Ecodesign of organic photovoltaic modules from Danish and Chinese perspectives

Electronic Supporting Information ESI-1

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This document includes:

- Supplementary Methods
- Supplementary Results and Discussion
- Supplementary References

Supplementary Methods

Detailed information is here documented about the building of the life cycle inventory associated with the manufacture, deployment and dismantling of a solar park that uses organic solar cells (OPV) technology. The OPV solar park is composed of several parts, as shown in Figure 1 in the manuscript. It is composed of OPV modules and several components, which are known as balance of system (BOS). It is a group of auxiliary components such as inverter, mounting structure, wiring and an aluminium wagon (used for the installation of the OPV module rolls). See Figure SM1 below for a detailed overview of the model, as well as the system boundaries for the solar park in Figure 1 in the manuscript. The different aspects addressed in Supplementary Methods cover:

1. General assumptions.
2. Materials for the solar cells.
3. The OPV manufacturing steps.
4. Deployment of the solar park.
5. End of life of solar park.
6. Life cycle inventories and impact assessment.
7. Supplementary data for the model.
8. Other modelling assumptions.
9. Scenarios for the assessment.

A resulting life cycle inventory corresponding to the annual supply of 1 kWh (high voltage) to the grid in Denmark (considering manufacturing in Denmark as well) is provided in ESI-2.

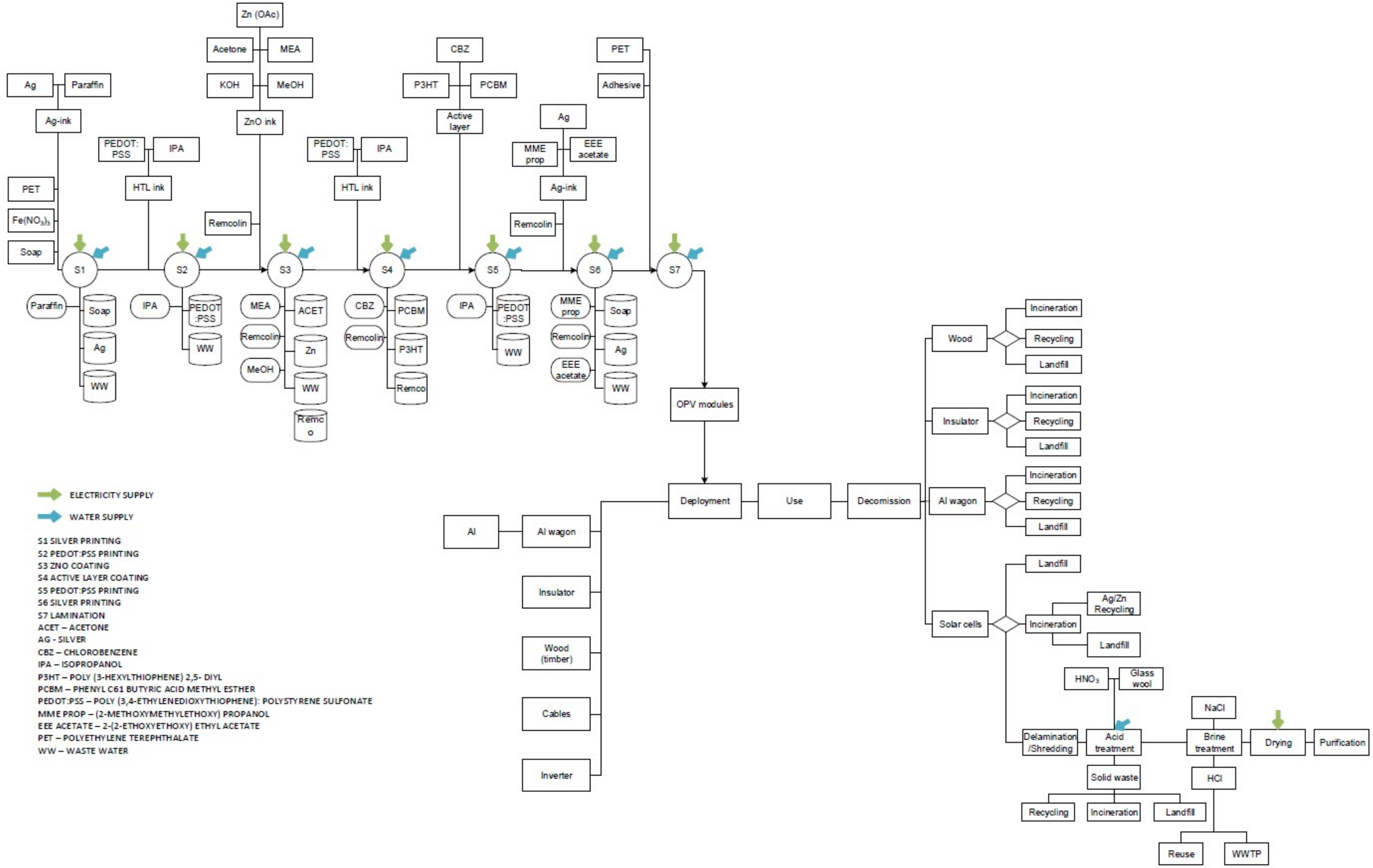

Figure SM 1. Flowchart of a detailed production of a solar park that includes all stages: modules manufacturing, assembly of the solar park, use and disposal.

1. General assumptions

We provide here an inventory for the OPV solar park in DK, per functional unit (FU). The FU has been described in the manuscript as the supply from the solar park of 1 kWh. The reference flow is 1 m^2, which is the unit to which the inputs and outputs of the product system are related, both in terms of material flows and potential environmental impacts. Then, 0,016 m^2 are needed to complete the total system, 1 kWh of solar park which is formed by inverters, wiring, structure and aluminium wagon. The lifetime of the system is the corresponding to the structure, 35 years. Replacements for modules and all BOS have been adjusted accordingly to their specific lifetimes. The general considerations about the lifetime of the components, the weather conditions and other details are listed in Table SM 1.

The model has been built in Simapro, using Ecoinvent database format. Global market processes were selected in Ecoinvent and they already include transportation.

Table SM 1. Model choices and general considerations

Location		
	Manufacturing	Denmark, China
	Installation	Denmark, China
Radiation (kWh/m^2 yr)		
	Denmark	1100
	China	1700
Year		2015
Time horizon (years)		35
Lifetime components (years)		
	Solar cells	1,5
	Inverter	10
	wood structure	15
	Wagon station	35
	Insulator	10
	Wiring	10

2. Material production for solar cells

Organic solar cells are printed in long rolls continually, where all individual cells are connected in series. The cells are typically formed by 6 layers that are deposited in a printing unit followed by a drying process in an oven. General sketch is shown in Figure SM 2. These techniques are solution-based processes, meaning that each layer is deposited from an ink state. Materials required for the inks have been modelled from literature and from synthesis made on purpose for this study, to be adapted to Ecoinvent standards as detailed below. The electricity/heat needed as well for the preparation of the inks have been included and are listed in Table SM 2. It is worth noting the material complexity in OPV in comparison for example to silicon or thin film solar cells. However, it is not equivalent to process complexity. Once synthesized, the materials for OPV can be deposited as thin films without inexpensive equipment and at low temperatures.

Figure SM 2. Production of solar cells steps, termed as OS, and supply of inputs of materials, electricity and heat needed for the manufacturing.

- Front electrode: is made of silver ink water-based commercially available from PChem (PFI-722), USA based company. Information for the composition retrieved from MSDS. Coded here as A1.
- Front PEDOT:PSS: it is poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) and serves an intermediate layer and that can be considered part of the electrode. Coded as A3 in Table SM 2 is commercially available from Agfa Chemicals as Orgacon (UK based company). Modelled and adapted to Ecoinvent from the original synthesis published in Garcia-Valverde et al. paper[1].
- ZnO ink: it is an intermediate layer that serves as hole transport material. It is manufactured at site following the recipe published in Espinosa et al.
- Active layer: it is made by dissolving a fullerene PCBM (A7) and a polythiophene P3HT (A8) in an organic solvent, here chlorobenzene, and the blend is labelled A9. The synthesis of P3HT and PCBM have been adapted to Ecoinvent from the original synthesis published in Garcia-Valverde et al. paper[1]. They are purchased from USA and Belgium respectively.
- Back PEDOT:PSS: the same polythiophene-based compound as in the front with a different formulation, that can serve as well as conducting in the rear part of the solar cell. Commercially available from Heraeus, in Germany. The synthesis of PEDOT has been modelled from Garcia-Valverde et al. paper[1] and coded as A11.
- Back electrode: silver ink commercially available from Dupont (UK based company) 5025 Silver ink. Information for the composition has been retrieved from MSDS and it has been coded here as A13.

The modules are finally encapsulated with PET and a UV curable adhesive to seal and provide barrier properties to the solar cells. Information for the adhesive and barrier retrieved from the manufacturers MSDS and included in the step of manufacturing.

Table SM 2. Materials and energy required for manufacturing the inks used in the solar cells in Denmark. The type of processes listed are: Outputs (O), input materials (IM), input of energy (IE), emissions to air (E-A), to water (E-W).

	Process name/variables	Type	Values	Unit	Notes
A1	Front Ag-ink	O	1	kg	Modeled from MSDS PChem
	Silver	IM	0,6	kg	
	Water, deionised, from tap water	IM	0,4	kg	
A3	Front PEDOT:PSS - EL-50	O	1	kg	Modeled from Garcia- Valverde et al.[1]
	Water, cooling, unspecified natural origin/kg	IM	1,03E+03	kg	
	Polystyrene, general purpose	IM	1,00E-02	kg	
	Toluene, liquid	IM	9,71E-01	kg	Proxy for thiophene
	Bromine	IM	7,80E-02	kg	
	Water, deionised, from tap water	IM	9,87E-01	kg	
	Electricity, low voltage {DE}	IE	2,4E+00	kWh	
	Heat, in chemical industry	IE	9,3E+01	MJ	
A5	ZnO ink	O	1	kg	Modelled from ProcessOne[2]
	Zinc oxide	IM	8,94E-02	kg	
	Potassium hydroxide	IM	4,33E-02	kg	
	Acetone, liquid	IM	5,72E-01	kg	
	Methanol	IM	2,86E-01	kg	
	MEA (methoxyethoxyacetic acid)	IM	0,0089	kg	Modelled from Process One[2]
	Methanol	IM	2,13E-03	kg	
	Ethylene oxide	IM	5,84E-03	kg	
	Potassium permanganate	IM	5,25E-03	kg	
	Electricity, low voltage	IE	5,53E-03	kWh	
A7	PCBM	O	1	kg	Modeled from Garcia Valverde[1] and Anctil[3]
	Water, cooling, unspecified natural origin/kg	IM	6,14E+03	kg	
	Toluene, liquid	IM	1,23E+02	kg	Proxy for thiophene
	Oxygen, liquid	IM	7,40E+01	kg	
	Methylcyclopentane	IM	8,50E-01	kg	
	Ammonia, liquid	IM	7,88E-01	kg	

