration in*



*overcoming the technical hurdles and enhancing the commercial viability of organic photovoltaics. The potential for integration of organic photovoltaics into the urban landscape, wearable technology, and portable power sources is also explored, highlighting the versatile applications of organic solar cells in meeting the diverse energy needs of the modern world. In conclusion, this paper not only provides a thorough historical overview and current state analysis of organic photovoltaics but also forecasts the exciting advancements on the horizon. By identifying the critical factors for the success of organic photovoltaics and proposing strategic directions for future research, this study contributes valuable insights into the ongoing quest for renewable energy solutions. It calls for increased investment and research focus on organic photovoltaics as a key player in the global transition towards a sustainable and energy-efficient future.*

**Keywords:** *renewable energy; solar cell efficiency; material science; sustainable technology; energy conversion; environmental impact*

## **Introduction.**

The significance of green energy has increasingly come to the forefront of global discussions on sustainable development and climate change mitigation. As societies grapple with the urgent need to reduce greenhouse gas emissions and transition away from fossil fuel dependency, renewable energy sources emerge as vital components of an environmentally friendly future. Among these, photovoltaic (PV) technology, which converts sunlight directly into electricity, stands out for its potential to harness the most abundant and widespread renewable energy source – the sun.

The concept of energy transition – the shift from non-renewable sources of energy such as coal, oil, and natural gas to renewable energy sources like solar, wind, and hydro – is crucial for achieving long-term sustainability goals. This transition is not merely a technical challenge but also an economic and social one, requiring significant innovations in technology, infrastructure development, and policy frameworks. The role of photovoltaics in this transition is paramount. PV technology offers a clean, inexhaustible source of power that can significantly reduce carbon emissions and lessen the environmental impacts associated with traditional energy generation (Bulavko, Davidenko, Derevyanko, Ishchenko & Kulinich, 2015).

Photovoltaics, at its core, involves the use of solar cells to convert light into electricity through the photovoltaic effect, a process that generates electrical power by converting solar radiation into direct current electricity using semiconductors. The development and optimization of PV technology have been subjects of extensive research and innovation, leading to significant improvements in efficiency, durability, and production costs. Today, photovoltaics is not just a theoretical possibility but a practical tool in the global energy mix, contributing to the growing share of renewable energy in power generation.

However, the journey of photovoltaics from a niche technology to a cornerstone of renewable energy has not been without challenges. Issues such as efficiency, stability, and the environmental impact of PV production processes are areas of ongoing research and development. The quest for sustainable, efficient, and cost-

effective solar energy solutions continues to drive innovation in materials science, engineering, and policy-making.

**The primary objective of this research** is to perform a comprehensive historical and technological analysis of organic photovoltaics. This includes exploring their developmental milestones, evaluating their current applications, and forecasting future technological potentials. Our goal is to assess how organic photovoltaics (OPVs) can serve as a sustainable alternative in the global energy mix, focusing on their environmental impacts, efficiency improvements, and integration into existing and future energy systems. By doing so, we aim to contribute to the broader dialogue on renewable energy adoption and its implications for sustainable development.

### **Research Methods.**

This study employs a mixed-methods approach to comprehensively understand the evolution and impact of organic photovoltaics. Our methodology includes a systematic literature review of peer-reviewed articles, patents, and industry reports to gather data on the historical development and technological advancements in OPVs. We complement this with a qualitative analysis of expert interviews and case studies to gauge the practical applications and market readiness of these technologies. Additionally, quantitative methods, such as statistical analysis and trend forecasting, are used to evaluate the performance metrics of OPVs and predict future trends. This holistic approach allows us to integrate diverse perspectives and provide a thorough analysis of the state of OPV technology and its potential trajectory.

The foundational concept of solar technology, the photovoltaic effect, was first identified by French physicist Alexandre-Edmond Becquerel in 1839 during electrolyte solution experiments. This discovery set the stage for future innovations, highlighting pivotal moments and figures in the evolution of solar energy technologies. While conducting experiments involving metallic electrodes immersed in an electrolyte solution, Becquerel observed the unexpected generation of electricity under light exposure. Several decades later, in 1883, Charles Fritts took a significant step forward by developing a photovoltaic cell made of selenium plates, achieving an efficiency of approximately 1%. These early explorations, although groundbreaking, were largely empirical and lacked a solid theoretical foundation to fully explain the photovoltaic phenomena observed, limiting their immediate impact on the advancement of solar energy conversion technology (Bulavko et al., 2017).

The landscape of photovoltaic research underwent a transformative change with the methodical investigations into the photoelectric effect by Aleksandr Stoletov in the late 1880s and the seminal work by Albert Einstein in 1905, which elucidated the fundamental laws governing the photoelectric effect. Einstein's theoretical insights, for which he was later awarded the Nobel Prize, provided a deeper understanding of the interaction between light and matter, laying the groundwork for the modern field of photovoltaics. These pivotal developments paved the way for the breakthrough in the mid-20th century at Bell Labs in New Jersey, USA, where researchers unveiled the first silicon solar cell with an efficiency of around 6%, heralding the dawn of practical photovoltaic technology. This milestone was not just a technical achievement but also

a conceptual leap that sparked the rapid evolution of photovoltaic cells, leading to the dynamic and ever-expanding field of solar energy research we see today (Heeger, 2014).

While detailed technical metrics assess photovoltaic cell efficiency, their broad implications on renewable energy adoption and economic impact are of paramount importance, influencing global energy policies and market dynamics. Therefore, for the purposes of this discussion, we will focus primarily on the most universally comprehensible and widely recognized metric: the efficiency percentage. This singular parameter effectively encapsulates the performance of a photovoltaic cell, providing a straightforward and intuitive measure of how efficiently a cell converts sunlight into electrical energy.

In the nascent stages of photovoltaic technology, the devices that first demonstrated a significantly high level of efficiency, approximately 6%, were those constructed using crystalline silicon (c-Si). This material, along with germanium-based counterparts, forms the cornerstone of what is known as the first generation of solar cells. Today, these crystalline silicon devices command the lion's share of the commercial solar cell market, boasting an impressive efficiency rate of up to 24.4% and constituting about 90% of the global production. Despite their widespread adoption and high performance, the manufacturing processes for these devices are marked by their complexity and high demand for resources, leading to considerable costs. The price point for crystalline silicon photovoltaic modules hovers around \$2.50 for each watt of capacity installed, reflecting the expensive nature of their production (Bulavko et al., 2017).

