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Organic Solar Cells—The Path to Commercial Success

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Organic solar cells have the potential to become the cheapest form of electricity, beating even silicon photovoltaics. This article summarizes the state of the art in the field, highlighting research challenges, mainly the need for an efficiency increase as well as an improvement in long-term stability. It discusses possible current and future applications, such as building integrated photovoltaics or portable electronics. Finally, the environmental footprint of this renewable energy technology is evaluated, highlighting the potential to be the energy generation technology with the lowest carbon footprint of all.

1. Introduction

Reducing our net carbon emissions towards net zero to slow the effect of global warming is one of the most pressing challenges of the 21st century. Efficiency measures and transitioning the electricity, transport, and heating sectors away fast from fossil fuels and towards sustainable technologies will be critical in achieving this within the time we have left for the 1.5 °C target.[1] This shift will include electrification of significant parts of these sectors, requiring large-scale deployment of renewable energy technologies, in particular wind and solar. Crystalline silicon photovoltaics has been growing rapidly and is currently dominating the solar market with more than 95% of the sold solar modules,[2] and there are several further technologies under development that have the potential to deliver electricity at even lower cost and accelerate this transition.

The most advanced one towards commercialization is organic solar cells (OSCs), i.e., solar cells and modules in which the photovoltaic active layer consists of carbon-based semiconductors.[3] Their key advantages are in particular that organic semiconductors can be tailored for purpose, are based on abundant and non-toxic raw materials, and the used manufacturing technologies, primarily vacuum coating and solution processing, are in principle capable of coating large areas

inexpensively and fast.[4,5] This, combined with little material consumption ($\approx$1 g organic semiconductor per m^2), low-temperature processing and the compatibility with flexible substrates enables light-weight devices made in roll-to-roll production and a large versatility in applications. This could make OSC the cheapest source of electricity in the world.

The main difference in operation between silicon solar cells and OSC, and the reason that OSCs lag silicon solar in their commercialization, is that light absorption in organic semiconductor thin films does not lead to efficient generation of free charge carriers, but to the generation of strongly bound excitons having limited diffusion length. A solution to the former was published by Tang in 1986:[6,7] efficient exciton separation was achieved at the planar interface between two different organic semiconductors, an electron donor and an electron acceptor, leading to a type II heterojunction. The key concept for overcoming the limited exciton diffusion length was introduced by Hiramoto et al.[8] in 1991 by co-evaporating donor and acceptor molecules, leading to a bulk heterojunction (BHJ) with a distributed donor–acceptor interface. Here, each exciton is generated within its diffusion length of the heterojunction. Such BHJs are at the core of all efficient OSC today, independent whether they are processed in vacuum or made via solution-based processes. A typical OSC stack structure, along with a monolithic series connection of subcells into a module, is shown in **Figure 1**.

Continuous research and development of organic semiconductors tailored for OSC, of processing techniques and stack design, have led to materials with better absorption and donor–acceptor energy offsets,[9,10] optimization of the BHJ microstructure,[11,12] and stack design,[13,14] pushing power conversion efficiencies (PCEs) to around 18% in single-junction solar cells.[15] PCEs of >20% appear to be within reach and module efficiencies are catching up with these values.

PCEs of OSC devices and modules are important, but due to the further balance of system cost in a photovoltaic system[16] a high PCE alone is not sufficient for OSC to contribute at scale to solving climate change. For this, sufficient lifetime and scalability to terawatts of installed capacity at competitive cost are required, as well. In the following, we highlight some of the key research challenges, discuss OSC markets, and give an outlook on the transformative potential of OSC in terms of cost and carbon emissions.
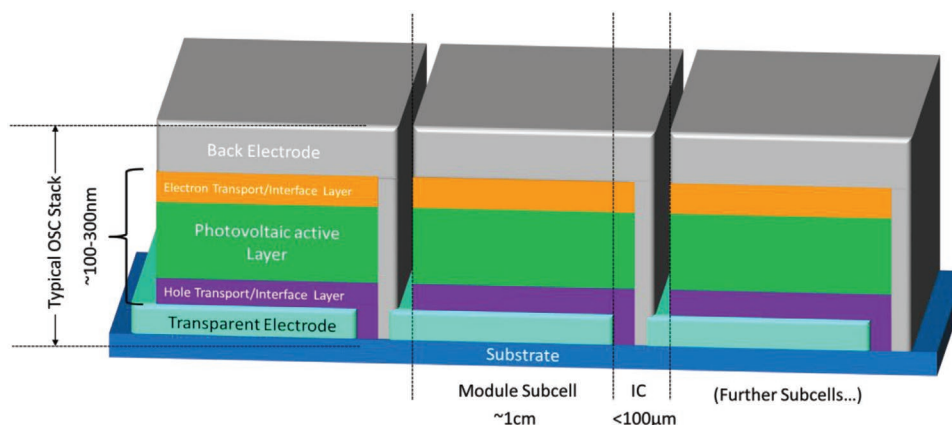
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2. Research Challenges

2.1. Voltage Losses

OSCs can achieve short circuit current densities[22] and fill factors[23] on par with the ones of GaAs or perovskite-based devices

Figure 1. Schematic stack structures of an OSC labeled on the left and the common monolithic serial connection for an OSC module both with typical dimensions of the module subcells and the serial interconnect (IC). The organic layers in the stack are a fraction of the thickness of the substrates, which are usually several hundred micrometres thick. The shown stack is in the "standard" geometry, i.e., hole contact on the substrate side, but inverted stacks are used frequently, as well, where the electron and hole transport/interface layers are swapped.

when taking the different optical gaps into account. However, their open-circuit voltage (V_{OC}) is still limited and far from the Shockley–Queisser limit (**Figure 2**), leading to a comparatively lower PCE of around 18% in single-junction devices.[15] Thus, this area has been focus of much research and in OSCs, voltage losses can be divided in three main categories.

2.1.1. Energy Transfer Losses

As we touched upon before, unlike their inorganic counterpart, in OSC, a strongly bound singlet exciton (also called local exciton (LE)) is formed upon light absorption due to their low dielectric constant. To be separated efficiently, the LE needs a heterointerface providing an energetic offset.[7,24,25] This process leads to the formation of a charge transfer state (CTS). It has been commonly assumed in the past that an efficient dissociation of the CTS into free charges requires a minimum energetic offset,[26] believed to be about 0.3 eV.[27] The recent introduction of non-fullerene acceptors (NFAs) and the shift away from previously de facto standard of fullerene derivatives as acceptor to NFAs, though, demonstrated the possibility to achieve an efficient generation of free charge carriers even with a negligible energetic offset,[28–30] below 10 meV.[31,32] When the energy difference between exciton and CTS decreases, the CTS obtain more excitonic character. Once their energy are very close, a hybrid LE-CTS is formed with a partial excitonic character and partial charge transfer.[33] This hybridization is needed to separate charges efficiently even with no driving force.

2.1.2. Radiative Recombination

According to the detailed balance theory for solar cells, introduced by Shockley and Queisser in 1961,[34] the highest V_{OC} is reached when recombination of charges can occur only radiatively, from the lowest energy excited state to the ground state. As these transitions are directly related to the inverse process of absorption, the presence of radiative voltage losses is unavoidable.[35] It can be reduced in OSCs, though, by decreasing the absorption strength of the CTS. For example, by lowering the donor–acceptor interfacial area.[36] It is not possible to reduce radiative losses beyond a minimum amount, set by the Shockley–Queisser limit and connected to the effective gap of the absorber material.