	Sodium hypochlorite, without water, in 15% solution state	IM	3,44E-01	kg	
	Hydrochloric acid, without water, in 30% solution state	IM	2,18E-01	kg	
	Sulfur trioxide	IM	4,79E-01	kg	
	Electricity, low voltage	IE	3,4E+02	kWh	
	Heat, in chemical industry	IE	6,5E+03	MJ	
A8	P3HT	O	1	kg	Modeled from Garcia Valverde[1]
	Water, cooling, unspecified natural origin/kg	IM	1,11E+04	kg	
	Toluene, liquid	IM	7,81E+00	kg	Proxy for thiophene
	Hexane	IM	2,58E+00	kg	
	Bromine	IM	8,97E+00	kg	
	Electricity, low voltage	IE	2,6E+01	kWh	
	Heat, in chemical industry	IE	4,6E+02	MJ	
A9	Active layer ink	O	1	kg	From Process one[2]
->A7	PCBM	IM	1,06E-02	kg	
->A8	P3HT	IM	1,32E-02	kg	
	Monochlorobenzene	IM	9,76E-01	kg	
	Transport, freight, sea, transoceanic ship	IM	8,1E-02	tkm	P3HT from USA
	Transport, freight, lorry 3.5-7.5 metric ton, EURO5	Transport	9,7E-03	tkm	PCBM from Netherlands
	Electricity, low voltage	IE	6,48E-03	kWh	
A11	Back PEDOT:PSS	O	1	kg	Modelled from MSDS Heraeus GmbH
	Water, cooling, unspecified natural origin/kg	IM	1,03E+03	kg	
	Polystyrene, general purpose	IM	1,00E-02	kg	
	Toluene, liquid	IM	9,71E-01	kg	Proxy for thiophene
	Bromine	IM	7,80E-02	kg	
	Propylene glycol, liquid	IM	9,70E-01	kg	
	Electricity, low voltage	IE	2,4E+00	kWh	
	Heat, in chemical industry	IE	9,3E+01	MJ	
A13	Back Ag ink	O	1	kg	Modelled from MSDS Dupont
	Silver	IM	7,00E-01	kg	
	Dipropylene glycol monomethyl ether	IM	2,20E-01	kg	Synonym for 2-Methoxymethylethoxy)propanol
	Ethoxylated alcohol (AE3) {GLO}	IM	8,00E-02	kg	Proxy for 2-(2-Ethoxyethoxy)ethyl acetate

3. The OPV manufacturing steps

These materials detailed in the previous section are deposited as thin films onto a PET substrate using printing and coating techniques as illustrated in Figure SM 3. The width of the web is 305 mm and the maximum length that can be printed in a run is 1000 m, due to some technical constraints of our particular set up. Further details about the process of manufacturing the OPV modules can be found elsewhere[4–6] here and here. In Figure SM 2, an overview for the stages of the manufacturing with the specific inputs and outputs can be observed, as well as the coding applied in this work. The following steps (OS) are followed in the manufacturing of OPV modules:

- OS-1. Deposition onto a plastic substrate, PET film, of a silver ink paste acting as electrode by flexography unit, located in E section in Figure SM 3. Silver ink is purchased from USA commercial brand ready to print. The printing unit is cleaned after a printing run with ferric nitrate, soap and water. With regard to the emissions, water from silver inks is totally evaporated in the oven and 4,8% silver is lost in the flexo roll; loss assumed to be kept over time.
- OS-2. Deposition by rotary screen printing of the second part of the electrode, PEDOT:PSS. See part H in Figure SM 3. PEDOT:PSS ink is purchased from a German commercial brand that is mixed with isopropanol to improve the printing. The printing mask is cleaned after a printing run with water. With regard to the emissions to air, 2 – propanol is considered to be evaporated in the oven, to water PEDOT, propylene glycol and water from PEDOT:PSS ink.
- OS-3. The zinc oxide ink prepared in house as explained above is deposited by means of slot- die coating The coating head is placed in part E in Figure SM 3.Acetone is used for cleaning the slot die coating unit after a printing run. The solvents of the ink are expected to be totally evaporated in the oven. Solvents are as well eliminated to water with the cleaning waste - percentage in default distribution taken here.
- OS-4. The active layer ink is as well made out in house as above detailed and deposited by means of slot- die coating. The coating head is placed in part E in Figure SM 3. Remcolin, a commercial product is used for cleaning the slot die coating unit after a printing run. The chlorobenzene of the ink is expected to be totally evaporated in the oven. The solvent and rest of components are as well eliminated to water together with the cleaning waste.
- OS-5. The deposition of this layer follows exactly the same procedure as OS-2 step, except that this PEDOT:PSS, acting here as a hole transport layer, has a different formulation. Accordingly, the cleaning agent used is not water but Remcolin and the emissions have a different distribution.
- OS-6. Deposition of the silver back electrode by rotary screen printing, takes place in part H (Figure SM 3). The unit is cleaned with Remcolin after the printing run and the emissions go directly to air, since this solvent has a high volatility. In the emissions to water from the cleaning operation we can find the solvents and silver.
- OS-7. Encapsulation of the solar cells with UV curable adhesive. This is done in a separated machine, a laminator. No emissions accounted here.

Printing units need to be cleaned to prevent clogging after approximately 4000 m run. The cleaning agents to clean the machinery are as well accounted in the inventory. For the modelling, the ecoinvent 3.1 database[7] provides average LCIs for electricity generation specific to 50 countries for 2008. Therefore the production of solar cells is modelled with processes representative for both Denmark and China. Electricity and heat supply mixes for Denmark, were built to represent 2013.

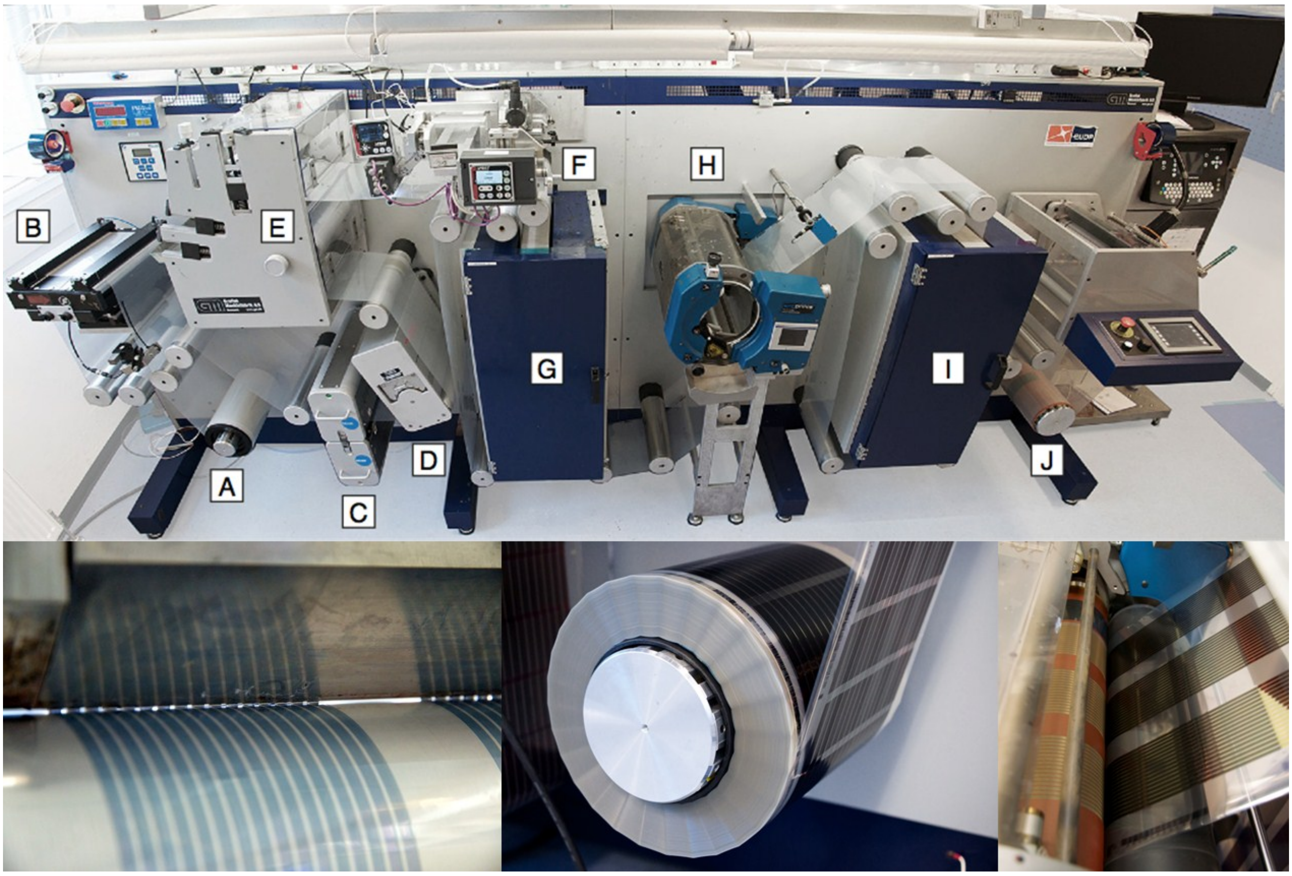

Figure SM 3. Pilot scale plant available to print the solar cells by roll to roll at DTU Energy, Denmark.

Table SM 3. Cumulative materials and energy required for the manufacturing of 1 m² of solar cells in Denmark (13,2 kWh/m² are generated in their lifetime). The type of processes listed are: Outputs (O), input materials (IM), input of energy (IE), emissions to air (E-A), to water (E-W).

