Title: Plextronics Final Report, DOE Contract DE-SC0003396

Introduction and Background:

Solar power based on photovoltaic (PV) technologies can address significant fraction of the world’s energy demand, provided it can be made cost-competitive with existing generation technologies. The incumbent silicon technology, though seeing adoption at commercial scales, has not proven to be grid-competitive in the absence of heavy subsidies. Based on inherently conducting polymers that can be printed like standard inks, OPV technology is a scalable, high throughput, low-cost process using ubiquitous materials solution which has the potential to provide low cost, renewable power.

OPV cell efficiencies have increased significantly over the last decade and verified champion efficiencies are currently at 8.3% for both single and multi-junction device types. These increases in efficiency have been driven through the development and optimization of the donor and acceptor materials in bulk heterojunction active layers. Plextronics and Solarmer Energy Inc. are two of the world leading developers of these donor and acceptor materials. Solarmer Energy has reported NREL certified 6.77% efficiencies using optimized low band gap donor materials in combination with PC$_{61}$BM and PC$_{71}$BM acceptors and recently reported a champion NREL certified efficiency of 8.1%. Plextronics has reported Newport certified efficiencies of 6.7% using PC$_{71}$BM acceptors with low band gap materials. In addition, Plextronics has also demonstrated that OPV efficiency of P3HT based materials can be improved by 50% by improving the Voc using alternative acceptors (indene substituted C$_{60}$ and C$_{70}$) to PC$_{61}$BM and PC$_{71}$BM. However, performance of these alternative acceptors in combination with low band gap materials has not been investigated and the potential for efficiency improvement is evident.

Utilizing the material expertise of both Solarmer and Plextronics, the goal of this project was to combine low band gap materials developed at Solarmer, which have demonstrated efficiencies >5% with PC$_{71}$BM, and with Plextronics’ indene substituted C$_{60}$ and C$_{70}$ acceptors to demonstrate OPV performance greater than 7%. This was to be accomplished primarily by improving the Voc as well as improving the current (Jsc) and FF. During the grant period, a combination was identified which produced 6.7% (internal measurement) with a Solarmer polymer and a Plextronics fullerene acceptor.

Materials selection & Experimental Design

To achieve efficiencies greater than 7%, donor and acceptor materials were chosen to modify the energy difference between the lowest unoccupied molecular orbital (LUMO) of the acceptor material and the highest occupied molecular orbital (HOMO) of the donor material.
Voc is directly related to the energy difference between LUMO of the acceptor and the HOMO of the donor. The strategy was to select Plextronics’ indene class acceptor materials with shallower LUMOs compared to PC₆₀BM and PC₇₁BM (depicted in Figure 1a) and Solarmer donor materials that simultaneously deepened the LUMO and HOMO (depicted in Figure 1b). The combination of thereof is believed to lead improvements in Jsc and Voc.

Figure 1. Energy diagram of Plextronics (a) & Solarmer’s (b) OPV technology. The LUMO(A) – HOMO (D) determines the Voc of the solar cells.

Both the Solarmer and Plextronics teams discussed the combination of energy levels need for both the donor and indene-class acceptor materials required to achieve >7% efficiencies and determined the following selection rules for the donor polymers:

- Has higher Jsc than P3HT when combined with PCBM
- Has efficiency higher than P3HT:PCBM, i.e., > 4%
- Voc < 0.7V (for sufficient exciton dissociation)
- Three polymers will be from two polymer families with different backbone structures

Initially, Solarmer Energy Inc. provided three polymers (codenamed Solarmer 7, 8, 9) to combine with the indene-class acceptors for device performance optimization. Two main indene class C₆₀ acceptors (codenamed Mono-indene[C60] Mono-indene[C60], Bis-indene[C60]) were screened with the Solarmer polymers. However, to help further understand device performance in these systems, a third acceptor, one based on C₇₀ (codenamed Bis-indene[C70]) was also screened with Solarmer 8. Polymers Solarmer 8 and 9 have the same backbones, but different side chain. These four polymers were screened and optimized with the indene class acceptors at both Plextronics and Solarmer. As the project progressed, two additional polymers (Solarmer 4, 10) were screened due to lower than expected performance from the initial polymer set with PC₇₁BM. Due to a limitation of material availability of Solarmer 4 and 10, device optimization with Solarmer 4 was only conducted at Plextronics and device optimization of Solarmer 10 was only conducted at Solarmer.