2.1.3. Nonradiative Recombination

In a typical OSC, a large portion of recombination is taking place without emitting a photon. Accordingly, the electroluminescence quantum yield (EQE_{EL}) of the solar cell, i.e., driving and measuring it as a light-emitting diode, is decreased. This directly relates to nonradiative voltage losses (ΔV_{nr}) by

$$\Delta V_{nr} = \frac{k_B T}{e} \ln\left(\frac{1}{EQE_{EL}}\right) \tag{1}$$

While in OSC, the CTS generates free carriers efficiently upon illumination, due to nonradiative losses, it emits photons inefficiently. Recently, nonradiative losses were attributed to the coupling to intramolecular vibrations of organic materials themselves and therefore intrinsic to this class of semiconductors.[37] Nonradiative voltage losses drastically increase if the energy of the CTS decreases. This trend agrees with the Marcus inverted regime for nonradiative transition rates in organic donor–acceptor systems, as described by the energy gap law of nonradiative voltage losses.

Of the three main V_{OC} loss mechanisms, reducing nonradiative losses is the main pathway to increase V_{OC} in OSC. While the formation of a LE-CTS seems necessary to obtain the lowest ΔV_{nr}[38,39] other studies pointed out that, due to an increase in the oscillator strength of the CTS, this could lead to increased radiative losses, resulting in higher overall recombination rates.[40] Understanding the parameters affecting nonradiative losses is, therefore, imperative to close the gap between OSC and other photovoltaic technologies. In a recent work[41] Azzouzi et al. developed a model relating the oscillator strength, emissive
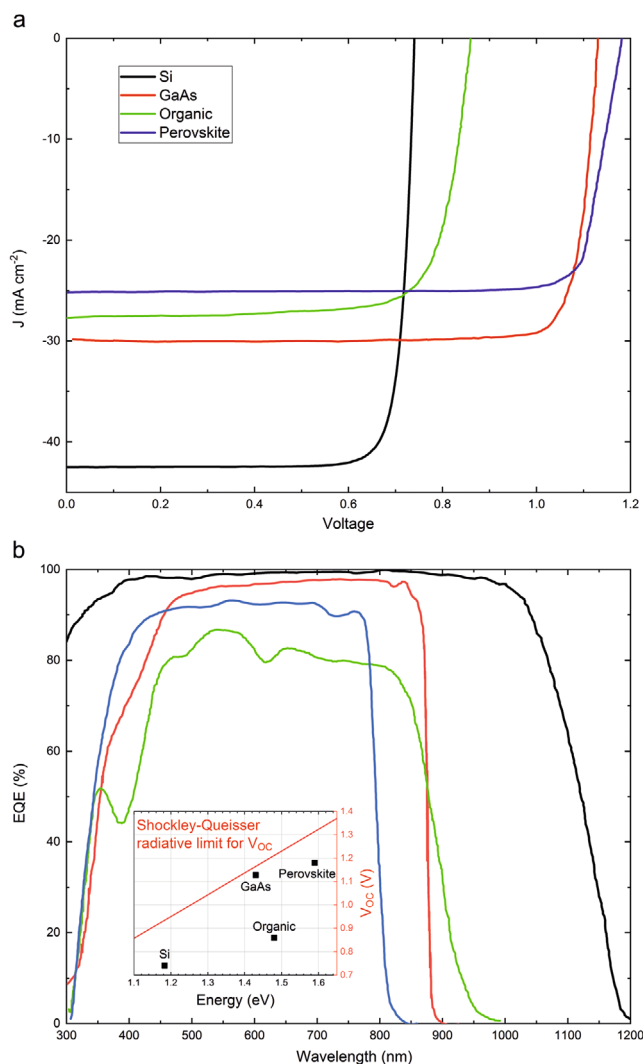
Figure 2. a) Current density-Voltage curves of the current best Si (26.7%),[17] GaAs (29.1%),[18] organic (17.6%),[15] and perovskite (25.2%)[19] solar cells. b) Corresponding external quantum efficiency curves.[15,18–20] In the inset, the V_{OC} of the devices are plotted versus the energy gap determined from the EQE according to the method outlined by Vandewal et al.[21] Here, the Shockley–Queisser radiative limit for V_{OC} is shown as red solid line.

state energies, relaxation energy, dipole moment, and electronic couplings to ΔV_{nr}. The suggested route to best decrease ΔV_{nr} is using stiff molecules with low relaxation energy and high static dipole moments and oscillator strengths, suggesting guidelines for the development and synthesis of novel molecules.

NFAs enabled the recent increase in PCE, but so far only for solution-processed systems.[15,42] No efficient vacuum-processed NFAs have been found up to now, but recent results suggest this is possible. By using visible light-emitting donor–acceptor systems (a pyrimidine derivative, B4PymPm), ΔV_{nr} was decreased to 100 meV in vacuum-processed OSCs. More than 150 meV lower than typical values in the highest performing OSC blends. These strongly reduced losses were attributed to an increased E_{CT}, effectively suppressing nonradiative decay by reducing electron phonon coupling.[43] High electroluminescence quantum yield and efficient photogeneration of free carriers are, therefore, not mutually exclusive in OSC, at least in large gap material combinations.

2.2. Stability

Given the relatively high PCEs reached now by OSC, improvements in long-term device stability are acquiring a new urgency and offer more room for reducing the cost of electricity from OSC than further efficiency increases. The origins of the degradation in device performance with time have been attributed to several phenomena in literature.[44–47]

2.2.1. Chemical Degradation

The most important factor of degradation is believed to be diffusion of molecular oxygen and water into the device. This is an extrinsic source of degradation; organic materials are sensitive to water and oxygen causing photooxidation of the organic layers and interfaces.[48,49] The higher the HOMO, the higher is the probability of an electron transfer to an oxygen molecule, increasing the free radical content in the device. This oxidation affects the electrical properties of the material, in particular conductivity and interface energetics,[50] as well as the optical properties, causing bleaching of the organic layer.[49] A similar mechanism takes place in the metal electrodes. Low work function metals act as reducing agents especially if hydrogen-donating reagents like water are present. Metal oxides are consequently formed at the interface between the metal and the rest of the device, acting as transport barriers. Encapsulating the device helps in avoiding oxygen and water-induced degradation,[51–53] as will be discussed in section 2.3. Intrinsic sources of degradation are particularly dangerous as they cannot, in general, be eliminated by better encapsulation barriers. Ultraviolet (UV) light is often considered an example of intrinsic source of degradation. It causes photochemical reactions, since the UV light's energy is sufficiently high to break up the carbon bonds of the organic material, as the dissociation energy is around 3.5 eV. The most harmful part of the solar spectrum can be mitigated by encapsulation layers acting as a UV filter.[51] Long lived excitons in organic materials have been reported as the cause of molecular fragmentation.[54] Rapid quenching of the exciton is, therefore, indicated as an important feature to avoid photooxidation of organic materials.[55] Another source of intrinsic chemical degradation is the photooligomerization of fullerenes, especially C_{60} and $PC_{61}BM$, causing burn in losses in the OSCs efficiency. It was first described by Eklund and co-workers in 1993,[56] and later it has been reported to cause substantial losses in performance for a number of polymer/fullerene BHJs and small molecule/C_{60} planar heterojunctions.[57–60] Raman and mass spectroscopy have shown the formation of C_{60} oligomers, upon irradiation of neat C_{60} films.[61]

2.2.2. Physical Degradation

Mechanical failures can happen in the device stack. OSCs are composed of multiple thin films and encapsulation failure by

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delamination of these layers is observed, particularly in flexible OSCs under thermal stress.[62] Delamination is an extrinsic source of degradation, while an intrinsic physical degradation source pertains the morphological stability of the device. When OSCs are illuminated, they heat up facilitating modification in the nanostructure of the device. BHJ active layers are a meta-stable structure that can evolve with time, in fact, even at ambient temperature and in dark.[63,64] Molecular rearrangement in the active layer or in the buffer layers can lead to segregation at the interfaces, hindering charge extraction. Eventually, the materials forming the active layer can phase separate at distances larger than the exciton diffusion length, reducing the ability of the device to create free carriers.[65,66] The temperature at which solar cells begin to degrade is related to the glass transition temperature (T_g) of the component materials, with degradation beginning at temperatures above the lowest T_g.