A2	OS1 - Front Ag	O	1,0E+00	m^2	From USA[8]
	Polyethylene terephthalate, granulate, bottle grade	I	1,8E-01	kg	Transport included in production of PET
	Thermoforming, with calendering	IM	1,8E-01	kg	
->A1	Front Ag-ink	IM	5,9E-04	kg	
	Transport, freight, lorry >32 metric ton, EURO5	IM	3,0E-04	tkm	
	Transport, freight, sea, transoceanic ship	IM	3,6E-03	tkm	
	Soap	IM	1,6E-05	kg	Cleaning
	Sinter, iron	IM	1,6E-05	kg	To manufacture ferric nitrate (cleaning)
	Nitric acid, without water, in 50% solution state	IM	1,4E-04	kg	To manufacture ferric nitrate (cleaning)
	Water, deionised, from tap water, at user	IM	8,2E-04	kg	Rinsing after cleaning
	Electricity, low voltage	IE	6,3E-02	kWh	
	Water	E-A	7,1E-02	kg	
	Silver	E-W	1,7E-05	kg	
	Waste water/m^3	E-W	8,36E-07	m^3	
A4	OS2 - Front PEDOT:PSS	O	1	m^2	From [8]
->A3	PEDOT:PSS	IM	7,57E-03	kg	
	Isopropanol	IM	2,27E-03	kg	
	Water, deionised, from tap water, at user	IM	7,63E-04	kg	Cleaning printing masks
	Transport, freight, lorry 3.5-7.5 metric ton, EURO5	IM	4,5E-03	tkm	
	Transport, freight, sea, transoceanic ship	IM	0,0E+00	tkm	
	Electricity, low voltage	IE	5,52E-02	kWh	
	2-Propanol	E-A	2,27E-03	kg	
	Waste water/m^3	E-W	7,63E-07	m^3	

	PEDOT:PSS	E-W	7,99E-07	kg	
	Propylene glycol	E-W	4,59E-05	kg	
A6	OS3 - ZnO layer	O	1	m^2	From [8]
->A5	ZnO ink	IM	3,12E-03	kg	
	Solvent, organic	IM	8,20E-05	kg	Proxy for cleaning agent Remcolin ®
	Acetone, liquid	IM	1,30E-04	kg	Cleaning
	Electricity, low voltage	IE	6,49E-02	kWh	
	Acetone	E-A	1,91E-03	kg	
	Propylene glycol methyl ether acetate	E-A	8,20E-05	kg	Proxy for cleaning agent Remcolin ®
	Methanol	E-A	6,94E-07	kg	
	2-[2-(2-Ethoxyethoxy)ethoxy]ethanol	E-A	2,74E-05	kg	Proxy for MEA
	Acetone	E-W	2,34E-07	kg	
	2-[2-(2-Ethoxyethoxy)ethoxy]ethanol	E-W	3,65E-07	kg	
	Methanol	E-W	3,65E-08	kg	
	Zinc	E-W	2,94E-06	kg	
A10	OS-4 - Active layer	O	1	m^2	From [8]
->A9	Active layer ink	IM	9,84E-05	kg	
	Monochlorobenzene	IM	4,19E-06	kg	For cleaning
	Solvent, organic	IM	8,20E-05	kg	Proxy for cleaning agent Remcolin ®
	Transport, freight, lorry 3.5-7.5 metric ton, EURO5	IM	9,1E-05	tkm	PCBM from NL (920 km)
	Electricity, low voltage	IE	2,54E-01	kWh	
	Benzene, chloro-	E-A	5,61E-05	kg	
	Propylene glycol methyl ether acetate	E-A	8,20E-05	kg	Proxy for cleaning agent Remcolin ®
	Benzene, chloro-	E-W	4,42E-05	kg	
	PCBM	E-W	4,33E-07	kg	

	P3HT	E-W	5,41E-07	kg	
A12	OS-5 PEDOT:PSS	O	1	m^2	From [8]
->A11	Back PEDOT:PSS	IM	8,20E-03	kg	
	Isopropanol	IM	1,64E-03	kg	
	Water, deionised, from tap water, at user	IM	8,20E-03	kg	For cleaning
	Transport, freight, lorry 3.5-7.5 metric ton, EURO5	IM	4,9E-03	tkm	PEDOT From Germany when in DK
	Electricity, low voltage	IE	4,14E-01	kWh	
	2-Propanol	E-A	1,63E-03	kg	
	Waste water/m3	E-W	8,20E-06	m^3	
	Propylene glycol	E-W	4,97E-05	kg	
	PEDOT:PSS	E-W	1,54E-06	kg	3% solid content
	2-Propanol	E-W	1,02E-05	kg	
A14	OS6 - Back Ag	O	1	m^2	From [8]
->A13	Back Ag-ink	IM	6,56E-03	kg	Comming from UK
	Solvent, organic	IM	4,30E-03	kg	Proxy for cleaning agent Remcolin ®
	Transport, freight, lorry 3.5-7.5 metric ton, EURO5	IM	0,0E+00	tkm	Silver ink from UK (1250 km)
	Transport, freight, sea, transoceanic tanker	IM	8,2E-03	tkm	Silver ink from UK (1250 km)
	Electricity, low voltage	IE	1,41E-01	kWh	
	Propylene glycol methyl ether acetate	E-A	4,30E-03	kg	Remcolin-very volatile all consider to air
	2-[2-(2-Ethoxyethoxy)ethoxy]ethanol	E-W	3,28E-06	kg	Ethoxylated alcohol (AE3)
	Propanol, (2-(2-methoxymethylethoxy)methylethoxy)-	E-W	8,87E-08	kg	Dipropylene glycol monomethyl ether
	Silver	E-W	2,82E-07	kg	
A15	OS7 - Encapsulation	O	1	m^2	From [8]
	Epoxy resin, liquid	IM	1,79E-02	kg	
	Polyethylene terephthalate, granulate, amorphous	IM	7,99E-02	kg	

	Extrusion, plastic film	IM	7,99E-02	kg	
	Transport, freight, sea, transoceanic tanker	IM	0,0E+00	tkm	Solar cells to the installation place
	Transport, freight, lorry 16-32 metric ton, EURO5	IM	9,8E-03	tkm	Solar cells to the installation place
	Electricity, low voltage	IE	2,43E-01	kWh	

4. Deployment of solar park

The building of the park and a preliminary analysis can be found in Krebs et al.[9] The assembly of the components for the solar park and their units required to accomplish the functional unit of 6 PJ, are shown in Figure SM3. The deployment of the solar cells can be done by rolling out the cylinder containing the solar cells that is mounted on an aluminium wagon. So far it has been done using human force; therefore no energy has been accounted. In the use phase we have either accounted for other input of neither energy nor material. It is of course included the replacement of the parts that have reached to their end of life before the lifespan of the whole installation; i.e. 35 years - the lifetime of all the particular components is listed in Table SM1.

The solar cells are mounted on a wood structure. To insulate the wood from the solar cells, it is necessary to place an insulator that has fire retardant properties. The current one is a PET grid. - See Table SM5.

The inverter and the necessary wiring, fuses and electric meter have been modelled taking existing processes in Simapro and editing them as shown in Table SM7.

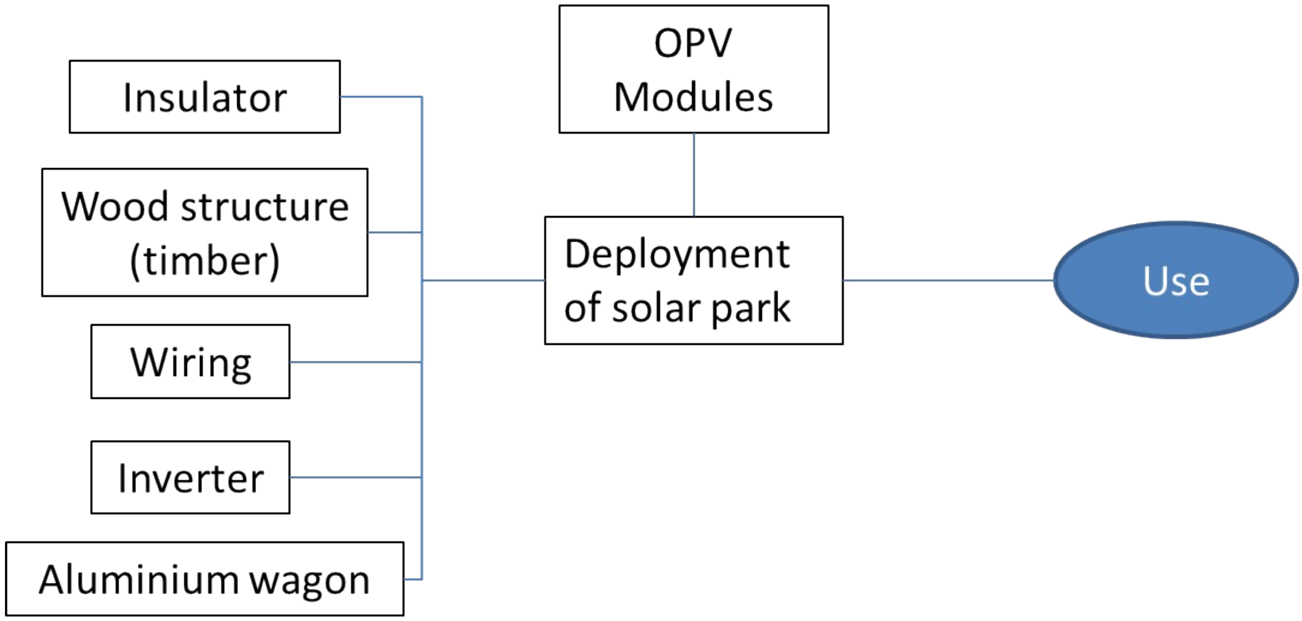

Figure SM 4. Deployment of organic solar modules with the rest of components of the installation, wagon, inverter, wiring and structure.

Table SM 4. Inventory for the wood structure that can hold 1 m^2 of solar cells in the park in Denmark (13,2 kWh/m^2 are generated in their lifetime). Output (O), Input material (IM).

A16	Woodenstructure		1	m^2	From [9]
	Laminated timber element, transversally prestressed, outdoor use	IM	0,018	m^3	
	Laminated timber element, transversally prestressed, outdoor use	IM	0,035	m^3	
	Galvanized steel sheet, at plant/RNA	IM	0,135	kg	Nails in the structure
	Wood preservative, creosote	IM	4,630	kg	88 kg/m^3 from [10]

Table SM 5. Inventory for the assembly of the solar park per functional unit; i.e. the supply of 1kWh electricity to grid averaged over a year.

	Solar Park components	1	kWh	
->A17	OPV modules	7,5E+07	kg	Modules assembled in A10 process
*	Inverter, 2.5kW {GLO}| market	4,9E+04	p	INVERTER (proportional units to power output only, not dependent on area of modules, hence only scaled based on value in 2014)
**	Photovoltaic plant, electric installation for 1 m^2 OPV module ground	2,4E+07	p	WIRING - Fuse box, electric cables, and the electric meter
	Window frame, aluminium, U=1.6 W/m2K	1,5E+01	m^2	WAGON - necessary for installing the whole park in 4 days of 9h
->A16	Woodenstructure	1,6E+07	m^2	STRUCTURE - Wood
	Polyethylene, high density, granulate	0,0E+00	kg	Insulator. Switch parameter
	Polyethylene, linear low density, granulate	0,0E+00	kg	Insulator. Switch parameter
	Polyethylene terephthalate, granulate, amorphous	0,0E+00	kg	Insulator. Switch parameter

* Edited process from SimaPro process: Inverter, 2.5kW {GLO}| market for | Conseq, U

** Edited process from SimaPro process: Photovoltaic plant, electric installation for 570 kWh open ground module {GLO}| photovoltaics, electric installation for 570 kWh module, open ground | Conseq, U

5. End of life of the solar park

There are different options available to handle products or systems reaching their end-of-life, like 1) reuse of products or components, 2) refurbishment of components for reuse in similar applications, 3) recycling of materials for further utilization, 4) incineration of materials, 5) disposal of material as wastes (e.g., land filling of solid and waste water treatment of liquid fractions).

