Electronic Supplementary Material (ESI) for Energy & Environmental Science


# Supplementary Information

# Large scale deployment of polymer solar cells on land, on sea and in the air

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## 1. Life cycle energy analysis

The inventory of input materials to manufacture one square meter of solar cells is gathered in Table S1. For the same functional unit in Table S2 and Table S3 is presented the Cumulative Energy Demand data to plot Figure 7 in the paper, representing the energy embedded in the materials (Figure 7 left) and the energy needing for the manufacturing (Figure 7 right).

**Table S 1. Life cycle inventory for OPV modules manufactured under Ione process, per FU – 1m$^2$.**

| Input materials and inks | Amount (g) |
|---|---|
| Substrate | 90.21 |
| Front Silver ink | 0.59 |
| Front PEDOT:PSS | 7.56 |
| Isopropanol | 3.91 |
| ZnO np | 0.20 |
| KOH | 0.29 |
| Methanol | 1.94 |
| Acetone | 3.89 |
| MEA | 0.06 |
| P3HT | 0.09 |
| PCBM | 0.08 |
| Chlorobenzene | 7.28 |
| Back PEDOT:PSS | 8.2 |
| Back Silver | 6.56 |
| UV adhesive | 17.91 |
| Barrier | 79.86 |

**Table S 2. Corresponding data to Figure 7 left in the paper.**

| Layer | Value ($MJ_{EPE}$) |
|---|---|
| Barrier | 6.448 |
| UV adhesive | 3.592 |
| Silver ink | 6.918 |
| PEDOT:PSS | 1.307 |
| Active layer | 1.497 |
| Flextrode | |
| Substrate | 7.285 |
| Silver | 0.531 |
| PEDOT:PSS | 1.206 |
| ZnO | 0.419 |

**Table S 3. Corresponding data to Figure 7 right in the paper.**

| Manufacturing Step | Direct Process Energy ($MJ_{EPE}$) |
|---|---|
| S1 Front electr., silver (Flexo) | 0.657 |
| S2 Front electr., PEDOT:PSS (RSP) | 0.573 |
| S3 ZnO layer (SD) | 0.732 |
| S4 Active layer (SD) | 2.709 |
| S5 Back electr., PEDOT:PSS (RSP) | 4.299 |
| S6 Back electr., silver (RSP) | 1.467 |
| S7 Encapsulation (R2R) | 2.529 |

The breakdown data of cumulative energy demand required for every component in the balance of system of each installation (in percentages) are shown in Table S4.

**Table S 4. Corresponding data to Figure 8 in the paper.**

| Category | Support/structure | Inverter | Cabling | Others (wagon, helium) | Modules |
|---|---|---|---|---|---|
| Park | 55.57 | 0.62 | 0.08 | 0.89 | 42.83 |
| Onshore | 48.18 | 0.74 | 0.3 | - | 50.78 |
| Offshore | 51.47 | 0.69 | 0.69 | - | 47.16 |
| Balloon | 47.03 | 3.55 | 6.1 | 21.12 | 22.20 |

Data to plot the energy payback time in years for the onshore tube installation, based on real energy produced and fed into the Danish electricity grid, shown in Table S5.

**Table S 5. Corresponding data to Figure 9 in the paper.**

| Egen kWh=Days | Egen MJ | EPBT |
|---|---|---|
| 1 | 10.29 | 406.94 |
| 31 | 318.86 | 13.13 |
| 61 | 627.43 | 6.67 |
| 91 | 936.00 | 4.47 |
| 121 | 1244.57 | 3.36 |
| 151 | 1553.14 | 2.69 |
| 181 | 1861.71 | 2.25 |
| 211 | 2170.29 | 1.93 |
| 241 | 2478.86 | 1.69 |
| 271 | 2787.43 | 1.50 |
| 301 | 3096.00 | 1.35 |
| 331 | 3404.57 | 1.23 |
| 365 | 3754.29 | 1.11 |
| 455 | 4680.00 | 0.89 |
| 545 | 5605.71 | 0.75 |
| 635 | 6531.43 | 0.64 |
| 725 | 7457.14 | 0.56 |
| 815 | 8382.86 | 0.50 |

## 2. Life cycle impact assessment

For the environmental assessment performed in section 4.2.2. in the paper, we have followed CML, ReCiPe and GHG methods, data corresponding to the Figures 10, 11 and 12 in the paper, data are listed in the following tables from Table S6 to Table S10.

In accordance with EN ISO 14044, normalisation is the calculation of the magnitude of the category indicator results relative to reference information, while weighting is a method in which the (normalised) indicator results for each impact category assessed are assigned to numerical factors according to their relative importance, multiplied by these factors and possibly aggregated.