In terms of materials, which is promising news, NFA-based OSCs were reported also to achieve greater photochemical and thermal stability,[67] as well as longer device lifetimes.[68,69] Also burn in losses was reported to be improved.[69] Unlike their fullerene counterparts, they do not seem to form nanocrystalline domains that tend to grow in size.

When comparing the stability between solution-processed and vacuum-processed OSCs, the latter were found to exhibit enhanced stability. The photochemical stability of the constituent materials certainly plays a role, as well as the high purity of the thermally evaporated organics and the lack of side chains that are most susceptible to degradation.[70,71] Also the morphological stability seems to be higher. It has been argued that this could be due to the fact that molecules find near equilibrium structures during film growth.[72]

2.3. Module Design and Encapsulation

The first small OSC modules consisting of several subcells were presented already early on to demonstrate the challenges and potential for scaling up this technology.[73,74] In crystalline silicon solar cells, the lateral conductivity in Si is high enough such that no extra transparent electrode is needed for efficient collection of charge carriers and the connections of the individual solar cells into a module. This is not the case for OSC and it has significant consequences on the design and fabrication of modules.

The common approach is to use a transparent conductive window layer into the solar cell stack, similar to established thin film solar cell technologies like CdTe and CIGS. In OSC research, indium tin oxide (ITO) is commonly used as transparent electrode (and reference material) to facilitate charge collection. ITO offers high conductivities (≈10–50 ohms per square) at a high transparency (≈>80% in the visible). This is sufficient for creating modules in a monolithic serial interconnect (see Figure 1) like CdTe and CIGS solar modules with subcells of ≈1cm width at optimized resistive losses and high geometric fill factors, i.e., high ratio of active area to module area.[75] However, the limited availability of indium[76,77] and ITO's brittleness[78] makes it unsuitable for large-scale OSC production. This has spurred much research in alternative materials and ITO-free module concepts.

The challenge for alternative electrode materials is to achieve high transparency in the solar spectrum, high conductivity, mechanical and environmental stability as well as only use abundant materials and be compatible with low-cost, large-scale production on metals and plastic foils.[79] The most promising approaches to replace ITO are increasing the conductivity of organic semiconductors, in particular PEDOT:PSS,[80] metallic nanowires,[81,82] carbon nanotubes,[83,84] and thin metal layers.[85,86] In case the lateral conductivity needs to be boosted further, these layers can be supported with metal grids.[87,88] All these approaches have been demonstrated to be compatible with roll-to-roll fabrication, achieve promising performance at better environmental impact, and lower cost than ITO.[89] More unconventional module designs make use of the unique properties of organic semiconductors and their processing techniques. These include for example wrapping the front electrodes to the back side,[90] alternating standard and inverted subcells that can be connected to a module,[91] or special light-trapping substrates.[92]

In addition to the materials challenge, patterning the active materials and electrodes in production-compatible processes to create the subcells and interconnects with little losses is essential.[75,93] While it is possible to print or vacuum process the needed structures directly, best results have been obtained by laser-structuring electrodes and active materials. This process, which is well established for the monolithic series connection of inorganic thin film technologies, has been used to achieve geometric fill factor of well above 95% and low interconnect losses for OSC modules.[94,95]

OSC modules will be exposed to relatively harsh environments during operation, requiring protection in particular against water vapor, oxygen, UV light, mechanical stresses, and combinations thereof, which can all lead to loss in performance (see also 2.2).[44,47]

The exact requirements for the encapsulation vary depending on the used materials and stack design as well as the products (wearable electronics, building integrated photovoltaics, etc.). Studies suggest that a water vapor transmission rate (WVTR), which is often used as measure of general gas permeation, of 10^{-4} g (m^2 day)$^{-1}$, potentially even as low as 10^{-2} g (m^2 day)$^{-1}$, can be sufficient for several years of lifetime.[96] This is much less than the typical quoted requirements of a WVTR of at least 10^{-6} g (m^2 day)$^{-1}$ for organic light-emitting diodes (OLEDs),[97] but much more than standard food or medical packaging (≈1g (m^2 day)$^{-1}$).[98]

Common in the laboratory setting is glass–glass encapsulation, which combined with a suitable adhesive and encapsulation design can lead to WVTR of less than 10^{-6} g (m^2 day)$^{-1}$ and enable some of the best OSC lifetimes reported because extrinsic degradation effects can be excluded.[72] While glass–glass encapsulation might be viable for building-integrated OSC in glass facades, this is not an option for most OSC markets, where cost, low weight, and mechanical flexibility is essential. Here, thin, robust, inexpensive, and transparent (at least on one side) encapsulation with sufficient barrier properties against water vapor and oxygen even when bent as well as UV filters are required.[99]

The two most common approaches compatible with roll-to-roll fabrication are laminating the OSC module with a thin barrier foil or depositing a thin film encapsulation (TFE) directly

onto the subcells of a module. For the former, the OSC can be either already fabricated on a flexible barrier foil as substrate and then laminated by a second foil on top, or fabricated on a flexible substrate and then sandwiched between two barrier foils.[96] Using separately prepared barrier foils, e.g., coated PET, has the advantage that here fabrication processes can be used that would damage OSC. However, safe handling and lamination, e.g., interactions with the adhesive or edge-ingress of gas, as well as mechanical stability against delamination can be challenging. TFE have seen significant process in recent years with the drive towards flexible OLEDs. Here, the barrier is directly deposited onto the device. This limits the available processes, as they should not damage the device, but reduces the risk of edge ingress of gasses and delamination.[100] Best results are in both cases obtained with multilayer structures.[100,101]

With the emergence of novel solar cell technologies, the International Electrotechnical Commission (IEC) has developed initial stability standards for "nano-enabled photovoltaics," which includes OSC.[102] For commercialization, however, OSCs currently have to pass existing standards on the module level that are applied to silicon solar cells, like qualification tests described in the IEC-61215 that are used by industry and insurance agencies.

3. Status of Commercial Application

3.1. Small Molecule versus Polymer-Based OSC

In the field of OSCs, two different deposition technologies are competing: one is using polymers, i.e., long molecular chains, and/or soluble small molecules, i.e., oligomers with defined molecular weight, which are deposited using solution-based processes like slot-die coating or screen printing. This approach is for example followed by the companies Armor/France and Sunew/Brazil. The other one is using only certain small molecules, which can be deposited by vacuum evaporation. Here, for example the company Heliatek/Germany is driving the commercialization. At first sight, solution processing seems to be preferable because it requires relatively simple techniques and does not need tools whose upfront cost is higher. However, to predict the development for OSC, it is very interesting to look at the commercialization of light emitting diodes: In this field, small-molecule devices[7] and polymer devices[103] were discovered almost simultaneously. In the first years of research, there was a general consensus that solution-processed devices would dominate the market due to the seemingly simpler and cheaper manufacturing.