The methodological approach of the end-of-life consideration in LCA is similar to other life cycle phases. Total required energies and ancillary materials flows as well as emissions due to the different end-of-life treatments are accounted for. In addition to the caused environmental impacts of end-of-life treatment there is also the challenge to account for the environmental benefits due to the recycling of materials or energy recovery correctly. Several approaches are used to reflect environmental benefits from material recycling or energy recovery in LCA. A commonly used approach is to account for recycling benefits (e.g., by substituting the production of respective materials) as credits. To do this, it is necessary to account for all caused emissions related to the whole recycling process of materials, e.g., for the remelting, as these are applied to produce the recycled materials. This assumes that there are no changes in the inherent properties of the recycled materials (see ISO 14044 11, chapter 4.3.4.3). In terms of waste incineration processes, the recovered energy from materials (e.g., from plastics) is accounted for a credit for substituting energy production from conventional energy production systems.

The disposal of the components has been created accordingly. For all recycled materials, custom made processes that contain the activities of recycling were created. This way the crediting of the virgin material avoided is made.

5.1. Disposal of components

5.1.1. Solar cells

Solar cells disposal is shown graphically in Figure SM 5 and in Table SM12. If solar cells are recycled they are assumed to be collected by a specialized company, which will extract valuable materials (PET + silver) before sending the remaining parts to incineration for energy recovery. Based on our experimental processing,[11] around 95% of the silver could be recovered for further treatment. The modules follows the processing steps detailed below , which include mechanical and hydrometallurgical processing, divided into five process steps which are subsequently (1) laminate foil separation, (2) Shredding, (3) Acid treatment, (4) Silver recycling and purification and (5) Incineration.

- **Laminate foil separation and rinsing**: Before shredding the front laminate was removed as the front laminate has no contact with the processed layers of the actual solar cell. The separated foil is then discharged and washed and ends up to recycling. The influence of the delamination process will have an effect on the shredding –because of the change in weight- and in the etching –because of the acid consumption. This step could be optional when using high concentrated acid, however ‘delaminated’ modules generally shows a slightly lower acid consumption and a larger portion of the silver is recovered.
- **Shredding**: The collected modules are first reduced in a shredder to small pieces.
- **Acid treatment**: The shredded material is exposed to 14.2 M HNO_3 which not only results in complete bleaching of the solar cell but also caused the shredded pieces to delaminate entirely resulting in a larger volume. 3 foils are used in the preparation of the solar cell – one substrate upon which all processing is carried out and two barrier foils to encapsulate the substrate on the front and backside.
- **Precipitation and filtration**: The metal compound containing extraction liquor is further treated by a three stage precipitation process with an increasing pH using sodium chloride.
- **Silver drying and purification**: a generic process in ecoinvent to purify metals has been chosen in which 76% of the silver would be recycled from the previous fraction.

If solar cells are incinerated, environmental benefits due to the heat recovery of incinerated plastics are considered as credits. The modelling assumptions and data for this scenario have been taken from the municipal incineration of PET process in ecoinvent adding the silver.

The landfill of solar cells is assumed to be the landfill of PET available in ecoinvent, where adjustments of emissions of silver have been made (Table SM15 for more details of modelling).

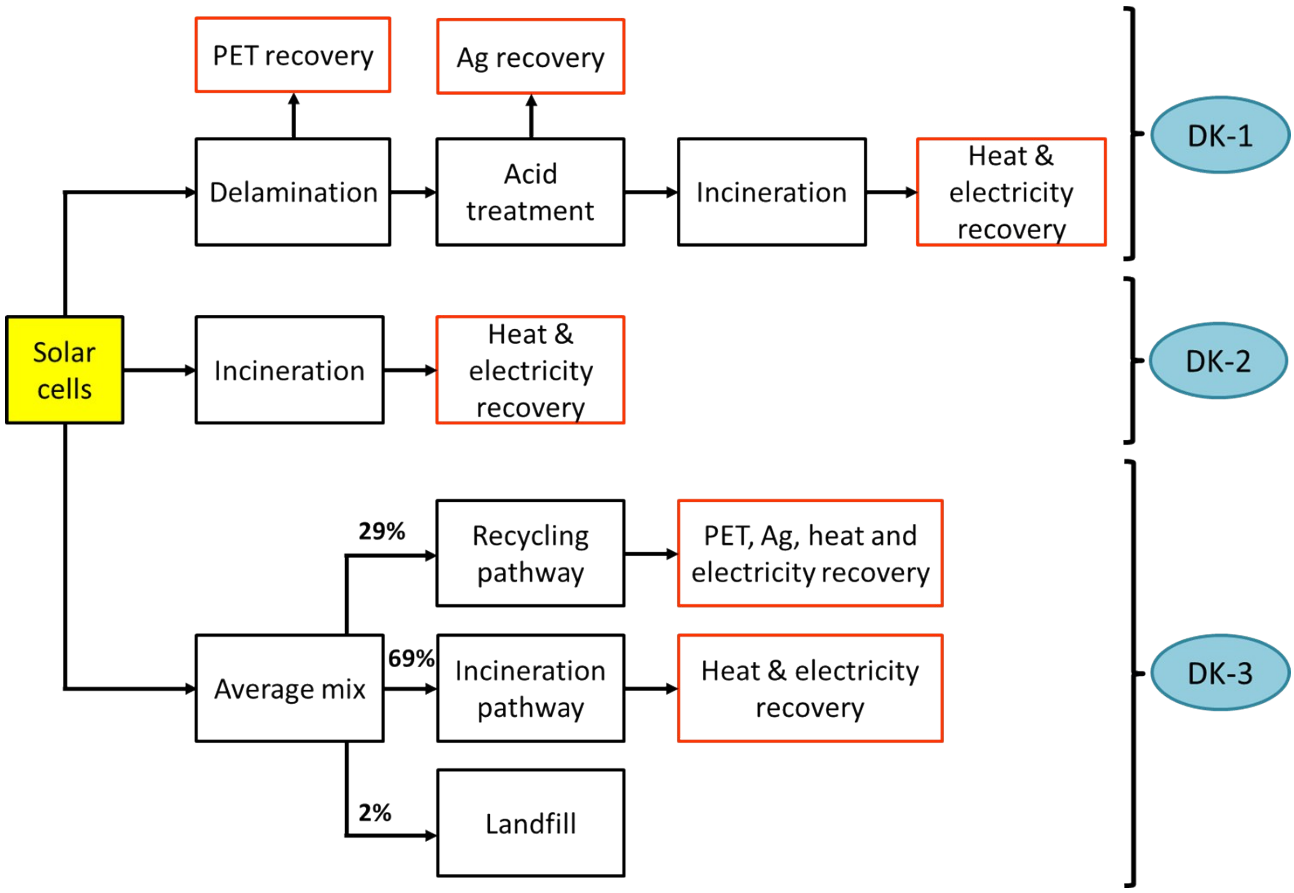

Figure SM 5. End of life scenarios considered for the organic solar cells in Denmark.

5.1.2. Disposal of the Wood Structure

Laminated timber and other wood parts of the structure will be incinerated or recycled following the processes determined in ecoinvent 3.1 and for the recycling a process has been selected to represent it waste wood sorting and shredding. (Table SM8).

5.1.3. Disposal of the Aluminium Wagon

The aluminium wagon will be recycled in all scenarios and processes considered are shown in Table SM 7.

5.1.4. Disposal of the inverter

The disposal of the inverter after use is included in the process selected in ecoinvent "Inverter, 2.5kW {GLO}| market for | Conseq, U". Waste polyethylene, used printed wiring boards, waste paperboard and waste polyethylene that are components of the inverter are modelled inside the Inverter process.

5.1.5. Disposal of the wiring

The disposal of the wiring after use is included in the process selected in ecoinvent and adapted from "Photovoltaic plant, electric installation for 570kWh open ground module {GLO}| photovoltaics" to Photovoltaic plant, electric installation for 1kWh open ground module {GLO}| photovoltaics, electric installation for 1 kWh module, open ground | Conseq, U". Waste electric wiring, scrap copper and steel, and waste polyvinylchloride are modelled inside the PV electrical installation.

5.2. Disposal scenarios

With the aim to provide a sensitivity analysis for the disposal of the solar park, three scenarios for Denmark (DK) and six for China (CN) are considered. Geographical influence of the location of manufacturing and installation is expected both in the amount of materials and energy needed (due to the different area of modules required for DK or for CN to fulfil the FU due to the radiation levels). Subsequently there will be as well large differences in the impact scores due to the use of local energy or transports of materials from their original manufacturing place to the installation place included in the model. The scenarios are defined on the basis of what treatment follow the main component of the solar park, i.e. the solar cells. They are explained below and in Table SM8. Best estimates have been taken for DK and CN.

- Recycling: Solar cells are collected by a specialized company, which will extract valuable materials. In the case of China, solar par is assumed to be recycled via informal sector and the operators wishing to recover some value the informal sector and in general the recycling centres should be adapted with respect to emission factors and specific exposure situations (e.g. worker exposure)..
- Incineration: Solar cells are assumed to be collected and directly sent to municipal incineration. While in Denmark the figures for this activity are quite high, it has largely increased in the recent years in China[12–14] as well as the atmospheric pollution derived from the waste management.
- Average mix of MSW (landfill/incineration/recycling). It is assumed to represent a large and diffuse deployment of solar cells in the country. In China, there are several scenarios contemplated depending on the grade of incineration and informal recycling rates forecast.

Table SM 6. Inventory for the disposal of the solar park with FU of providing 1 kWh of electricity to the Danish grid.

Solar park disposal	1,00E+00	p
Wagon --> RE	5,89E+02	kg
Wood structure --> L& I	1,58E+07	m^2
Insulator disposal	1,63E+08	kg
Solar cells disposal	3,75E+07	kg

Table SM 7. Inventory for the disposal of 1 kg of aluminium wagon. It is considered to be recycled independently of the selected scenario. Material to waste treatment is coded as OW.

Wagon --> RE		1,0E+00	kg	Al assumed to be recycled in all cases
Aluminium scrap, new, treatment of, at remelter	OW	3,3E-01	kg	same proportion as manufacturing
Aluminium scrap, new, treatment of, at remelter	OW	6,7E-01	kg	same proportion as manufacturing

Table SM 8. Inventory for the disposal of the wood structure, that holds 1 m² of solar cells.* Values depend on the scenario.

Wood structure	
Waste wood untreated, treatment of municipal incineration	Incineration scenario
Waste wood, untreated, treatment of, sanitary landfill	Landfill scenario
Waste wood, post-consumer, treatment sorting and shredding	Recycling scenario

** Density has been considered to be 700kg/m3 (softwood)*

Table SM 9. Inventory for the generic disposal of the solar cells.