Summary of Results
Of the five Solarmer polymers and the three indene Plex acceptors tested, it was found that a combination of Solarmer 10 and Mono-indene[C60] Mono-indene[C60] resulted in an improved power conversion efficiency as compared with PC61BM. The best efficiency of OPV with Solarmer10:PC61BM yielded 6.1% efficiency; the optimized condition for Solarmer10:Mono-indene[C60] Mono-indene[C60] led to 6.7% power conversion efficiency. The following sections delineate the experimental design, process, and detailed results as well as a discussion on how to further improve polymer solar cell performance with these polymers and acceptors.

**Device Fabrication and Testing.**

Devices fabricated and tested at Solarmer had the following device structure:
Glass/ITO/PEDOT:PSS (Clevios 4083)/Polymer: Acceptor/Ca (25 nm)/Al (80 nm). The patterned ITO substrates (15 x 15 mm) were first cleaned through a series of detergent, de-ionized water, acetone, IPA cleaning processes. After drying, a ~ 40 nm of PEDOT:PSS was spin coated onto the substrates followed by drying in air at 120°C and then transferred to glovebox for active layer coating.

Devices fabricated and tested at Plextronics had the following devices structure:
Glass/ITO/PEDOT:PSS (Clevios 4083) or Plexcore OC/Polymer: Acceptor/Ca (20 nm)/Al (200 nm). The patterned ITO substrates (15 x 15 mm) were first cleaned through a series of detergent, de-ionized water, acetone, IPA cleaning processes. After drying, a ~ 40 nm of PEDOT:PSS or 40nm of Plexcore OC was spin coated onto the substrates followed by drying in air at 120°C and then transferred to glovebox for active layer coating.

Active layer optimization occurred independently at both Solarmer and Plextronics. At each location, the solvent system including additives, donor acceptor weight ratio, total solids, and solution/film processing conditions were varied to find the optimal conditions to achieve the highest device performance.

The active layer solution was spin coated onto the ITO/PEDOT:PSS or ITO/Plexcore OC substrates to a target thickness of ~80nm. The metal electrodes were evaporated (10^-6 Torr). The device active area was 0.1 cm², measured by microscope.

At Solarmer, a Newport 12” x 12” xenon solar simulator with AM1.5G filter was used to measure the device performance. At Plextronics a xenon light source, also made by Newport, was used to measure the device performance. The light intensity for both solar simulators was calibrated using an NREL certified KG-5 filtered mono-silicon photo-detector. To ensure reproducibility of the device performance, Solarmer’s KG-5 filtered mono-silicon photo-detector was sent to Plextronics to verify the Isc and Voc response of the detector. A spectral mismatch of ~0.96 was calculated for Solarmer 7 and 10 and ~0.93 for Solarmer 8 and 9 using the EQE spectral response of device measured at Solarmer.

For each device fabricated at Plextronics, the UV-VIS absorption profile, EQE spectral response and optical micrograph of the active layers was acquired to determine the spectral and optical response of each donor and acceptor blend as well as characterize the film uniformity, respectively. In addition, the morphological characteristics of each active layer were measured at Plextronics using atomic force microscopy (AFM).

**Results:**

1. **Device Performance of Solarmer 7 with Plextronics Acceptors**
Solarmer 7 was first synthesized prior to the start of this project and found to achieve a 5% power conversion efficiency (PCE) with PC$_{71}$BM. This device had a Jsc of 13.8 mA/cm$^2$, a Voc of 0.56V, and a fill factor of 64%. Given the promising results, a second batch of Solarmer 7 was synthesized and used for testing at Solarmer and Plextronics. Solarmer 7 was independently tested in blends of PC$_{71}$BM, Bis-indene[C60], and Mono-indene[C60] at both locations. Table 1 and Figure 2 shows a summary of the comparison of champion solar cell performance and the J-V characteristics of these devices achieved using Solarmer 7 with PC$_{71}$BM, Bis-indene[C60] and Mono-indene[C60] at Solarmer (S) and Plextronics (P).

**Table 1.** Device performance of OPV devices fabricated at Solarmer (S) and Plextronics (P) comprised of Solarmer 7 and PC$_{71}$BM, Bis-indene[C60] Bis-indene[C60], and Mono-indene[C60].