However, the real development was quite different: very soon, it turned out that vacuum manufacturing has many advantages that were initially overlooked and which could apply to OSC commercialization, as well: vacuum processing allows to easily define multilayer systems with very precise thickness, which is of key importance for multijunction cells[104,105] needed to close the PCE gap to conventional photovoltaic technologies. A second point is that vacuum deposition does not need solvents, making it easier to meet environmental regulations. Finally, it turned out that OCSs prepared with dry techniques tend to show much better stability[72] than devices deposited from solution. This observation was made previously for OLEDs.[106]

There is one argument, however, that speaks against vacuum processing: The efficiency of polymer-based OSCs has in the past few years rapidly improved and has reached values that are significantly higher[15] than those for the best vacuum-processed small-molecule OSC.[107] There are two main reasons for this advantage: 1) polymer devices absorb the sun light better, because the higher mobility of the polymer in BHJs allows for thicker absorbing layers; 2) second, as discussed above in section 2.1.3, the recent efficiency improvements of polymer devices were based on NFA[108] replacing the weakly absorbing C_{60}. So far, efficient NFA absorbers for small-molecule solar cells, which can be used in evaporated cells, have not been published. However, recent progress in solution-processed NFA-based small molecule cells[109] with efficiency beyond 14% indicates that there is potential for NFA for vacuum-processed OSC, as well.

3.2. Application Fields and Markets

Crystalline silicon solar is today the dominating technology in photovoltaics (PV). It has high efficiencies above 20% in commercial modules, excellent stability, and in a growing number of regions the lowest generation cost of electricity ever observed.[110,111] In all three parameters, OSCs cannot compete for the time being. To be successful, OSC needs to look for niches where crystalline silicon and other inorganic PV technologies cannot be used and get on the learning curve to reduce cost.
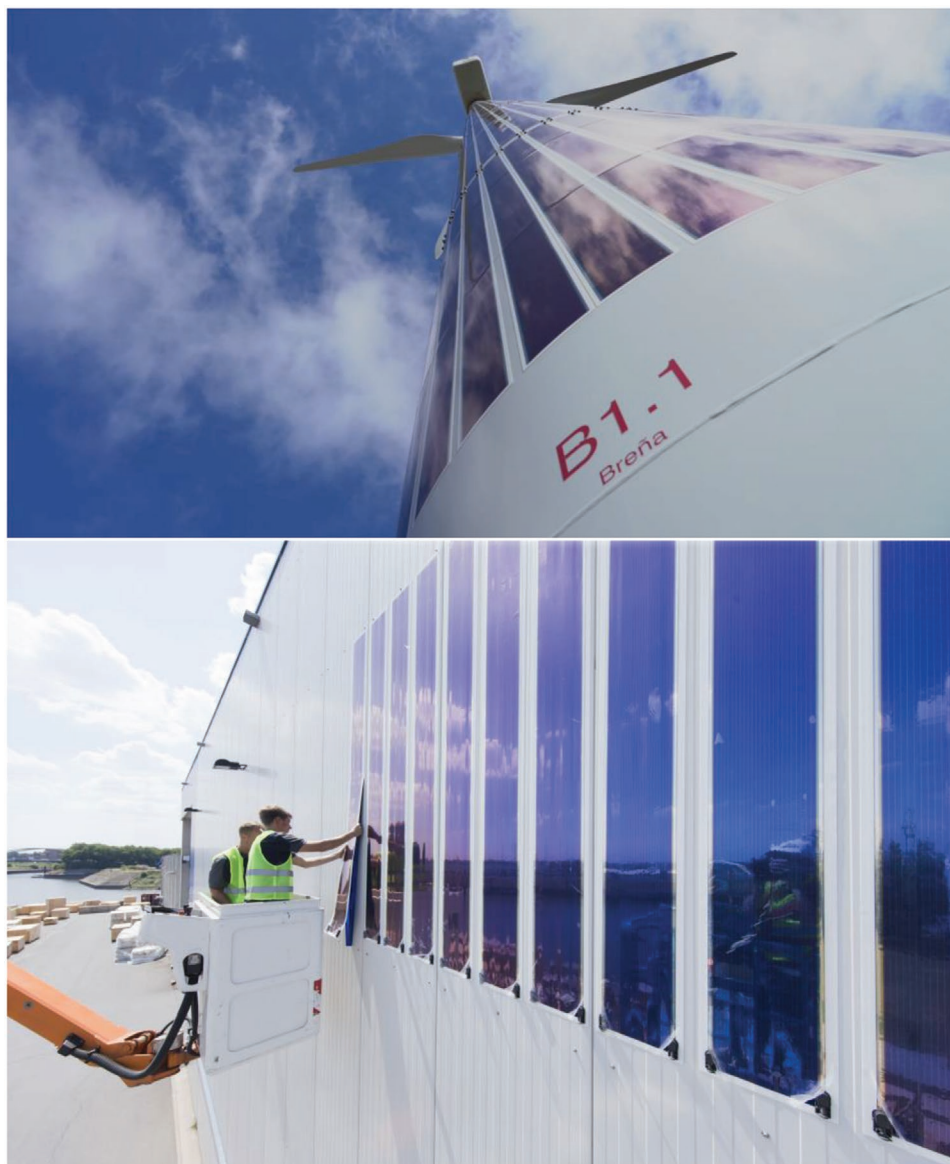
There are basically two such niches: one is building integrated photovoltaics (BIPV).[112] In the simplest form of BIPV, OSC is used on the roofs and walls of storage buildings (**Figure 3**). Such buildings are usually not designed to carry larger loads, and OSC as a plastic foil with less than 1 kg m^{-2} is superior to crystalline silicon modules, which weigh typically at least ten times more. A further argument in favor or OSC is the very simple fixation: the OSC modules are simply mounted by double-sided sticky tape.[113,114] Since such simple industrial buildings are furthermore commonly designed only for 20 years usage, the limited lifetime of OPV is less important.

A more sophisticated application is building integrated semitransparent photovoltaics.[115] OSC is an excellent candidate for this application since it achieves semitransparency with reasonable losses compared to non-transparent cells and color neutral absorption.[116–118] There are also opportunities for traditional PV to realize semitransparent modules, e.g., by leaving gaps between the cells. However, the homogeneous semitransparency that can be realized by semitransparent OSC is superior.[119]

The markets for BIPV are small compared to the overall PV market, on the order of 5%. However, it could still reach a market size of over €30 billion[120] in the next years, being a very attractive quickly growing market.

The second niche regards consumer applications that profit from flexibility, such as OSC in clothing, bags, or in camping products.[121,122] This will allow for a range of new and exciting consumer applications, but the total area that is needed for these markets is much smaller than that of the "power" applications and is thus not further discussed here.

Despite the current limitation of OSC to niche markets, it is quite interesting to speculate whether OSC has the potential

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Figure 3. Top: Heliatek's solar modules on a wind turbine. Bottom: ≈185 m² of Heliatek's solar modules applied on the façade of an industrial building in the port of Duisburg, Germany. Reproduced with permission.[12] Copyright 2019, Heliatek GmbH.

to enter the mainstream PV market, which is largely dominated by outdoor solar parks. What finally counts in these "power" PV applications is the energy generation cost in cents per kilowatt-hour. This already removes an often-used argument in favor of OSC: "if it is cheap enough, efficiency does not matter." The cost of land and balance of system costs like module mounting structures enter into the generation cost and a significantly lower PCE than the state-of-the-art of established technologies prevents market entry. Therefore, OSC can only compete with crystalline silicon if it reaches module efficiencies around 20%, lifetimes of more than 20 years, and cost well below silicon. The most easily reachable parameter is probably the 20 years lifetime: results from laboratories and companies indicate that this number can be reached if the quality of the module encapsulation is sufficiently good: the solar cells

themselves can easily reach more than 20 years lifetime, at least if the UV radiation is blocked which can be achieved with suitable filters.[50]

