Agrivoltaics—The Perfect Fit for the Future of Organic Photovoltaics

*Rico Meitzner, Ulrich S. Schubert, and Harald Hoppe**

This Essay presents a possible pathway for the advancement of organic photovoltaics toward broader commercial success and enlarged market size. This vision aims at broad scale applications in photovoltaic greenhouses and polytunnels, which harvest those portions of the solar spectrum that are not used or required by plants. Based on the assumptions of the Shockley–Queisser–Limit, respectively detailed balance, and the additional postulation of using no absorption in the visible part of the AM 1.5G solar spectrum a power conversion efficiency of ≈17% is theoretically predicted. The suggestion is supported by the existence of a number of organic compounds, which already exhibit a good spectral compatibility with the typical photosynthetic action spectrum of chloroplasts. It is hoped that more suitable materials development shall be triggered and fertilized as a result of this Essay.

1. Introduction

Organic photovoltaics (OPV) combines advantages like usage of earth-abundant materials, compatibility with high-throughput roll-to-roll (R2R) processing, as well as a low energy demand in production (low embedded energy cost) and thus short energy pay-back times. OPV panels can be fitted to any size, and shape (flexibility and conformity) and—evenly important—many colors. While OPV has been long-term considered as a game changer due to its potentially low prices, so far this promise did not successfully come to fruition and even might never do so with the advent of perovskite photovoltaics, which can still promise close to the same features (except for being colorful), but with significantly higher efficiencies. However, one big advantage of OPV is that it may not only be processed from environmentally friendly solvents but also the constituting materials do not necessarily display any harm for health or environment. On the other side, alternative existing photovoltaic technologies involve considerably more environmentally questionable and toxic chemicals in the layer stacks and their production.[1] And such a factor may play out for applications in buildings or anywhere within reach of intelligent lifeforms or food production.

Thus, to achieve market penetration within a wide-scale and high-volume application for OPV, which would be the necessary precondition for any economies of scale and therefore major price reductions, requires finding an application, where its specific properties offer clear advantages over any other technology in the market. The internet-of-things applications could be viewed as one potential market for increased usage of OPV. However, this very market lacks behind the expectations, and thus there might be considerable doubts in the overall market size. Second, IoT may require rather small devices as compared to power applications. Hence, IoT might not offer the chance for scaling up OPV sufficiently, to obtain competitive prices for penetration into other markets. Furthermore, it is required to address the question where does OPV display an advantage over the application of silicon PV in IoT, even if costs do not matter? Thus, even though there are plenty of applications foreseeable for IoT or smart buildings, it remains a question, whether these markets could provide a breakthrough for OPV. For the latter, sheer quantity or rather sheer area of photovoltaic modules may be required. At the same time, besides silicon PV, also perovskite PV provides comparable performances with efficiencies of roughly 25% power conversion efficiency (PCE) for very small devices in the lab[2] and 16% PCE for small modules[3] (which may approach the size of a standard silicon solar cell). Currently, OPV is still lagging behind these numbers with above 18% for small lab-scale devices[4] and 12% for small modules.[3] Under such strong competition and difficult markets, the question is, what then to do with OPV?

2. The Strategy for a Way Forward

While traditional photovoltaic applications might not be in reach for a competitive product based on OPV, the situation changes, when carefully selecting an application in line with the specific advantages of OPV. At this point, we could even go one step further: what generally needs to be considered as a downside for reaching high-level power-conversion efficiencies, namely the incomplete absorption throughout a

R. Meitzner, Prof. U. S. Schubert, Dr. H. Hoppe
Center for Energy and Environmental Chemistry Jena (CEEC Jena)
Friedrich Schiller University Jena
Philosophenweg 7a, Jena 07743, Germany
E-mail: harald.hoppe@uni-jena.de

R. Meitzner, Prof. U. S. Schubert, Dr. H. Hoppe
Laboratory of Organic and Macromolecular Chemistry (IOMC)
Friedrich Schiller University Jena
Humboldtstrasse 10, Jena 07743, Germany

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aenm.202002551.

The copyright line for this article was changed on 27 May 2021 after original online publication.