Solar cells disposal	
Waste solar cells {DK}| treatment of municipal incineration	When installation in Denmark. Modeled from incineration of PET + recycling of Ag.

Waste solar cells {DK}| treatment of sanitary landfill	When installation in Denmark. Modelled as landfilling of PET + addition of the estimated emissions of Ag and Zn to soil.
Waste PET {CN}| treatment of municipal incineration	When installation in China.
Waste PET {CN}| treatment of sanitary landfill	When installation in China.
Recycling of solar cells	Process created in Table SM 10.

Table SM 10. Processes involved in the recycling of solar cells (disposal routes DK-1, DK-3, CN-1 and CN-3).

Recycling of solar cells		
Delamination of cells / processing	3,16E+00	m^2
Shredding of the solar cells	7,48E-01	kg
Acid treatment	3,16E+00	m^2
Silver Drying+Purification	3,16E+00	m^2

Table SM 11. Inventory for the acid treatment of the solar cells when they are recycled in Denmark. (disposal routes DK-1, DK-3)

Acid treatment of cells *		
Nitric acid, without water, in 50% solution state	0,275	kg
Tap water, at user {Europe without Switzerland}	9,90E-01	kg
Sodium chloride, brine solution {GLO}	0,02	kg
Hydrochloric acid, without water, in 30% solution state {RER}	-0,26	kg
Wastewater, average {CH}| treatment of, capacity 1E9l/year	1,00E-03	kg
Disposal of mixed plastics in solar cells	0,231	kg

* From Sondergaard*et al.*

Table SM 12. Inventory for the delamination of the solar cells in Denmark. 4,1 kWh is the energy for shredding 1 kg of the solar cells in a medium size capacity industrial machine

Delamination of cells *				Adapted from lamination / processing | Conseq, U
PET recycling	O			
Electricity required *	IE	4.1	kWh	

** A total of 4.1 kWh per kg of solar cells is assumed, taking the energy requirements of the shredding the solar cells in a medium size capacity industrial machine*

Table SM 13. Inventory for the shredding of 1kg of the solar cells in the scenarios of recycling. Energy requirements for the shredding the solar cells have been taken from a medium size capacity industrial machine - 175 ton/h

Shredding of the solar cells		1	kg	
Electricity, low voltage	IE	2,5E-02	kWh	

Table SM 14. Inventory for the process of disposal of mixed plastics. After the recycling of the solar cells via the wet process, there is a fraction of waste that is assumed that goes to incineration by default – it is mainly PET from the substrate with the traces of P3HT, PEDOT and PCBM.

Disposal of mixed plastics in solar cells		
PET recycling	IM	Recycling of solar cells, process created (
Waste PET {DK}| treatment of, municipal incineration	IM	Represents incineration in Denmark
Waste PET {DK}| treatment of, sanitary landfill	IM	Represents landfill in Denmark
Waste PET {CN}| treatment of municipal incineration	IM	Represents incineration in China
Waste PET {CN}| treatment of sanitary landfill	IM	Represents landfill in China

Table SM 15. Disposal treatments in Denmark and China for the end of life of the solar park and its components.

Disposal	Description	Modelling and Assumptions	Recycling (%)	Incineration (%)	Landfill/ Open Dump (%)
Denmark					
DK-1	Recycling	Recycling pathways with PET recovered from delamination (sent to recycling) and silver recovered from acid treatment and incineration of the mixed plastics and remains (with energy recovery).	100	0	0
DK-2	Incineration	Incineration modelled as PET municipal incineration (energy recovery); no differentiation due to composition of solar cells.	0	100	0
DK-3	Average mix of MSW (landfill/incineration/recycling)	Recycling path follows Scenario DK-1. Incineration path follows Scenario DK-2. Landfill is modelled as landfill of PET with amount of Ag corrected to match content of Ag of the solar cells: distinction between short-term and long-term emissions is performed: 1% vs. 99% done.	29	69	2
China					
CN-1	Recycling	The recycling centres should be adapted with respect to emission factors and specific exposure situations (e.g. worker exposure). Different health impacts would thus be expected, but present knowledge in LCI and LCIA do not allow such differentiated modelling, hence it is modelled as normal situation (similar to European conditions). Underestimation of impacts is therefore expected.	100	0	0
CN-2	Incineration	Technology is different in China (stoker and fluidized bed) than in Europe (grate), but not accounted for here (all incinerators for plastics are grate-type in ecoinvent; data from CH and representative of EU, NA and JP); efficiencies and APC should be thus different, but there is no LCI available. PET incineration in Europe has been taken and dioxins in incinerators adjusted[15].	0	100	0
CN-3	Average mix of MSW (landfill/incineration/recycling). Low incineration and low informal recycling rates forecast.	Data from a literature review[12–18]. Recycling path follows Scenario CN-1. Incineration path follows Scenario CN-2. Landfill is modelled as landfill of PET with 2 different processes: (1) landfill with treatment of leachate is taken similar to European conditions (absence of better data): the amount of Ag is corrected to match content of Ag of the solar cells, and a distinction between short-term and long-term emissions is performed: 1% vs. 99% done; (2) landfill with no leachate treatment and open dumps: the amount of Ag is corrected to match content of Ag in the solar cells, and all emissions of heavy metals are considered as emissions within 100 yr (no long-term emissions assumed)	17	22	21/40[a]
CN-4	Average mix of MSW (landfill/incineration/recycling) Low incineration and high informal recycling rates forecast.	Same modelling as in CN-3, values for the average mix changed	38	22	21/19[a]
CN-5	Average mix of MSW (landfill/incineration/recycling) High incineration and low informal recycling rates forecast.	Same modelling as in CN-3, values for the average mix changed	17	30	17/36[a]
CN-6	Average mix of MSW (landfill/incineration/recycling) High incineration and high informal recycling rates forecast.	Same modelling as in CN-3, values for the average mix changed	38	30	17/15[a]

[a] *Open Dump landfill: landfill with no leachate treatment.*

6. Life cycle inventories and impact assessment

Although 16 commonly-assessed impact categories have been evaluated in this study, only 15 are fully analysed. Ionising radiation impacting ecosystems was deemed of insufficient representativeness for the study. When assessing electricity generation systems, climate change scores have been demonstrated to act as an acceptable proxy for other environmental impacts, including acidification, ground-level ozone formation and terrestrial eutrophication. The ten retained impact categories therefore include climate change, toxicity of chemicals on human health (termed 'human toxicity'), differentiated between carcinogenic effects and non-carcinogenic effects, toxicity of chemicals impacting freshwater ecosystems (termed 'freshwater ecotoxicity'), eutrophication in freshwater and marine environments, respiratory impacts caused by inorganics via formation of particulate matters (termed 'respiratory inorganics'), ionising radiation impacting human health, land use, and non-renewable resource depletion. Table SM 16 documents the description and sources of the different LCIA methods for each of these impact categories

Table SM 16. Background information on the LCIA methods considered in the study [a]

Impact category	Indicator	Unit
Climate change	Radiative forcing as global warming potential (GWP100)	kg-CO_2eq/pers
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification	Accumulated Exceedance (AE)	molc H+ eq
Freshwater eutrophication	Residence time of nutrients in freshwater end compartment (P)	kg-Peq/pers
Marine eutrophication	Residence time of nutrients in marine end compartment (N)	kg-Neq/pers
Freshwater ecotoxicity	Comparative toxic unit for ecosystems (CTUe)	CTUe/pers
Human toxicity (cancer effects)	Comparative toxic unit for human health (CTUh)	CTUh/pers
Human toxicity (non-cancer effects)	Comparative toxic unit for human health (CTUh)	CTUh/pers
Respiratory inorganics	Intake fraction for fine particles (PM2.5)	kg-$PM_{2.5}$eq/pers
Ionising radiation (human health)	Human exposure efficiency relative to U235	kBq-U_{235}eq/pers
Land use	Soil organic matter (soil quality)	kg-C/pers
Water resource depletion	Water use related to local scarcity of water	m3 water
Resource depletion	Scarcity (metals and fossils)	kg-Sbeq/pers

[a] Table adapted from Laurent et al.[19]

7. Supplementary data for the model

Additional details or calculated figures for the model are shown in Table SM 17.

Table SM 17. Supplementary data for the model

Weight of 1m2 of OPV modules	3,2E-01	kg/m^2

Thickness of insulator	0,005	M

OPV modules parameters

Width of modules	0,3	M
Module efficiencies	1,6%	%
Geometric factor	50,0%	%
Coverage - front PEDOT:PSS	0,2	m^2/m
Coverage - back PEDOT:PSS	0,2	m^2/m
Solid content - front PEDOT:PSS	1,3%	%
Solid content - back PEDOT:PSS	3,0%	%
Thickness layer - front PEDOT:PSS	0,0	m
Thickness layer - back PEDOT:PSS	0,0	m
Thickness layer - ZnO	0,0	m
Thickness layer - Active layer	0,0	m
Capacity length in a run (m)	4000	m

Amount of ink left in the reservoir

OS1	2,00E-02	kg
OS2	7,50E-02	kg
OS3	5,00E-02	kg
OS4	5,00E-02	kg
OS5	7,50E-02	kg
OS6	5,00E-02	kg

Distances between countries

in KM	Front Ag ink	Front PEDOT:PSS	PCBM	P3HT
Installation countries \ Production countries	CN/ USA	CN/USA/DE	BE/USA	CN/USA
CN	1000	1000	1000	1000
DK	6131	600	920	6131

In addition, for the disposal, there are considerations like recovery rates and the efficiency in the incineration of plastics to obtain energy; heat and electricity.

Table SM 18. Recovery rates for materials in recycling processes and for energy in incineration processes.

	Modelled	**References**
Recycling rate		
Acid	95%	Sonderggard
Copper	76%	from Schmidt (2012)
Silver in recycling of solar cells	76%	from Schmidt (2012)
Silver in incineration of solar cells	76%	from Schmidt (2012)
Silver (during acid treatment)	95%	From Sondergaard
Glass reinforced fiber	100%	Assumed same as plastics. from Schmidt (2012)
PC	88%	from Schmidt (2012)
PE	88%	from Schmidt (2012)
PET	88%	from Schmidt (2012)
PMMA	88%	from Schmidt (2012)
PP	88%	from Schmidt (2012)
PS	88%	from Schmidt (2012)
PUR	88%	from Schmidt (2012)
PVC	88%	from Schmidt (2012)
Steel	90%	from Schmidt (2012)
Incineration of waste -recovered energy		
Efficiency in recovering heat	74%	Technology Data for Energy Plants (2012) Energinet. Page 65
Efficiency in recovering electricity	24%	Technology Data for Energy Plants (2012) Energinet. Page 65
Lower Calorific/Heating value (MJ/kg)		
PET	24	From
Plastics mix	40	Schmidt (2012).