When ReCiPe method is used, used, the metric of the impacts is given in the dimensionless unit Pt, obtained by weighting all the impact loads. World H/H refers to the normalisation values of the world with the weighting set belonging to the hierarchist perspective in the ReCiPe hierarchist version. This version is a consensus model, as often encountered in scientific models, this is often considered to be the default model. Human health has a weighting value of 300 DALY, ecosystems of 400 species/yr and resources 300 $.

In the case of CML methodology it is an inherent characteristic of this particular method to present the scores normalized. For each baseline indicator, normalisation scores are calculated for three reference situations: the world in 1990, Europe in 1995 and the Netherlands in 1997. Normalisation data are described in the report: Huijbregts et al LCA normalisation data for the Netherlands (1997/1998), Western Europe (1995) and the World (1990 and 1995) – citation 29 in the paper. The normalized result for a given impact category and region is then obtained by multiplying the characterisation factors by their respective emissions. The sum of these products in every impact category gives the normalization factor.

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**Table S 6. Corresponding data to Figure 10 - top - in the paper.**

| Category | PET film | Silver | Isopropanol | Solvent silver ink | P3HT:PCBM | o-dichlorobenzene | ZnO | PEDOT:PSS | Potassium hydroxide | Methanol | Acetone | UV adhesive | MEA | Electricity mix / DK U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Climate change Human Health | 2.91E-02 | 1.76E-02 | 1.45E-04 | 1.46E-04 | 5.31E-03 | 4.69E-04 | 1.81E-05 | 5.69E-03 | 1.79E-05 | 4.88E-05 | 1.44E-04 | 3.78E-03 | 4.75E-06 | 2.22E-02 |
| Human toxicity | 2.36E-05 | 1.55E-01 | 9.88E-06 | 1.88E-05 | 4.61E-04 | 1.17E-04 | 1.65E-06 | 4.18E-04 | 4.37E-06 | 2.58E-06 | 1.79E-05 | 1.97E-04 | 6.79E-07 | 2.56E-03 |
| Photochemical oxidant formation | 1.94E-06 | 5.61E-06 | 1.71E-08 | 2.11E-08 | 2.40E-07 | 7.93E-08 | 6.13E-10 | 2.56E-07 | 1.13E-09 | 3.69E-09 | 1.92E-08 | 6.68E-07 | 4.66E-10 | 9.31E-07 |
| Particulate matter formation | 7.68E-03 | 2.16E-02 | 3.00E-05 | 4.21E-05 | 7.80E-04 | 1.05E-04 | 1.31E-06 | 8.14E-04 | 3.92E-06 | 6.82E-06 | 2.80E-05 | 2.27E-03 | 9.55E-07 | 3.32E-03 |
| Ionising radiation | 0 | 2.56E-05 | 1.15E-07 | 2.73E-07 | 1.12E-05 | 1.55E-06 | 1.46E-08 | 1.06E-05 | 9.46E-08 | 4.36E-08 | 2.50E-07 | 1.73E-08 | 1.08E-08 | 3.51E-05 |
| Climate change Ecosystems | 3.44E-03 | 2.09E-03 | 1.72E-05 | 1.73E-05 | 6.29E-04 | 5.55E-05 | 2.14E-06 | 6.73E-04 | 2.12E-06 | 5.78E-06 | 1.71E-05 | 4.47E-04 | 5.62E-07 | 2.62E-03 |
| Agricultural land occupation | 0 | 5.57E-05 | 1.96E-07 | 2.75E-05 | 5.35E-06 | 1.23E-06 | 1.98E-08 | 6.04E-06 | 6.02E-08 | 1.56E-08 | 3.37E-07 | 2.20E-07 | 1.10E-08 | 1.47E-04 |
| Urban land occupation | 0 | 2.63E-04 | 8.08E-08 | 5.21E-07 | 2.91E-06 | 4.51E-07 | 1.04E-08 | 3.10E-06 | 5.59E-08 | 5.00E-08 | 1.55E-07 | 1.44E-07 | 5.20E-09 | 3.08E-05 |
| Metal depletion | 6.59E-08 | 1.35E-03 | 1.66E-07 | 2.55E-07 | 8.93E-07 | 8.32E-07 | 1.48E-08 | 8.08E-07 | 3.54E-08 | 3.49E-08 | 2.48E-07 | 1.44E-07 | 7.86E-09 | 5.32E-06 |
| Fossil depletion | 8.88E-02 | 3.61E-02 | 7.86E-04 | 6.02E-04 | 1.30E-02 | 2.03E-03 | 5.13E-05 | 1.40E-02 | 4.09E-05 | 3.85E-04 | 9.07E-04 | 1.14E-02 | 1.92E-05 | 4.71E-02 |

