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PeroCUBE – High-Performance Large Area Organic Perovskite devices for lighting, energy and Pervasive Communications

Deliverable 7.4

Quantitative fully integrated life cycle assessment (LCA) with Human Health Risk Assessment (HHRA)

WP 7 – Human health risk assessment and life cycle assessment

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Contents

Acronyms

ALPES	Alpes Lasers SA
AURA	Aura Light Italy srl
CdTe	Cadmium Telluride solar cell
CIGS	Copper Indium Gallium Selenide Solar cell
CNRS	Centre national de la recherche scientifique
CSEM	Swiss Center for Electronics & Microtechnology
EoL	End of life
EULAM	Eulambia Advanced Technologies Ltd.
FRAUNH	Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP
FU	Functional unit
GWP	Global Warming Potential
H2020	Horizon 2020
HHRA	Human health Risk assessment
HSS	Hot Spot Scan
ITO	Indium Tin Oxide
LCA	Life cycle Assessment
MSWI	Municipal Solid waste incineration
NOESIS	Noesis Technologies
OM	Optiva Media
PeLED	PeroCUBE perovskite LED
PePV	PeroCUBE perovskite PV
PSC	Perovskite solar Cell
R2R	Roll to Roll
S2S	Sheet to sheet
TNO	Netherlands Organisation for Applied Scientific Research
TUW	Technische Universität Wien
UOXF	University of Oxford
UPAT	University of Patras
VODAF	Vodafone Innovus
VTT	Technical Research Center of Finland
WEEE	Waste Electrical and Electronic equipment
WP	Work Package

Executive Summary

This deliverable describes the work carried out within Task 7.4 of WP7 of the PeroCUBE project. Task 7.4 aims at performing the life cycle assessment (LCA) of three PeroCUBE devices integrated with a Human Health Risk Assessment (HHRA). This deliverable brings together the efforts carried out in deliverables in previous deliverables of WP7: D7.2 for the identifications of concerning hotspots related to emissions in the environment that could pose a potential risk for human health, and the full human health risk assessment carried out in deliverable D7.3 that calculated the Characterisation factors for the substances of concern.

Objectives of the Deliverable

The objectives of this deliverable are to

- Carry out the LCA for three PeroCUBE devices (flexible and rigid perovskite photovoltaic modules (PePV), and perovskite light emitting diodes (PeLEDs)) with integrated HHRA
- Individuate the life cycle phases where the largest environmental impact and/or human health risks arise for the selected PeroCUBE devices
- Individuate the products or processes responsible for the largest environmental risk for the three PeroCUBE devices
- Compare the environmental and human health impact of the PeroCUBE devices with commercially available products

Outcomes

This extensive study analysed several aspects of the manufacturing of PePV and PeLED devices and placed it in the context of existing commercial alternatives. It can be concluded that the PePV devices show a similar environmental impact to the current commercially available technologies, especially in the case of the PePV on flexible substrates. A thorough modelling of the potential emissions of perovskites during the use phase of the device highlighted the importance of developing fail safe encapsulation methods to avoid PbI_2 reaching the environment.

Next steps

This is the conclusive deliverable of WP7 of the PeroCUBE project, further work on LCA and HHRA will need to be carried out in future projects.

1 Introduction

This deliverable describes the work carried out within Task 7.4 of WP7 of the PeroCUBE project. Task 7.4 aims at performing the life cycle assessment (LCA) of three PeroCUBE devices integrated with a human health risk assessment (HHRA). This is done by outlining three different case studies, one for each chosen device. In continuation with the work carried out in Task 7.3, the selected devices are the flexible PePV, the rigid PePV and the PeLED. While Tasks 7.2 and 7.3 focussed specifically on the perovskite inks developed by the partners, Task 7.4 extends the scope of the research to include the whole device where the perovskite inks are applied. The LCA calculations build on the work carried out in Task 7.2 and 7.3 where the emissions arising during the production process and use phase were estimated (Task 7.2) and their relative characterisation factors for human health toxicity were calculated (Task 7.3). The information produced in tasks 7.2 and 7.3 leads to a more accurate LCA integrated with HHRA of the perovskite devices because, in this way, the LCA can be tailored specifically for the perovskite inks developed in this project. In general, when carrying out an LCA of newly developed materials, lack of data to characterize the new material is a strong limitation of the assessment study. In this way, Human Health Risk Assessment (HHRA) is a powerful tool that allows the generation of reliable and ad-hoc data regarding the toxicity of the new materials and therefore allows to capture accurately these effects in the LCA study. Furthermore, this work extends the previous efforts by analysing different waste treatment routes in detail in order to understand better the risks associated to perovskites during the end of life (EoL) phase.

The chosen case studies allowed the investigation of some of the innovative characteristics of the devices designed in this consortium e.g. the flexible substrate vs the rigid substrate, integration into wearable devices, the roll to roll (R2R) manufacturing process and an evaluation of PeLED devices. To place these devices in the context of other existing products, their environmental performance has been compared to the environmental performance of Copper Indium Gallium Selenide (CIGS) panels, Cadmium Telluride (CdTe) panels and, for the PeLED, conventional OLED screens.

It has to be kept in mind that the goal of this report is not to assess whether the current products and production methods are "safe" in absolute terms. The LCA is a comparative tool by nature and even if a product results better than an alternative (of if the impact of one process step is small compared to the remaining steps) it does not automatically mean that the emissions arising from the product are safe or comply with the regulations. The results of the LCA should be taken as a guidance for further product development.

The remaining part of this report is structured as follows: Chapter 2 gives a detailed description of LCA methodology, including the integration of the HHRA into the LCA, followed by the definition of goal scope, impact assessment method chosen for this work and an in-depth overview of the modelling of each case study. Chapter 3 presents the results of the calculations obtained. Chapter 4 discusses the results and finally Chapter 5 draws the conclusions from all the work presented.

2 LCA method and case studies

2.1 What is an LCA

Life cycle assessment (LCA) is a method to systematically quantify and compare the effects of a product, system, service or geographical entity. As the name suggests, an important characteristic of LCA is that it takes into account the complete life cycle of a product (cradle-to-grave) from resource extraction to waste treatment, including transport in between. In some cases (e.g. if the environmental performance of a company making consumer products is assessed), the analysis is constrained to the production phase (cradle-to-gate). Another important characteristic of LCA is that a wide range of environmental problems can be addressed, such as climate change and toxicity to humans or ecosystems. This way, trade-offs between life cycle stages and/or environmental problem areas are prevented. Finally, LCA is generally considered a comparative rather than an absolute tool. LCA is conducted in four interrelated steps: 1) Goal and scope definition; 2) life cycle inventory; 3) impact assessment; 4) interpretation and conclusions (ISO14040/44).

2.2 Goal, scope and functional unit

In the goal and scope definition, where the products to be compared are defined, the functional unit or reference unit, the type of LCA, system boundaries, and impacts and impact assessment methodology are set. A functional unit (FU) is the unit of comparison to which all flows in the inventory are related. It is important that the functional unit is defined in such way that all systems under comparison fulfil the same function. A reference unit is the unit into which all flows are normalised to and it is used in the analysis of a product.

As mentioned in the introduction, the goal of this report is to evaluate the environmental impact of three devices developed within the PeroCUBE consortium: Flexible PePV, Rigid PePV and PeLED. Since the scope is slightly different for each device, this is discussed separately for each case study in the upcoming paragraphs.

2.3 Description of the case studies

2.3.1 Flexible PePV device

The first case study, aims to investigate in depth the environmental impact of the flexible PePV device that can be integrated in a wearable device such as a badge from its manufacturing to its disposal. Furthermore the scope includes the comparison of the impacts of different EoL options for the treatment of perovskite devices. In this case, the full recycling processes have been modelled, including the environmental burdens generated by the material use and energy use of the recycling process but also included the benefits of the energy and material recovery as avoided burdens. The avoided burdens account for the benefits associated to the recycled materials: these are equivalent to the environmental impacts that would otherwise arise from the production and processing of additional virgin materials (in our case plastic and energy production from conventional sources). The emissions arising during the ink synthesis and the R2R deposition have been accounted for, as reported in deliverable D7.2. Also the potential emissions arising from the use phase have been modelled, including four different emissions scenarios as in deliverable D7.3. To compare the effects of different waste management strategies on the life cycle of the PeroCUBE device, three EoL options have been taken in consideration, see section 3.1.1 for further details on their LCA modelling. Further details on the type and compartments of emissions considered is given in section 2.4.1. Figure 1 displays a diagram showing the system boundaries of the LCA for the flexible PePV device.

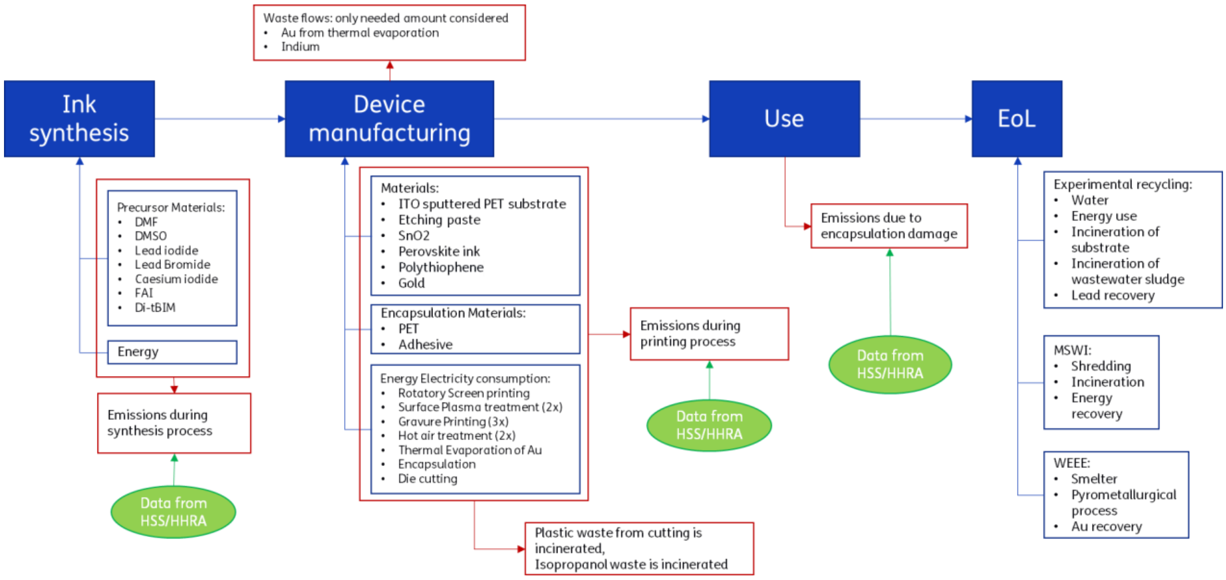


Figure 1: LCA boundaries for the flexible PePV life cycle from Ink synthesis to waste disposal. (Note: HSS indicates the Hotspot scan carried out in deliverable D7.2, HHRA indicates the human health risk assessment carried out in deliverable D7.3, MSWI stands for municipal solid waste incineration and WEEE stands for Waste electric and electronic equipment)

This is therefore a cradle to grave LCA and the chosen reference unit is 1 m^2 of flexible PePV device. While it is unlikely that a badge will reach that dimension, the functional unit of 1 m^2 was chosen to simplify the comparability with other studies in this field.

2.3.2 Rigid PePV device and comparison with existing technology

The second LCA study, aims to compare the environmental impact of the PePV devices developed by the consortium to other PV devices available in the market such as Copper indium gallium selenide (CIGS; flexible and rigid) and Cadmium telluride (CdTe). This case study considers fully commercial modules, not only PV cells as in the previous case study. This means that beyond the materials necessary to create a PV cell also the materials and energy to create a module are considered (e.g. bus bar tabbing, edge sealants, junction boxes, cables to interconnect the modules etc.). This second set of processes will be referred to as “integration”. Further information on the data used for the integration is given in section 3.4.1. Finally, this LCA includes a EoL treatment for each device and therefore also this case is a Cradle to grave study. Still, in this case, the EoL processes have been modelled following the cut-off principle (except for the CdTe panel, which has a specific recycling process to recover the Cadmium). The cut-off principle considers the waste treatment processes only up to the point of lowest material value and therefore excludes all the burdens (and benefits) of transforming the waste into a secondary material. In the case of the rigid modules considered here, this includes the crushing and shredding of the panels. This choice was made to be consistent with the CIGS benchmark model. The chosen functional unit in this case is one kilowatt peak (kWp).

Both case studies presented above exclude the electricity generation, as at the time of writing, the lifespan of the devices is still uncertain.

2.3.3 PeLED case study

Finally, the last study investigates the environmental performance of the PeLED devices developed by the PeroCUBE consortium. Even if the originally intended application of the PeLED was the production of large surface lighting, the experimental developments did not allow to fulfil this goal. Still, due to the general lack of LCA studies on perovskites LEDs, it was deemed interesting to perform such an assessment. For this reason it was chosen to compare the PeLED to and OLED screen, for which a relevant reference study could be found (1). The PeLED devices considered, are produced by the partner VTT and printed on a flexible PET substrate, as the flexible PePV. Due to the early research development of perovskite LED and lack of literature on LCA studies specifically focussing on perovskite LEDs and OLEDs, this is to be considered a screening LCA, due to the large uncertainties that the data unavailability implies. This study does not include a use phase and EoL treatment (as in the available literature reference (1)) and focusses solely on the manufacturing process. It is therefore a cradle to gate LCA and the chosen reference unit is 1 m^2.