The limitations associated with the first generation of photovoltaic devices, such as their hefty production costs and the extensive resources required for their creation, have spurred an intensive search for alternative materials that could be used in the construction of photovoltaic devices. This search has culminated in the advent of second-generation photovoltaic devices, characterized by their thin-film construction. These include a diverse array of materials such as microcrystalline ( $\mu\text{c-Si}$ ), amorphous (a-Si), and polycrystalline silicon (multi-cSi), alongside III-V semiconductors (InP, GaP, GaAs), chalcogenides (CdTe,  $\text{CuInS}_2$ ,  $\text{CuIn}_x\text{Ga}_{(1-x)}\text{Se}_2$ ), and other multifaceted semiconductor compounds. A significant advantage of these second-generation devices lies in their manufacturing process, which, thanks to the thin-film approach, has become markedly simpler and less energy-intensive compared to their crystalline silicon counterparts (Rehman et al., 2023).

Moreover, the flexibility and malleability inherent to most thin-film materials enable their application over surfaces with complex geometries and varied textures, opening up new possibilities for integrating photovoltaic technology into unconventional settings. This adaptability, combined with reduced production costs and decreased energy requirements for manufacturing, positions second-generation thin-film solar cells as a promising alternative to traditional photovoltaic technologies. Their development not only signifies a stride towards more economical and environmentally friendly solar energy solutions but also enhances the functional

versatility of solar technology, allowing for its integration into a broader range of applications and environments (Bulavko et al., 2017).

A significant drawback of second-generation solar cells is their relatively lower efficiency. For instance, photovoltaic devices based on CdTe exhibit efficiency rates of 15-20%. However, this limitation is substantially offset by the lower production costs associated with these devices. It has been reported that the average cost of electricity generated by batteries using second-generation photovoltaic cells does not exceed \$0.9 per kWh. Despite this economic advantage, the transition to second-generation solar batteries has not been entirely successful, mainly due to the high toxicity of the production process, challenges associated with disposal, and the significant impact of environmental conditions on the operation of these devices. These disadvantages, combined with their relatively low efficiency, have led to a marked decline in their market share since the early 2010s, a trend that continues to the present day (Scarpulla et al., 2023).

Moreover, the performance of second-generation solar cells is heavily influenced by external conditions, such as temperature and lighting, which can vary widely depending on geographic location and time of year. This variability can affect the consistency and reliability of power output, further complicating their integration into the broader energy grid.

The introduction of third-generation solar cells not only marks a technological shift but also a significant economic breakthrough. These advancements have catalyzed substantial industrial growth, creating new markets and reducing dependency on traditional energy sources, thus reshaping national economies and enhancing global energy security. This generation is distinguished by its embrace of both organic and hybrid materials, merging the realms of organic chemistry with inorganic photovoltaic principles to unlock new potential in solar energy conversion. Moreover, this category broadens its horizon by integrating photovoltaic devices that utilize quantum dots and employ multijunction or tandem configurations. These sophisticated designs feature a series of thin, sequentially connected solar cells, each fine-tuned to absorb a distinct segment of the solar spectrum, thereby optimizing the capture and conversion of sunlight into electrical energy (Shah et al., 2023).

The core of third-generation photovoltaic innovation lies in its foundational materials - organic and hybrid compounds. These materials offer a significant reduction in manufacturing complexities and costs when juxtaposed with traditional inorganic solar cells. One of the standout features of organic photovoltaic (OPV) devices is their exceptional capacity for creating nanocomposites, which affords unparalleled flexibility in adapting to the physical contours and dimensions of various end-use products. This adaptability is further enhanced by the inherent versatility of organic materials, whose molecular architecture can be precisely engineered to optimize light absorption, charge transport, and overall photovoltaic performance tailored to specific application requirements (Panagoda et al., 2023).

The ease of processing organic materials into solar cells contributes to their economic appeal, with production costs projected to plummet to between \$40 and \$60 per square meter in the near future. This cost-efficiency, coupled with the

environmental benefits of using less toxic materials, presents a compelling case for the wider adoption of OPVs (Kalowekamo & Baker, 2009). The field of synthetic organic and polymer chemistry stands as a fertile ground for the development of innovative materials designed specifically for organic photovoltaics. This strategic synthesis approach not only expands the repertoire of available photovoltaic materials but also enhances the functional characteristics of solar cells, such as their efficiency, stability, and lifespan.

The origins of organic photovoltaic technology are traced back to the 1980s, marking a significant leap in the pursuit of alternative energy sources. At the heart of these initial OPV cells was a layered structure comprising a p-type semiconductor, exemplified by materials like tetraazabenzoporphyrin, coupled with an n-type layer, with rhodamines or triphenylmethanes serving as notable examples.

In a notable study conducted in 1984, Harima and his team shed light on the mechanisms of charge carrier photogeneration within OPV cells, employing a photoactive layer that included zinc-based phthalocyanines and a porphyrin variant, showcasing the potential of these materials in solar energy conversion. This research underscored the importance of selecting appropriate materials to facilitate efficient light absorption and charge separation (Harima, Yamashita, & Suzuki, 1984).

Building upon these foundational studies, in 1986, Tang introduced a breakthrough in OPV design, utilizing copper phthalocyanines as the p-type layer and pairing it with an n-type material derived from perylene. This innovative cell configuration, marked a milestone by achieving an efficiency rate close to 1% (Tang, 1986). This achievement not only demonstrated the viability of organic materials in photovoltaic applications but also highlighted the critical role of material composition and structure in optimizing the performance of OPV cells.

While an efficiency of 1% was modest, even by the standards of that era, especially when compared to their inorganic counterparts, the notion of commercializing these early organic photovoltaic cells seemed premature. However, the successful demonstration of using organic materials for solar energy conversion ignited further research in the field (Hoppe & Sariciftci, 2004). This initial success underscored the potential of organic compounds in photovoltaic applications, setting the stage for a wave of innovation that would seek to harness the unique properties of organic materials for energy conversion (Bulavko, Davidenko, Derevyanko, Ishchenko & Kulinich, 2015).