DOI: 10.1002/aenm.202002551

broad wavelength range severely limiting the photocurrent generation, can even be turned into a blessing. In contrast to any inorganic semiconductor and hybrid perovskites, organic semiconductors or conjugated molecules and polymers do show over the wavelength (respectively photon energy) limited absorption bands, leaving room for the absorption of the plants below/above ≈730 nm/1.7 eV. The simple solution is to use this semi-transparent window of non-absorption for a combination with agriculture. Thus, using transmitted light for plant growth may essentially turn the weakness of a limited absorption band into an advantage for dual use on the same land.

In order to leave as much light as possible for the plants growing underneath the photovoltaic modules, it will be necessary to move the absorption window of the active layer material entirely away from the visible into the near-infrared (NIR) part of the electromagnetic spectrum.

The benefits from such an approach can be manifold for both sides of the equation: at first, the costs of the PV system would not need to include costs for land acquisition anymore, as the land already is in use for agriculture. Besides the immediate costs of land acquisition, which mostly impact more developed nations, there are also zoning issues that can be circumvented, as countries might forbid installation of PV on agricultural land, therefore making more land available for PV applications, which are not hundreds of kilometers away from habitation, like in entirely uninhabited deserts. As next, such a photovoltaic installation would replace traditional greenhouses as well as polytunnels, swapping these investment costs directly, by which the PV system would be made more competitive or even make the usage of greenhouses or polytunnels financially viable, where they would have been not viable before. On top of that, there is a manifold of benefits for the agricultural side of the equation that come along with a precise control of the climatic conditions for the plants. For example, in semi-arid and arid climates, where irrigation is essential for doing any agriculture, greenhouses, and polytunnels can strongly reduce evaporation losses and therefore reduce watering requirements. In addition, the electricity generation could be used to keep humidity at a stable level by the application of active ventilation systems with humidity recuperation. Such effort is usually not done for greenhouses or polytunnels due to the additional costs for energy that would have to be provided from the outside. In turn, better controlled humidity is enabling a higher crop yield, especially for those plants, which stop photosynthesis at too low moisture levels, to prevent drying out. Such conditions normally occur in the middle of the day in warm and arid or semi-arid climates when solar irradiation is at its peak. Furthermore, a reduction in evaporation reduces the risk of soil salinization, which is till date a major problem of many areas requiring irrigation for agriculture.

These points make a deployment of transparent photovoltaic polytunnels especially attractive for developing nations in semi-arid and arid climate like Africa's countries along its and in its large deserts like the Sahara and the Namib. The same should apply also for the dryer regions of the Indian subcontinent.

Also, temperature control in these greenhouses or polytunnels would be easier, as on the one hand, the solar modules already reduce the heat influx from absorbing part of the solar irradiation, and on the other hand, part of the generated electricity could be employed for air ventilation.

In such a scenario, the photovoltaic modules would actually upgrade the value of land by its double usage. On the other hand, this application thus would also increase the available land area for utility-scale PV installations by multiples of its current amount. **Figure 1** summarizes a number of the mentioned aspects in a schematic depiction. Even if the double use is not in the focus of the consideration, locally generated electricity may provide sufficient benefit for upgrading existing greenhouses and consumers nearby.

Currently, the interest in this topic is rising and there are by now a few reports[5] on the use of Si-PV for agrivoltaics. The challenge Si-PV is facing in this context is connected with it being in-transparent, rigid, and brittle in nature. Such installations obviously cannot cover the full area, or are only compatible with crops that require low light intensities. Furthermore, such installations are by necessity quite heavy, as they have to bear the load of full-size Si-PV modules and are thus not as quickly installable or removable. We on the other hand are advocating for installations that can be quickly installed or removed., that