2.3.4 Processes outside the system boundaries

In all of the LCA cases considered above, the following processes have been left outside the system boundaries:

Transport

- The transport of the raw materials for the synthesis of PePV and PeLED inks to the CSEM and VTT labs has been excluded as it will not deliver a significant contribution to the impact of PePV and PeLED devices. This has been established in the following manner: in a worst case scenario, it has been assumed that all the ink precursors had to be imported by freight ship (50%) or freight aircraft (50%) from a distance of 7000 km. In this case, the impact of the ship transport would contribute to 0.2% of the ink impact and the impact of aircraft transport would contribute to 14.5% of the ink impact. Still, the impact of the ink is less than 1% in the case of the PePV device with carbon back contact, making the overall impact of transport negligible on the final results.

- The transport of the precursors of the secondary materials (i.e. the materials necessary to produce the raw materials needed for the ink synthesis) has been included by selecting process in the databased considered which already included average transport values.

Energy for the production of precursor materials

The inventories for the synthesis of precursor materials, (when not available in the chosen database (ecoinvent v 3.8 (2)) for the PePV and PeLED inks have been taken from literature sources (see Table 13 to Table 30). Where literature references where not available, the inventory was based on proxies or stochiometric reactions. In the latter case, the energy for production was not included. The authors are aware that for certain chemicals the energy production process represents an important source of environmental footprint but further research in this was deemed out of scope for this project. This forms a limitation of this study.

The energy used for mixing the production of the PePV and PeLED ink at lab scale in VTT and CSEM has been excluded as it has a small contribution on the lifecycle of the PePV and PeLED devices studied here.

Packaging

Packaging materials (e.g. cardboard or plastics for the packaging of PV modules) have been excluded from the system boundaries as their impact will be limited.

2.3.5 Geographical scope and expected audience

The geographical scope for all the devices is Europe, unless country specific data were available for the manufacturing process considered. The primary audience for which these studies are carried out are the PeroCUBE consortium partners but we intend to publish the results of this work in relevant scientific journals, in order to amplify the impacts of these studies.

The following section explains in detail the methodology followed to carry out the LCA studies, describes the production processes for all the devices and benchmarks, EoL pathways modelled and describe the inventories for all the different study cases.

2.4 Impact Assessment Method and Modelling in SimaPro

Impact assessment describes the phase, where the long list of emissions to the environment (or interventions) is translated into a number of so-called midpoint impact categories by modelling the underlying environmental mechanism. The impact assessment method chosen for this LCA study is the ReCiPe 2016 method (3). ReCiPe 2016 is the most complete impact assessment method currently available. In ReCiPe 2016, two levels of environmental impact indicators are distinguished: 18 midpoint indicators and 3 endpoint indicators. Midpoint indicators focus on single environmental problems, e.g. climate change, acidification and eco-toxicity. Endpoint indicators give a picture of environmental damage at a higher aggregation level, namely the impact on human health, biodiversity and resource scarcity. Essentially, this is a "weighting" of the impact of different midpoint indicators on areas of protection that are closer to the general reader and therefore endpoints are easier to interpret. The downside of this is that the extra aggregation increases uncertainty in the results. Figure 2**Error! Reference source not found.** displays a diagram of the ReCiPe indicators

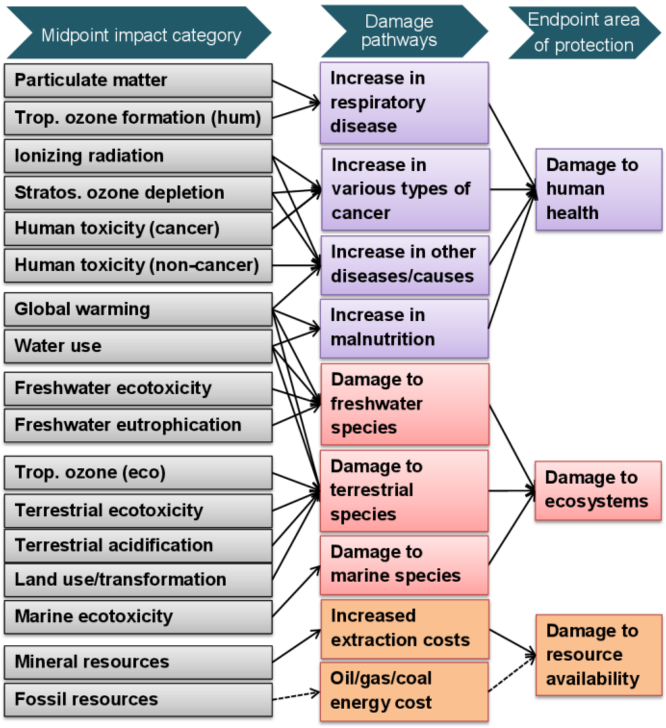


Figure 2: Diagram showing the midpoint and endpoint indicators of the ReCiPe 2016 method

This translation between emissions and the effect on a specific impact category is calculated by using "characterization factors" (CF) and allows to add all interventions that contribute to the same environmental problem in one common unit. For example, for the carbon footprint, emissions of greenhouse gases are re-calculated to kg CO2-equivalents (by means of the characterization factors) by using Global Warming Potentials (GWP) that express the contribution of a gas to radiative forcing relative to that of CO_2. Each impact assessment method contains all the CFs for all the emissions considered in that method. Ideally, all emissions should have a corresponding characterization factor, but especially for new materials this is often not the case, making it a challenge to make an accurate life cycle assessment for these materials. This is the case for the perovskite inks and crystals under investigation in this study. These are of particular concern for the impact categories related to human toxicity, due to the presence of lead in the perovskites. In order to fill this knowledge gap, this LCA study integrated the CF calculated as part of the HHRA presented in deliverable D7.3 in the ReCiPe 2016 method. Deliverable 7.3 presented the endpoint characterisation factors, but to include these results in the LCA, the midpoint characterisation factors were used. The midpoint CF were also calculated using USEtox (4) based on the substance-specific properties in fate and human exposure factors.

2.4.1 Inclusion of new Characterisation factors in ReCiPe

The USEtox midpoint characterisation factors reported the characterisation factors for emissions in several compartments: household indoor air, industrial indoor air, urban air, rural air, freshwater, sea water, natural soil, and agricultural soil. Not all these emission compartments are relevant for the LCA studies carried out in this work, and a selection of the compartments has been made based on the system boundaries of the first case study:

1. Emissions during ink synthesis: These emissions arise from the synthesis of the ink (in a lab or factory environment). Only industrial indoor air and urban air have been considered. From deliverable D7.2 also emissions to soil and wastewater had been considered. These are emissions that arise during the relevant cleaning processes of the laboratory facilities and these operations have been excluded from the scope of this LCA.
2. Emissions during device fabrication: These emissions arise from the synthesis of the ink (in a lab or factory environment). Only industrial indoor air and urban air have been considered, following the same considerations expressed above.
3. Emissions during use phase: these emissions arise from the potential breakage of the encapsulation e.g. due to weather agents giving rise to potential run off of perovskite crystals. Only freshwater emissions and urban, non-industrial soil have been considered here.

Table 1 gives an overview of the USEtox midpoint characterisation factors for the substances included in the HHRA. The cells highlighted in yellow indicate the values included in the LCA calculations performed in this study.

Table 1: Midpoint Human health characterisation factor [cases/kg emitted] calculated with USEtox for the relevant emission compartments and included in the LCA calculations performed in this study. The cells highlighted in yellow show the Characterisation factors of Dimethyl Sulfoxide for freshwater and natural soil. These factors have not been included in the LCA since their emissions arise from the lab cleaning processes that are outside the scope of this LCA study.

	Industrial indoor air		Urban air		Freshwater		Natural soil	
Substance	Cancer	Non-cancer	Cancer	Non-cancer	Cancer	Non-cancer	Cancer	Non-cancer
Dimethyl sulfoxide	n/a	4.65E-08	n/a	7.92E-09	n/a	9.97E-09	n/a	3.35E-09
Perovskite ink and crystals	1.02E-05	3.58E-03	7.33E-06	2.57E-03	1.79E-07	6.29E-05	8.93E-08	3.13E-05

In order to be included in ReCiPe 2016 the USEtox midpoint characterisation factors (expressed in cases/kg) have been converted to Endpoint characterisation factors (DALY/kg) (Disability Adjusted life years) for cancer and non-cancer separately (in D7.3 the endpoints were expressed as a single endpoint and could not be separated in cancer and non-cancer correctly). This operation was done by means of the USEtox conversion factors reported in the USEtox documentation (4), see Table 2. The results can be seen in Table 3.

Table 2: USEtox 2.12 conversion factors (4). (Note: PDF stands for Potentially Disappeared fraction and PAF stands for Potentially Affected Fraction)

Damage category	Unit	Impact category	Factor	Unit
Human health	DALY/kg	Human toxicity, cancer	11,5	DALY/cases
Human health	DALY/kg	Human toxicity, non-cancer	2,7	DALY/cases
Ecosystems	PDF.m3.day	Freshwater ecotoxicity	0,5	PDF.m3.day/PAF.m3.day

Table 3: Calculated USEtox endpoint characterisation factors included in the LCA calculations performed in this study. The cell highlighted in yellow show the Characterisation factors of Dimethyl Sulfoxide for freshwater and natural soil. These factors have not been included in the LCA since their emissions arise from the lab cleaning processes that are outside the scope of this LCA study.

	Industrial indoor air		Urban air		Freshwater		Natural soil	
Substance	Cancer DALY/kg	Non cancer DALY/kg	Cancer DALY/kg	Non cancer DALY/kg	Cancer DALY/kg	Non cancer DALY/kg	Cancer DALY/kg	Non cancer DALY/kg
Dimethyl sulfoxide	n/a	1.26E-07	n/a	2.14E-08	n/a	2.69E-08	n/a	9.04E-09
Perovskite	1.17E-04	9.66E-03	8.43E-05	6.94E-03	2.06E-06	1.70E-04	1.03E-06	8.46E-05

The USEtox endpoint characterization factor thus calculated for cancer and non-cancer human toxicity categories could be entered directly in the ReCiPe Endpoint method as also recipe expresses the Endpoint characterisation in DALY/kg. Following this step, the ReCiPe midpoint characterisation factors for the substances considered could be calculated using the midpoint to endpoint conversion factors reported in (3). Table 4 reports the conversion factors and Table 5 reports the obtained results.

Table 4: ReCiPe 2016 midpoint to endpoint conversion factors (3). (Note: DCB stands for Dichlorobenzene, which is takes as a reference substance for the measurement of toxicity effects in ReCiPe 2016)

Midpoint to endpoint conversion factor	Unit	Value
Human toxicity (cancer)	DALY/kg 1,4DCB eq	3.32E-06
Human toxicity (non cancer)	DALY/kg 1,4DCB eq	2.28E-07

Table 5: Calculated ReCiPe midpoint characterisation factors included in the LCA calculations performed in this study. The cell highlighted in yellow show the Characterisation factors of Dimethyl Sulfoxide for freshwater and natural soil. These factors have not been included in the LCA since their emissions arise from the lab cleaning processes that are outside the scope of this LCA study.

	Industrial indoor air		Urban air		Freshwater		Natural soil	
	cancer kg 1,4DCB eq	non cancer kg 1,4DCB eq	cancer kg 1,4DCB eq	non cancer kg 1,4DCB eq	cancer kg 1,4DCB eq	non cancer kg 1,4DCB eq	cancer kg 1,4DCB eq	non cancer kg 1,4DCB eq
Dimethyl sulfoxide	n/a	5.51E-01	n/a	9.38E-02	n/a	1.18E-01	n/a	3.96E-02
Perovskite	3.53E+01	4.24E+04	2.54E+01	3.04E+04	6.21E-01	7.45E+02	3.09E-01	3.71E+02

The LCA modelling has been made using the commercial software SimaPro v. 9.5, the background data have been taken from the database ecoinvent 3.8, (Cut-off processes). The ecoinvent database already includes the infrastructure processes (e.g. factory use, equipment etc). Long-term emissions (i.e. arising 100 years after the activity took place) are excluded from the calculations.

3 Inventories

This section gives a detailed description of the case studies and shows how the inventories have been built for each device.

3.1 Flexible PePV device

The first case study focusses on a flexible PePV device integrated in a wearable, such as a badge. This device has been fabricated by partner VTT, who provided the data for material and energy consumption measured at their demonstrator R2R printing machine. At first, the perovskite inks for printing in the R2R VTT facilities were synthetized in the VTT labs, by mixing the components. This was done in a lab scale mixer. The energy required for this task was excluded from the calculations as the impact of this operation is in all likelihood small and not significant on the final results. Table 6 gives an overview of the components necessary to synthesize the ink. As it can be seen from Table 6, most of the ink components are speciality chemicals that are not available in ecoinvent. For each component a suitable inventory has been retrieved from literature, in order to model the ink material production as accurately as possible. The full inventory of the perovskite inks, including details on the inventory modelling can be seen in Table 13 in the appendix.

Table 6: List of the flexible PePV ink components for the production of 1kg of flexible PePV ink

Material	Mass	Unit
Formamidinium iodide (FAI)	0.472	kg
Cesium iodide (CsI)	0.015	kg
Lead iodide	0.137	kg
Lead Bromide	0.012	kg
Dimethyl sulfoxide (DMSO)	0.352	kg
Methylammonium Chloride	0.002	kg
Maize starch	0.011	kg

Once the ink components were synthesized, they could be used directly in the R2R printing facilities of VTT (No transport was included as both operations occurred on VTT facilities). Roll to roll printing, in this case, refers to the process of creating electronic devices on a roll of flexible plastic by applying coatings (or other types of material deposition techniques) starting with a roll of a flexible material and re-reeling after the process to create an output roll. Figure 3 shows a diagram of the R2R production.