<table>
<thead>
<tr>
<th></th>
<th>Voc (V)</th>
<th>Jsc (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>P</td>
<td>S*</td>
<td>P</td>
</tr>
<tr>
<td>Solarmer 7: PC$_{71}$BM</td>
<td>0.60</td>
<td>0.68</td>
<td>11.3</td>
<td>7.10</td>
</tr>
<tr>
<td>Solarmer 7: Bis-indene[C60]</td>
<td>0.82</td>
<td>0.86</td>
<td>8.95</td>
<td>5.87</td>
</tr>
<tr>
<td>Solarmer 7: Mono-indene[C60]</td>
<td>0.70</td>
<td>0.72</td>
<td>7.10</td>
<td>5.48</td>
</tr>
</tbody>
</table>

$*$ Jsc has been adjusted for spectral mismatch.

Figure 2. J-V curves of the champion OPV devices fabricated with Solarmer 7 and PC$_{71}$BM, Bis-indene[C60] and Mono-indene[C60] at Solarmer (a) and Plextronics (b).

Comparison of the device results obtained at Solarmer and Plextronics show good agreement in Voc and FF. Unlike the first batch of Solarmer 7, the highest PCE% achieved with PC$_{71}$BM was only 3.3%. This was unexpected and attributed to differences in the polymer physical characteristics as a result of synthetic batch variations. As a result of the lower than expected performance of Solarmer 7, minimal optimization with this material was carried out with work focusing instead on the higher performing polymer/acceptor blends.
As expected, the Voc for devices fabricated with Bis-indene[C60] and Mono-indene[C60] were higher compared to PC$_{71}$BM as a result of the LUMO offsets of the Bis-indene[C60] and Mono-indene[C60] acceptors relative to PC$_{71}$BM. For the devices fabricated at Plextronics, no difference was observed in the performance of the devices screened with either PEDOT:SS or Plexcore HIL. In general, the Jsc obtained from the blends fabricated at Plextronics were slightly lower than those fabricated at Solarmer. The lower Jsc is attributed to unoptimized processing conditions needed to maximize the nanoscale morphology to achieve the best charge transport for these blends.

Overall, devices fabricated with Solarmer 7 with Bis-indene[C60] and Mono-indene[C60] did not perform as well as blends of Solarmer 7 and worse for the Solarmer 7:Mono-indene[C60] blends. The lower than expected performance is attributed mainly to solubility issues of Mono-indene[C60] with Solarmer 7 which resulted in macroscale aggregates visible in the optical micrographs. These aggregates can be observed in Figure 3 as compared to the more uniform films of devices fabricated with Solarmer 7 and PC$_{71}$BM and Bis-indene[C60] .

![Figure 3](image)

**Figure 3.** Optical micrographs of devices films of A Solarmer 7: PC$_{71}$BM (fabricated at Plextronics), B. Solarmer 7: Bis-indene[C60] (fabricated at Plextronics), C. Solarmer 7: Mono-indene[C60] (fabricated at Solarmer), D. Solarmer 7: Mono-indene[C60] (fabricated at Plextronics).

Although the films of Solarmer 7: PC$_{71}$BM and Solarmer 7: Bis-indene[C60] show uniform film qualities in the optical micrographs, AFM phase images reveal that the nanoscale morphology is not ideal. In Figure 4, films of Solarmer 7: PC$_{71}$BM reveal large, rough domains comprised of finely mixed phases. Films of Solarmer 7: Bis-indene[C60] reveal smaller domains comprised of phase separated elements.
Despite the lower than expected performance of Solarmer 7 with PC$_71$BM, the advantages that the Bis-indene[C60] and Mono-indene[C60] acceptors provide through Voc enhancement indicate that combinations of Solarmer donor polymers and Plextronics’ acceptors have the potential to have a 50% enhancement in the overall PCE%.

2. Device Performance of Solarmer 8 with Plextronics Acceptors

The second polymer used to achieve the goals of this project was Solarmer 8 which had a different backbone compared to Solarmer 7. Solarmer 8 has a band gap of ~1.5eV and yields an absorption profile beyond 800 nm. Like Solarmer 7, Solarmer 8 was independently tested in blends of PC$_71$BM, Bis-indene[C60] and Mono-indene[C60] at both Plextronics and Solarmer. In addition, a third acceptor, Bis-indene[C70], a C$_70$–based analogue of Bis-indene[C60] was also blended with Solarmer 8 to test the hypothesis that the decreased absorption in the 500-700nm region as a result of using C$_{60}$ derivatives resulted in lower than expected performance.