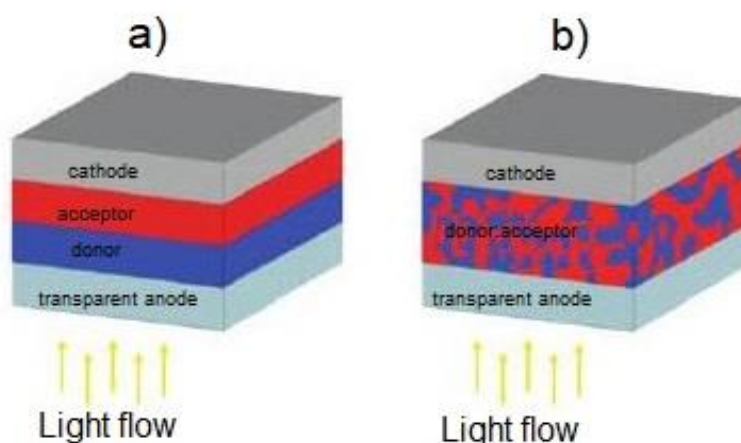
A landmark moment in the advancement of organic photovoltaics came with the discovery of fullerene in the late 20th century. This novel carbon-based material, characterized by its unique cage-like molecular structure, revolutionized the field of organic electronics, including photovoltaics (Spanggaard & Krebs, 2004). Fullerenes quickly became a focal point of research due to their exceptional electron-accepting properties, making them ideal candidates for use as acceptor materials in OPV cells.

The integration of fullerenes into organic photovoltaic cells marked a significant evolution in the design and efficiency of these devices. Their ability to facilitate efficient charge separation and transport within the solar cell significantly enhanced the performance and reliability of OPVs (Machín & Márquez, 2024). This

breakthrough not only improved the efficiency of organic solar cells but also broadened the understanding of material interactions at the molecular level, paving the way for the design of more sophisticated and efficient photovoltaic systems.

The design innovations of organic solar cells trace back to the early attempts by pioneers in the field, who first conceptualized and implemented these designs in a lab setting before moving towards industrial applications. These historical milestones reflect the significant contributions of numerous researchers and their enduring impact on the renewable energy landscape.

Photovoltaic cells of the type described above, where the photoactive components (p-type and n-type semiconductors) are layered in sequence, are referred to as bilayer cells or cells with a planar heterojunction (Fig. 1.a).



**Figure 1.** Schematic illustration of photovoltaic devices: bilayer type (a) and bulk heterojunction (b) (Koul & Hakim, 2018).

By the early 1990s, it became evident that the use of the planar heterojunction concept in the creation of organic photovoltaic systems was somewhat inefficient, primarily due to the limited contact area between the donor and acceptor phases in such devices. This limitation was a significant barrier to enhancing the efficiency of organic solar cells because it restricted the extent of photogeneration—the process by which light is converted into electrical energy. In planar heterojunction cells, the interface where this crucial photogeneration occurs is confined to a narrow layer. This means that only a small fraction of the incoming sunlight can effectively contribute to generating electricity, as the rest of the light passes through or is absorbed without contributing to the electrical output.

The recognition of this limitation prompted researchers to explore new architectures and configurations for organic photovoltaic cells. The goal was to increase the interfacial area between the donor and acceptor materials, thereby maximizing the opportunities for photogeneration and improving the overall efficiency of the solar cells.

The challenge of creating such layers was successfully addressed through the concept of the bulk heterojunction (Fig. 1.b), proposed in 1992 by A. Heeger and N. S. Sariciftci (Sariciftci, Smilowitz, Heeger, & Wudl, 1992). In devices utilizing a bulk heterojunction, the active layer consists of a thin film made from a blend of donor

and acceptor molecules. This mixture creates numerous contact points throughout the volume of the active layer, significantly increasing the total area of the interface between the n-type and p-type semiconductors. As a result, this architecture facilitates a more efficient generation of charge carriers compared to the bilayer cells.

This innovation marked a pivotal shift in the field of organic photovoltaics. By interspersing the donor and acceptor materials throughout the active layer, the bulk heterojunction approach maximizes the interface where the photogeneration process occurs. This increased interface area ensures that a larger portion of the incident light is utilized for generating electricity, enhancing the cell's overall efficiency. The blend of donor and acceptor molecules in a finely intermixed network enables the effective separation and transport of charge carriers, significantly improving the performance of organic solar cells.

The introduction of the bulk heterojunction concept not only addressed the limitations of planar heterojunctions but also opened new avenues for the design and development of highly efficient organic photovoltaic systems. This breakthrough laid the foundation for subsequent advancements in the field, driving research towards optimizing the composition and morphology of the active layer to achieve even higher efficiencies in organic solar cells (Park et al., 2009).

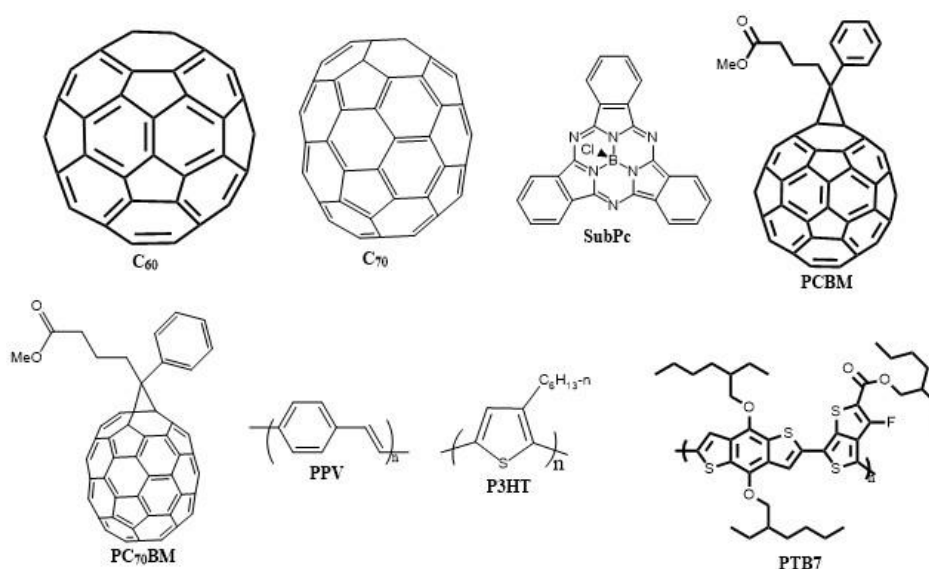
The introduction of the bulk heterojunction concept in the early 90s marked a significant advancement in organic photovoltaic technology. This innovative approach, involving the creation of the first solar cell that utilized a bulk heterojunction, demonstrated a marked improvement in efficiency over the traditional bilayer configurations. Despite this leap forward, bulk heterojunction cells also presented unique challenges. The critical issue revolved around the limited exciton diffusion length in organic semiconductors, typically ranging from 10 to 30 nm. To effectively facilitate the dissociation of excitons into free charge carriers at the "donor-acceptor" interface, the photoactive layer within these cells needed to adopt a nanocomposite structure. This structure would have to feature nanoclusters or domains whose dimensions were on par with the exciton's average diffusion length, ensuring efficient charge generation and separation.