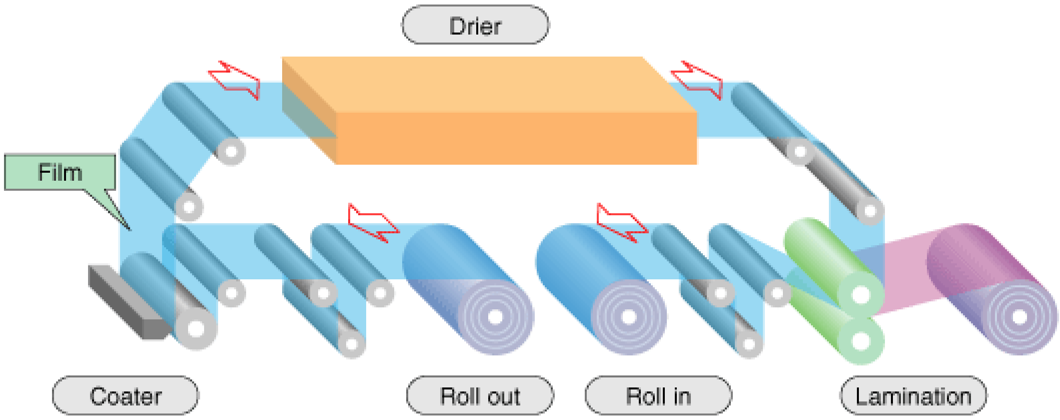


Figure 3: Diagram representing the general R2R printing process.

In the case of the PePV, the substate used was and ITO coated PET layer which was used as received. The ITO was etched applying an etching paste by rotary screen printing and subsequently underwent surface plasma treatment. The etching paste was then washed away using isopropanol. A layer of SnO_2 was added by gravure printing and cured by surface plasma treatment. The perovskite ink was deposited by gravure printing and cured by hot air treatment. The P3HT was added by gravure printing. The back contact was deposited by thermal evaporation. This could not be made on the R2R machine but had to be made on a separate thermal evaporation chamber. Finally the module was encapsulated front and back using PET with SiOx adhesive. Figure 4 summarises these steps in a diagram and the full inventory of the device manufacturing has been reported in Table 15 in the appendix.

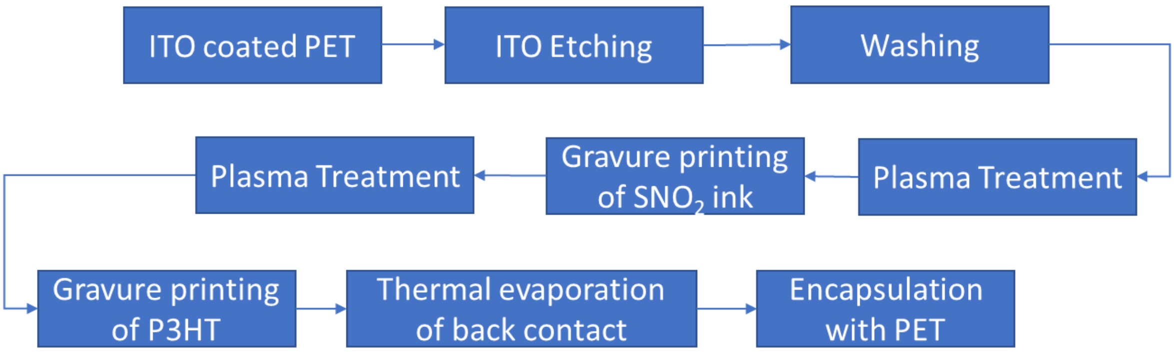


Figure 4: Diagram showing the manufacturing steps of the flexible PePV device.

Initially, the material used as a back contact was gold. Gold is often used in perovskite cells research and development for its excellent conductive properties, but it presents extremely high environmental impacts, as can be seen from the results presented in section 4.1. For this reason, it is expected that this material will be replaced in the future manufacturing of the PV cell with a carbon back contact. To allow future comparability of the results presented in this work, also the PePV with a carbon back contact has been modelled. The carbon paste inventory was based on (5) and the inventory is reported in Table 15. The device manufacturing procedure was slightly modified, since it is assumed that the carbon back contact was deposited by screen printing. Another advantage of using carbon as a back contact is that in the future this could be deposited by R2R, as described in (5).

3.1.1 Inventory for EoL processes

Three different EoL processes have been considered for this study. In the first case, it was assumed that the badge would be disposed as general waste, crushed and incinerated. This will be referred to as “Standard EoL”. In the second case it was assumed that the process followed in (6) was implemented for the recovery of PbI_2, while the remaining solid waste was incinerated and the remaining wastewater was disposed of as hazardous wastewater. This second scenario is referred to as “Experimental EoL”. In the third case, it was assumed that the PePV badge was disposed of as WEEE (Waste electronic and electric equipment) and gold was recovered through a pyrometallurgical process, this last case is referred as “WEEE EoL”.

Standard EoL

The standard EoL scenario assumes the shredding and incineration of the waste. It is assumed that the incineration takes place in a municipal incineration plant (7) with energy recovery, transport to the waste treatment facility has been assumed to be made by an average lorry for a distance of 100km. This EoL scenario mirrors the assumptions reported in deliverable 7.3, where a distinction between 4 scenarios has been made, according to the amounts of PePV ink that reaches the waste treatment phase.

Table 7: Summary of the 4 scenarios considered for use phase and standard EoL modelling according to deliverable 7.3

Scenario	Description
Scenario 1	Encapsulation remains intact, 100% PePV crystals reaches the EoL
Scenario 2	Minor encapsulation damage, 95% of PePV crystals reaches the EoL and 5% is emitted during lifetime
Scenario 3	Major encapsulation damage, 50% of PePV crystals reaches the EoL and 50% is emitted during lifetime
Scenario 4	Total encapsulation damage, 100% of PePV crystals is emitted during lifetime

In order to tailor the incineration process to the specificity of the PePV wearable device waste different incineration process cards have been produced using the ecoinvent EoL tools (8), for the four different scenarios described in Table 7.

Table 8: Materials used in the R2R deposition and encapsulation process of PePV in VTT, Materials available and proxies used in the ecoinvent EoL tools used to model the composition of the PePV waste and relative mass percentages per m².

Material used	Material in ecoinvent EoL tools	Scenario 1 (mass %)	Scenario 2 (mass %)	Scenario 3 (mass %)	Scenario 4 (mass %)
PET	PET	84.688%	84.715%	84.955%	85.224%
ITO coating	ITO coating	0.201%	0.201%	0.201%	0.202%
Adhesive	Pe sealing sheet	13.488%	13.492%	13.530%	13.573%
PePV Crystals	PePV crystals*	0.629%	0.597%	0.315%	0.000%
Gold	Inert Metals	0.253%	0.253%	0.254%	0.255%
SnO_2	Tin Slag	0.393%	0.393%	0.394%	0.395%
P3HT	Polythiophene**	0.253%	0.253%	0.254%	0.255%
Total mass kg/m²		*0.458*	*0.458*	*0.457*	*0.455*

**The PePV crystals were modelled as a separate waste component based on the elemental composition of the ink provided by the partners, as in Deliverable D7.2. **P3HT was modelled as a separate waste component based on its chemical formula, $(C_{10}H_{14}S)_n$*

Experimental EoL

This scenario has been developed based on the data reported in (6) and close communication with project partner VTT. This waste treatment process prescribed that the PePV badge is shredded in pieces of approximately 0.5cm² and soaked in water. The water is then heated to 50ºC in order to dissolve the perovskite layer, the solids are then separated from the liquid solution and the lead iodide is precipitated from the solution and recovered. This process is repeated twice in order to recover 96% of the original lead iodide input contained in the perovskite ink. Figure 5 displays a diagram of the Experimental waste treatment process.

The amount of input water was calculated to obtain a final concentration of 1 g/L of PbI_2 as reported in the paper. In the case considered here, this resulted in 0,4 L of water input to treat 1m² of PePV. The water could be reused multiple times, according to what is reported in (6) but at the moment it is not known how many times as this was not an object of investigation in (4). For this work, it has been assumed that the water could be reused twice and then is disposed as spent solvent.

In the procedure described in the paper (6), the solid is removed by hot aqueous extraction, a procedure that requires energy. It was assumed that this was a lab scale procedure and that in industrial conditions it would be possible to separate the liquid and the solid waste without using energy, e.g. by letting the solids fall in a separate chamber. For this reason energy demand for filtration was excluded from the LCA calculations. Energy demands for the extraction of the PbI_2 from the water solution was accounted for as it was estimated that a process such as centrifugation would have been necessary at industrial scale. The full inventory for this EoL treatment has been reported in Table 23 of the Appendix.

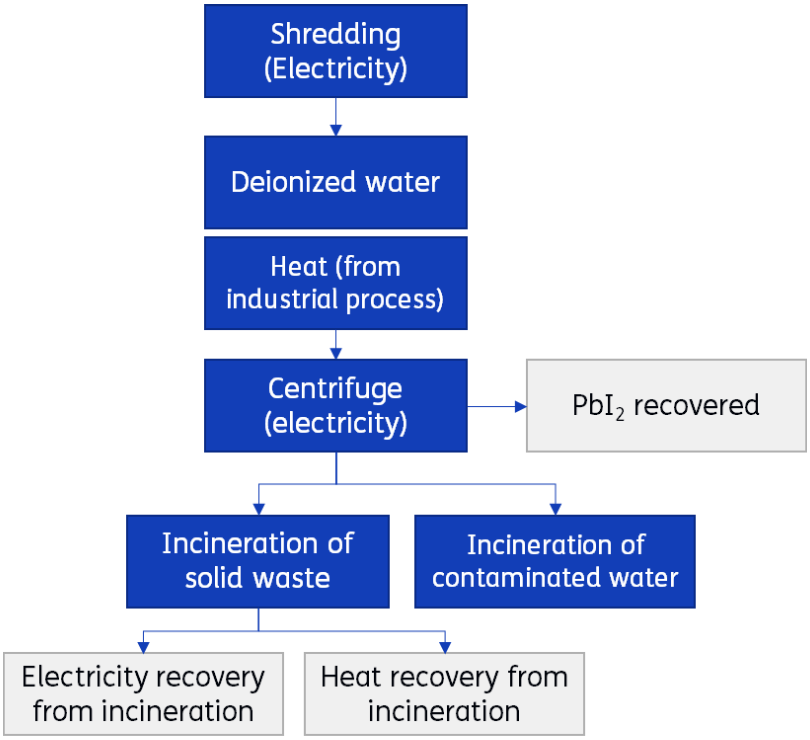


Figure 5: Diagram showing the Experimental EoL process as derived from (6)

WEEE EoL

This EoL process has been modelled based on the information reported in the ecoinvent report "Life Cycle Inventories of Metals", Part IX, Gold and Silver (9). The process modelled here is the pyrometallurgical technique used by a copper smelter plant that treats also WEEE. The WEEE enters the process at the Kaldo plant. The valuable metals distribute into the copper matte which is further processed into copper. There, the precious metals go into the anode slime which is specifically treated in the precious metal recovery plant.

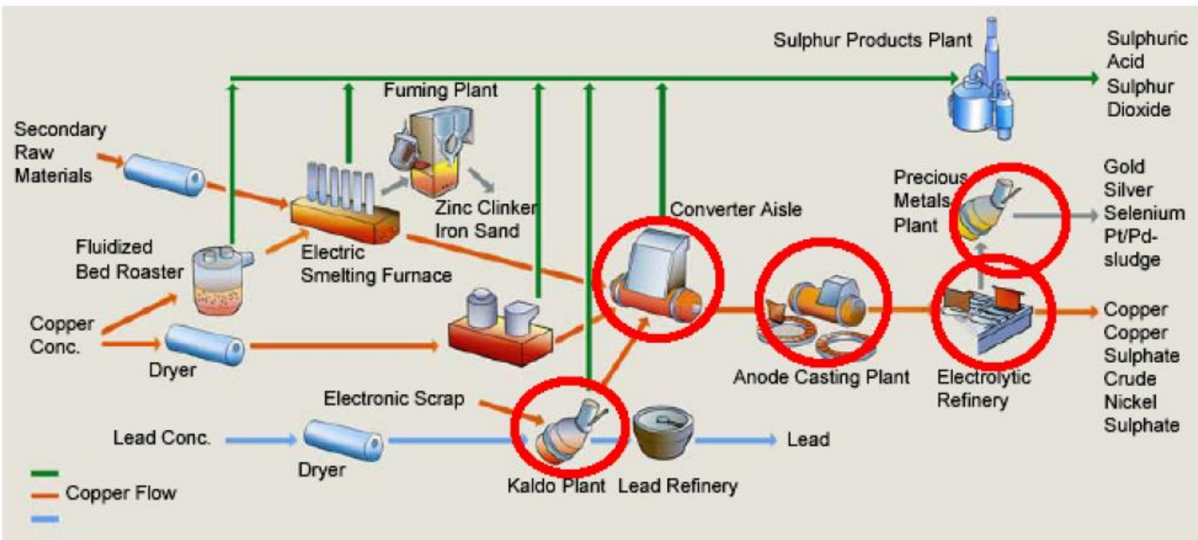


Figure 6: Concept of the pyrometallurgical gold recovery process as described in the ecoinvent report. The stages circled in red are those relevant for the gold recovery process.

The recovery process has a relatively low efficiency, as only 35% of the gold is won back. Considering that the gold is only used for R&D purposes and it is unlikely that it will reach industrial production, this EoL route has not been modelled in further detail and the ecoinvent process “Gold {SE}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Cut-off, U” has been used as a proxy for the gold recovery process without further modifications. The full Life cycle inventory (LCI) for this EoL process has been reported in Table 24 of the Appendix.