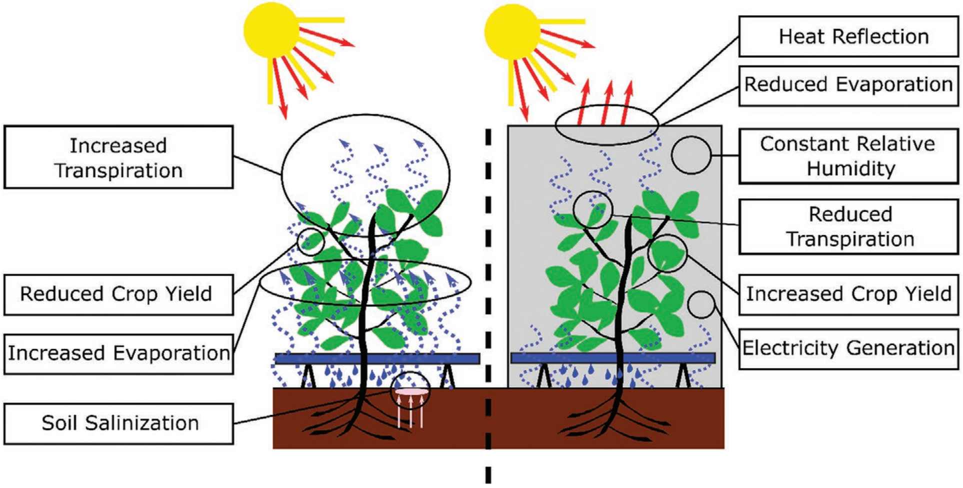

Figure 1. Schematic depiction of the advantages of the proposed agrivoltaics approach. The current situation in scenarios of irrigation dependent agriculture (left) versus the situation of an agrivoltaic application scenario (right), in which specific properties of organic photovoltaics provide a perfect match.

is, in the case of dryland agriculture, whereupon sowing irrigation is deployed and upon deployment large OPV polytunnels could be installed, that cover these fields and which can be quickly removed before harvest is due. Therefore, as the first step for OPV agrivoltaics, we advocate for deployment of OPV-polytunnels in arid and semi-arid climates to re-green deserts and other drylands and make them arable for a long-term and sustainable agriculture. The added value will be to provide access to cheap electricity to rural communities inhabiting such areas. Thus, OPV agrivoltaics could be considered as one major step toward the sustainable development goals (SDGs) of the United Nations. Due to the combination of the benefits of sustainable agriculture, reduced irrigation and water consumption as well as sustainable energy generation, obviously not only the elimination of hunger (SDG 2) and the provision of clean energy (SDG 7) follow as a direct consequence, but indirectly also most other SDGs will be positively and sustainably influenced.

The benefits from a specific OPV development for agrivoltaics could then—in a second step—be transferred toward the building-integrated OPV (BIOPV) sector. The aforementioned transparency for plants in the visible spectrum range is obviously a benefit for energy producing building glazing.

However, since most glazing is vertical, the angle of incidence is somewhat unfavorable leading to a reduced potential in power generation. Though organic solar cells exhibit only a minor dependence of the performance on the angle of incidence as all thin film photovoltaic technologies,[6] when the angle of incidence is basically parallel during the most sun intense hours of the day, as is the case in latitudes between the tropic of Cancer and tropic of Capricorn, still only indirect irradiation can be collected in the middle of the day. There are also two targets for a sustainable city development, which are in direct opposition to efficient usage of any PV technology, these are densification, that is, closely built as well as taller buildings, resulting in mutual shading between buildings. The other target is vertical gardens along facades of buildings,[7] these obviously would compete with space for solar energy generation, though this actually could be alleviated with the developments that have to be made for organic agrivoltaics. While in dense cities potentially compromises will have to be made, BIOPV applications will certainly benefit from the herein promoted agrivoltaics with OPV.

3. Limits, Current Status, and Next Steps

As we have now laid out our vision for a bright future of OPV, it is time to assess, which parameters such technology should have. The properties are largely determined by the necessities of plants to be able to have as much light as possible for photosynthesis. This requires high transparency of the photovoltaic module in the range between 1.77 to 3.55 eV, as this is the region of the solar spectrum where the photosynthetic activity takes place. Based on the general idea of the Shockley–Queisser–Limit for photovoltaics, that is, a box-shaped external quantum efficiency, we calculated the maximally obtainable efficiency for such given limitations. A very encouraging efficiency of ≈17% at a bandgap of 1.125 eV displays a local theoretical limit, see **Figure 2**.