8. <u>Other modelling assumptions</u>

Inconsistencies with the disposal of capital goods might occur because they are decommissioned and disposed of after one or several decades. As the disposal stage of the capital goods is included in the LCI of the production process, it means that after one year a share of the capital goods will be disposed according to the conditions in this year. For example, the inverter should be decommissioned after 15 yrs. But in the system, its disposal has been modelled as 1/15th of the decommissioning happens in one year (with crediting of materials and energy in that year). The resulting inconsistencies are assumed to be negligible. The energy processes for the countries that are considered in the study as incineration is location-specific and the crediting should be done with the right average/marginal mix specific to that location.

• Solar cells waste when incinerated is modelled as PET plus Silver. Incineration processes were adapted since they are transferred to Ecoinvent 3 from the second version, were they were allocation based and they do not include energy crediting. Incineration processes have been then credited with energy production (electricity + heat) adapted to each location (check in the system where that occurs).

• Modelling of recycling of solar cells: a specific process was created with avoided production of the material. We develop our customized modelling, for waste scenarios, we still create waste scenarios; we call processes in the section “Inputs from technosphere”. With regard to metals: Zinc is not considered to be recycled since it is ten times lower than silver. The slag quality assumed is OK for recycling and matching the grade of silver in Ecoinvent process of silver recovery. Steel and copper recycling processes were adapted.

• With regard to the landfill, solar cells are modelled as PET adding the emissions estimated to groundwater, long-term for silver.

• The crediting of some by-products inherent to the consequential approach makes that some impact categories are negative. To solve this, a number of assumptions were necessary. System expansion for some metals (Ag, Cu, Pd, Pb, In, Ni, Te, Hg, Zn and Mo) were removed and allocation was done in situations where the performed consequential modelling in ecoinvent was deemed debatable (e.g. silver production bringing significant environmental benefits on all impact categories due to the crediting of co-mined metals). These are reported together with the inventory in Table SM3.

• For the outsourcing sensitivity analysis, the local electricity mixes have been used. As for example, in the case that the OPV Solar Park is located in Denmark, and OPV modules used have been produced in China, Denmark average grid electricity mix is used to assess other life cycle processes while Chinese average grid electricity mix is used to analyse environmental impacts generated from PV modules production.

9. Scenarios

A table with the different systems we have is presented below with the scenarios that have been assessed (Table SM 19). The systems and the corresponding data are provided in the subsequent sections. Parameters used for the disposal scenarios, giving the three Danish and Chinese six scenarios used to analyse the sensitivity to disposal and geographical issues are further detailed in Supplementary Information1†.

Table SM 19. Parameters and corresponding model settings included in the assessment (total of 28 scenarios, including baseline). RE refers to recycling, IN to incineration, DK is Denmark and CN is the label for China.

Scenarios	Manufacturing country	Installation country	Insulator material	Disposal scenario	Insulator disposal	Wood disposal	Lifetime of the solar cells	Efficiency	Sensitivity parameters
1	DK	DK	PET	DK1	RE	RE	1,5	1	Disposal scenario of solar cells, DK
2	DK	DK	PET	DK2	RE	RE	1,5	1	Disposal scenario of solar cells, DK
3	DK	DK	PET	DK3	RE	RE	1,5	1	Disposal scenario of solar cells, DK
4	DK	DK	PET	DK1	IN	IN	1,5	1	Disposal scenarios for insulator and wood structure
5	DK	DK	PVC	DK1	RE	RE	1,5	1	Type of insulator material
6	DK	DK	PE	DK1	RE	RE	1,5	1	Type of insulator material
7	DK	DK	PC	DK1	RE	RE	1,5	1	Type of insulator material
8	DK	DK	GLASS FIBER	DK1	RE	RE	1,5	1	Type of insulator material
9	DK	DK	PMMA	DK1	RE	RE	1,5	1	Type of insulator material
10	DK	DK	PP	DK1	RE	RE	1,5	1	Type of insulator material
11	DK	DK	PS	DK1	RE	RE	1,5	1	Type of insulator material
12	DK	DK	PUR	DK1	RE	RE	1,5	1	Type of insulator material
13	DK	DK	PET	DK1	RE	RE	2	1	Lifetime of solar cells
14	DK	DK	PET	DK1	RE	RE	3	1	Lifetime of solar cells
15	DK	DK	PET	DK1	RE	RE	4	1	Lifetime of solar cells
16	DK	DK	PET	DK1	RE	RE	5	1	Lifetime of solar cells
17	DK	DK	PET	DK1	RE	RE	1,5	2	Power Conversion Efficiency
18	DK	DK	PET	DK1	RE	RE	1,5	3	Power Conversion Efficiency
19	DK	DK	PET	DK1	RE	RE	1,5	4	Power Conversion Efficiency
20	DK	DK	PET	DK1	RE	RE	1,5	5	Power Conversion Efficiency
21	CN	DK	PET	DK1	RE	RE	1,5	1	Manufacturing site (outsourcing)
22	DK	CN	PET	CN-1	RE	RE	1,5	1	Installation site (exporting)
23	CN	CN	PET	CN-1	RE	RE	1,5	1	Disposal scenario of solar cells, CN
24	CN	CN	PET	CN-2	RE	RE	1,5	1	Disposal scenario of solar cells, CN
25	CN	CN	PET	CN-3	RE	RE	1,5	1	Disposal scenario of solar cells, CN
26	CN	CN	PET	CN-4	RE	RE	1,5	1	Disposal scenario of solar cells, CN
27	CN	CN	PET	CN-5	RE	RE	1,5	1	Disposal scenario of solar cells, CN
28	CN	CN	PET	CN-6	RE	RE	1,5	1	Disposal scenario of solar cells, CN

Supplementary Results and Discussion

This section includes

- Additional results from the weak point analysis
- Supplementary Figure S1.
- Supplementary Tables S1-S15.

* Because of layout constraints, Table S15 is reported in Electronic Supporting Information ESI-2 (Microsoft Excel file).

Additional results from the weak point analysis

Table S 1. Contribution analysis from the different for the baseline scenario (installed in Denmark, disposal route DK-1).

	Wagon	Wood structure	Insulator	Inverter	Cabling	OPV modules
Climate change	0%	21%	9%	1%	0%	69%
Ozone depletion	0%	-24%	16%	5%	0%	103%
Photochemical ozone formation	0%	40%	3%	1%	0%	56%
Acidification	0%	20%	5%	1%	0%	74%
Terrestrial eutrophication	0%	21%	2%	1%	0%	75%
Freshwater eutrophication	0%	10%	1%	2%	0%	87%
Marine eutrophication	0%	26%	4%	1%	0%	69%
Freshwater ecotoxicity	0%	4%	3%	2%	2%	90%
Human toxicity, cancer effects	0%	31%	2%	2%	0%	64%
Human toxicity, non-cancer effects	0%	7%	1%	2%	0%	90%
Respiratory inorganics	0%	80%	1%	0%	0%	18%
Ionizing radiation HH	0%	63%	2%	1%	0%	34%
Land use	0%	41%	1%	0%	0%	58%
Water resource depletion	0%	27%	10%	1%	0%	62%
Resource depletion	0%	2%	0%	1%	0%	97%

Table S 2. Contribution analysis from the modules in baseline scenario #1: disposal route DK-1 with recycling of wood and insulator.

	Decrease at LT=5 yrs	Maximum decrease (asymptote)
Climate change	48%	69%
Ozone depletion	72%	103%
Ionizing radiation HH	24%	34%
Photochemical ozone formation	40%	56%
Acidification	52%	74%
Terrestrial eutrophication	53%	75%
Freshwater eutrophication	61%	87%
Marine eutrophication	48%	69%
Freshwater ecotoxicity	63%	90%
Human toxicity, cancer effects	45%	64%
Human toxicity, non-cancer effects	63%	90%

Particulate matter	13%	18%
Land use	40%	58%
Water resource depletion	43%	62%
Mineral, fossil & ren resource depletion	68%	97%

Table S 3. ILCD impact characterized scores for the three scenarios of disposal in Denmark, including long-term emissions.

Impact category	DK-1	DK-2	DK-3
Climate change	6,88E-01	1,01E+00	9,43E-01
Ozone depletion	7,45E-09	5,30E-08	4,04E-08
Photochemical ozone formation	4,33E-03	8,64E-03	7,46E-03
Acidification	4,65E-03	1,02E-02	8,93E-03
Terrestrial eutrophication	1,43E-02	3,28E-02	2,77E-02
Freshwater eutrophication	1,36E-03	4,25E-03	3,43E-03
Marine eutrophication	1,22E-03	2,86E-03	2,41E-03
Freshwater ecotoxicity	5,19E+01	1,61E+02	1,32E+02
Human health (cancer effects)	1,19E-07	2,90E-07	2,42E-07
Human toxicity (non-cancer effects)	2,01E-06	6,58E-06	5,27E-06
Respiratory inorganics	1,58E-03	2,08E-03	1,95E-03
Ionizing radiation HH	7,59E-02	1,62E-01	1,45E-01
Land use	4,53E+00	1,06E+01	8,79E+00
Water resource depletion	2,26E-03	3,43E-03	3,06E-03
Resource depletion	1,19E-03	4,19E-03	3,32E-03

Table S 4. Normalised results for baseline scenario assuming equal weighting across impact categories[a]

Impact category	ILCD		ReCipe	
	Incl. long-term emissions	Excl. long-term emissions	Incl. long-term emissions	Excl. long-term emissions
Climate change	7,57E-05	7,57E-05	6,14E-05	6,14E-05
Ozone depletion	3,45E-07	3,36E-07	3,84E-07	3,75E-07
Photochemical ozone formation	1,36E-04	1,36E-04	7,64E-05	7,64E-05
Acidification (Terrestrial acidificatin ReCiPe)	9,85E-05	9,85E-05	1,04E-04	1,04E-04
Terrestrial eutrophication	8,20E-05	8,20E-05		-
Freshwater eutrophication	9,20E-04	3,23E-04	3,28E-03	1,15E-03
Marine eutrophication	7,28E-05	6,64E-05	3,07E-05	1,79E-05
Freshwater ecotoxicity	5,97E-03	7,86E-05	4,45E-03	3,87E-05
Human toxicity	-	-	3,28E-03	7,57E-05
Human health (cancer effects)	3,24E-03	4,31E-04	-	-

Human toxicity (non-cancer effects)	3,79E-03	3,14E-04	-	-
Respiratory inorganics	3,28E-04	3,28E-04	1,33E-04	1,33E-04
Ionizing radiation HH	6,71E-05	2,47E-05	1,22E-05	4,49E-06
Land use	7,20E-06	7,20E-06	7,62E-05	7,62E-05
Water resource depletion	2,87E-05	2,87E-05	0,00E+00	0,00E+00
Metal depletion	-	-	6,18E-04	6,18E-04
Resource depletion (Fossil depletion ReCiPe)	1,19E-02	1,19E-02	1,30E-04	1,30E-04

[a] Two sensitivity analyses were performed on the results: (1) inclusion/exclusion of long-term emissions, which are controversial in the LCA community, (2) change in LCIA methodologies, which may affect the results.[20]

Table S 5. ILCD impact scores for the three scenarios of disposal in Denmark, including long-term emissions.