3.2 Rigid PePV device

Project partner CSEM developed PePV devices on a rigid glass substrate and provided the material and energy consumption measured at their laboratory facilities. As in the case of the Flexible PePV, initially the perovskite inks were synthetized by mixing at CSEM facilities, also in this case, the mixing energy at lab scale was not included. As in the case of the ink for the flexible PePV, the inventories for each ink component were modelled according to online literature. A full inventory of the rigid PePV ink with is reported in Table 14 in the Appendix.

Table 9: List of the rigid PePV ink components for the production of 1kg of rigid PePV ink

Material	Mass	Unit
N,N-dimethylformamide (DMF)	0.5670	kg
Lead (II) Iodide (PbI2)	0.2344	kg
Formamidinium Iodide (FAI)	0.0720	kg
Cesium Iodide (CsI)	0.0232	kg
Lead (II) Bromide (PbBr2)	0.0329	kg
Methylammonium Bromide (MABr)	0.0100	kg
Methylammonium Chloride (MACl)	0.0061	kg
Additive A	0.0083	kg
Additive B	0.0433	kg
Additive C	0.0001	kg
Additive D	0.0027	kg

Once the inks were synthetized, they could be deposited by blade coating in the CSEM laboratory facilities. As in the case of the Flexible PePV, the PV is constructed “upside down” starting the deposition process on the glass substrate that will become the front glass and depositing the back contact at last. Figure 7 displays the manufacturing steps of the rigid PePV device.

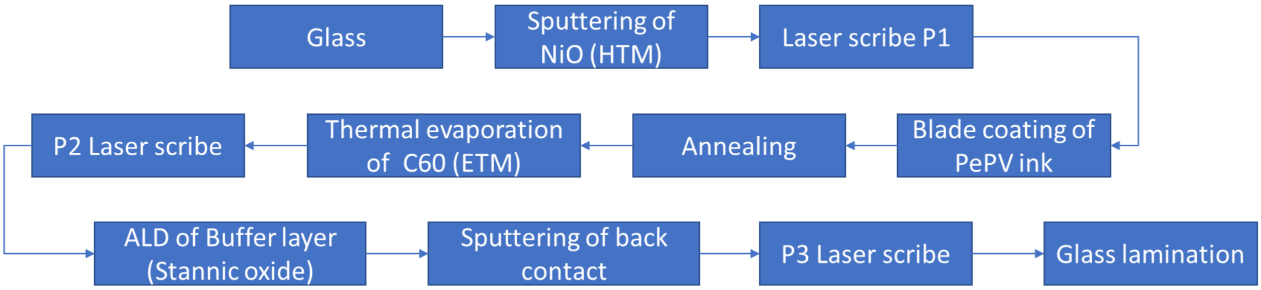


Figure 7: Diagram showing the manufacturing steps of the rigid PePV device

Two possible material back contacts were considered: Silver (for opaque PV) and ITO for transparent PV. Initially, the total energy consumption was estimated only based on the data supplied by CSEM but after an initial consultation with internal TNO sources, it appeared that the estimated energy amounts for the sputtering and atomic layer deposition processes was extremely high. This was attributed to the small scale of the facilities used and it was decided to substitute this with internal TNO data on energy consumption of sputtering processes which are representative of a semi-industrial scale. Since this data is confidential, the energy consumption is presented as an aggregated number. The inventory can be found in Table 17 in the appendix. As the scope of this LCA study includes the comparison of the Rigid PePV panel with commercially available modules, the comparison has been done per kWp. It was assumed that the Rigid PePV device considered here would reach an efficiency of 18%, thus requiring an area of 5,56 m^2 to generate 1 kWp of power. The measured efficiency of the PePV devices is currently between 12%-14%. The higher efficiency assumption has an important effect on the results presented here: if calculated with an efficiency of 13%, the area required to generate 1kWp would reach 7,69m^2 (27% higher), and therefore the input materials per kWp would be proportionally larger. Still, based on the best efficiencies already achieved by perovskite cells at research level (26,1%) (10), it is reasonable to expect that at industrial scale, the PePV devices would achieve 18% efficiency. It was therefore chosen to base the calculations on 18% efficiency in order to generate a fair comparison with the selected industrially produced benchmark products.

In this case, emissions during the use phase have not been considered here, as their impact is extensively discussed in the previous case study. The EoL processes included only the transport and shredding of the device but not the incineration with energy recovery, in accordance with the cut-off principle.

3.3 PeLED device

The third LCA focussed on the analysis of the PeLED devices. The PeLED devices were manufactured by partner VTT who provided the inventory data for material and energy consumption for the ink synthesis and R2R printing. As in the case of the PePV devices, the speciality chemicals used in the synthesis of the PeLED inks were modelled according to literature sources and where this was not possible proxies were selected. Table 10 to Table 12 provide the list of components for the inks, the full inventory can be found in Table 18, Table 19 and Table 20 of the Appendix.

Table 10: List of the Green PeLED ink components for the production of 1kg of Green PeLED ink

Material	Mass	Unit
butylammonium bromide (BABr)	0.1519	kg
Cesium bromide (CsBr)	0.2950	kg
Lead bromide ($PbBr_2$)	0.5071	kg
18-crown-6	0.0360	kg
DMSO	0.0099	kg

Table 11: List of the Red PeLED ink components for the production of 1kg of Red PeLED ink

Material	Mass	Unit
butylammonium bromide (BABr)	0.1711	kg
Cesium iodide (CsI)	0.5045	kg
Lead iodide (PbI_2)	0.2856	kg
18-crown-6	0.0305	kg
DMSO	0.0084	kg

Table 12: List of the Blue PeLED ink components for the production of 1kg of Blue PeLED ink

Material	Mass	Unit
M-Cl	0.1417	kg
Cesium bromide (CsBr)	0.2993	kg
Lead bromide (PbI_2)	0.5155	kg
18-crown-6	0.0340	kg
DMSO	0.0094	kg

The PeLED were deposited on a PET substrate, following a manufacturing procedure similar to the Flexible PePV manufacturing. Figure 8 displays a diagram showing the steps of the PeLED manufacturing. The full inventory for the PeLED deposition is displayed in Table 21 of the appendix.

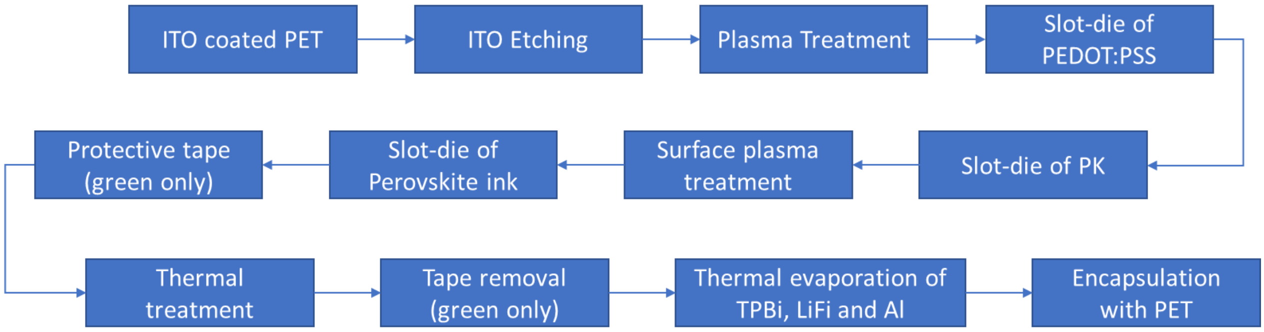


Figure 8: Diagram showing the manufacturing steps of the PeLED devices

Comparing the components of the PeLED inks and manufacturing with the components of the PePV inks and manufacturing, it can be seen that more speciality chemicals were used. Unfortunately, replicating speciality chemicals is still a challenge in ecoinvent and therefore in several cases a proxy or the average chemical ecoinvent process card had to be used.

3.4 Benchmark devices

3.4.1 PV reference devices

The benchmark devices to be compared with the PePV devices are commercially available CIGS and CdTe technologies. These technologies have been chosen because they are also thin film PV technologies, that can also be deposited on flexible substrates.

The CdTe inventory has been taken from the IEA task 12 report (11) and it is representative for the First Solar series 6 panel, manufactured by First Solar. The reported energy efficiency of the CdTe panel is 18.6%. The CdTe waste treatment and recycling process has been modelled according to the data displayed in (11), Tables 33 and 34 of the appendix. In this case, the recycling process includes the benefits associated to the energy and material recovery, since, due to the presence of cadmium, the recycling process has to include the steps necessary to recover cadmium. In this case therefore, the EoL process could not be modelled using a single cut-off strategy, as it was not possible to separate the inputs relative to the waste treatment and the recovery of secondary materials. A detailed LCA analysis of this device can be found in (12)

The Rigid CIGS inventory is based on the inventory reported in (13) for the pilot production of a Rigid CIGS. The same procedures followed in (13) have been applied to upscale the production of rigid CIGS to industrial level, with an efficiency of 18%. Furthermore, the energy consumption has been double checked with (14), which base their energy consumption estimate on measured data at a CIGS factory facility. The data reported in (13) excluded processes necessary to make a fully functional module from a PV cell e.g. bus bar tabbing, edge sealants, cables to interconnect the modules, junction boxes etc. These data have been taken from (15) and adapted to a CIGS panel based on internal TNO conversations with PV production experts. This set of data has been applied also to model the integration of the rigid PePV into a fully functional PV module. See Figure 9 for a diagram shoving the structure of the LCA inventory followed for the case study 2. A similar procedure has been used to create the inventory for the integration of the flexible PePV in a module: this has been based on internal TNO data used to integrate flexible CIGS cell on roof tiles to create building integrated PV panels. The full inventory for the integration of the flexible PePV into a module has been reported in Table 28 and Table 29 of the Appendix.

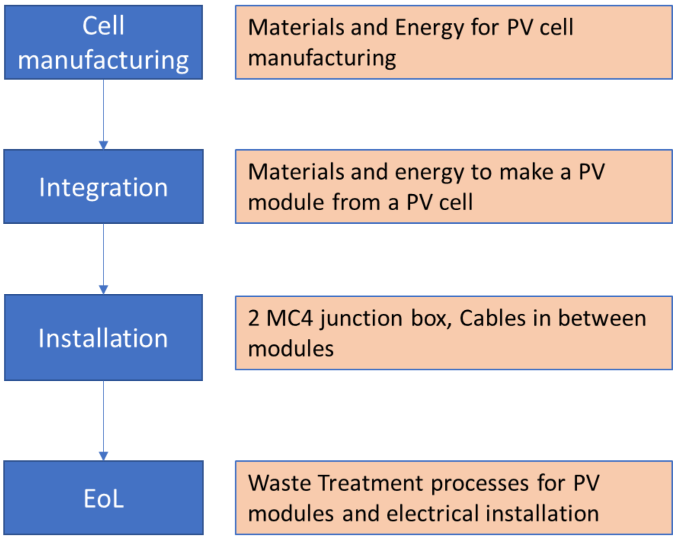


Figure 9: Diagram explaining the inventory of the benchmark models used in case study 2

3.4.2 Reference OLED device

While the literature on LCA of perovskite solar cells is vast, no papers were found on the LCA of perovskites LEDs. Still, in order to improve this LCA study on PeLED, it was decided to include an OLED screen as reference device. The reference OLED screen was modelled according to (1) which reported a partial inventory for the manufacturing of the screen. The data reported in (1) incomplete, as, in order to carry out the LCA, the mass of the materials per functional unit is required but it was not available from the reported inventory. Furthermore, not all the materials were specified. This lack of data was complemented by calculating the mass of the materials based on the volume of the layers for a screen size of 136.6x69.8mm and making assumptions on the lacking material types based on literature information. Finally, the data were converted to a reference unit of $1m^2$ to compare with the PeLED devices. The full inventory of the OLED reference device is reported in Table 30 of the Appendix.

The data presented In (1) refer to the industrial production of a five inch display component for smartphones manufactured in South Korea. OLED fabrication begins with pre-treatment of ITO substrate, and multiple organic layer and metal layer are deposited by vacuum vapor deposition process. The substrate then moves to the load and lock room where it rests for the preparation of packaging step to complete. Lastly, packaging of the display proceeds via glass frit sealing, which is a bonding technique with an intermediate glass layer. All production processes are assumed to take place in one industrial manufacturing site, so transportation between processes within the system boundary are not considered. The emissive layer and the hole transport layer were assumed to be made of organometallic dyes, Alq3 (Tris-(8-hydroxyquinoline)aluminium) and Copper (II) phthalocyanine (CuPc), respectively. The inventories for Alq3 and CuPc were available in the supporting information of (1) and were adapted to the ecoinvent database.

4 Results

This section presents the results obtained from the three case studies outlined in section 2.

4.1 Flexible PePV device

Initially the complete life cycle (i.e. from ink formulation to waste treatment, use and EoL of 1m^2 of Flexible PePV with carbon back contact (assuming the standard EoL scenario) and gold back contact (assuming the WEEE end of life scenario) were analysed with the modified ReCiPe Endpoints method. This step was made to determine what are the midpoint indicators that weight most on the impact of the flexible device. This was done in all leakage scenarios, in order to see if the emissions to the environment of the perovskite crystals during the use phase would lead to significant differences in the midpoint categories to be analysed. In all cases, the most relevant midpoint categories remained the same: Global warming, Fine particulate matter formation, terrestrial acidification, Ozone formation, Human non-carcinogenic toxicity, Land use and Fossil resource scarcity, see Figure 10.