Table 2 summarizes the champion solar cell performance of these devices achieved at Solarmer (S) and Plextronics (P).

<table>
<thead>
<tr>
<th></th>
<th>Voc (V)</th>
<th>J$_{sc}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>P</td>
<td>S</td>
<td>P</td>
</tr>
<tr>
<td>Solarmer 8: PC$_71$BM</td>
<td>0.68</td>
<td>0.68</td>
<td>11.88</td>
<td>11.15</td>
</tr>
<tr>
<td>Solarmer 8: Bis-indene[C60]</td>
<td>0.91</td>
<td>0.90</td>
<td>7.19</td>
<td>6.97</td>
</tr>
<tr>
<td>Solarmer 8: Mono-indene[C60]</td>
<td>0.70</td>
<td>0.70</td>
<td>9.74</td>
<td>9.74</td>
</tr>
<tr>
<td>Solarmer 8: Bis-indene[C70]</td>
<td>---*</td>
<td>0.90</td>
<td>---*</td>
<td>3.74</td>
</tr>
</tbody>
</table>

* Due to limitation of material availability, Bis-indene[C70] was only screened at Plextronics.
Consistent with the Solarmer 7 experiments, device results obtained at Solarmer and Plextronics show good agreement between the two locations. As expected, the Voc for devices fabricated with Bis-indene[60] was higher (~0.2V) compared to PC_{71}BM as a result of the LUMO offsets of the Bis-indene[60] acceptors relative to PC_{71}BM. The Voc enhancement with Mono-indene[60], however, is small (0.02v) compared to devices made with Mono-indene[60] Solarmer 7:Mono-indene[60] (0.1v). Although the Voc offset achieved was expected based on the material properties of the donor and acceptor components, the Jsc and FF were much less than what was achieved PC_{71}BM. To understand the reduction in Jsc, the external quantum efficiency (EQE) spectra of Solarmer 8 with each acceptor was measured with devices made at each location and compared, shown in Figure 5.

![Figure 5](image)

**Figure 5.** External quantum efficiency (EQE) spectra from OPV devices using Solarmer 8 with PC_{71}BM, Jalapano and Mono-indene[60] made at Solarmer (a) and Plextronics (b). The grey regions delineated in each spectra highlight the key region of spectra difference that could potentially lead to lower Jsc.

It can be seen from the integrated area under the EQE spectra that PC_{71}BM indeed yields an overall higher Jsc, mainly due to increased absorption in the 400-600nm region (highlighted in grey) from the C_{70} component of PC_{71}BM. To test the hypothesis that the main reason lower Jsc was achieved with Mono-indene[60] and Bis-indene[60] was due to the C60 component of the respective acceptors, a third acceptor, Bis-indene[C70] was tested with Solarmer 8. In Table 2, it can be seen that even lower Jsc was achieved with this acceptor.

In Figure 6, the EQE of Bis-indene[60] and Bis-indene[C70] are compared to PC_{71}BM. As expected, more relative absorption in the 400-600nm spectra range is observed with Bis-indene[C70] compared to Bis-indene[60]. However, the overall EQE is lower for Bis-indene[C70], consistent with the lower device Jsc. This result suggests that simple substitution with the C_{70} version of Bis-indene[60] (a broader absorption profile) depends critically on the self-assembly of the donor and acceptor components and their relation to transport properties, which is not a well founded issue with the C_{60} indene-based acceptors. To further illustrate this point, Figure 5 shows that, in the 600-800nm region, it can be seen that Mono-indene[60] actually outperforms PC_{71}BM.
No further optimization of Solarmer 8 with Plextronics acceptors was conducted since the highest efficiency (4.35% with PC$_{71}$BM) is still far from the 7% target of this project. Moreover, since the third preselected donor polymer, Solarmer 9, belongs to the same family as Solarmer 8, but had even lower efficiency when tested with PC$_{71}$BM, optimization with Solarmer 9 was omitted and instead two additional polymers, Solarmer 4 and Solarmer 10, which come from a similar polymer family as Solarmer 7 were screened in its place.