In terms of cost, OSC is currently well above the cost of the mainstream technology crystalline silicon, which has reached module cost below €0.3 per W_p leading to PV tender prices below €0.05 kWh⁻¹ in Germany and a fraction of that in some other countries.[2] With OSC mass production just at the beginning, it is difficult to state a precise number but it can be argued that first OSC mass products, expected in 2021, will be a factor more expensive. This is not surprising since OSC is a completely new technology and all tools and materials are mass-produced for the first time. In contrast, silicon PV has seen a decades-long cost scaling history. Currently, it is impossible to precisely predict how quickly OSC cost will

come down. However, there are some publication available that estimated the potential for OSC cost reduction,[123–126] with highly interesting results: the calculations show that the main cost factor responsible for about three-fourth of the total cost are materials. One direct corollary here is that the difference in cost between vacuum and solution processing equipment needed for industrial fabrication is likely to be secondary. Properties like performance and lifetime will carry more weight in the overall OSC cost. Of the material cost, it is the substrate that is most relevant, simply because the active layers are orders of magnitude thinner, making them much less relevant yet there is still significant work ahead in simplifying the molecular structures of the organic semiconductors and increasing the OSC lifetime at high efficiencies. One result of these publications is that OSC cost could come down to approximately USD 8 m^{-2}. If we optimistically assume an efficiency of about 15%, this would result in €/W_p prices about a factor of 5 lower than today's crystalline PV modules, and research has shown that OSC lifetimes >20 years are possible.[72] Whether this is sufficient to "beat" crystalline silicon PV, which has many decades of optimization and continues to rapidly reduce their cost further, remains to be seen.

3.3. Environmental Footprint/CO$_2$ Budget

The climate change due to CO$_2$ and other greenhouse gases (GHGs) emitted by burning fossil fuels is a key challenge for humankind.[1] The most important step here to reduce its impact is to reduce the GHG emissions from energy conversion. However, it is not sufficient to just replace fossil sources by renewables: even "renewable" energy sources cause CO$_2$ emission and other GHGs for their creation and operation. To judge the potential in GHG reduction, it is thus necessary to consider the total CO$_2$e (CO$_2$ and other GHGs) footprint of an energy generation technology. For fossil sources, CO$_2$e emission per kilowatt-hour is on the order of 400–500 g kWh^{-1} for gas and 900–1000 g kWh^{-1} for coal. For renewable sources, values are much lower but still not negligible. For silicon photovoltaics, values wildly differ depending on technology and location of manufacturing, with values roughly around 50 g kWh^{-1}.

Recently, Heliatek has presented the results of a study for OSC in which two of their vacuum deposited modules were investigated in detail.[127] The very encouraging result is that such OSC turned out to be the electricity generation technology with the lowest CO$_2$e footprint of all. The study performed by TÜV Rheinland, Germany, performed a life cycle assessment according to DIN EN ISO 14040:2009 and DIN EN ISO 14044:2018 and obtained for German solar insolation a carbon footprint of less than 16 kg CO$_2$e m^{-2} of OSC module produced. For southern Europe, this translates into a carbon footprint of only 5–7 g CO$_2$e kWh^{-1} (7–9 g CO$_2$e kWh^{-1} in central Europe) which is significantly below all commercial solar technologies and competing with wind and hydro energy. The investigated organic solar films allow to recover the CO$_2$e arising during the entire life cycle (assumed 10% module efficiency, lifetime 20 years, degradation 1% per year), from manufacture to disposal, after less than 3 months.

4. Conclusion

OSC has excellent potential for novel photovoltaic applications where their main advantages, such as low weight, flexibility, and transparency can be exploited. In the long term, OSC has the potential to even reach efficiencies and cost that allow the application in the mainstream PV "power" market.

Our review has concentrated on small-molecule OSCs, which are typically produced by vacuum evaporation. While being much less researched than their solution-processed typically polymer-based counterpart, they currently have an edge in commercial exploitation since they exploit the well-designed vacuum technology techniques used by the mass-produced OLED displays. The main challenges for small molecule OSC are to increase the open circuit voltage and to increase the short-circuit current while retaining excellent device stabilities. The former requires a better design of the active donor–acceptor system reducing the non-intrinsic losses. For the latter, materials with better transport properties are needed which allow to use much thicker active layers. The development of efficient vacuum processed NFA would help the technology to get a foothold in the market. We hope that our article stimulates further research into these directions.

Conflict of Interest

K.L. is one of the founders of Heliatek GmbH, a company that works towards the commercialization of OSCs.

[1] Global warming of 1.5 °C, https://www.ipcc.ch/sr15/, (accessed: August 2020).

[2] S. Philipps, F. Ise, W. Warmuth, PSE Projects GmbH, Photovoltaics report, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf, (accessed: October 2020).

[3] C. Deibel, V. Dyakonov, *Rep. Prog. Phys.* **2010**, *73*, 096401.

[4] B. Qu, S. R. Forrest, *Appl. Phys. Lett.* **2018**, *113*, 053302.

[5] R. Abbel, Y. Galagan, P. Groen, *Adv. Eng. Mater.* **2018**, *20*, 1701190.

[6] G. A. Chamberlain, *Sol. Cells* **1983**, *8*, 47.

[7] C. W. Tang, *Appl. Phys. Lett.* **1986**, *48*, 183.

[8] M. Hiramoto, H. Fujiwara, M. Yokoyama, *Appl. Phys. Lett.* **1991**, *58*, 1062.

[9] G. Zhang, J. Zhao, P. C. Y. Chow, K. Jiang, J. Zhang, Z. Zhu, J. Zhang, F. Huang, H. Yan, *Chem. Rev.* **2018**, *118*, 3447.

[10] Y. Tong, Z. Xiao, X. Du, C. Zuo, Y. Li, M. Lv, Y. Yuan, C. Yi, F. Hao, Y. Hua, T. Lei, Q. Lin, K. Sun, D. Zhao, C. Duan, X. Shao, W. Li, H.-L. Yip, Z. Xiao, B. Zhang, Q. Bian, Y. Cheng, S. Liu, M. Cheng, Z. Jin, S. Yang, L. Ding, *Sci. China Chem.* **2020**, *63*, 758.

[11] S. E. Shaheen, R. Radspinner, N. Peyghambarian, G. E. Jabbour, *Appl. Phys. Lett.* **2001**, *79*, 2996.

[12] L. Ye, H. Hu, M. Ghasemi, T. Wang, B. A. Collins, J.-H. Kim, K. Jiang, J. H. Carpenter, H. Li, Z. Li, T. McAfee, J. Zhao, X. Chen, J. L. Y. Lai, T. Ma, J.-L. Bredas, H. Yan, H. Ade, *Nat. Mater.* **2018**, *17*, 253.

[13] B. Maennig, J. Drechsel, D. Gebeyehu, P. Simon, F. Kozlowski, A. Werner, F. Li, S. Grundmann, S. Sonntag, M. Koch, K. Leo, M. Pfeiffer, H. Hoppe, D. Meissner, N. S. Sariciftci, I. Riedel, V. Dyakonov, J. Parisi, *Appl. Phys. A* **2004**, *79*, 1.

[14] D. D. C. Rasi, R. A. J. Janssen, *Adv. Mater.* **2019**, *31*, 1806499.

[15] Q. Liu, Y. Jiang, K. Jin, J. Qin, J. Xu, W. Li, J. Xiong, J. Liu, Z. Xiao, K. Sun, S. Yang, X. Zhang, L. Ding, *Sci. Bull.* **2020**, *65*, 272.

[16] Z. Zhou, M. Carbajales-Dale, *Energy Environ. Sci.* **2018**, *11*, 603.

[17] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, K. Yamamoto, *Nat. Energy* **2017**, *2*, 17032.

[18] M. A. Green, Y. Hishikawa, E. D. Dunlop, D. H. Levi, J. Hohl-Ebinger, M. Yoshita, A. W. Y. Ho-Baillie, *Prog. Photovoltaics* **2019**, *27*, 3.