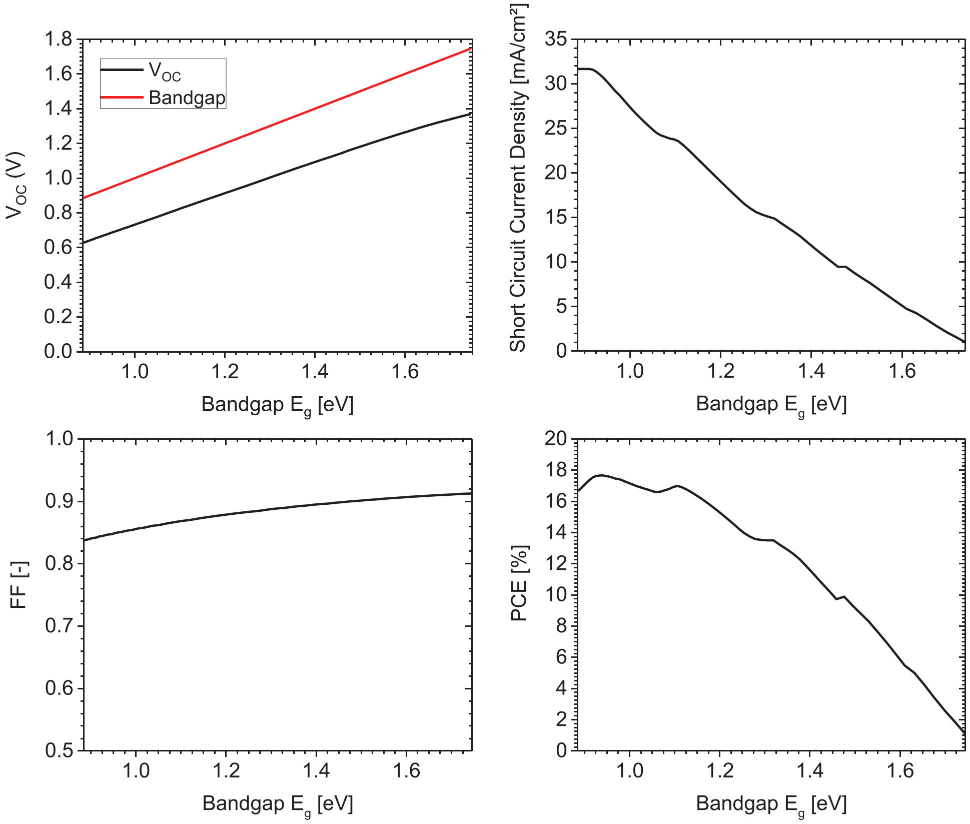

Figure 2. Photovoltaic parameters (short circuit photocurrent, open circuit voltage, fill factor) and resulting power conversion efficiency for a solar cell based on the Shockley–Queisser–Limit for an absorption window starting with an onset energy (band gap) given by the *x*-axis of the graph and ending at 1.77 eV.

Note that this is not the global maximum, but since smaller bandgap organic semiconductors should exhibit a higher relative energy loss, it should be the more smart choice. These results were obtained by using the following equations for calculation.

$$J_{\mathrm{SC}} = q \int_{E_{\mathrm{g}}}^{1.77\,\mathrm{eV}} \phi_{\mathrm{Sun}}(E)\, dE \tag{1}$$

$$J_0 = q \int_{E_{\mathrm{g}}}^{1.77\,\mathrm{eV}} \phi_{\mathrm{bb}}(E, T = 300\ K)\, dE \tag{2}$$

$$V_{\mathrm{OC}} = \frac{kT}{q} \ln\left(\frac{J_{\mathrm{SC}}}{J_0} + 1\right) \tag{3}$$

$$J = J_0 \left[\exp\left(\frac{qV}{kT}\right) - 1\right] - J_{\mathrm{SC}} \tag{4}$$

While the Shockley–Queisser–Limit has to be regarded as the ultimate limit for application of photovoltaics in agriculture, it should be mentioned here that additional losses may apply for OPV due to the specific properties of organic semiconductors. This performance loss by in total few absolute percent does originate from energy, respectively open circuit voltage (V_{OC}), losses which may be attributed to a) considerable exciton binding energies, which have to be overcome for successful charge generation processes and to b) increased recombination losses in organic solar cells of smaller bandgap, due to the overlap of the vibronic energy levels of the ground state, which may interfere more severely with the charge transfer state at the decisive charge separating step (compare with Benduhn et al.).[8] While the first may result either in smaller photocurrent or photovoltage, the latter adds to the non-radiative losses of solar cells and thus to a reduced V_{OC}.