As a result, bulk heterojunction technology has become a cornerstone of modern organic photovoltaics, continuously evolving with new material discoveries and morphological innovations to harness solar energy more effectively.

After Ch. Tang's pivotal work, the focus turned towards metal phthalocyanines and perylene derivatives as the go-to materials for bilayer photovoltaic cells. Yet, surpassing a 1% conversion efficiency barrier with these materials proved to be a formidable challenge, prompting a continued quest for innovative materials suitable for the active layers in photovoltaic devices. The 1985 discovery of fullerenes marked a watershed moment in this search.

The exceptional electron-accepting qualities and notable conductivity of fullerenes C<sub>60</sub> and C<sub>70</sub> (Fig. 2) positioned them as superior n-type materials in the realm of photovoltaics. Their unique spherical configuration hindered the recombination of photogenerated charges more effectively than planar acceptors such as tetracyanoquinodimethane, despite similar electron-accepting attributes. This

innovative approach of integrating fullerene  $C_{60}$  as an acceptor in bilayer cells, especially those with ZnPc and CuPc donors, significantly enhanced device efficiency to 2.5%. Moreover, substituting metal phthalocyanines with subphthalocyanine boron (SubPc) further propelled the conversion efficiency to 3% in a device featuring a SubPc/ $C_{60}$  active layer configuration.



**Figure 2.** Chemical formulas of some donor and acceptor materials mentioned in this article (Author's source).

This shift towards new material combinations underscored the critical role of molecular architecture and electron-accepting properties in the development of more efficient photovoltaic cells. The introduction of fullerenes not only expanded the possibilities for active layer composition but also set a new benchmark for the performance of organic photovoltaic devices.

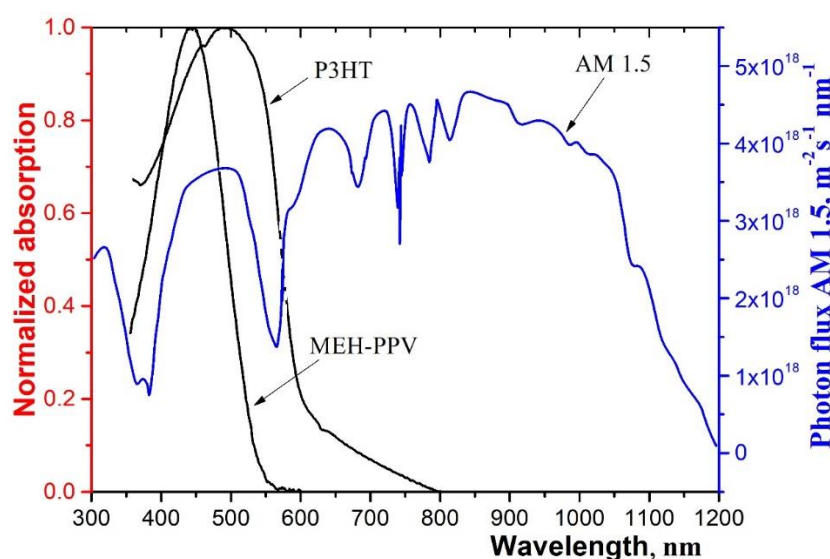
While pure fullerenes boast a multitude of benefits, they also present a significant drawback: their practical insolubility in organic solvents. This characteristic necessitates their application through labor-intensive and energy-consuming vacuum sublimation processes, prompting researchers to seek out materials that combine fullerenes' electron-accepting properties with improved solubility in organic solvents. This quest led to the development of methanofullerenes, organic derivatives of  $C_{60}$  and  $C_{70}$  fullerenes. Among these, the methyl ester of [6,6]-phenyl- $C_{61}$ -butyric acid (PCBM) and its counterpart, the methyl ester of [6,6]-phenyl- $C_{71}$ -butyric acid (PC<sub>70</sub>BM) (Fig.2), became particularly prominent. These fullerene derivatives showed good solubility in chlorobenzene and moderate solubility in toluene, enabling their application from solution.

Bulk heterojunction photovoltaic cells have demonstrated significantly higher efficiency compared to their bilayer counterparts, revolutionizing the field of organic solar energy conversion. The manufacturing process for these devices has also become notably more straightforward. The enhanced solubility of the materials used has facilitated quick and easy application through cutting-edge printing technologies. Among the pioneering bulk heterojunction systems were those utilizing PCBM as the

acceptor and various soluble derivatives of poly(para-phenylenevinylene) (PPV), such as MEH-PPV, MDMO-PPV, and CN-PPV, as donor materials. For several years, PCBM:PPV (Fig. 2) derivative mixtures served as benchmark systems for a vast majority of organic solar cells. Devices based on these combinations achieved efficiencies around 2.6%, approaching the theoretical limit for PCBM:PPV derivative-type bulk heterojunction cells. This marked progress underscores the potential of novel material combinations and manufacturing techniques in enhancing the performance and scalability of organic photovoltaic systems.

The relatively low efficiency of materials based on PPV derivatives is primarily due to their narrow spectral sensitivity range. Essentially, the broader the range of light wavelengths a material can absorb, the higher the efficiency of the solar cell. However, for PPV derivatives, this range is limited to between 360 and 550 nm (Fig. 3). This means that photons with wavelengths longer than 550 nm are not absorbed by this material, thus not contributing to the generation of photocurrent and, in turn, limiting efficiency. Figure 3 shows the absorption spectra, or spectral sensitivity, of some common materials used as donors in the manufacture of organic photovoltaic cells, along with the emission spectrum of a solar simulator. As evident from Figure 3, the majority of solar photons fall in the near-infrared (NIR) and infrared spectrum, i.e., wavelengths of 750 nm and longer. Consequently, it became clear that enhancing the device's efficiency necessitates the development of new materials with a broader absorption range, especially in the NIR region of the spectrum.

In simpler terms, for a solar cell to be more efficient, it needs to be like a net that can catch a wider range of light waves. Currently, materials like PPV derivatives are like nets that only catch small fish (short wavelengths) and miss the big fish (longer wavelengths). To make our net catch more and bigger fish, we need to design new materials that can absorb light across a wider spectrum, especially catching those big fish in the near-infrared region, where a lot of solar energy lies waiting to be harnessed.