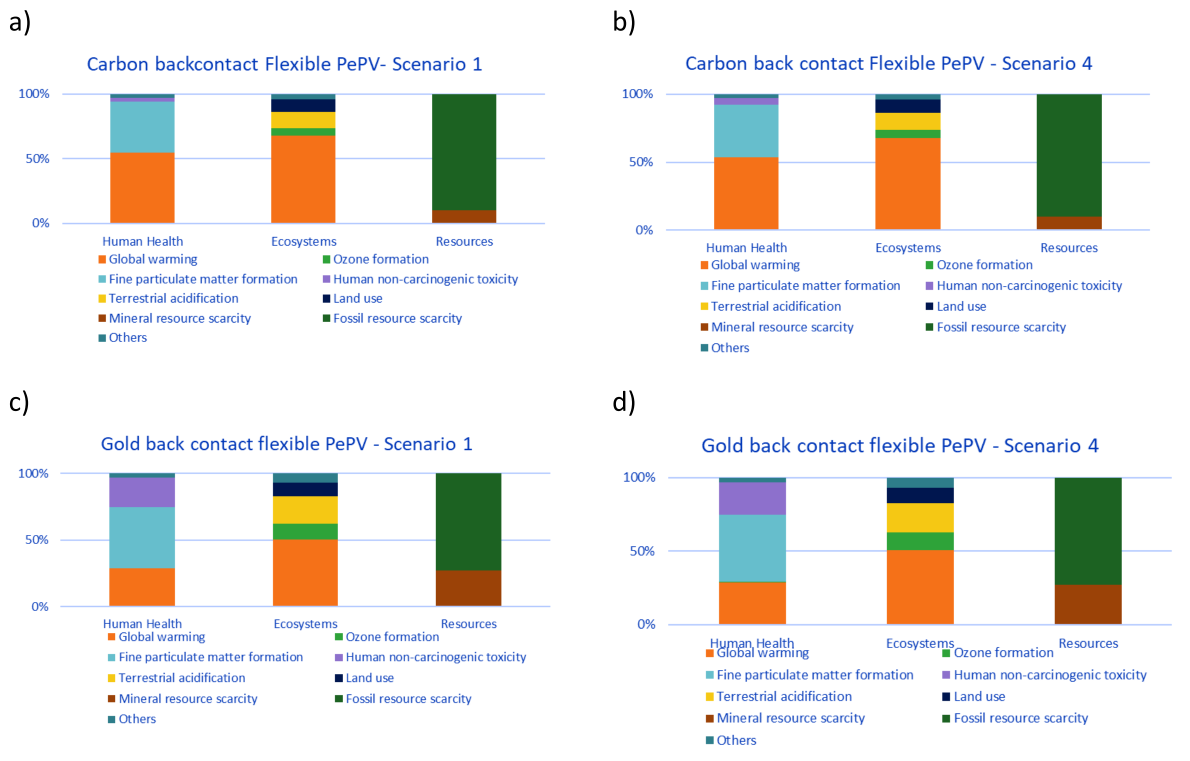


Figure 10: Relative impact of the midpoint categories on the Endpoint indicators for 1m^2 of Flexible PePV, with carbon back contact and gold back contact, full life cycle, in the case of 0% leakage to the environment (scenario 1) and 100% leakage to the environment (scenario 4).

This analysis has been performed to restrict the number of midpoint indicators used when presenting the results in graph form, to improve the legibility of the results ensuring to include the most relevant information. The complete endpoint results are reported in Table 31 in the appendix.

Figure 11 shows the relative contribution per life phase for the selected midpoints indicators for 1m^2 of Flexible PePV, with gold back contact, per life cycle in scenario 4, i.e. assuming that all the perovskite crystals would leach into the environment. It can be seen that the largest contribution is delivered by the manufacturing phase in all midpoint categories and from the WEEE end of life processes. The use phase delivers a very small contribution to the human non-carcinogenic toxicity due to the leaching of perovskite crystals. The recovery of gold in the WEEE EoL offers a considerable mitigation of the environmental impact, due to the benefits associated with the avoided production of gold, except in the toxicity category since the gold recovery process has a considerable impact on human toxicity as well.

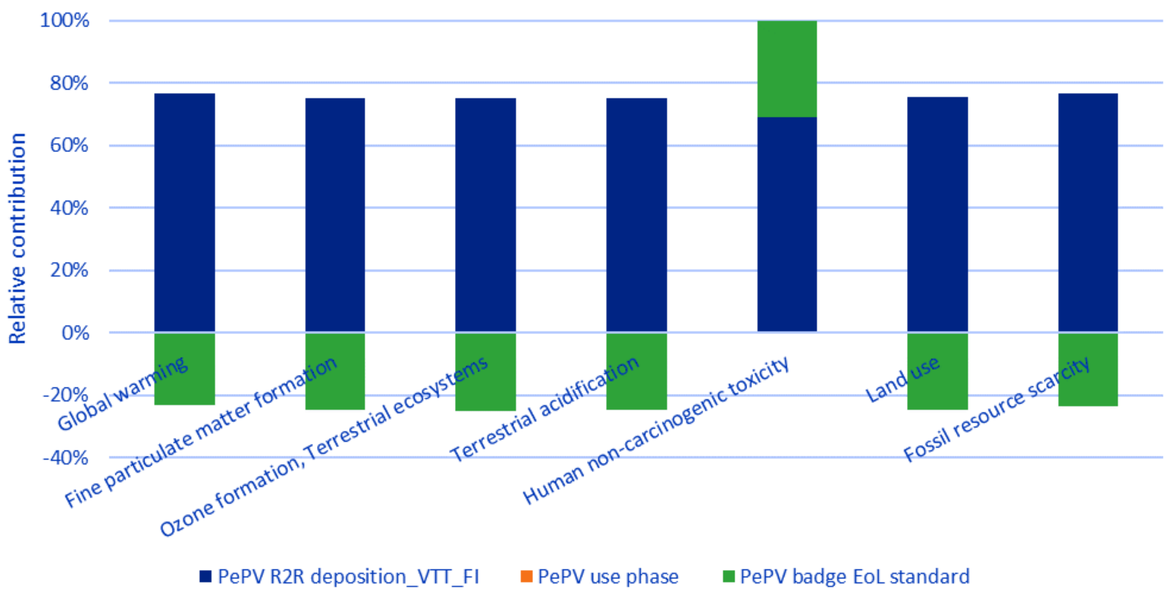


Figure 11: Relative contribution of different life phases of 1m² of Flexible PePV with gold back contact, full life cycle with WEEE EoL to the midpoints indicators.

Zooming into the impact of the manufacturing process (see Figure 12), it can be seen that most of the impact is generated by the gold back contact in all the midpoint impact categories. The complete results for the manufacturing of the flexible PePV device with gold back contact are available in Table 27.

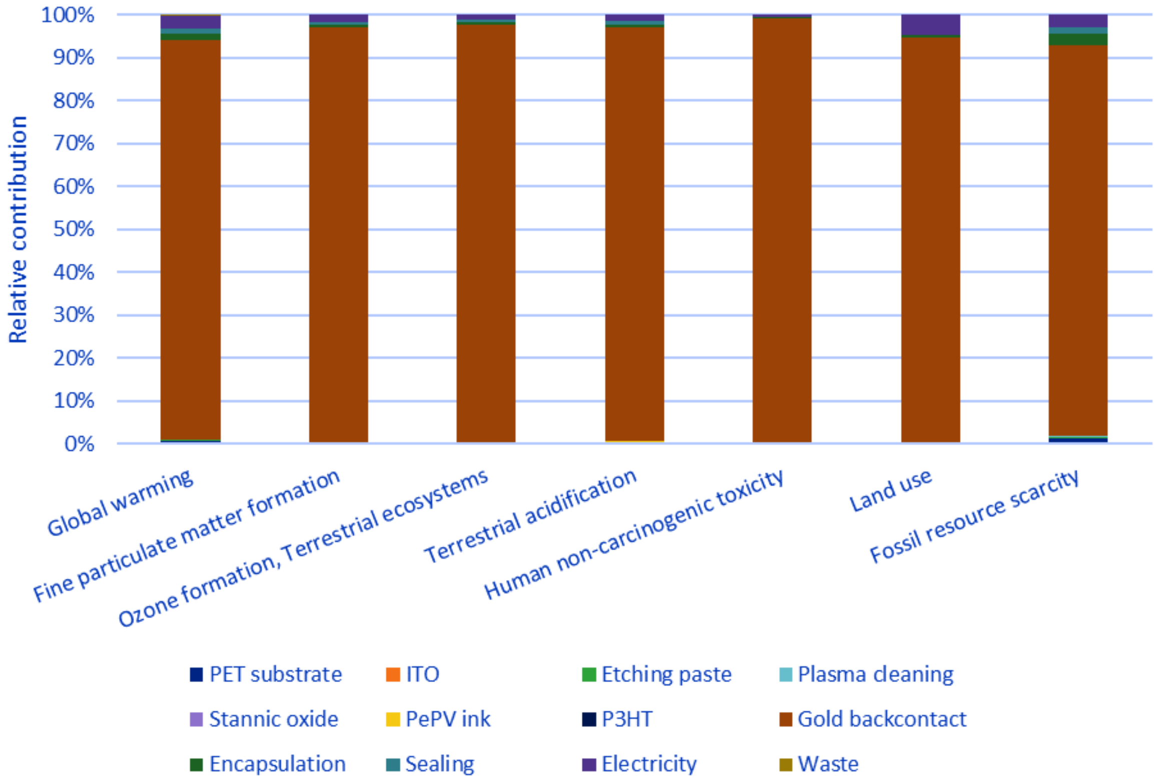
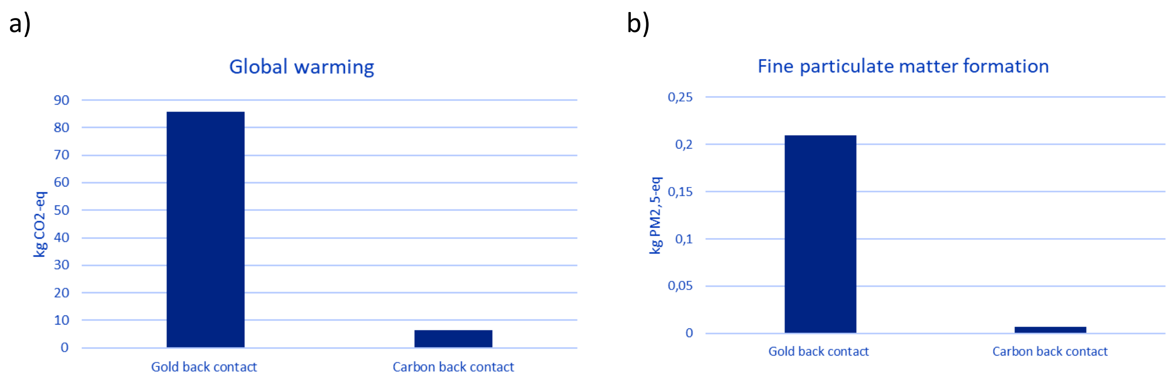


Figure 12: Relative contribution of different manufacturing steps of 1m² of Flexible PePV, with gold back contact to the selected midpoints indicators.

As mentioned in section 3.1, gold is used as a back contact for research and development purposes and it is expected that in the future, the back contact will be made of carbon. In order to show the difference in impact between the device with carbon back contact and gold back contact, the following figures display the absolute results for each midpoint category of the two deceives (assuming Standard EoL treatment for both devices to keep the systems as comparable as possible), see Figure 13. It can be seen that the impact of a carbon back contact PV is considerably smaller than the impact of the gold back contact PV cell. The reduction factor for each category ranges between 9 (Fossil resource efficiency) and 67 (Human non-carcinogenic toxicity).



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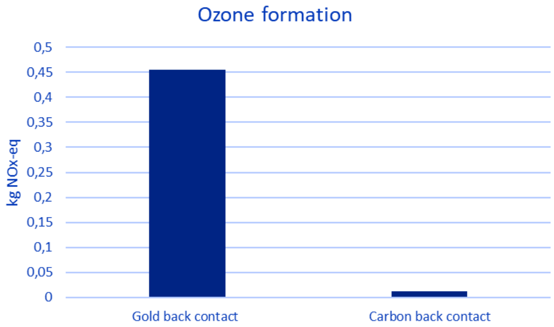

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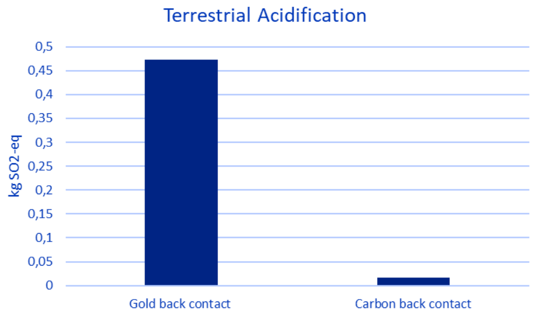

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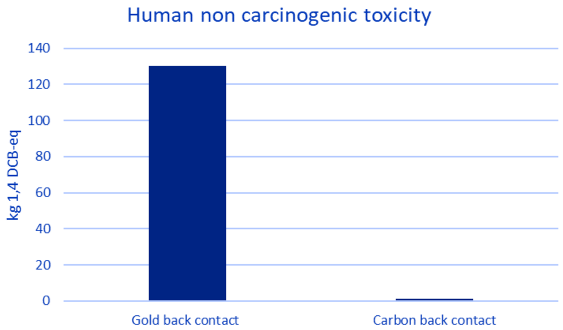

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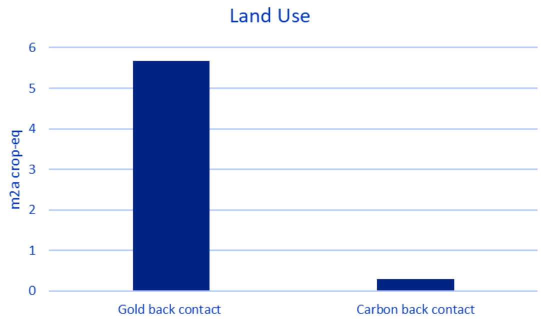

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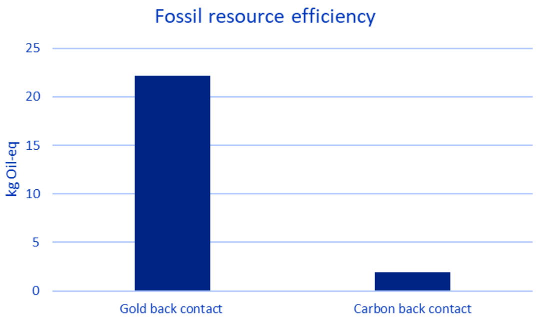


Figure 13: Comparison of the environmental impact assessment of 1m² of Flexible PePV with Gold back contact and Carbon back contact in the most relevant impact categories: a) Global warming potential b)Fine particulate matter formation c) Ozone formation Potential d) Terrestrial Acidification e)Human non-carcinogenic toxicity potential f) Land Use g) Fossil resource efficiency.