**Table S 7. Corresponding Data to Figure 10 bottom in the paper.**

| Category | PET film (production only) E | Silver, at regional storage/RER U | Isopropanol, at plant/RER U | Alkyd resin, long oil, 70% in white spirit, at plant/RER U | P3HT:PCBM | O-dichlorobenzene, at plant/RER U | Zinc oxide, at plant/RER U | PEDOT:PSS | Potassium hydroxide, at regional storage/RER U | Methanol, at regional storage/CH U | Acetone from butane, at plant/RER U | Epoxy resin, liquid, at plant/RER U | Acetic acid from acetaldehyde, at plant/RER U | Electricity mix/DK U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abiotic depletion | 4.89E-14 | 1.16E-13 | 1.29E-15 | 2.78E-16 | 8.11E-15 | 1.19E-15 | 5.2E-17 | 7.99E-15 | 4.43E-17 | 3.8E-16 | 8.43E-16 | 3.76E-17 | 2.62E-15 | 2.63E-14 |
| Acidification | 1.09E-14 | 3.08E-14 | 1.74E-16 | 6.04E-17 | 1.52E-15 | 1.92E-16 | 3.61E-18 | 1.45E-15 | 1.12E-17 | 1.95E-17 | 7.63E-17 | 1.25E-17 | 3.76E-16 | 4.17E-15 |
| Eutrophication | 1.66E-15 | 9.78E-14 | 2.33E-16 | 1.01E-16 | 1.15E-15 | 5.85E-16 | 3.38E-18 | 9.68E-16 | 1.54E-17 | 1.3E-17 | 6.84E-17 | 4.99E-18 | 3.68E-16 | 4.34E-15 |
| Global warming (GWP100) | 1.87E-14 | 1.02E-14 | 3.04E-16 | 8.46E-17 | 3.84E-15 | 3.37E-16 | 2.22E-17 | 3.76E-15 | 2.11E-17 | 5.84E-17 | 1.72E-16 | 1.51E-17 | 7.94E-16 | 1.2E-14 |
| Human toxicity | 9.91E-15 | 1.3E-13 | 6.35E-17 | 3.2E-17 | 6.92E-16 | 2.0E-14 | 4.72E-18 | 6.35E-16 | 9.38E-18 | 1.0E-17 | 6.12E-17 | 8.19E-19 | 2.53E-16 | 1.75E-15 |
| Terrestrial ecotoxicity | 6.42E-16 | 5.78E-14 | 1.03E-16 | 7.13E-17 | 9.81E-16 | 4.56E-16 | 9.95E-18 | 6.92E-16 | 1.23E-17 | 1.25E-17 | 7.53E-17 | 1.1E-17 | 3.23E-16 | 1.99E-15 |
| Photochemical oxidation | 1.86E-15 | 3.35E-15 | 1.43E-16 | 1.04E-17 | 2.36E-16 | 3.01E-16 | 7.78E-19 | 2.28E-16 | 1.55E-18 | 8.49E-18 | 4.29E-17 | 1.12E-18 | 2.21E-16 | 6.03E-16 |
| Ozone layer depletion (ODP) | 0 | 2.97E-17 | 4.64E-19 | 4.35E-19 | 1.34E-17 | 9.61E-18 | 9.95E-20 | 1.33E-17 | 6.07E-20 | 4.13E-19 | 3.02E-18 | 1.1E-22 | 1.36E-18 | 1.96E-17 |

**Table S 8. Corresponding data to Figure 11 left in the paper.**

| Category | Park | Offshore | Onshore | Balloon |
|---|---|---|---|---|
| Climate change | 0.1341 | 0.1125 | 0.1121 | 0.108 |
| Human toxicity | 0.1367 | 0.1327 | 0.1327 | 0.1295 |
| Photochemical oxidant formation | 1.28E-05 | 1.29E-05 | 1.29E-05 | 1.23E-05 |
| Particulate matter formation | 0.049 | 0.0385 | 0.0383 | 0.037 |
| Ionising radiation | 0.0001 | 8.44E-05 | 8.44E-05 | 7.9E-05 |
| Climate change Ecosystems | 0.0159 | 0.0133 | 0.0133 | 0.0128 |
| Agricultural land occupation | 0.0212 | 0.0002 | 0.0002 | 0.0002 |
| Urban land occupation | 0.0007 | 0.0003 | 0.0003 | 0.0002 |
| Metal depletion | 0.0014 | 0.0012 | 0.0012 | 0.0012 |
| Fossil depletion | 0.3737 | 0.411 | 0.4098 | 0.3882 |