With these given constraints, where are we at the moment? In **Figure 3** the chemical structures of various low bandgap active layer materials are shown and in **Figure 4** their normalized absorbance is plotted in comparison to the normalized photosynthetic activity of a chloroplast of a green plant. Among these are a few candidates that already show a very minor overlap with the spectrum of chloroplasts: only one is found among the electron donors: C3-DPPTT-Te.[9] In case of electron acceptors, there are indeed several candidates that are suitable: IEICO-4F,[10] IEICO-4Cl,[11] IXIC-4Cl,[12] Y14,[13] and DTPC-DFIC.[14] The latter represents an interesting special case, as it exhibits a second absorption peak matching closely to the spectral region where chloroplasts have an activity minimum. This might allow for a correspondingly higher photocurrent and performance, with only minor detriment to plant growth. As all of these materials exhibit a small spectral overlap with the chloroplast absorption, they do not yet present a perfect fit. Thus, organic chemists are invited and invoked to develop new electron donors and acceptors, which will fulfill the requirement of exhibiting a sufficiently large absorption window to be employed for plant growth.

Besides the optical requirements for the photoactive layer, it will be of high importance to develop semi-transparent electrode materials which provide significantly increased transmission in the NIR spectral range (specifically between 1.13 and 3.5 eV) as compared to the existing ones. Hence, we see the development of such materials that fulfill these requirements as an important additional challenge, which should be tackled to reach a bright future for OPV.

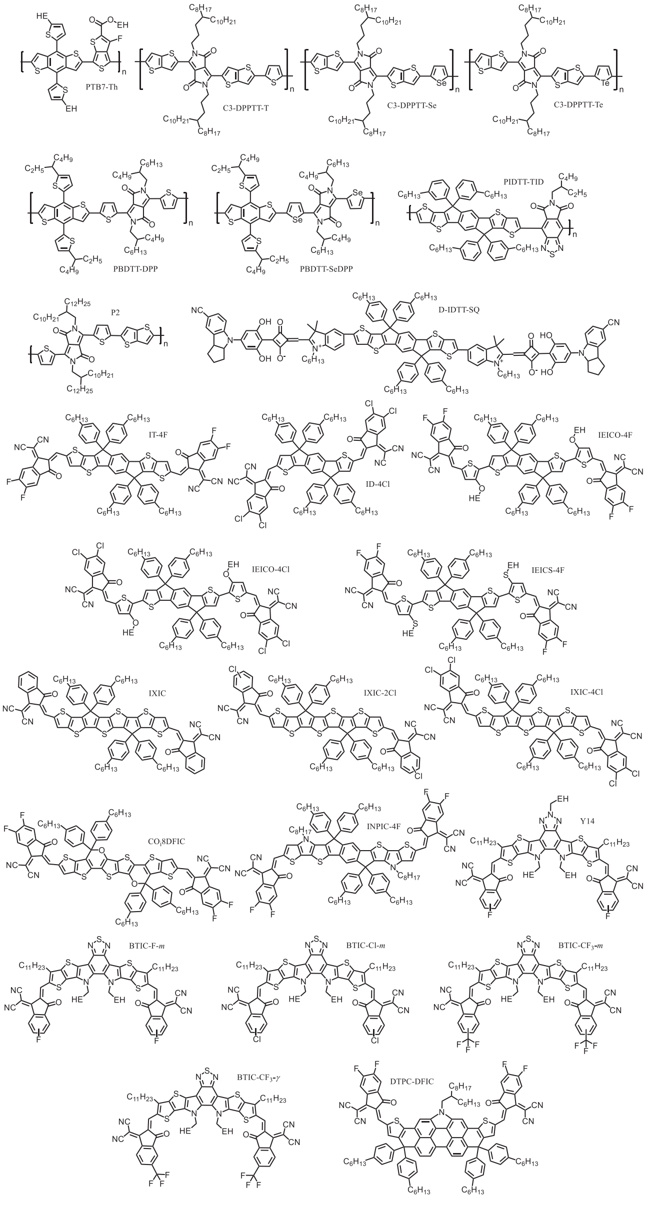

Figure 3. Chemical structures of various low bandgap donors and acceptors reported throughout the literature.[9–15] EH: Ethylhexyl.