Figure 14 displays the contribution to the environmental impact per life stage of the flexible PePV with carbon back contact, assuming 100% leakage of the perovskite crystals to the environment and the standard EoL scenario (incineration with energy recovery). Also in this case, it can be seen that the manufacturing process gives rise to the largest environmental impact during the lifetime of the device in all the midpoint categories displayed. The incineration with energy recovery provides some benefits due to the energy recovered during the incineration process. In this case though, the effect of the perovskites leaking into the environment is clearly visible in the Human non-carcinogenic toxicity impacts as it contributes to nearly 43% of the impact. It must be underlined here that the results reported in Figure 14 are relative to the total impact per category of the flexible PePV with carbon back contact. The impact of the leaching (beware that this is the worst case scenario) becomes suddenly more visible because the non-carcinogenic toxicity of the production process is significantly decreased due to the absence of gold. Further considerations on toxicity are reported in section 5.1.2.

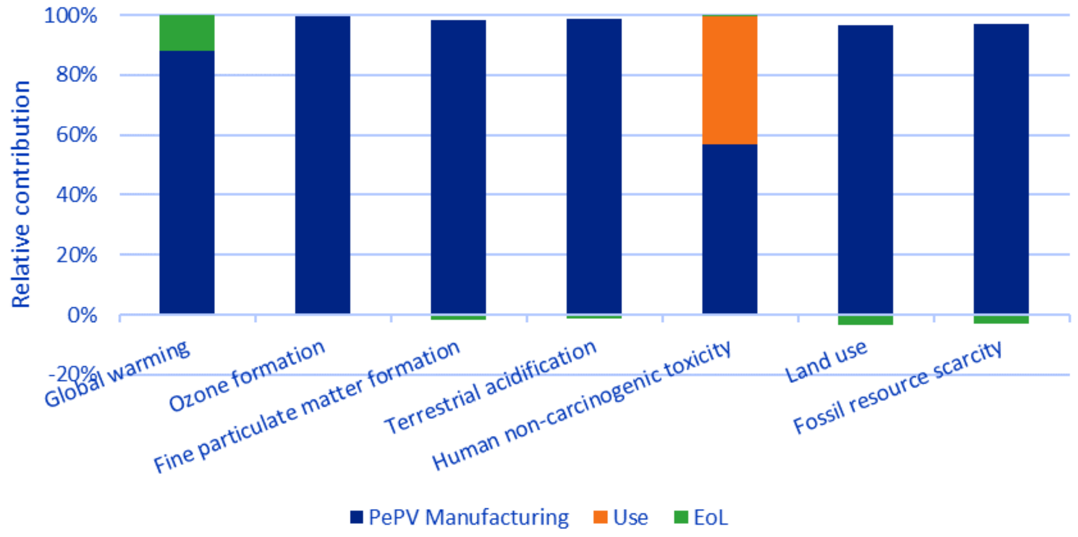


Figure 14: Relative contribution of different life phases of 1m² of Flexible PePV with carbon paste back contact, full life cycle with Standard EoL to different midpoint categories

Figure 15 gives an in-depth overview of the environmental impact of each manufacturing step for the flexible PePV with carbon back contact. In this case, the largest contribution is given by the electricity used in the manufacturing process and followed by the PET. The complete results can be seen in Table 34.

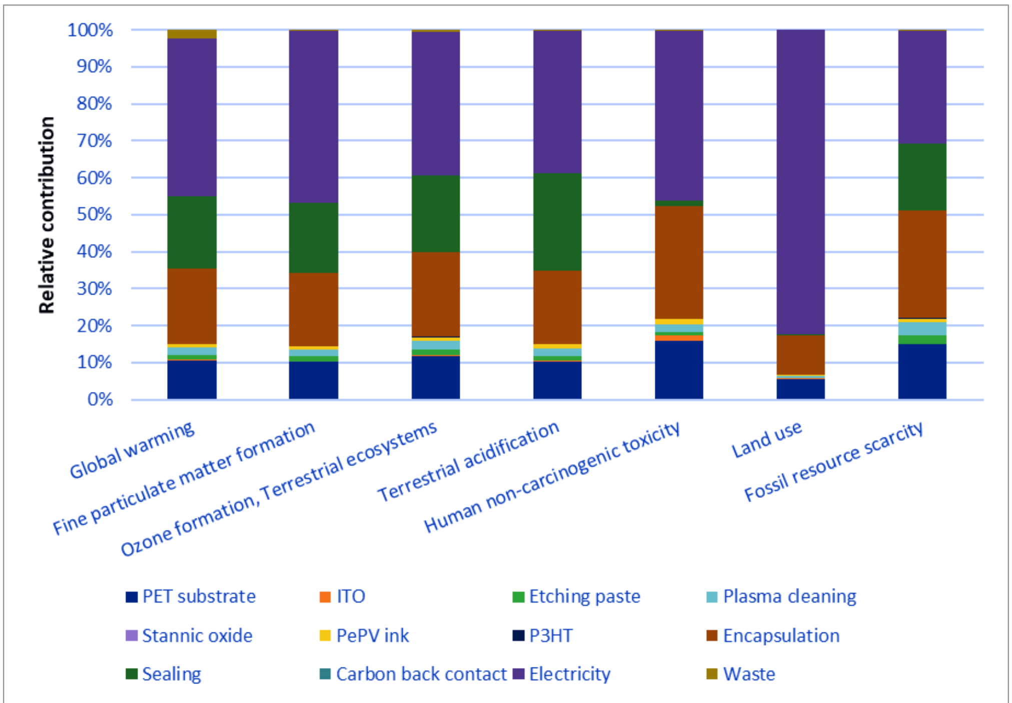


Figure 15: Relative contribution of different manufacturing steps of 1m² of Flexible with carbon back contact to the selected midpoint indicators.

4.1.1 Further results on toxicity

As mentioned in section 2.4, the ReCiPe impact assessment has been modified in order to include the characterisation factors of the solvents used in the ink manufacturing, the Perovskite inks and crystals calculated in deliverable 7.3. This section shows the impact that this modification has on the results obtained. The results in the human carcinogenic and non-carcinogenic toxicity midpoints are displayed in Figure 16 for the carbon back contact flexible PePV, for the different leaching scenarios outlined in section 3.1.1. Looking at Figure 16, it can be seen that the non-carcinogenic impacts are higher than the carcinogenic impacts. The modification of the ReCiPe method allows to capture the impact of the leached perovskite: the non-carcinogenic toxicity, in fact, increases from 1.4 kg 1.4DCB-eq to 2.5 kg 1.4DCB-eq. The unmodified recipe method would have not been able to register this increase in toxicity, due to the emissions of perovskites into the environment.

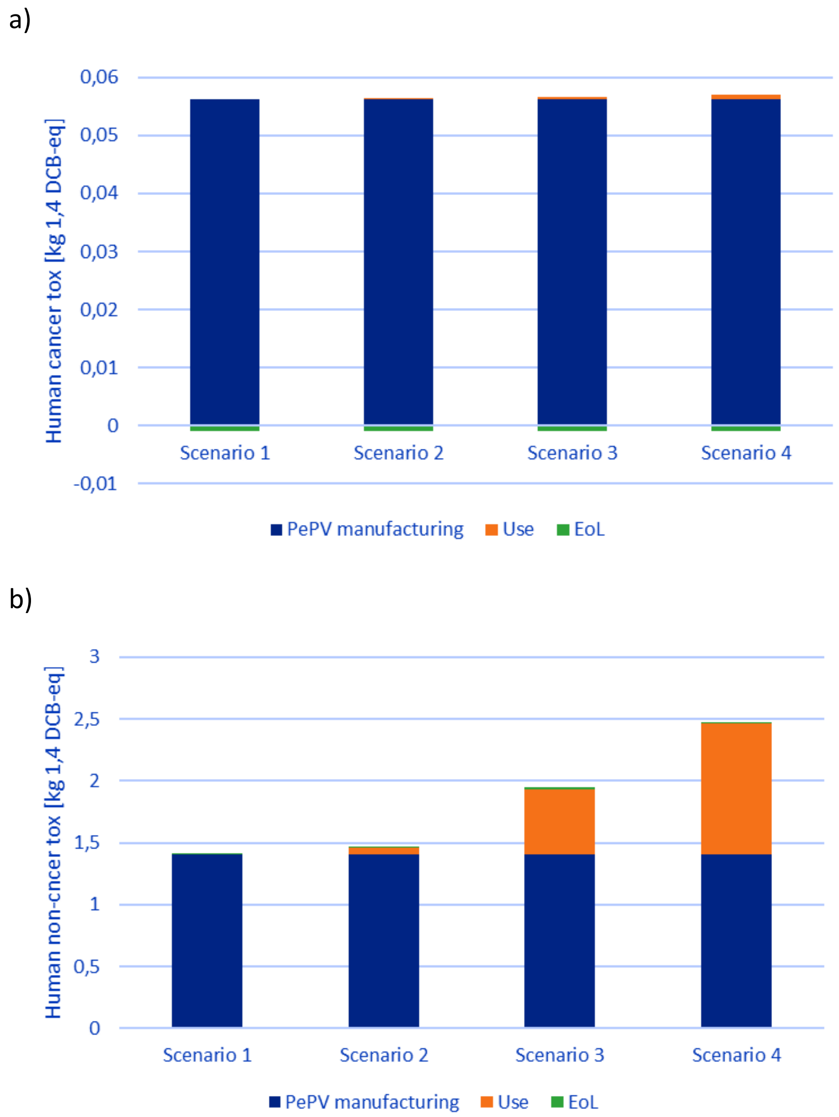
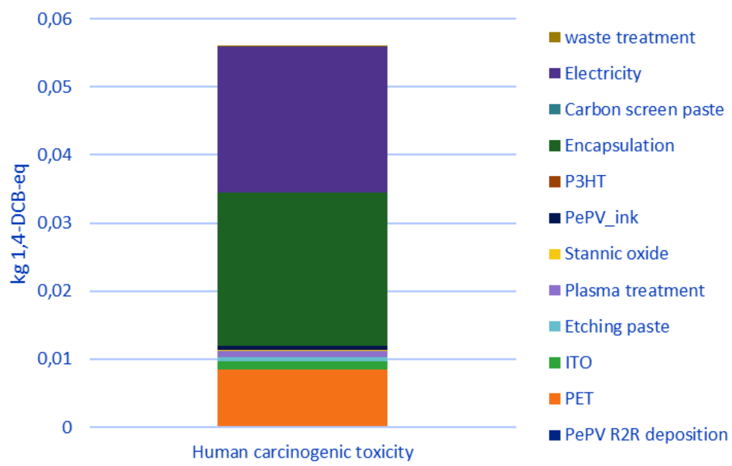


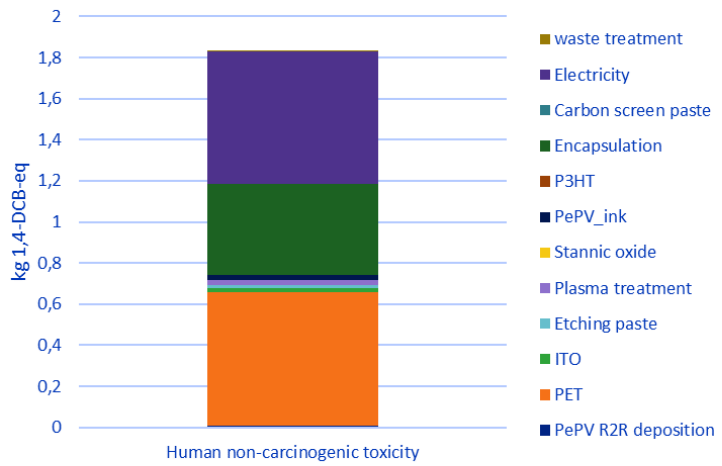
Figure 16: Human carcinogenic (a) and non-carcinogenic toxicity (b) for different perovskite leaching scenarios for 1 m^2 of Flexible PePV with carbon back contact and standard EoL scenario.

The emissions of PePV ink that arise during the deposition process are also captured by the modified ReCiPe method. These have an extremely small contribution to human toxicity (0.01% in the case of the cancer toxicity and 0.33% in the case of the non-carcinogenic toxicity) when compared to the toxicity of the remaining materials and electricity use. See Figure 17, "PePV R2R deposition". The impact of the PePV ink to human non carcinogenic toxicity is approximately 1,5% of the total. This impact is caused by the materials used in the production process (especially lead iodide and FAI), the emissions arising from the ink synthesis do not deliver any significant contribution to the human toxicity categories.