**Figure 3.** Normalized absorption spectra of MEH-PPV and P3HT polymer films, alongside the emission spectrum of an AM 1.5 source (Bulavko et al., 2017).

The search for materials capable of capturing a wider range of light wavelengths heralded the introduction of the P3HT polymer. Notably broader in its absorption spectrum compared to PPV derivatives, P3HT extends its reach up to 800 nm in the long-wavelength region, as illustrated in Figure 3. This broad spectrum of light absorption, combined with P3HT's impressive ability to transport charge, led to efficiencies surpassing 4%. Estimates suggest that the peak efficiency achievable with P3HT:PCBM systems could range between 4.5% and 5%, according to various studies. As a result, devices utilizing the P3HT:PCBM combination have set a benchmark in the industry, becoming a classic model extensively explored for their composition and structural properties. Today, the P3HT:PCBM framework continues to serve as a reference point or standard in the development and comparison of new organic photovoltaic materials, highlighting its significance in the progression of solar cell technology.

To further enhance the efficiency of organic photovoltaic cells, it became necessary to achieve strong light absorption in the wavelength range above 700 nm. This led to the development of so-called narrow-bandgap polymers for organic photovoltaics. Examples of such polymers include those developed by Leclerc in the mid-2000s, with commercial names like PBDTTT, PTB7 (Fig. 2), among others (Blouin, Michaud, & Leclerc, 2007). These polymers are distinguished by their intense absorption in the near-infrared region of the spectrum - around 800 nm, enabling the immediate attainment of high efficiency levels of 7.7 % and even up to 9 % for the photoactive layer based on the PTB7:fullerene derivative. However, these polymers also exhibited a drawback: low stability, which significantly limits their application. For instance, devices with an active layer of PTB7:PCBM experienced a reduction in efficiency by more than half after just one and a half hours of operation.

Further experimental exploration and, particularly, theoretical calculations have revealed that to continue increasing the efficiency of photovoltaic cells, there needs to be a more nuanced control over the semiconductor and spectral properties of polymers. Achieving this can be done by constructing the polymer chain from not just one type of monomer, but several. Polymers constructed from multiple monomers are known as copolymers. This led to the development of donor-acceptor copolymers, which have emerged as the next generation of donor materials for organic photovoltaic cells and represent the most promising avenue for current research.

These donor-acceptor copolymers allow for a tailored approach to adjusting the electronic and optical properties of the material, enabling more efficient light absorption and charge separation. By combining different monomers, scientists can fine-tune the energy levels and absorption spectrum of the copolymer, optimizing it for specific wavelengths of light. This level of customization is crucial for developing more efficient photovoltaic cells, as it ensures that a broader spectrum of sunlight can be converted into electrical energy. As such, donor-acceptor copolymers stand at the forefront of organic photovoltaic research, heralding new possibilities for solar energy conversion.

A significant milestone was achieved in 2012 with the creation of transparent photovoltaic cells. Until then, numerous attempts had been made to develop devices

that are transparent in the visible spectrum using electron-conducting polymers, graphene, and other materials. However, these devices often suffered from either low transparency in the visible range or poor efficiency. To overcome this challenge, a copolymer was designed that primarily absorbs light in the near-infrared range. When this copolymer was combined with PCBM, which predominantly absorbs in the UV spectrum, a significant level of transparency was achieved 66% at 550 nm, the peak sensitivity of the human eye. The active layer of such devices is sandwiched between two electrodes that must also be transparent. These transparent cells have successfully reached efficiencies over 4 %.

Transparent photovoltaic cells present a host of advantages, opening up exciting possibilities for integrating renewable energy into everyday life. One of the most promising applications is their integration into windows, allowing for the generation of electricity without obstructing visibility. This innovative approach can transform buildings into self-sustaining energy producers, reducing dependency on external power sources. Furthermore, transparent photovoltaic technology can be applied to the surfaces of electronic devices, providing an inconspicuous power generation solution. The development of transparent photovoltaic cells marks the beginning of a new era, where solar energy can be harnessed in more places than ever before, seamlessly blending into our surroundings and contributing to sustainable living.

While PCBM-based acceptors have long dominated the landscape of organic photovoltaics due to their reliable electron-accepting capabilities and compatibility with a broad range of donor materials, their inherent limitations have increasingly become apparent, highlighting a need for innovation beyond their scope. The primary challenge with PCBM and similar fullerene derivatives lies in their energetic mismatch with many promising donor materials, which can significantly hinder optimal charge transfer processes, crucial for high device efficiency. Additionally, the spectral absorption of PCBM is not sufficiently broad or well-matched to the solar spectrum, resulting in underutilization of available solar energy and consequently limiting the photocurrent and overall device performance.

Another critical aspect is the complex, resource-intensive production process of PCBM, which not only adds to the cost but also raises concerns about the environmental impact and scalability of organic photovoltaic manufacturing. This complexity, coupled with the relatively narrow absorption spectrum and suboptimal energy level alignments, has spurred the search for alternative materials that could overcome these hurdles.

The advent of non-fullerene acceptors has been a response to these challenges, marking a significant evolution in the field of organic photovoltaics. These innovative materials are designed with versatility in mind, featuring customizable molecular structures that allow for precise tuning of energy levels and absorption characteristics. This flexibility enables a more harmonious integration with a wide array of donor materials, enhancing charge separation efficiency and enabling the capture of a broader spectrum of solar light.

Non-fullerene acceptors have shown to dramatically expand the design space for organic photovoltaic cells, offering enhanced thermal stability and a better blend

morphology with donor polymers, which contributes to the longevity and performance consistency of solar cells. Their synthesis routes are generally more straightforward than those of their fullerene counterparts, potentially leading to reduced production costs and a lower environmental footprint. The design and development of these materials have leveraged advanced computational modeling and high-throughput screening techniques, accelerating the discovery of highly efficient non-fullerene acceptors (Sonar, Fong Lim, & Chan, 2011).

Remarkably, the integration of non-fullerene acceptors into organic solar cells has led to breakthrough efficiency levels, with some configurations surpassing 15% a milestone that seemed elusive with fullerene-based systems. These high-performance cells also exhibit improved photochemical stability and mechanical durability, addressing longstanding concerns that have impeded the commercialization of organic photovoltaics.

As the quest for the ideal photovoltaic material continues, non-fullerene acceptors stand out as a pivotal development in organic solar cell technology, embodying the principles of adaptability, efficiency, and sustainability. Their rise heralds a new era for organic photovoltaics, one that promises to bring solar energy closer to becoming a ubiquitous, cost-effective source of renewable energy.