![Figure 6. External quantum efficiency (EQE) spectra from OPV devices using Solarmer 8 and Bis-indene[C$_{70}$]. These spectra are compared to PC$_{71}$BM and Bis-indene[C$_{60}$]. The grey region highlights the key spectral differences that could potentially lead to lower Jsc as a result of the different absorptions of C$_{70}$ and C$_{60}$ components.](image)

### 3. Device Performance of Solarmer 4 with Plextronics Acceptors

Device performance optimization with Solarmer 4 and Plextronics acceptors was carried out at Plextronics. Solarmer 4 was selected from the same polymer family as Solarmer 7; Table 3 and Figure 7 show a summary of the comparison of champion solar cell performance and the J-V characteristics of these devices achieved using Solarmer 4 with PC$_{71}$BM, Bis-indene[C$_{60}$] and Mono-indene[C$_{60}$].

<table>
<thead>
<tr>
<th>Solarmer 4: PC$_{71}$BM</th>
<th>Voc (V)</th>
<th>Jsc (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.72</td>
<td>14.1</td>
<td>63.0</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Solarmer 4: Bis-indene[C$_{60}$]</td>
<td>0.92</td>
<td>8.8</td>
<td>46.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Solarmer 4: Mono-indene[C$_{60}$]</td>
<td>0.80</td>
<td>6.3</td>
<td>46.0</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Similar to Solarmer 7 and Solarmer 8, the Voc for devices fabricated with Bis-indene[C60] and Mono-indene[C60] were higher compared to PC$_{71}$BM as a result of the LUMO offsets of the Bis-indene[C60] and Mono-indene[C60] acceptors relative to PC$_{71}$BM. Unlike Solarmer 7 and Solarmer 8, devices optimized with Bis-indene[C60] were observed to have a higher current than those with Mono-indene[C60]. Reverse bias measurements of the Solarmer 4:Bis-indene[C60] devices indicate that 13 mA/cm$^2$ of current can be extracted. This suggests that if the morphology of the films could be improved, Bis-indene[C60] has the potential to outperform Mono-indene[C60] and PC$_{71}$BM.

Comparison of the EQE spectra of Mono-indene[C60] and Bis-indene[C60] to the UV-VIS spectra (Figure 8) reveals that the EQE is flatter than UV-VIS spectrum. The reason is currently not understood but may be related to electro-optical differences in the blend photophysics, which could be further modulated by unknown differences in morphology.
Figure 8. EQE spectra (A) and optical absorbance (B) from OPV devices using Solarmer 4 and PC$_{71}$BM, Bis-indene[C$_{60}$] and Mono-indene[C$_{60}$].

4. Device Performance of Solarmer 10 with Plextronics Acceptors

Device performance optimization with Solarmer 4 and Plextronics acceptors was carried out at Plextronics. Solarmer 10 was selected from the same polymer family as Solarmer 7. To understand the relative performance of the C60 acceptors (Bis-indene[C$_{60}$] and Mono-indene[C$_{60}$]) with respect to PC$_{71}$BM, PC$_{61}$BM was also included for comparison. Table 4 and Figure 9 show a summary of the comparison of champion solar cell performance and the J-V characteristics of these devices achieved using Solarmer 10 with PC$_{71}$BM, PC$_{61}$BM, Bis-indene[C$_{60}$] and Mono-indene[C$_{60}$].