In order to fully interpret these results, a clarification is needed: the toxicity generated by the PePV ink calculated based on the USEtox characterisation factors reflect the risk and exposure of the workers during the production process via the indoor air of the facility where the production process is performed. The toxicity of the remaining materials instead reflects the exposure of the general population to a substance via different routes. An initial emission to continental air might lead to potential inhalation of the substance by the general public and will expose ecosystems to the substance via e.g. emission or deposition of the substance to freshwater, seawater and soils. Via the air the substance can thus also expose the general population via their dietary intake. The same goes for initial emissions to water and soil. So, lead emissions from the incineration of e.g. hard coal in power plants will expose the general population to lead and uptake of lead via inhalation and the diet.



a)



b)

Figure 17: Human carcinogenic and non-carcinogenic impact of 1 m2 of flexible PePV deposition process

4.1.2 End of Life analysis

This section focusses specifically on the analysis of the Standard and Experimental EoL processes. Figure 18 and Figure 19 display the relative contributions to the midpoint impact categories for the Experimental and Standard EoL processes. As it can be seen from Figure 18, in the Standard EoL process, the benefits attributed to the heat and electricity recovery of the PePV generally offset the burdens associated with the incineration process (except in the case of global warming and human non-carcinogenic toxicity). In the case of the Experimental EoL instead, the additional burdens associated with the water heating, wastewater disposal and electricity use for centrifuging are not entirely offset by the benefits associated with the PbI_2 recovery. It is important to remember here that the wastewater disposal is based on the assumption that the water can only be used twice before being disposed of. This has a major impact on the results and therefore it should be investigated further experimentally. Overall, the impact of both treatments is comparable, as it can be seen from the comparison per midpoint category reported in Figure 20 and the absolute results reported in Table 35 and Table 36.

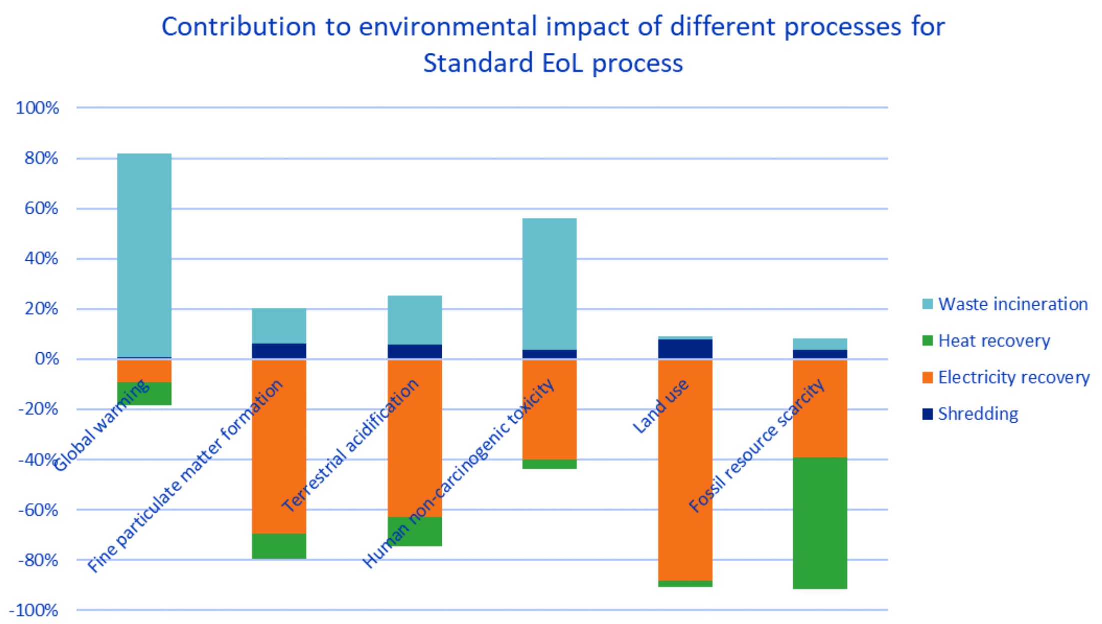


Figure 18: Midpoint results for the Standard EoL for 1m² of PePV device. Each bar has an absolute height of 100%.

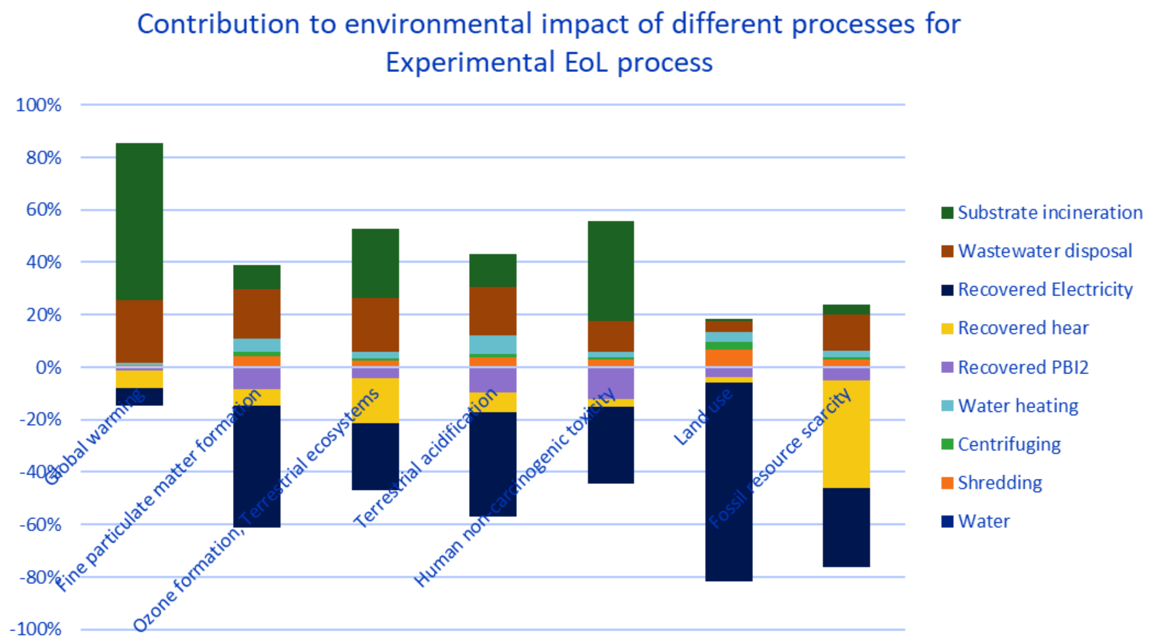


Figure 19: Midpoint results for the Experimental EoL process of 1 m2 of PePV device. Each bar has an absolute height of 100%.

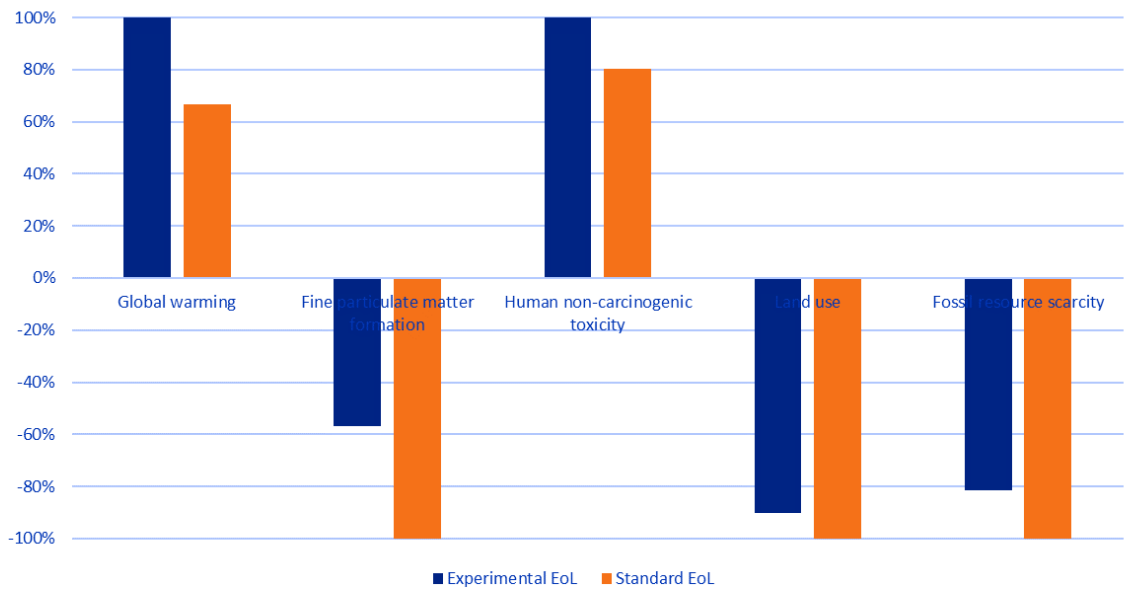


Figure 20: relative comparison for the Standard and Experimental EoL processes for the different midpoint categories taken in consideration. The results are normalised to the process with highest impact e.g. in the case of global warming, the Experimental scenario has the largest impact and the standard scenario produces "only" 67% of the impact of the experimental scenario. For the absolute results see Table 35 and Table 36 in the appendix.

A clarification must be made related to the results presented in deliverable D7.3, where it was shown that a large amount of lead emissions arises during the EoL processes. The figures reported in D7.3 refer to long term emissions, i.e. emissions, usually from landfills which are released to the air or ground water 100 years after the landfilling happened. So far, no consensus has been reached among LCA experts if and how long-term emissions should be taken into account and usually are excluded from the calculations.

4.2 Rigid PePV device

In this case, the calculations were carried out per functional unit of 1 kWp, in order to facilitate the comparison with other existing LCA studies on PV technologies. It was assumed that the rigid PePV cell could reach an efficiency of 18%, resulting in a surface of 5,56 m^2 per kWp. As in the case of the flexible PePV, at first the ReCiPe Endpoint results were calculated, to highlight the most relevant midpoint impact categories. These are displayed in Figure 21. As in the previous case, the most relevant midpoint categories are global warming, fine particulate matter formation, terrestrial acidification, ozone formation, human non-carcinogenic toxicity, land use and fossil resource scarcity.

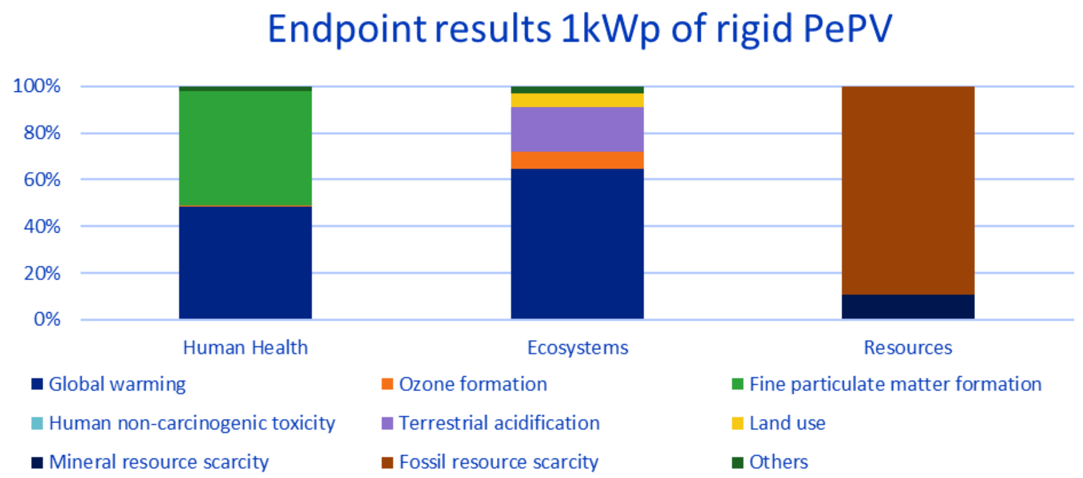


Figure 21: ReCiPe endpoints results for 1 kWp of rigid PePV

The results displayed in this section refer to the Rigid PePV with silver back contact. An initial comparison between the two types of back contact (silver and ITO) revealed that the environmental impacts for both types of PV are quite similar, so for ease of reading only the results for silver back contact are reported in this section. The full results for silver and ITO back contact can be seen in Table 37 and Table 38 in the appendix.

Figure 22 shows the contribution per life cycle phase for the selected midpoints indicators for 1 kWp of Rigid PePV with silver back contact per life cycle stage. It can be seen that the largest contribution is delivered by the manufacturing phase in all midpoint categories, see Figure 22. The impact of module integration (i.e. the processes and materials to produce a PV module from a PV cell) and the EoL processes (crushing and shredding) present similar contributions.