In summary, three important design parameters result from the above consideration:

1. Active layer materials ideally show an absorption window between 1.13 to 1.77 eV
2. Charge transport layers and transparent electrodes should be transmitting the light in the range of 1.13 to 3.5 eV
3. Transparent electrodes have to replace opaque ones and current collectors are to be minimized in area

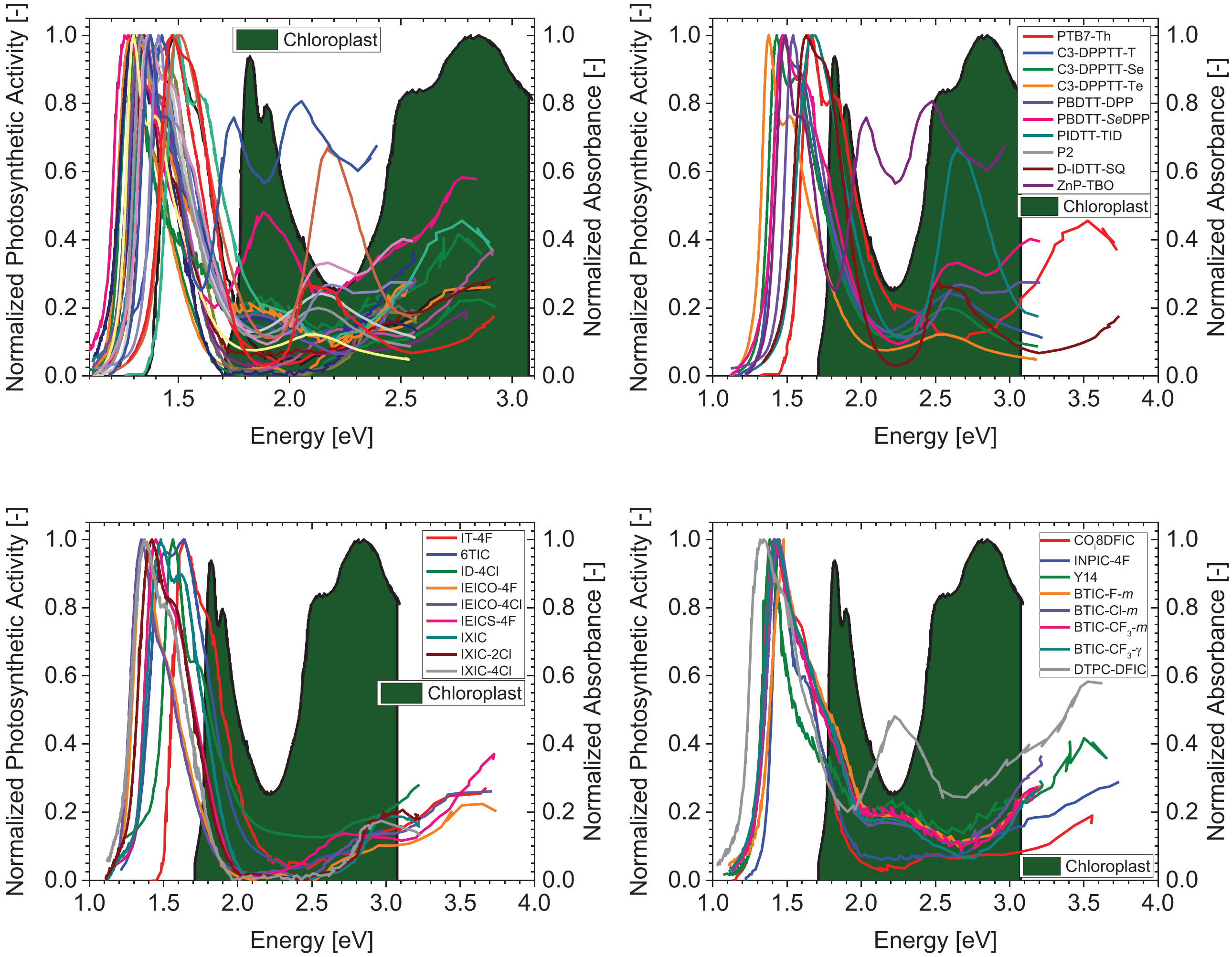

Figure 4. Photosynthetic action spectrum of a Chloroplast (dark green) and normalized absorbance spectra of different low bandgap donors and non-fullerene acceptors that are reported in the literature.[9–16]

4. Conclusion

In conclusion, employing OPV for agricultural greenhouses and polytunnels may be the key for a proper market development of this PV-technology, since all the properties—may it official be an advantage or disadvantage—of organic solar modules could be played outright: The device flexibility resulting from the low total thickness of the layer stack will enable its application in a similar way as polytunnels, being used today in agriculture. If the absorption range of such active layer materials is placed properly around those of the plants, the situation shifts from competition to synergism, as part of the energy provided by the photovoltaic system could be used to have better controlled humidity levels and temperatures inside greenhouses and polytunnels. Finally, such easy to install agrivoltaic units could contribute beyond the means of food production toward sustainable development in rural areas that suffer from aridity, by providing clean energy to the communities around.