Impact category	DK-1		DK-2		DK-3	
	Incl. long-term emissions	Excl. long-term emissions	Incl. long-term emissions	Excl. long-term emissions	Incl. long-term emissions	Excl. long-term emissions
Climate change	6,88E-01	6,88E-01	1,01E+00	1,01E+00	9,43E-01	9,43E-01
Ozone depletion	7,45E-09	7,26E-09	5,30E-08	5,28E-08	4,04E-08	4,02E-08
Photochemical ozone formation	4,33E-03	4,33E-03	8,64E-03	8,64E-03	7,46E-03	7,46E-03
Acidification	4,65E-03	4,65E-03	1,02E-02	1,02E-02	8,93E-03	8,93E-03
Terrestrial eutrophication	1,43E-02	1,43E-02	3,28E-02	3,28E-02	2,77E-02	2,77E-02
Freshwater eutrophication	1,36E-03	4,78E-04	4,25E-03	1,57E-03	3,43E-03	1,26E-03
Marine eutrophication	1,22E-03	1,12E-03	2,86E-03	2,61E-03	2,41E-03	2,20E-03
Freshwater ecotoxicity	5,19E+01	6,83E-01	1,61E+02	9,86E-01	1,32E+02	8,48E-01
Human health (cancer effects)	1,19E-07	1,59E-08	2,90E-07	1,77E-08	2,42E-07	1,75E-08
Human toxicity (non-cancer effects)	2,01E-06	1,67E-07	6,58E-06	3,44E-07	5,27E-06	2,93E-07
Respiratory inorganics	1,58E-03	1,58E-03	2,08E-03	2,07E-03	1,95E-03	1,95E-03
Ionizing radiation HH	7,59E-02	2,79E-02	1,62E-01	5,61E-02	1,45E-01	5,15E-02
Land use	4,53E+00	4,53E+00	1,06E+01	1,06E+01	8,79E+00	8,79E+00
Water resource depletion	2,26E-03	2,26E-03	3,43E-03	3,43E-03	3,06E-03	3,06E-03
Resource depletion	1,19E-03	1,19E-03	4,19E-03	4,19E-03	3,32E-03	3,32E-03

Table S 6. ILCD normalised impact scores for the three scenarios of disposal route in Denmark, including and excluding long-term emissions.

Impact category	DK-1	DK-2	DK-3

	Incl. longterm emissions	Excl. longterm emissions	Incl. longterm emissions	Excl. longterm emissions	Incl. longterm emissions	Excl. longterm emissions
Climate change	7,57E-05	7,57E-05	1,11E-04	1,11E-04	1,04E-04	1,04E-04
Ozone depletion	3,45E-07	3,36E-07	2,45E-06	2,44E-06	1,87E-06	1,86E-06
Photochemical ozone formation	1,36E-04	1,36E-04	2,71E-04	2,71E-04	2,34E-04	2,34E-04
Acidification	9,85E-05	9,85E-05	2,16E-04	2,16E-04	1,89E-04	1,89E-04
Terrestrial eutrophication	8,20E-05	8,20E-05	1,89E-04	1,89E-04	1,59E-04	1,59E-04
Freshwater eutrophication	9,20E-04	3,23E-04	2,87E-03	1,06E-03	2,32E-03	8,51E-04
Marine eutrophication	7,28E-05	6,64E-05	1,70E-04	1,55E-04	1,43E-04	1,31E-04
Freshwater ecotoxicity	5,97E-03	7,86E-05	1,86E-02	1,13E-04	1,52E-02	9,75E-05
Human health (cancer effects)	3,24E-03	4,31E-04	7,87E-03	4,81E-04	6,58E-03	4,75E-04
Human toxicity (non-cancer effects)	3,79E-03	3,14E-04	1,24E-02	6,47E-04	9,90E-03	5,51E-04
Respiratory inorganics	3,28E-04	3,28E-04	4,30E-04	4,30E-04	4,04E-04	4,04E-04
Ionizing radiation HH	6,71E-05	2,47E-05	1,44E-04	4,96E-05	1,29E-04	4,56E-05
Land use	7,20E-06	7,20E-06	1,68E-05	1,68E-05	1,40E-05	1,40E-05
Water resource depletion	2,87E-05	2,87E-05	4,35E-05	4,35E-05	3,88E-05	3,88E-05
Resource depletion	1,19E-02	1,19E-02	4,19E-02	4,19E-02	3,32E-02	3,32E-02

Table S 7. ILCD normalized impact scores for the solar park manufactured with several insulators, scenarios #5-12, and disposal route for the park DK-1.

Impact category	PVC	PE	PC	Glass fibre	PMMA	PP	PS
Climate change	5,46E-05	7,26E-05	7,98E-05	8,08E-05	7,07E-05	7,31E-05	6,92E-05
Ozone depletion	3,30E-07	2,99E-07	3,02E-07	5,40E-07	3,01E-07	2,98E-07	2,97E-07
Photochemical ozone formation	1,25E-04	1,33E-04	1,38E-04	1,44E-04	1,34E-04	1,34E-04	1,33E-04
Acidification	6,15E-05	9,46E-05	1,01E-04	1,03E-04	1,01E-04	9,61E-05	9,40E-05
Freshwater eutrophication	7,28E-05	8,04E-05	8,31E-05	8,45E-05	7,98E-05	8,09E-05	8,00E-05
Terrestrial eutrophication	8,99E-04	9,13E-04	9,16E-04	9,26E-04	9,23E-04	9,13E-04	9,08E-04
Marine eutrophication	6,39E-05	7,07E-05	7,38E-05	7,55E-05	6,82E-05	7,12E-05	7,02E-05
Freshwater ecotoxicity	5,54E-03	5,91E-03	5,92E-03	6,01E-03	5,87E-03	5,90E-03	5,82E-03
Human health (cancer effects)	1,53E-03	3,17E-03	3,26E-03	3,29E-03	3,14E-03	3,20E-03	3,17E-03
Human toxicity (non-cancer effects)	3,68E-03	3,77E-03	3,79E-03	3,82E-03	3,77E-03	3,77E-03	3,76E-03
Respiratory inorganics	2,11E-04	3,25E-04	3,39E-04	3,32E-04	3,27E-04	3,26E-04	3,24E-04
Ionizing radiation HH	6,66E-05	6,62E-05	6,62E-05	6,67E-05	6,62E-05	6,61E-05	6,60E-05
Land use	7,14E-06	7,14E-06	7,15E-06	7,28E-06	7,15E-06	7,14E-06	7,12E-06
Water resource depletion	4,79E-05	2,56E-05	2,70E-05	2,89E-05	2,59E-05	2,62E-05	2,60E-05
Resource depletion	1,19E-02	1,19E-02	1,19E-02	1,19E-02	1,19E-02	1,19E-02	1,19E-02

[a] Normalised scores are obtained by dividing the PET impact scores. Normalised scores above 1 are marked in grey.

Table S 8. ILCD normalized impact scores for the solar park considering several lifetimes for the OPV modules, scenarios #13 - 16, and disposal route for the park DK-1.

Impact category	L=2 y	L=3 y	L=4 y	L=5 y
Climate change	5,69E-01	4,51E-01	3,91E-01	3,56E-01
Ozone depletion	5,53E-09	3,61E-09	2,65E-09	2,07E-09
Photochemical ozone formation	3,72E-03	3,11E-03	2,80E-03	2,62E-03
Acidification	3,79E-03	2,93E-03	2,50E-03	2,24E-03
Freshwater eutrophication	1,16E-02	8,88E-03	7,53E-03	6,72E-03
Terrestrial eutrophication	1,07E-03	7,69E-04	6,21E-04	5,32E-04
Marine eutrophication	1,01E-03	8,03E-04	6,98E-04	6,35E-04
Freshwater ecotoxicity	4,02E+01	2,86E+01	2,28E+01	1,93E+01
Human health (cancer effects)	1,00E-07	8,10E-08	7,15E-08	6,57E-08
Human toxicity (non-cancer effects)	1,56E-06	1,11E-06	8,85E-07	7,49E-07
Respiratory inorganics	1,51E-03	1,44E-03	1,41E-03	1,38E-03
Ionizing radiation HH	6,94E-02	6,29E-02	5,96E-02	5,77E-02
Land use	3,88E+00	3,23E+00	2,90E+00	2,71E+00
Water resource depletion	1,91E-03	1,56E-03	1,39E-03	1,28E-03
Resource depletion	9,01E-04	6,11E-04	4,66E-04	3,79E-04

Table S 9. ILCD impact scores for the solar park manufactured with several power conversion efficiency (PCE), scenarios #17 - 20, and disposal route for the park DK-1.

Impact category	PCE=2%	PCE=3%	PCE=4%	PCE=5%
Climate change	3,44E-01	2,29E-01	1,72E-01	1,38E-01
Ozone depletion	3,73E-09	2,48E-09	1,86E-09	1,49E-09
Photochemical ozone formation	2,16E-03	1,44E-03	1,08E-03	8,66E-04
Acidification	2,32E-03	1,55E-03	1,16E-03	9,29E-04
Freshwater eutrophication	7,13E-03	4,75E-03	3,56E-03	2,85E-03
Terrestrial eutrophication	6,81E-04	4,54E-04	3,40E-04	2,72E-04
Marine eutrophication	6,12E-04	4,08E-04	3,06E-04	2,45E-04
Freshwater ecotoxicity	2,59E+01	1,73E+01	1,30E+01	1,04E+01
Human health (cancer effects)	5,97E-08	3,98E-08	2,98E-08	2,39E-08
Human toxicity (non-cancer effects)	1,01E-06	6,71E-07	5,04E-07	4,03E-07
Respiratory inorganics	7,92E-04	5,28E-04	3,96E-04	3,17E-04
Ionizing radiation HH	3,79E-02	2,53E-02	1,90E-02	1,52E-02
Land use	2,27E+00	1,51E+00	1,13E+00	9,06E-01
Water resource depletion	1,13E-03	7,54E-04	5,66E-04	4,52E-04
Resource depletion	5,96E-04	3,97E-04	2,98E-04	2,38E-04