<table>
<thead>
<tr>
<th></th>
<th>VOC (V)</th>
<th>JSC (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solarmer 10: PC$_{71}$BM</td>
<td>0.70</td>
<td>15.7</td>
<td>65.6</td>
<td>7.2</td>
</tr>
<tr>
<td>Solarmer 10: PC$_{61}$BM</td>
<td>0.73</td>
<td>13.7</td>
<td>60.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Solarmer 10: Bis-indene[C$_{60}$]</td>
<td>0.90</td>
<td>11.2</td>
<td>52.2</td>
<td>5.3</td>
</tr>
<tr>
<td>Solarmer 10: Mono-indene[C$_{60}$]</td>
<td>0.76</td>
<td>13.8</td>
<td>63.6</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Consistent with the results from the previous three polymers studied, devices made with Bis-indene[C$_{60}$] showed an increase in Voc. However, despite the increase in Voc, the Jsc and FF could not be optimized to the same values as PC$_{71}$BM, PC$_{61}$BM or Mono-indene[C$_{60}$]. In the case of Mono-indene[C$_{60}$], it was found that a different donor acceptor ratio was necessary to achieve an optimized performance compared to the other acceptors. This is attributed to the solubility of Mono-indene[C$_{60}$] in the main solvent of choice, chlorobenzene. When the concentration of the blend solution was reduced, an improvement in Voc of 0.06 and 0.03V
compared to PC$_{71}$BM and PC$_{61}$BM, respectively, was observed. The fill factor improved from 60.0% to 63.6% for Mono-indene[C60] in comparison to PC$_{61}$BM and the same Jsc (13.7 vs. 13.8 mA/cm$^2$) was achieved in comparison to PC$_{61}$BM.

Figure 9. J-V curves of the champion OPV devices fabricated with Solarmer 10 and PC$_{71}$BM, Bis-indene[C60] and Mono-indene[C60] at Solarmer.

The results with Mono-indene[C60] and Solarmer 10 are encouraging and indicate that it’s possible to combine low bandgap polymers with tuned LUMO acceptors to improve OPV efficiency, through concurrent enhancement of both photocurrent and photovoltage. Bis-indene[C60] did not result in improved performance compared to PC$_{61}$BM or PC$_{71}$BM. The rationale behind this is not fully understood but could be a result of the LUMO level being too shallow such that the driving force for exciton dissociation becomes weaker, which leads to reduced charge separation and thus lower photocurrent. On the other hand, Mono-indene[C60] raises the LUMO by a smaller amount, which gives smaller Voc and PCE than Bis-indene[C60] when mixed with P3HT case, but this seems to have a more suitable energy level for the low bandgap polymer case to be able to retain the photo-current while improve the photovoltage, and thus the overall PCE.

Besides the selection of matched energy levels to drive exiton dissociation, the quality of the photoactive layer film turns out to be very important for the material combination to be successful. Through improvements in ink formulation and processing conditions, such as was seen in the case of Mono-indene[C60], an improvement in the homogeneity and morphology of the active layer film is observed and is believed to significantly improve the solar cell efficiency.

Conclusions and Future Work

In conclusion, it has been found that by combining donor polymers designed to have the potential to reach 7% with PC$_{71}$BM that nearly 7% PCE can be achieved when mixed with Plextronics acceptors. To achieve efficiency beyond the 7% goal of this project by combining
Plextronics acceptors with Solarmer donor polymers, the following three approaches are suggested as the basis of future work:

1. **Donor Modification** - Solarmer has independently developed new polymers with increased absorption profiles which yield OPV cell efficiency over 8% when combined with PC$_{71}$BM. Since three of the polymers selected for this study did not demonstrate PCE% greater than 5% with PC$_{71}$BM, a larger initial selection of high efficiency polymers materials would be expected to yield even higher efficiencies when combined with Plextronics acceptors. It is expected that the approach taken in the current proposal could lead to 9-10% OPV efficiency is used with these materials.

2. **Acceptor modification** – Increasing and broadening the absorption profile of the polymer:fullerene blends through the replacement of C60 with C70 in the molecular structure of Mono-indene[C60] could further enhance the absorption, and thus the EQE, in the short wavelength range. As see in Figure 5, devices made with Mono-indene[C60] yield a higher EQE in the 650 – 720 nm range compared to the higher performing PC$_{71}$BM device. However, a lower EQE 400-600nn range leads to a overall lower Jsc and PCE. A C70 based Mono-indene[C60] holds the promise to have 10% PCE enhancement over polymer: PC$_{71}$BM device, which could yield an 8% device.

3. **Morphology & Interface engineering** – Mono-indene[C60] mixed with P3HT yields a larger Voc enhancement than with Solarmer 10 (~0.1 v vs. 0.02v). If the same Voc enhancement was achieved using the Solarmer materials, 8% efficiency could also be achieved. It is expected that the ink formulation, morphology control and interface engineering will maximize the benefit of this combined polymer/acceptor system.

4. **Much remains unknown about the design rules involving polymer/fullerene BHJ blends for OPV, this work is a great start to understand the key measureable features of BHJ blends and their material-property-device relationships.**