[19] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, A. W. Y. Ho-Baillie, *Prog. Photovoltaics* **2020**, *28*, 3.

[20] M. A. Green, Y. Hishikawa, W. Warta, E. D. Dunlop, D. H. Levi, J. Hohl-Ebinger, A. W. H. Ho-Baillie, *Prog. Photovoltaics* **2017**, *25*, 668.

[21] K. Vandewal, J. Benduhn, V. C. Nikolis, *Sustainable Energy Fuels* **2018**, *2*, 538.

[22] W. Zhao, S. Li, H. Yao, S. Zhang, Y. Zhang, B. Yang, J. Hou, *J. Am. Chem. Soc.* **2017**, *139*, 7148.

[23] Z. Zheng, Q. Hu, S. Zhang, D. Zhang, J. Wang, S. Xie, R. Wang, Y. Qin, W. Li, L. Hong, N. Liang, F. Liu, Y. Zhang, Z. Wei, Z. Tang, T. P. Russell, J. Hou, H. Zhou, *Adv. Mater.* **2018**, *30*, 1801801.

[24] V. D. Mihailetchi, L. J. A. Koster, J. C. Hummelen, P. W. M. Blom, *Phys. Rev. Lett.* **2004**, *93*, 216601.

[25] T. M. Clarke, J. R. Durrant, *Chem. Rev.* **2010**, *110*, 6736.

[26] G. Grancini, M. Maiuri, D. Fazzi, A. Petrozza, H.-J. Egelhaaf, D. Brida, G. Cerullo, G. Lanzani, *Nat. Mater.* **2013**, *12*, 29.

[27] M. A. Faist, T. Kirchartz, W. Gong, R. S. Ashraf, I. McCulloch, J. C. de Mello, N. J. Ekins-Daukes, D. D. C. Bradley, J. Nelson, *J. Am. Chem. Soc.* **2012**, *134*, 685.

[28] J. Liu, S. Chen, D. Qian, B. Gautam, G. Yang, J. Zhao, J. Bergqvist, F. Zhang, W. Ma, H. Ade, O. Inganäs, K. Gundogdu, F. Gao, H. Yan, *Nat. Energy* **2016**, *1*, 16089.

[29] S. Chen, Y. Wang, L. Zhang, J. Zhao, Y. Chen, D. Zhu, H. Yao, G. Zhang, W. Ma, R. H. Friend, P. C. Y. Chow, F. Gao, H. Yan, *Adv. Mater.* **2018**, *30*, 1804215.

[30] H. Yao, Y. Cui, D. Qian, C. S. Ponseca, A. Honarfar, Y. Xu, J. Xin, Z. Chen, L. Hong, B. Gao, R. Yu, Y. Zu, W. Ma, P. Chabera, T. Pullerits, A. Yartsev, F. Gao, J. Hou, *J. Am. Chem. Soc.* **2019**, *141*, 7743.

[31] V. C. Nikolis, J. Benduhn, F. Holzmueller, F. Piersimoni, M. Lau, O. Zeika, D. Neher, C. Koerner, D. Spoltore, K. Vandewal, *Adv. Energy Mater.* **2017**, *7*, 1700855.

[32] C. Sun, S. Qin, R. Wang, S. Chen, F. Pan, B. Qiu, Z. Shang, L. Meng, C. Zhang, M. Xiao, C. Yang, Y. Li, *J. Am. Chem. Soc.* **2020**, *142*, 1465.

[33] V. Coropceanu, X.-K. Chen, T. Wang, Z. Zheng, J.-L. Brédas, *Nat. Rev. Mater.* **2019**, *4*, 689.

[34] W. Shockley, H. J. Queisser, *J. Appl. Phys.* **1961**, *32*, 510.

[35] P. Würfel, *Physics of Solar Cells: From Basic Principles to Advanced Concepts*, Wiley-VCH, Weinheim, Germany **2009**.

[36] K. Vandewal, J. Widmer, T. Heumueller, C. J. Brabec, M. D. McGehee, K. Leo, M. Riede, A. Salleo, *Adv. Mater.* **2014**, *26*, 3839.

[37] J. Benduhn, K. Tvingstedt, F. Piersimoni, S. Ullbrich, Y. Fan, M. Tropiano, K. A. McGarry, O. Zeika, M. K. Riede, C. J. Douglas, S. Barlow, S. R. Marder, D. Neher, D. Spoltore, K. Vandewal, *Nat. Energy* **2017**, *2*, 17053.

[38] D. Qian, Z. Zheng, H. Yao, W. Tress, T. R. Hopper, S. Chen, S. Li, J. Liu, S. Chen, J. Zhang, X.-K. Liu, B. Gao, L. Ouyang, Y. Jin, G. Pozina, I. A. Buyanova, W. M. Chen, O. Inganäs, V. Coropceanu, J.-L. Bredas, H. Yan, J. Hou, F. Zhang, A. A. Bakulin, F. Gao, *Nat. Mater.* **2018**, *17*, 703.

[39] X.-K. Chen, V. Coropceanu, J.-L. Brédas, *Nat. Commun.* **2018**, *9*, 5295.

[40] F. D. Eisner, M. Azzouzi, Z. Fei, X. Hou, T. D. Anthopoulos, T. J. S. Dennis, M. Heeney, J. Nelson, *J. Am. Chem. Soc.* **2019**, *141*, 6362.

[41] M. Azzouzi, J. Yan, T. Kirchartz, K. Liu, J. Wang, H. Wu, J. Nelson, *Phys. Rev. X* **2018**, *8*, 031055.

[42] J. Hou, O. Inganäs, R. H. Friend, F. Gao, *Nat. Mater.* **2018**, *17*, 119.

[43] S. Ullbrich, J. Benduhn, X. Jia, V. C. Nikolis, K. Tvingstedt, F. Piersimoni, S. Roland, Y. Liu, J. Wu, A. Fischer, D. Neher, S. Reineke, D. Spoltore, K. Vandewal, *Nat. Mater.* **2019**, *18*, 459.

[44] M. Jørgensen, K. Norrman, F. C. Krebs, *Sol. Energy Mater. Sol. Cells* **2008**, *92*, 686.

[45] M. Jørgensen, K. Norrman, S. A. Gevorgyan, T. Tromholt, B. Andreasen, F. C. Krebs, *Adv. Mater.* **2012**, *24*, 580.

[46] S. A. Gevorgyan, N. Espinosa, L. Ciammaruchi, B. Roth, F. Livi, S. Tsopanidis, S. Züfle, S. Queirós, A. Gregori, G. A. dos Reis Benatto, M. Corazza, M. V. Madsen, M. Hösel, M. J. Beliatis, T. T. Larsen-Olsen, F. Pastorelli, A. Castro, A. Mingorance, V. Lenzi, D. Fluhr, R. Roesch, M. Maria Duarte Ramos, A. Savva, H. Hoppe, L. S. A. Marques, I. Burgués, E. Georgiou, L. Serrano-Luján, F. C. Krebs, *Adv. Energy Mater.* **2016**, *6*, 1600910.

[47] W. R. Mateker, M. D. McGehee, *Adv. Mater.* **2017**, *29*, 1603940.

[48] K. Norrman, M. V. Madsen, S. A. Gevorgyan, F. C. Krebs, *J. Am. Chem. Soc.* **2010**, *132*, 16883.

[49] A. Rivaton, A. Tournebize, J. Gaume, P.-O. Bussière, J.-L. Gardette, S. Therias, *Polym. Int.* **2014**, *63*, 1335.

[50] M. Hermenau, M. Riede, K. Leo, S. A. Gevorgyan, F. C. Krebs, K. Norrman, *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 1268.

[51] F. C. Krebs, *Sol. Energy Mater. Sol. Cells* **2006**, *90*, 3633.