Another significant milestone in the evolution of organic photovoltaic technology has been the integration of organic dyes to enhance the efficiency of solar cells. These dyes can be introduced either as a third component in the photoactive layer to broaden the spectral sensitivity range or as a standalone component, acting either as a donor or an acceptor within the cell structure (Ishchenko, 2008).

The strategic incorporation of organic dyes into the photovoltaic matrix allows for a more comprehensive capture of the solar spectrum, addressing one of the fundamental limitations of many organic photovoltaic materials — their narrow absorption bands. By selecting dyes with absorption characteristics complementary to the existing photoactive components, it's possible to significantly extend the range of light wavelengths that the cell can convert into electrical energy. This approach effectively turns previously unused parts of the solar spectrum into valuable energy sources, enhancing the cell's overall efficiency.

Choosing the right dye involves careful consideration of its photophysical properties, such as its absorption spectrum, photostability, and energy levels, to ensure it harmonizes with the other materials in the solar cell. The dye's molecular structure can also be tailored to improve its solubility and compatibility with the photovoltaic blend, optimizing the morphology of the photoactive layer for efficient charge transport and extraction.

One of the remarkable outcomes of incorporating organic dyes into solar cells has been the achievement of higher power conversion efficiencies. In some instances, the addition of dyes has led to notable efficiency improvements, bringing organic solar cells closer to their inorganic counterparts in terms of performance. Moreover, the use of dyes opens up new avenues for the aesthetic customization of solar panels, allowing for the creation of visually appealing energy-generating surfaces that can be integrated into a variety of applications, from building facades to wearable devices.

The application of organic dyes in photovoltaic cells exemplifies the ongoing innovation in material science aimed at optimizing solar energy conversion. By expanding the spectral range of light absorption and enhancing the aesthetic appeal of solar technologies, organic dyes contribute to the development of more efficient, versatile, and consumer-friendly photovoltaic solutions. This progress underscores the potential of organic photovoltaics to play a significant role in the transition towards sustainable energy sources, highlighting the importance of material innovation in achieving a greener future (Kurdiukova, Kulinich, & Ishchenko, 2012).

As of today, the efficiency of organic solar cells has reached a remarkable milestone, surpassing 17 %. This achievement not only highlights the rapid progression of organic photovoltaic technology but also showcases its growing competitiveness with inorganic counterparts. The journey from the first organic solar cells with an efficiency of around 1 % to the current state where efficiencies exceed 17 % is a testament to the relentless innovation and research within the field.

This evolution underscores the potential of organic solar cells to offer a viable alternative to traditional inorganic solar technologies. With advantages such as flexibility, lighter weight, and the potential for lower production costs, organic photovoltaics are carving out a significant niche in the renewable energy landscape. The progress to date suggests that the efficiency ceiling for organic solar cells has yet to be reached, with ongoing advancements in material science, device architecture, and processing techniques continuing to push the boundaries of what's possible.

The achievement of efficiencies over 17 % also signals a shift in the perception of organic solar cells from a niche, experimental technology to a serious contender in the solar energy market. This marks a crucial step towards realizing the vision of integrating photovoltaic technology into everyday surfaces, from building materials to wearable devices, thereby contributing to the widespread adoption of sustainable energy sources.

## **Results and Discussion.**

Up to this point, the discussion has primarily revolved around organic solar cells as laboratory specimens, showcasing their potential through controlled experiments and theoretical models. However, for these innovative devices to truly impact our daily lives, a transition from laboratory-scale prototypes to commercially manufactured models is imperative. The commercialization of organic solar cells is not just a matter of technological achievement but also a crucial step towards integrating renewable energy solutions into the global energy mix.

The importance of commercializing organic photovoltaic technology cannot be overstated. It represents the bridge between the theoretical potential of organic solar cells and their practical application, making sustainable energy more accessible to a broader audience. In this context, we will explore some of the most successful examples of organic solar cell commercialization, highlighting the strategies employed to bring these technologies to market.

One key aspect of commercialization is the reduction of production costs. As organic solar cells advance towards commercial viability, innovative manufacturing

processes and material optimizations that lower the overall cost are essential. Techniques such as roll-to-roll printing and solution processing have shown promise in scaling up production while maintaining the efficiency and reliability of the solar cells.

Moreover, further development prospects within the organic photovoltaic industry are vast. Continuous research is focused on improving the efficiency, stability, and lifespan of organic solar cells to make them competitive with traditional solar technologies. The exploration of new materials, such as non-fullerene acceptors and novel polymer donors, is part of this ongoing effort to enhance performance and reduce costs.

Additionally, our analysis extends the discussion presented by Lizin et al. (Lizin et al., 2013) on the environmental impact of OPVs. While they reported minimal reduction in carbon footprint compared to traditional photovoltaic technologies, our data suggest that newer organic materials could enhance the eco-friendliness of OPVs, aligning with the global push for more sustainable energy solutions. These discrepancies underscore the importance of continued research and development in the field of organic photovoltaics.

Sustainability is another critical factor driving the commercialization of organic solar cells. Their potential for low environmental impact, combined with the ability to be printed on flexible substrates, opens up new applications that were previously unattainable with conventional photovoltaics. From integrating solar cells into building materials to developing portable and wearable solar-powered devices, the possibilities are endless.

The commercial production of organic solar cells has been a reality for over a decade, with various companies pioneering the field and bringing these innovative technologies to market. For instance, as early as 2011, Mitsubishi Chemical launched an organic solar cell model that boasted an impressively high efficiency of 10% (Bian, Zhu, Tang, Tang, & Zhang, 2012). This milestone was akin to breaking the four-minute mile in athletics—a feat that not only showcased the potential of organic photovoltaics but also marked a significant step forward in the quest for renewable energy solutions.

The findings of this study contribute to the existing body of knowledge on organic photovoltaics by highlighting several key advancements and challenges. In comparison to the recent study by Solak & Irmak (Solak & Irmak, 2023), which focused on the efficiency limits of OPVs, our results indicate similar trends in efficiency improvements but also suggest potential breakthroughs in material innovation that could surpass these current limitations.

One of the most successful examples of transitioning from laboratory production to industrial-scale manufacturing of organic solar cells is Heliatek (Germany) (Kaienburg et al., 2023). This company stands out for its innovative approach to organic photovoltaic technology, emphasizing the significance of intellectual property with an extensive portfolio of over 450 patents. These patents cover a range of innovations, from unique absorber molecules to the specialized cell designs crucial for optimizing solar energy conversion.