Acknowledgements

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

agriculture, agrivoltaics, efficiency limit, organic photovoltaics, sustainability

Received: August 7, 2020
Revised: October 15, 2020
Published online: November 17, 2020

---

[1] a) NIH evaluation of CdTe, https://ntp.niehs.nih.gov/ntp/htdocs/chem_background/exsumpdf/cdte_508.pdf (accessed: September 2020); b) *MSDS Cadmium Telluride*, https://www.fishersci.com/store/msds?partNumber=AA1436703&productDescription=CADMIUM+TELLURIDE%2C+99.999%25+1G&vendorId=VN00024248&countryCode=US&language=en (accessed: September 2020);

c) *MSDS Hydrofluoric Acid*, https://www.nano.pitt.edu/sites/default/files/MSDS/Acids/Hydroflouric%20Acid.pdf (accessed: September 2020); d) *MSDS Arsine*, https://www.airgas.com/msds/001217.pdf (accessed: September 2020); e) *MSDS Phosphine*, https://produkte.linde-gas.at/sdb_konform/PH3_10021727EN.pdf (accessed: September 2020); f) *Phosphorous Oxychloride*, https://www.sigmaaldrich.com/MSDS/MSDS/DisplayMSDSPage.do?country=DE&language=EN-generic&productNumber=262099&brand=ALDRICH&PageToGoToURL=https%3A%2F%2Fwww.sigmaaldrich.com%2Fcatalog%2Fproduct%2Faldrich%2F262099%3Flang%3Dde (accessed: November 2020); g) N. Hadrup, A. K. Sharma, K. Loeschner, *Regul. Toxicol. Pharmacol.* **2018**, *98*, 257; h) Z. Ferdous, A. Nemmar, *Int. J. Mol. Sci.* **2020**, *21*, 2375.

[2] NREL Solar Cell Chart: https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20200925.pdf (accessed: May 2020).

[3] NREL Module Efficiency Chart: https://www.nrel.gov/pv/assets/pdfs/champion-module-efficiencies.20200708.pdf (accessed: May 2020).

[4] 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.

[5] a) E. H. Adeh, S. P. Good, M. Calaf, C. W. Higgins, *Sci. Rep.* **2019**, *9*, 11442; b) E. Hassanpour Adeh, J. S. Selker, C. W. Higgins, *PLoS One* **2018**, *13*, e0203256; c) www.agrophotovoltaik.de (accessed: May 2020).

[6] a) M. S. S. Rahman, M. K. Alam, *AIP Adv.* **2017**, *7*, 065101; b) T. Adrada Guerra, J. Amador Guerra, B. Orfao Tabernero, G. De La Cruz García, *Energies* **2017**, *10*, 772.

[7] C. Abel, *Counc. Tall Build. Urban Habitat* **2010**, *5*, 20.

[8] 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.

[9] R. S. Ashraf, I. Meager, M. Nikolka, M. Kirkus, M. Planells, B. C. Schroeder, S. Holliday, M. Hurhangee, C. B. Nielsen, H. Sirringhaus, I. Mcculloch, *J. Am. Chem. Soc.* **2015**, *137*, 1314.

[10] H. Yao, Y. Cui, R. Yu, B. Gao, H. Zhang, J. Hou, *Angew. Chem., Int. Ed.* **2017**, *56*, 3045.

[11] Y. Cui, C. Yang, H. Yao, J. Zhu, Y. Wang, G. Jia, F. Gao, J. Hou, *Adv. Mater.* **2017**, *29*, 1703080.

[12] Y. Chen, T. Liu, H. Hu, T. Ma, J. Y. L. Lai, J. Zhang, H. Ade, H. Yan, *Adv. Energy Mater.* **2018**, *8*, 1801203.

[13] M. Luo, C. Zhao, J. Yuan, J. Hai, F. Cai, Y. Hu, H. Peng, Y. Bai, Z. Tan, Y. Zou, *Mater. Chem. Front.* **2019**, *3*, 2483.