**Table S 9. Corresponding data to Figure 11 right in the paper.**

| Category | Park | Offshore | Onshore | Balloon |
|---|---|---|---|---|
| Abiotic depletion | 3.34E-13 | 3.45E-13 | 3.45E-13 | 3.32E-13 |
| Acidification | 7.97E-14 | 6.71E-14 | 6.69E-14 | 6.48E-14 |
| Eutrophication | 1.22E-13 | 1.16E-13 | 1.16E-13 | 1.13E-13 |
| Global warming (GWP100) | 9.64E-14 | 8.08E-14 | 8.05E-14 | 7.76E-14 |
| Ozone layer depletion (ODP) | 1.16E-16 | 9.74E-17 | 9.72E-17 | 9.53E-17 |
| Human toxicity | 2.41E-13 | 1.74E-13 | 1.74E-13 | 1.7E-13 |
| Terrestrial ecotoxicity | 9.92E-14 | 6.95E-14 | 6.93E-14 | 6.68E-14 |
| Photochemical oxidation | 1.27E-14 | 1.01E-14 | 1.01E-14 | 9.58E-15 |

**Table S 10. Corresponding data to Figure 12 right in the paper.**

| Category | CO_2 uptake | CO_2 from land transformation | Biogenic CO_2 eq | Fossil CO_2 eq |
|---|---|---|---|---|
| PET film | 0.9311 | 0 | 0 | 0 |
| Silver ink | 0.5651 | 0.0095 | 0.0095 | 0.0107 |
| Isopropanol | 0.0046 | 3.18E-05 | 3.41E-08 | 2.38E-05 |
| P3HT:PCBM | 0.1695 | 0.0009 | 2.47E-06 | 0.001 |
| o-Dichlorobenzene | 0.015 | 0.0002 | 3.98E-07 | 0.0002 |
| ZnO | 0.0006 | 2.54E-06 | 4.95E-09 | 2.7E-06 |
| PEDOT:PSS | 0.1814 | 0.0014 | 2.35E-06 | 0.0015 |
| Potassium hydroxide | 0.0006 | 1.15E-05 | 2.4E-08 | 1.2E-05 |
| Methanol | 0.0016 | 5.57E-06 | 1.58E-08 | 5.25E-06 |
| Acetone from butane | 0.0046 | 3.88E-05 | 7.28E-08 | 4.01E-05 |
| Epoxy resin. liquid | 0.1201 | 0.0006 | 1.8E-09 | 1.58E-05 |
| Acetic acid from acetaldehyde | 0.0002 | 2.16E-06 | 2.76E-09 | 1.63E-06 |
| Electricity mix/DK U | 0.7062 | 0.1036 | 9.31E-06 | 0.105 |

### 3. Salt spray test

Finally, in response to one of the reviewer comments we also explored the effect of salt spray and dried salt on the solar cells surface which can be expected for the off-shore installation (even if we did not observe it). This demonstrated a relatively small drop in efficiency similar to the LDPE foil employed in the tubes which we ascribe to the optically transparent nature of sea salt which scatters light – see Figure S1:

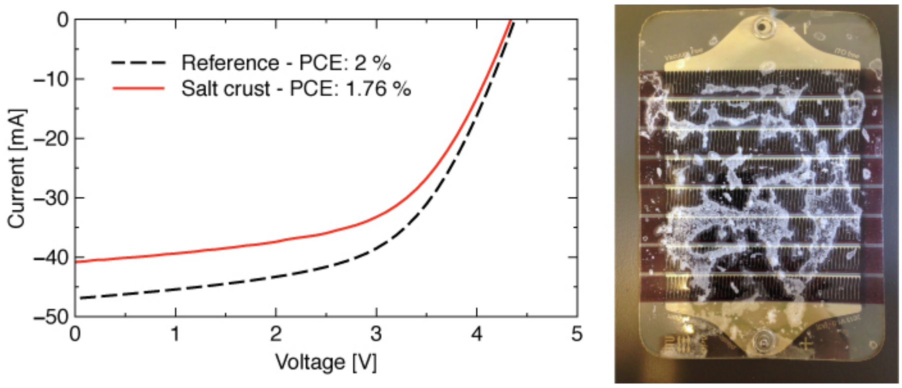


**Figure S 1. IV curves (left) for the test with and without salt spray (left). Photograph of module with dried salt (right).**