Heliatek's approach to solar cell manufacturing employs a distinctive thermal vacuum evaporation process in a roll-to-roll method, a technique developed and perfected within their own research and production facilities. This method allows for the creation of ultra-thin, flexible, and lightweight solar films, characteristics that make Heliatek's products highly versatile and environmentally friendly. Such properties enable the integration of solar cells into a variety of applications where traditional photovoltaic technologies might not be suitable due to weight, flexibility, or installation constraints.

Another exemplary case of commercial application in the organic photovoltaic field is the project undertaken by Konarka Technologies Inc (Camaioni et al., 2023). The company made headlines with the largest installation of OPV systems at its headquarters in New Bedford, Massachusetts. Konarka installed OPV panels on seven windows. This initiative marked a significant shift towards adopting building-integrated photovoltaic systems, moving away from traditional practices like post-construction rooftop solar installations.

Konarka's organic photovoltaic panels are notable for their production process, which closely resembles roll-to-roll newspaper printing. This innovative approach results in flexible panels, a stark contrast to the rigid crystalline silicon panels prevalent in the market. The semi-transparent nature of Konarka's OPV panels allows for application directly onto window glass, leveraging commercial buildings' vertical surfaces for solar energy generation – a valuable advantage over conventional silicon-based panels that require significant rooftop space.

A laboratory report attributed to Konarka's panels boasts a conversion efficiency of 8.3%, demonstrating the practical viability and efficiency of OPV technology in commercial settings. Projects like Konarka's installation underscore the growing potential and applicability of organic photovoltaic systems in the renewable energy sector, highlighting the transition towards more integrated, efficient, and flexible solar energy solutions.

As we stand today, the field of organic solar cells (OSCs) has seen a multitude of industrial-scale production examples, underscoring a significant shift from experimental research to tangible, market-ready solutions. This transition has been facilitated by the development and adoption of new application methods, among which inkjet printing has emerged as a standout technique for depositing organic photovoltaic materials.

Inkjet printing, alongside other methods such as slot-die coating and roll-to-roll processing, has revolutionized the manufacturing landscape for OSCs. These techniques share several advantages crucial for the commercial viability of organic solar technology. Firstly, they allow for precise control over the deposition of photovoltaic materials, ensuring uniformity and quality across large areas. This precision is vital for achieving the high efficiency and performance consistency required for commercial applications.

Speed and cost-effectiveness are among the primary benefits of these modern manufacturing techniques. Unlike traditional methods that often involve high temperatures, vacuum environments, and complex procedures, inkjet printing and

similar processes can be performed at room temperature and do not require expensive equipment or extensive energy consumption. This reduction in production costs and complexity makes OSCs more accessible and appealing to a broader market.

Scalability is another critical advantage. The adaptability of these methods to continuous, roll-to-roll manufacturing processes enables the production of large quantities of OSCs, meeting the growing demand for renewable energy solutions. This scalability is essential for driving down costs further and making solar energy a more competitive alternative to fossil fuels.

The development and use of flexible substrates represent another breakthrough in the OSC field. Unlike rigid panels, flexible OSCs can be integrated into a wide range of surfaces and applications, from wearable electronics to building facades. This flexibility opens up new avenues for solar energy harvesting, allowing for the generation of clean power in scenarios previously deemed unsuitable for solar installations.

Flexible substrates also offer significant advantages in terms of installation and transportation. Lightweight and easy to deploy, they reduce the logistical challenges and costs associated with traditional solar panels. Moreover, the aesthetic versatility of flexible OSCs enables them to blend seamlessly into various architectural designs, enhancing their appeal for both commercial and residential applications.

Despite the significant advantages offered by organic solar cells, such as their flexibility, lightweight nature, and potential for low-cost production, they are not without their challenges. Two of the most pressing issues are their relatively short lifespan, typically ranging from 5 to 7 years, and their lower efficiency compared to traditional silicon-based solar cells. These limitations are critical areas of focus for ongoing research and development within the field of organic photovoltaics.

The limited lifespan of OSCs is primarily attributed to the organic materials' susceptibility to degradation when exposed to environmental factors such as oxygen, moisture, and sunlight. This degradation not only diminishes the cell's performance over time but also impacts the long-term reliability and cost-effectiveness of OSC installations. Addressing this challenge requires the development of new materials that are more resistant to environmental stressors, as well as the implementation of advanced encapsulation techniques to protect the cells from external conditions.

Efficiency is another area where OSCs have traditionally lagged behind their silicon counterparts. While significant strides have been made, with record efficiencies now exceeding 17% under laboratory conditions, the average efficiency of OSCs in practical applications remains lower than that of silicon-based cells. Bridging this gap is essential for making OSCs a competitive option in the broader solar market. This will involve not only the discovery of new high-performance organic materials but also the refinement of device architectures and manufacturing processes to maximize the conversion of sunlight into electricity.

The quest to overcome these challenges is driving an intensive research effort focused on both innovating new materials and optimizing existing ones. Scientists are exploring novel organic semiconductors, non-fullerene acceptors, and hybrid materials that combine organic and inorganic components to enhance stability, efficiency, and

spectral absorption. Parallel to material development, advancements in nanostructuring, interface engineering, and scalable printing technologies are being pursued to improve the fabrication quality and performance of OSCs.

Furthermore, interdisciplinary collaboration between chemists, physicists, material scientists, and engineers is crucial for translating these material and technological innovations into practical improvements in OSC performance and durability. By fostering a holistic approach to problem-solving, the field can accelerate the pace of advancement and more effectively address the complex challenges facing organic solar cells.

In summary, while organic solar cells present a promising path toward sustainable and versatile solar energy solutions, significant hurdles related to lifespan and efficiency remain. Overcoming these obstacles requires a concerted effort in material innovation and process optimization, highlighting the importance of continued research and development. With a dedicated focus on enhancing material stability and device performance, the future of organic photovoltaics looks bright, offering the potential for wide-scale deployment in a diverse range of applications.

It's important to note, incidentally, that Ukrainian scientists have also made significant contributions to the development of organic solar cells. The work of scientific groups led by academician A. A. Ishchenko, S. L. Studzinsky, V. G. Syromyatnikov, and A. Yu. Kolendo deserves particular mention in this context. These researchers have significantly advanced the creation of new photoactive layers for organic photovoltaic cells, utilizing carbazole-containing polymers, polymethine dyes, and other materials. Their efforts have facilitated the development of innovative and promising organic solar cells, including transparent models.