[14] Z. Yao, X. Liao, K. Gao, F. Lin, X. Xu, X. Shi, L. Zuo, F. Liu, Y. Chen, A. K.-Y. Jen, *J. Am. Chem. Soc.* **2018**, *140*, 2054.

[15] a) S. Chen, H. Yao, B. Hu, G. Zhang, L. Arunagiri, L.-K. Ma, J. Huang, J. Zhang, Z. Zhu, F. Bai, W. Ma, H. Yan, *Adv. Energy Mater.* **2018**, *8*, 1800529; b) H. Choi, S.-J. Ko, T. Kim, P.-O. Morin, B. Walker, B. H. Lee, M. Leclerc, J. Y. Kim, A. J. Heeger, *Adv. Mater.* **2015**, *27*, 3318; c) H. Lai, Q. Zhao, Z. Chen, H. Chen, P. Chao, Y. Zhu, Y. Lang, N. Zhen, D. Mo, Y. Zhang, F. He, *Joule* **2020**, *4*, 688; d) X. Li, H. Meng, F. Shen, D. Su, S. Huo, J. Shan, J. Huang, C. Zhan, *Dyes Pigm.* **2019**, *166*, 196; e) J. Sun, X. Ma, Z. Zhang, J. Yu, J. Zhou, X. Yin, L. Yang, R. Geng, R. Zhu, F. Zhang, W. Tang, *Adv. Mater.* **2018**, *30*, 1707150; f) C. Wang, X. Xu, W. Zhang, J. Bergqvist, Y. Xia, X. Meng, K. Bini, W. Ma, A. Yartsev, K. Vandewal, M. R. Andersson, O. Inganäs, M. Fahlman, E. Wang, *Adv. Energy Mater.* **2016**, *6*, 1600148; g) Z. Xiao, X. Jia, D. Li, S. Wang, X. Geng, F. Liu, J. Chen, S. Yang, T. P. Russell, L. Ding, *Sci. Bull.* **2017**, *62*, 1494; h) D. Yang, H. Sasabe, T. Sano, J. Kido, *ACS Energy Lett.* **2017**, *2*, 2021; i) L. Yang, S. Zhang, C. He, J. Zhang, Y. Yang, J. Zhu, Y. Cui, W. Zhao, H. Zhang, Y. Zhang, Z. Wei, J. Hou, *Chem. Mater.* **2018**, *30*, 2129; j) Y. M. Yang, W. Chen, L. Dou, W.-H. Chang, H.-S. Duan, B. Bob, G. Li, Y. Yang, *Nat. Photonics* **2015**, *9*, 190.

[16] S.-Y. Chang, P. Cheng, G. Li, Y. Yang, *Joule* **2018**, *2*, 1039.

Rico Meitzner is currently doing his Ph.D. in the group of Dr. Harald Hoppe at the Friedrich-Schiller-University Jena. His interests are in the stability and application of organic solar cells. He further focuses on the destruction-free characterization of organic semiconductor devices. Before he joined the group of Dr. Hoppe to do his Ph.D. he did research at the Fraunhofer Center for Silicon Photovoltaics in Halle on encapsulation materials for solar modules.

Ulrich S. Schubert studied chemistry in Frankfurt and Bayreuth (both Germany). His Ph.D. studies were performed at the Universities of Bayreuth and South Florida. After a post-doctoral training with J.-M. Lehn at the University of Strasbourg (France), he moved to the TU Munich (Germany) and obtained his Habilitation in 1999. During 2000–2007 he was Full-Professor at the TU Eindhoven (the Netherlands). Since 2007, he has been a Full-Professor at the Friedrich Schiller University Jena, Germany.

Harald Hoppe received his Ph.D. in 2004 from the Johannes-Kepler-University Linz, where he started his work in organic photovoltaics (OPV) by investigation of material and phase morphologies within organic bulk heterojunction blends and their impact on device properties. Thereafter he built up a research group at Ilmenau University of Technology. In 2015 he joined the Friedrich-Schiller-University of Jena at the Center for Energy and Environmental Chemistry Jena (CEEC Jena). His current research interests are materials and strategies for improved solution processing, device performance and long-term stability of OPV, as well as imaging methods for offline and inline inspection.