[52] J. Adams, G. D. Spyropoulos, M. Salvador, N. Li, S. Strohm, L. Lucera, S. Langner, F. Machui, H. Zhang, T. Ameri, M. M. Voigt, F. C. Krebs, C. J. Brabec, *Energy Environ. Sci.* **2015**, *8*, 169.

[53] J. Adams, M. Salvador, L. Lucera, S. Langner, G. D. Spyropoulos, F. W. Fecher, M. M. Voigt, S. A. Dowland, A. Osvet, H.-J. Egelhaaf, C. J. Brabec, *Adv. Energy Mater.* **2015**, *5*, 1501065.

[54] C. Jeong, C. Coburn, M. Idris, Y. Li, P. I. Djurovich, M. E. Thompson, S. R. Forrest, *Org. Electron.* **2019**, *64*, 15.

[55] A. J. Heeger, *Adv. Mater.* **2014**, *26*, 10.

[56] A. M. Rao, P. Zhou, K.-A. Wang, G. T. Hager, J. M. Holden, Y. Wang, W.-T. Lee, X.-X. Bi, P. C. Eklund, D. S. Cornett, M. A. Duncan, I. J. Amster, *Science* **1993**, *259*, 955.

[57] A. Distler, T. Sauermann, H. J. Egelhaaf, S. Rodman, D. Waller, K. S. Cheon, M. Lee, D. M. Guldi, *Adv. Energy Mater.* **2014**, *4*, 1300693.

[58] H. Zhang, A. Borgschulte, F. A. Castro, R. Crockett, A. C. Gerecke, O. Deniz, J. Heier, S. Jenatsch, F. Nüesch, C. Sanchez-Sanchez, A. Zoladek-Lemanczyk, R. Hany, *Adv. Energy Mater.* **2015**, *5*, 1400734.

[59] N. Wang, X. Tong, Q. Burlingame, J. Yu, S. R. Forrest, *Sol. Energy Mater. Sol. Cells* **2014**, *125*, 170.

[60] Q. Burlingame, X. Tong, J. Hankett, M. Slootsky, Z. Chen, S. R. Forrest, *Energy Environ. Sci.* **2015**, *8*, 1005.

[61] I. Ramirez, A. Privitera, S. Karuthedath, A. Jungbluth, J. Benduhn, A. Sperlich, D. Spoltore, K. Vandewal, F. Laquai, M. Riede, unpublished.

[62] C. Bruner, R. Dauskardt, *Macromolecules* **2014**, *47*, 1117.

[63] J. Vandenbergh, B. Conings, S. Bertho, J. Kesters, D. Spoltore, S. Esiner, J. Zhao, G. Van Assche, M. M. Wienk, W. Maes, L. Lutsen, B. Van Mele, R. A. J. Janssen, J. Manca, D. J. M. Vanderzande, *Macromolecules* **2011**, *44*, 8470.

[64] Y. Ning, L. Lv, Y. Lu, A. Tang, Y. Hu, Z. Lou, F. Teng, Y. Hou, *Int. J. Photoenergy* **2014**, *2014*, 354837.

[65] S. Bertho, I. Haeldermans, A. Swinnen, W. Moons, T. Martens, L. Lutsen, D. Vanderzande, J. Manca, A. Senes, A. Bonfiglio, *Sol. Energy Mater. Sol. Cells* **2007**, *91*, 385.

[66] B. Conings, S. Bertho, K. Vandewal, A. Senes, J. D'Haen, J. Manca, R. A. J. Janssen, *Appl. Phys. Lett.* **2010**, *96*, 163301.

[67] C. Yan, S. Barlow, Z. Wang, H. Yan, A. K.-Y. Jen, S. R. Marder, X. Zhan, *Nat. Rev. Mater.* **2018**, *3*, 18003.

[68] D. Baran, R. S. Ashraf, D. A. Hanifi, M. Abdelsamie, N. Gasparini, J. A. Röhr, S. Holliday, A. Wadsworth, S. Lockett, M. Neophytou, C. J. M. Emmott, J. Nelson, C. J. Brabec, A. Amassian, A. Salleo, T. Kirchartz, J. R. Durrant, I. McCulloch, *Nat. Mater.* **2017**, *16*, 363.

[69] N. Gasparini, M. Salvador, S. Strohm, T. Heumueller, I. Levchuk, A. Wadsworth, J. H. Bannock, J. C. de Mello, H.-J. Egelhaaf, D. Baran, I. McCulloch, C. J. Brabec, *Adv. Energy Mater.* **2017**, *7*, 1700770.

[70] M. Manceau, M. Helgesen, F. C. Krebs, *Polym. Degrad. Stab.* **2010**, *95*, 2666.

[71] M. Manceau, E. Bundgaard, J. E. Carlé, O. Hagemann, M. Helgesen, R. Søndergaard, M. Jørgensen, F. C. Krebs, *J. Mater. Chem.* **2011**, *21*, 4132.

[72] Q. Burlingame, X. Huang, X. Liu, C. Jeong, C. Coburn, S. R. Forrest, *Nature* **2019**, *573*, 394.

[73] C. J. Brabec, N. S. Sariciftci, J. C. Hummelen, *Adv. Funct. Mater.* **2001**, *11*, 15.

[74] F. C. Krebs, H. Spanggard, T. Kjær, M. Biancardo, J. Alstrup, *Mater. Sci. Eng., B* **2007**, *138*, 106.

[75] H. Hoppe, M. Seeland, B. Muhsin, *Sol. Energy Mater. Sol. Cells* **2012**, *97*, 119.

[76] N. Espinosa, R. García-Valverde, A. Urbina, F. C. Krebs, *Sol. Energy Mater. Sol. Cells* **2011**, *95*, 1293.

[77] S. Davidsson, M. Höök, *Energy Policy* **2017**, *108*, 574.

[78] K. A. Sierros, N. J. Morris, K. Ramji, D. R. Cairns, *Thin Solid Films* **2009**, *517*, 2590.

[79] Y. Zhang, S.-W. Ng, X. Lu, Z. Zheng, *Chem. Rev.* **2020**, *120*, 2049.

[80] H. Shi, C. Liu, Q. Jiang, J. Xu, *Adv. Electron. Mater.* **2015**, *1*, 1500017.

[81] J.-Y. Lee, S. T. Connor, Y. Cui, P. Peumans, *Nano Lett.* **2008**, *8*, 689.

[82] S. Ye, A. R. Rathmell, I. E. Stewart, Y.-C. Ha, A. R. Wilson, Z. Chen, B. J. Wiley, *Chem. Commun.* **2014**, *50*, 2562.

[83] P. Wu, T.-X. Jiang, S. Suksaweang, R. B. Widelitz, C.-M. Chuong, *Science* **2004**, *305*, 1465.

[84] G. Mazzotta, M. Dollmann, S. N. Habisreutinger, M. G. Christoforo, Z. Wang, H. J. Snaith, M. K. Riede, R. J. Nicholas, *ACS Appl. Mater. Interfaces* **2019**, *11*, 1185.

[85] L. Cattin, M. Morsli, F. Dahou, S. Y. Abe, A. Khelil, J. C. Bernède, *Thin Solid Films* **2010**, *518*, 4560.

[86] A. T. Barrows, R. Masters, A. J. Pearson, C. Rodenburg, D. G. Lidzey, *Sol. Energy Mater. Sol. Cells* **2016**, *144*, 600.

[87] Y. Galagan, B. Zimmermann, E. W. C. Coenen, M. Jørgensen, D. M. Tanenbaum, F. C. Krebs, H. Gorter, S. Sabik, L. H. Slooff, S. C. Veenstra, J. M. Kroon, R. Andriessen, *Adv. Energy Mater.* **2012**, *2*, 103.