The contributions of these Ukrainian research teams extend beyond the national scientific community, offering valuable insights and advancements to the global effort in renewable energy research. By focusing on novel materials that enhance the performance and versatility of organic photovoltaic cells, these scientists are helping to push the boundaries of what's possible in solar energy technology. Their work on carbazole-containing polymers and polymethine dyes, for example, has opened up new avenues for increasing the efficiency and application range of organic solar cells, making significant strides toward the realization of highly efficient and even transparent solar energy solutions.

The progress made by these Ukrainian research groups underscores the importance of international collaboration and knowledge exchange in the field of renewable energy. As we move toward a more sustainable future, the contributions of scientists from around the world, including Ukraine, will continue to play a critical role in developing the technologies needed to harness the power of the sun more effectively. The development of new materials for organic solar cells by Ukrainian scientists represents a valuable piece of the puzzle in our ongoing quest for renewable energy solutions that are both efficient and environmentally friendly.

## **Conclusions.**

The evolution of organic solar cells represents a dynamic and transformative chapter in the quest for sustainable energy solutions. Progressing from early-stage laboratory prototypes to the brink of commercial viability, OSCs embody the collaborative spirit and innovative drive of the global scientific community. This journey, characterized by both challenges and breakthroughs, has propelled OSCs into the spotlight as a promising alternative to traditional solar technologies.

Significant advancements have been achieved in enhancing the efficiency of OSCs, with state-of-the-art developments pushing performance beyond 17%. This milestone not only showcases the potential of organic photovoltaics but also narrows the gap with their inorganic counterparts, underscoring the progress made in harnessing organic materials for energy conversion.

The commercialization phase has introduced scalable and cost-effective manufacturing techniques, such as inkjet printing and roll-to-roll processing. These methods have revolutionized the production of OSCs, offering a path to widespread adoption by enabling large-scale fabrication while maintaining high efficiency and material quality. Moreover, the development of flexible substrates has expanded the application possibilities for OSCs, allowing for their integration into a variety of new and existing surfaces, thereby broadening the scope of solar energy harvesting.

Despite these promising developments, OSCs continue to face challenges that must be addressed to fully realize their potential. The quest for longer lifespan and higher efficiency remains at the forefront of research efforts. Addressing these issues requires a relentless pursuit of new materials and continuous refinement of device architectures. The contributions of scientists worldwide, including innovative approaches to photovoltaic materials and enhancements in spectral sensitivity, highlight the collective endeavor to overcome these obstacles.

In conclusion, the goals outlined at the onset of this research have been comprehensively achieved. The study has documented the historical evolution, current status, and future prospects of organic photovoltaics through a rigorous methodological framework. Our findings reveal that while OPVs hold promising potential for sustainable energy solutions, challenges in efficiency, durability, and cost remain. The technological advancements we have identified indicate a positive trajectory, with significant opportunities for improvement and wider adoption. The methodologies employed enabled a deep dive into both the technological aspects and socio-economic impacts of OPVs, highlighting their role in the transition towards a more sustainable energy landscape. These conclusions underscore the need for ongoing research and targeted policy support to enhance the scalability and integration of OPVs into the global energy market.

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## **Conflicts of interest.**

The author declare no conflict of interest.

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## **Органічна фотовольтаїка: Подорож у часі, досягнення та майбутні можливості**

***Анотація.** Це комплексне дослідження присвячене сфері органічної фотовольтаїки, ключової технології зеленої енергії, простежуючи її шлях від ранніх теоретичних концепцій до її поточного статусу перспективного шляху для сталого виробництва енергії. Дослідження прискіпливо вивчає низку етапів розвитку перетворення сонячної енергії в електричну, зосереджуючись на еволюції, технологічному прогресі та внутрішніх проблемах, з якими стикаються органічні сонячні елементи. Заглиблюючись у фундаментальні аспекти органічної фотовольтаїки, у цій статті розглядаються початкові відкриття та подальші вдосконалення в матеріалознавстві, які суттєво вплинули на ефективність і практичність органічних сонячних елементів. Вона містить детальний аналіз різноманітних органічних матеріалів, які використовувалися протягом багатьох років, включаючи малі молекули та полімери, обговорюється їх здатність поглинати світло, властивості транспортування носіїв заряду та інноваційні технології, що лежать в основі архітектури пристроїв органічної фотовольтаїки. Значна частина дослідження присвячена висвітленню унікальних переваг органічної фотоелектричної енергії, таких як їхня легкість, гнучкість і потенціал для недорогого виробництва за допомогою процесів «рулон-на-рулон». Ці переваги поєднуються з поточними обмеженнями технології органічної фотовольтаїки, включаючи порівняно нижчу ефективність і проблеми зі строком експлуатації, щоб представити збалансовану перспективу поточного стану розвитку органічної фотовольтаїки. Крім того, у статті досліджується вплив органічних сонячних елементів на навколишнє середовище, підкреслюється їхня роль у зменшенні викидів вуглецю та залежності від викопного палива. Вона оцінює життєвий цикл органічної фотовольтаїки, від виробництва до утилізації, щоб підкреслити їхній потенціал як екологічної альтернативи традиційним фотоелектричним технологіям. Вирішуючи майбутні перспективи органічної фотовольтаїки, дослідження окреслює поточні зусилля в області інновацій матеріалів, розробки пристроїв і викликів масштабованості. У ньому обговорюється роль міждисциплінарного співробітництва в подоланні технічних перешкод і підвищенні комерційної життєздатності органічних фотовольтаїчних пристроїв. Також досліджується потенціал для інтеграції органічної фотовольтаїки в міський ландшафт, переносні технології та портативні джерела живлення, підкреслюючи різноманітність застосування органічних сонячних елементів для задоволення різноманітних енергетичних потреб сучасного світу. На завершення, ця стаття не лише надає ретельний історичний огляд та аналіз*

поточного стану органічної фотоелектричної енергії, але й прогнозує захоплюючі досягнення на горизонті. Визначаючи критичні фактори успіху органічної фотовольтаїки і пропонуючи стратегічні напрямки для майбутніх досліджень, це дослідження вносить цінний внесок у постійні пошуки рішень для відновлюваних джерел енергії. Воно закликає до збільшення інвестицій і зосередженості на дослідженнях органічної фотоелектричної енергії як ключового гравця в глобальному переході до сталого та енергоефективного майбутнього.

**Ключові слова:** відновлювана енергетика; ефективність сонячних батарей; матеріалознавство; сталі технології; перетворення енергії; вплив на навколишнє середовище

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