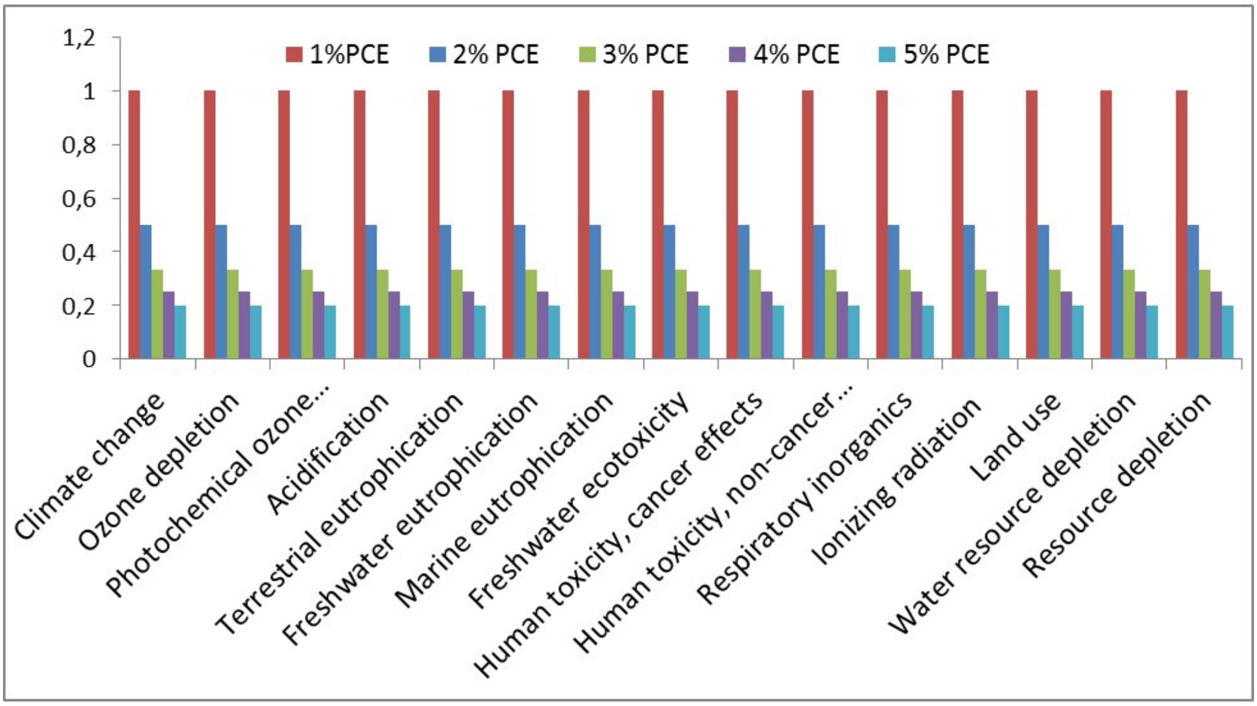

Fig. S 1. Normalized ILCD impact scores for the solar park manufactured with modules where power conversion efficiency (PCE) ranges from 1 to 5%, scenarios #17 - 20, and disposal route for the park DK-1.

Table S 10. ILCD normalised impact scores for the solar park manufactured in Denmark/China and installed in China/Denmark. Scenarios #21 and #22.

Impact category	DK-CN	CN-DK
Climate change	5,30E-05	7,43E-01
Ozone depletion	-4,05E-09	8,34E-09
Photochemical ozone formation	3,14E-03	4,71E-03
Acidification	4,06E-03	5,77E-03
Freshwater eutrophication	1,07E-02	1,56E-02
Terrestrial eutrophication	8,64E-04	1,35E-03
Marine eutrophication	8,98E-04	1,35E-03
Freshwater ecotoxicity	3,42E+01	5,17E+01
Human health (cancer effects)	7,61E-08	1,19E-07
Human toxicity (non-cancer effects)	1,31E-06	2,02E-06
Respiratory inorganics	1,26E-03	1,83E-03
Ionizing radiation HH	4,78E-02	7,84E-02
Land use	3,02E+00	4,55E+00
Water resource depletion	1,65E-03	2,54E-03
Resource depletion	7,72E-04	1,19E-03

Table S 11. ILCD impact scores across different stages in the life cycle of the solar park manufactured and installed in Denmark (scenario 1)

Impact category	Manufacturing	Use	End-of life		
			DK-1	DK2	DK3
Climate change	1,07E+00	-	-3,83E-01	-6,36E-02	-1,56E-01
Ozone depletion	8,29E-08	-	-7,55E-08	-2,98E-08	-4,29E-08
Photochemical ozone formation	9,14E-03	-	-4,82E-03	-5,02E-04	-1,75E-03
Acidification	1,08E-02	-	-6,15E-03	-6,17E-04	-2,22E-03
Freshwater eutrophication	3,43E-02	-	-2,00E-02	-1,50E-03	-6,87E-03
Terrestrial eutrophication	4,23E-03	-	-2,87E-03	8,04E-07	-3,16E-04
Marine eutrophication	2,92E-03	-	-1,69E-03	-7,29E-05	-5,05E-04
Freshwater ecotoxicity	1,63E+02	-	-1,11E+02	1,43E-01	5,02E-02
Human health (cancer effects)	2,97E-07	-	-1,77E-07	-3,06E-09	-3,59E-09
Human toxicity (non-cancer effects)	6,60E-06	-	-4,58E-06	1,06E-08	-4,05E-08
Respiratory inorganics	1,05E-03	-	5,36E-04	1,03E-03	8,86E-04
Ionizing radiation (human health)	1,28E-01	-	-5,24E-02	9,20E-03	1,04E-03
Land use	1,35E+01	-	-8,96E+00	-2,91E+00	-4,67E+00
Water resource depletion	4,84E-03	-	-2,58E-03	-1,41E-03	-1,75E-03
Resource depletion	4,21E-03	-	-3,02E-03	-1,36E-05	-8,84E-04

Table S 12 ILCD impact scores across different stages in the life cycle of the solar park manufactured in China and installed in Denmark (scenario 21)

Impact category	Manufacturing	Use	End-of life	Total
			DK-1	
Climate change	1,13E+00		-3,83E-01	7,43E-01
Ozone depletion	8,38E-08		-7,55E-08	8,34E-09
Photochemical ozone formation	9,53E-03		-4,82E-03	4,71E-03
Acidification	1,19E-02		-6,15E-03	5,77E-03
Terrestrial eutrophication	3,56E-02		-2,00E-02	1,56E-02
Freshwater eutrophication	4,22E-03		-2,87E-03	1,35E-03
Marine eutrophication	3,04E-03		-1,69E-03	1,35E-03
Freshwater ecotoxicity	1,63E+02		-1,11E+02	5,17E+01
Human health (cancer effects)	2,96E-07		-1,77E-07	1,19E-07
Human toxicity (non-cancer effects)	6,60E-06		-4,58E-06	2,02E-06
Respiratory inorganics	1,29E-03		5,36E-04	1,83E-03
Ionizing radiation HH	1,31E-01		-5,24E-02	7,84E-02
Land use	1,35E+01		-8,96E+00	4,55E+00
Water resource depletion	5,11E-03		-2,58E-03	2,54E-03
Resource depletion	4,21E-03		-3,02E-03	1,19E-03

Table S 13. ILCD impact scores across different stages in the life cycle of the solar park manufactured in Denmark and installed in China (scenario 22).

Impact category	Manufacturing	Use	End-of life	Total
			CN-1	
Climate change	6,95E-01		-2,12E-01	4,82E-01
Ozone depletion	5,40E-08		-5,80E-08	-4,05E-09
Photochemical ozone formation	5,94E-03		-2,79E-03	3,14E-03
Acidification	7,02E-03		-2,96E-03	4,06E-03
Terrestrial eutrophication	2,23E-02		-1,16E-02	1,07E-02
Freshwater eutrophication	2,74E-03		-1,87E-03	8,64E-04
Marine eutrophication	1,89E-03		-9,96E-04	8,98E-04
Freshwater ecotoxicity	1,05E+02		-7,12E+01	3,42E+01
Human health (cancer effects)	1,92E-07		-1,16E-07	7,61E-08
Human toxicity (non-cancer effects)	4,27E-06		-2,96E-06	1,31E-06
Respiratory inorganics	6,80E-04		5,79E-04	1,26E-03
Ionizing radiation HH	8,31E-02		-3,53E-02	4,78E-02
Land use	8,73E+00		-5,71E+00	3,02E+00
Water resource depletion	3,13E-03		-1,48E-03	1,65E-03
Resource depletion	2,72E-03		-1,95E-03	7,72E-04

Table S 14. ILCD impact scores across different stages in the life cycle of the solar park manufactured and installed in China (scenarios 23-28).

Impact category	Manufacturing	Use	End-of life					
			CN-1	CN-2	CN-3	CN-4	CN-5	CN-6
Climate change	7,27E-01	-	-2,12E-01	-2,56E-02	-5,97E-02	-9,81E-02	-5,94E-02	-9,78E-02
Ozone depletion	5,41E-08	-	-5,80E-08	-1,78E-08	-2,46E-08	-3,30E-08	-2,46E-08	-3,31E-08
Photochemical ozone formation	6,15E-03	-	-2,79E-03	-2,63E-04	-6,32E-04	-1,18E-03	-6,40E-04	-1,19E-03
Acidification	7,68E-03	-	-2,96E-03	-2,84E-04	-5,44E-04	-1,17E-03	-5,70E-04	-1,20E-03
Freshwater eutrophication	2,30E-02	-	-1,16E-02	-7,75E-04	-2,40E-03	-4,74E-03	-2,42E-03	-4,76E-03
Terrestrial eutrophication	2,73E-03	-	-1,87E-03	9,40E-06	-3,08E-04	-7,04E-04	-3,09E-04	-7,05E-04
Marine eutrophication	1,96E-03	-	-9,96E-04	-2,09E-05	-1,67E-04	-3,79E-04	-1,70E-04	-3,81E-04
Freshwater ecotoxicity	1,05E+02	-	-7,12E+01	2,71E-01	-1,28E+01	-2,75E+01	-1,27E+01	-2,73E+01
Human health (cancer effects)	1,92E-07	-	-1,16E-07	-4,54E-09	-2,33E-08	-4,68E-08	-2,33E-08	-4,68E-08
Human toxicity (non-cancer effects)	4,27E-06	-	-2,96E-06	-9,80E-10	-5,04E-07	-1,12E-06	-5,04E-07	-1,12E-06
Respiratory inorganics	8,35E-04	-	5,79E-04	7,06E-04	7,24E-04	6,84E-04	7,19E-04	6,79E-04
Ionizing radiation HH	8,45E-02	-	-3,53E-02	2,20E-02	1,28E-02	5,53E-04	1,27E-02	4,89E-04
Land use	8,74E+00	-	-5,71E+00	-1,85E+00	-2,50E+00	-3,31E+00	-2,50E+00	-3,31E+00
Water resource depletion	3,31E-03	-	-1,48E-03	-9,02E-04	-9,52E-04	-1,09E-03	-9,59E-04	-1,10E-03
Resource depletion	2,72E-03	-	-1,95E-03	-8,59E-06	-3,39E-04	-7,46E-04	-3,39E-04	-7,46E-04

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