[88] H. J. van de Wiel, Y. Galagan, T. J. van Lammeren, J. F. J. de Riet, J. Gilot, M. G. M. Nagelkerke, R. H. C. A. T. Lelieveld, S. Shanmugam, A. Pagudala, D. Hui, W. A. Groen, *Nanotechnology* **2013**, *24*, 484014.

[89] C. J. M. Emmott, A. Urbina, J. Nelson, *Sol. Energy Mater. Sol. Cells* **2012**, *97*, 14.

[90] B. Zimmermann, M. Glatthaar, M. Niggemann, M. K. Riede, A. Hinsch, A. Gombert, *Sol. Energy Mater. Sol. Cells* **2007**, *91*, 374.

[91] G. Adam, B. Munkhbat, P. Denk, C. Ulbricht, C. Hrelescu, M. C. Scharber, *Front. Mater.* **2016**, *3*, 39.

[92] K. Tvingstedt, V. Andersson, F. Zhang, O. Inganäs, *Appl. Phys. Lett.* **2007**, *91*, 123514.

[93] F. C. Krebs, *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 394.

[94] G. D. Spyropoulos, P. Kubis, N. Li, D. Baran, L. Lucera, M. Salvador, T. Ameri, M. M. Voigt, F. C. Krebs, C. J. Brabec, *Energy Environ. Sci.* **2014**, *7*, 3284.

[95] P. Kubis, J. Winter, A. Gavrilova, M. Hennel, S. Schlosser, I. Richter, A. Distler, M. Heyder, S. Kery, P. Lenk, S. Geiger, C. J. Brabec, H. P. Huber, H.-J. Egelhaaf, *Prog. Photovoltaics* **2019**, *27*, 479.

[96] L. Müller-Meskamp, J. Fahlteich, F. C. Krebs, in *Stability and Degradation of Organic and Polymer Solar Cells*, (Ed: F. C. Krebs), John Wiley & Sons, Chichester, UK **2012**, pp. 269–329.

[97] P. E. Burrows, G. L. Graff, M. E. Gross, P. M. Martin, M. Hall, E. Mast, C. C. Bonham, W. D. Bennett, L. A. Michalski, M. S. Weaver, J. J. Brown, D. Fogarty, L. S. Sapochak, in *Int. Symp. on Optical Science and Technology*, (Ed: Z. H. Kafafi), SPIE, Bellingham, WA **2001**, pp. 75–83.

[98] J. Lewis, *Mater. Today* **2006**, *9*, 38.

[99] S. Cros, R. de Bettignies, S. Berson, S. Bailly, P. Maisse, N. Lemaitre, S. Guillerez, *Sol. Energy Mater. Sol. Cells* **2011**, *95*, S65.

[100] E. G. Jeong, J. H. Kwon, K. S. Kang, S. Y. Jeong, K. C. Choi, *J. Inf. Disp.* **2020**, *21*, 19.

[101] D. M. Tanenbaum, H. F. Dam, R. Rösch, M. Jørgensen, H. Hoppe, F. C. Krebs, *Sol. Energy Mater. Sol. Cells* **2012**, *97*, 157.

[102] Nanotechnology—reliability assessment—Part 2-1: Nano-enabled photovoltaic devices—stability test, https://webstore.iec.ch/publication/26699, (accessed: August 2020).

[103] J. H. Burroughes, D. D. C. Bradley, A. R. Brown, R. N. Marks, K. Mackay, R. H. Friend, P. L. Burns, A. B. Holmes, *Nature* **1990**, *347*, 539.

[104] R. Meerheim, C. Körner, K. Leo, *Appl. Phys. Lett.* **2014**, *105*, 063306.

[105] R. Meerheim, C. Körner, B. Oesen, K. Leo, *Appl. Phys. Lett.* **2016**, *108*, 103302.

[106] R. Meerheim, K. Walzer, M. Pfeiffer, K. Leo, *Appl. Phys. Lett.* **2006**, *89*, 061111.

[107] X. Che, C.-L. Chung, C.-C. Hsu, F. Liu, K.-T. Wong, S. R. Forrest, *Adv. Energy Mater.* **2018**, *8*, 1703603.

[108] W. Xu, F. Gao, *Mater. Horiz.* **2018**, *5*, 206.

[109] R. Zhou, Z. Jiang, C. Yang, J. Yu, J. Feng, M. A. Adil, D. Deng, W. Zou, J. Zhang, K. Lu, W. Ma, F. Gao, Z. Wei, *Nat. Commun.* **2019**, *10*, 5393.

[110] Solar and Wind Cheapest Sources of Power in Most of the World, https://www.bloomberg.com/news/articles/2020-04-28/solar-and-wind-cheapest-sources-of-power-in-most-of-the-world, (accessed: October 2020).

[111] International Energy Agency World Energy Outlook **2020** (ISBN: 978-92-64-4 4923-7).

[112] E. Biyik, M. Araz, A. Hepbasli, M. Shahrestani, R. Yao, L. Shao, E. Essah, A. C. Oliveira, T. del Caño, E. Rico, J. L. Lechón, L. Andrade, A. Mendes, Y. B. Atlı, *Eng. Sci. Technol., Int. J.* **2017**, *20*, 833.

[113] Solar refresh for an industrial façade, https://www.heliatek.com/blog/solar-refresh-for-an-industrial-facade/, (accessed: July 2020).

[114] Printed organic photovoltaics: S+L Selbstklebeprodukte and OPVIUS, sign co-operation, https://www.opvius.com/sl-selbstklebeprodukte-and-opvius-sign-co-operation-agreement-for-the-development-of-opv-stickers.html, (accessed: August 2020).

[115] E. Pulli, E. Rozzi, F. Bella, *Energy Convers. Manage.* **2020**, *219*, 112982.

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[116] Y. Li, G. Xu, C. Cui, Y. Li, *Adv. Energy Mater.* **2018**, *8*, 1701791.

[117] A. Anctil, E. Lee, R. R. Lunt, *Appl. Energy* **2020**, *261*, 114429.

[118] A. Colsmann, A. Puetz, A. Bauer, J. Hanisch, E. Ahlswede, U. Lemmer, *Adv. Energy Mater.* **2011**, *1*, 599.

[119] S. Dai, X. Zhan, *Adv. Energy Mater.* **2018**, *8*, 1800002.

[120] BIPV market size worth $36.74 billion by 2025: CAGR 18.8%, https://www.grandviewresearch.com/press-release/global-building-integrated-photovoltaics-bipv-market, (accessed: July 2020).

[121] M. Kaltenbrunner, M. S. White, E. D. Głowacki, T. Sekitani, T. Someya, N. S. Sariciftci, S. Bauer, *Nat. Commun.* **2012**, *3*, 770.

[122] K. Fukuda, K. Yu, T. Someya, *Adv. Energy Mater.* **2020**, *10*, 2000765.

[123] J. Kalowekamo, E. Baker, *Sol. Energy* **2009**, *83*, 1224.

[124] C. J. Mulligan, M. Wilson, G. Bryant, B. Vaughan, X. Zhou, W. J. Belcher, P. C. Dastoor, *Sol. Energy Mater. Sol. Cells* **2014**, *120*, 9.

[125] A. Gambhir, P. Sandwell, J. Nelson, *Sol. Energy Mater. Sol. Cells* **2016**, *156*, 49.

[126] R. Xue, J. Zhang, Y. Li, Y. Li, *Small* **2018**, *14*, 1801793.

[127] Heliatek, Whitepaper: organic photovoltaics—truly green energy: ultra-low carbon footprint, https://www.heliatek.com/de/blog/whitepaper-organic-photovoltaics-truly-green-energy-ultra-low-carbon-footprint/, (accessed: October 2020).

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