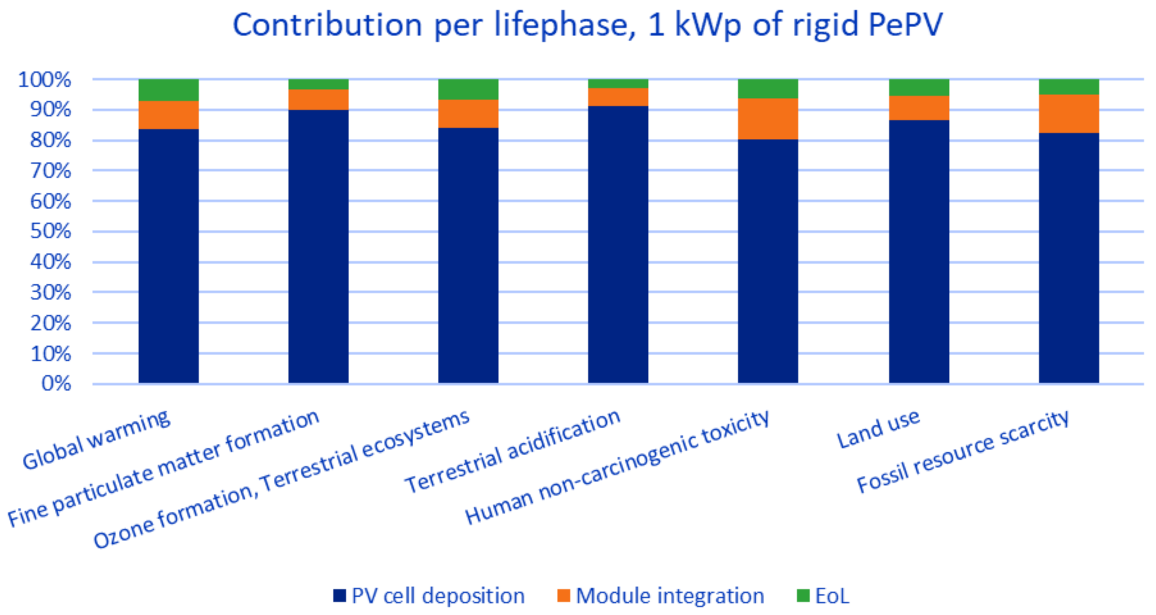


Figure 22: Relative contribution of different life phases of 1 kWp of Rigid PePV to the selected midpoint indicators.

Figure 23 and Figure 24 show the process contribution to the Rigid PePV manufacturing process, in the case of using ITO back contact (Figure 23) or silver back contact (Figure 24). In both cases, it can be seen that the largest share of the impact is given by the electricity consumption and the glass substrate and front glass. While it is true that the electricity is one of the largest contributors to the environmental impact of CIGS (13), it must be remembered that the energy consumption considered here is still largely based on experimental data and that its relative impact is expected to decrease significantly when moving to a more industrialised manufacturing process. The impact of the PV cells with the two different back contacts, is extremely similar also in absolute terms, e.g. the global warming potential for 1kWp of rigid PePV is approximately 201 kg CO_2-eq for both PV cell types. The full absolute results can be seen in the appendix (Table 37 and Table 38).

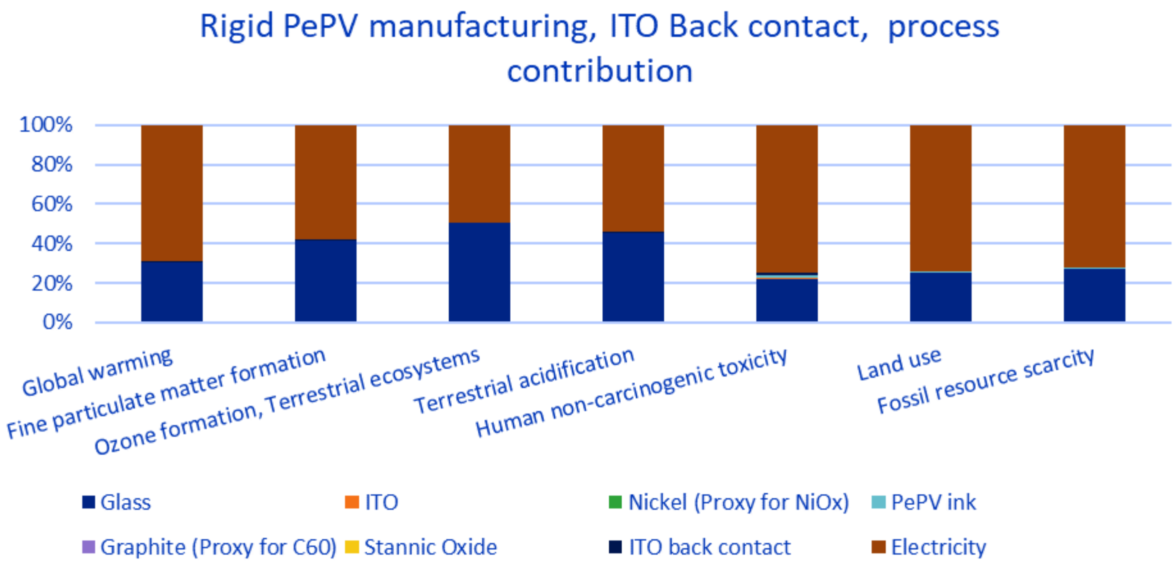


Figure 23: Process contribution to the Rigid PePV manufacturing, ITO back contact

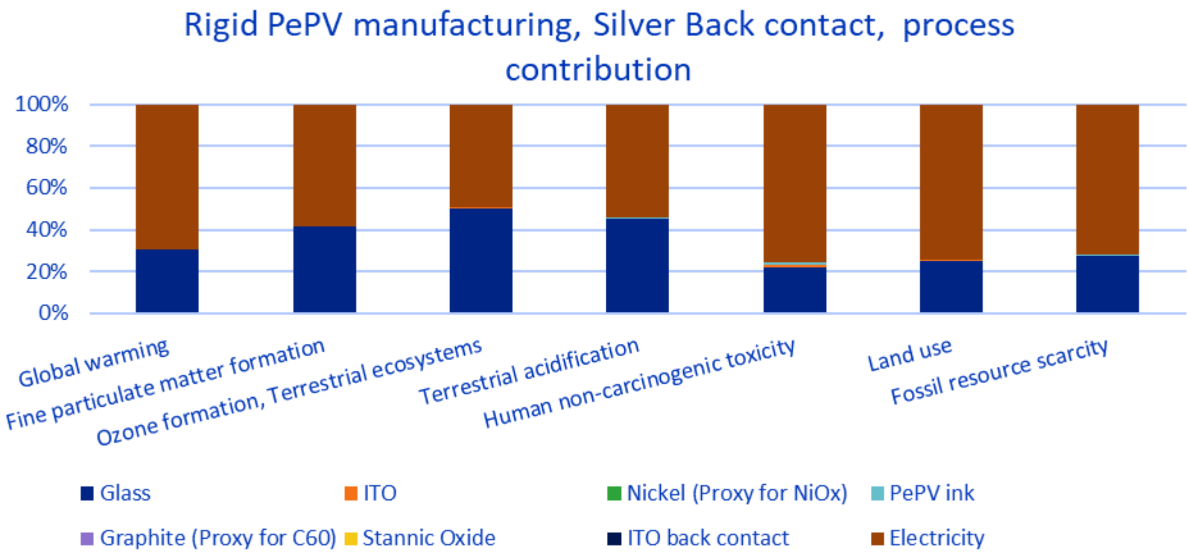


Figure 24: Process contribution to the Rigid PePV manufacturing, silver back contact

4.2.1 Comparison of PePV with other market-ready technologies

This section displays the results of the comparison between the rigid PePV, flexible PePV with carbon back contact and existing thin film technologies like CIGS and rigid CdTe. Figure 25 to Figure 31 display the impacts of these four technologies in the midpoint impact categories analysed in this work.

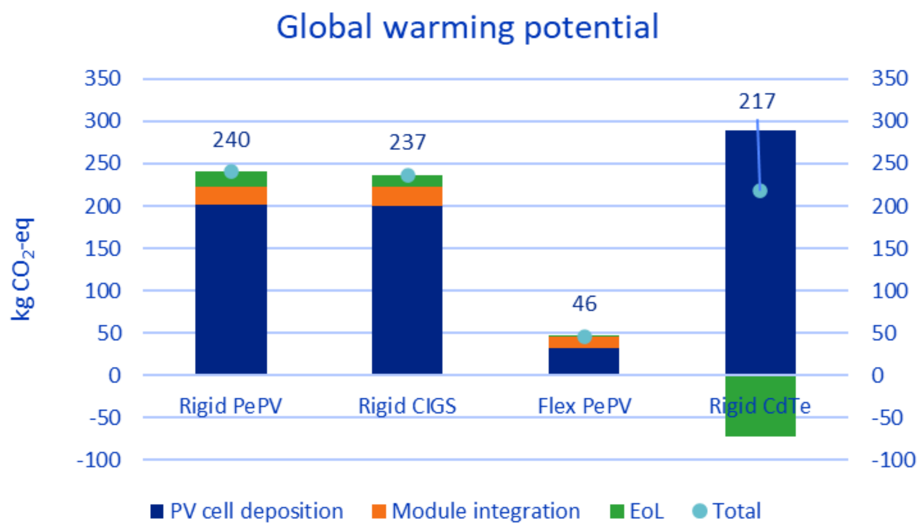


Figure 25: Global Warming Potential for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe.

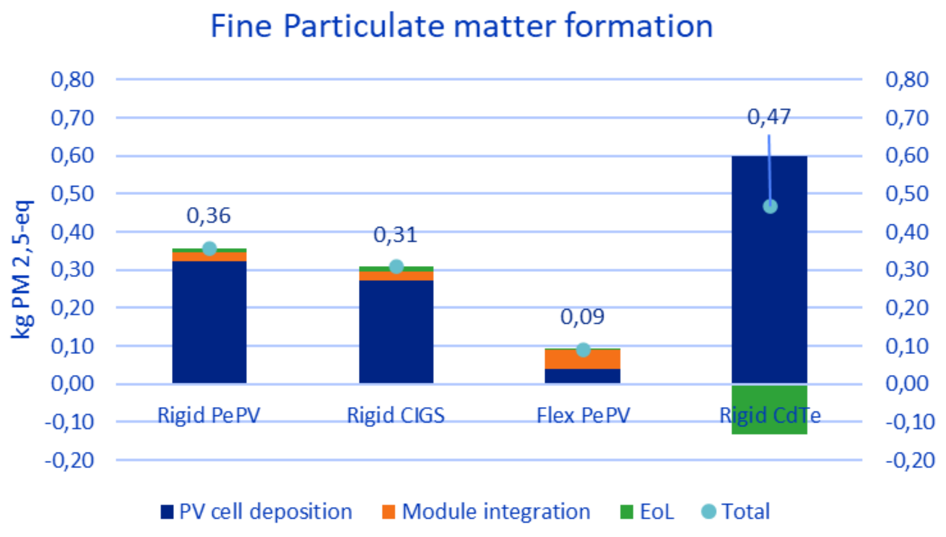


Figure 26: Fine particulate matter formation for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe.

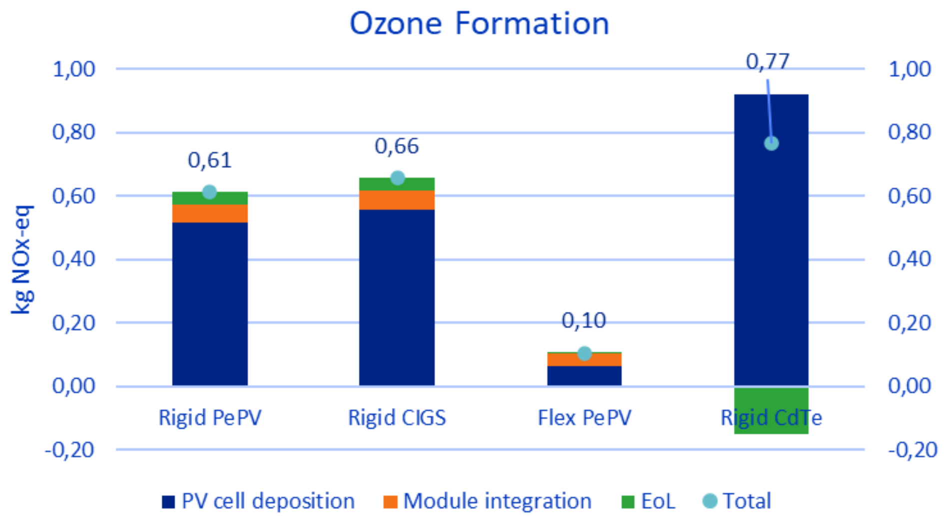


Figure 27: Ozone formation Potential for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe.

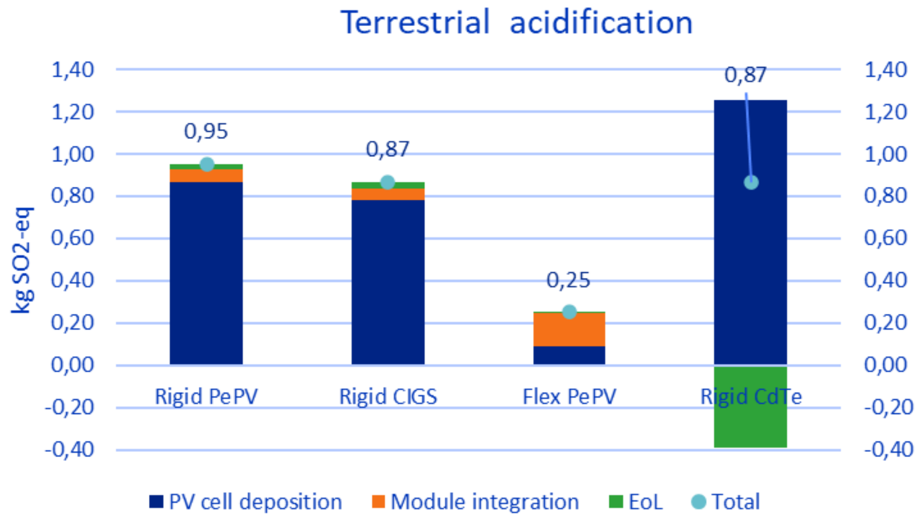


Figure 28: Terrestrial Acidification Potential for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe.

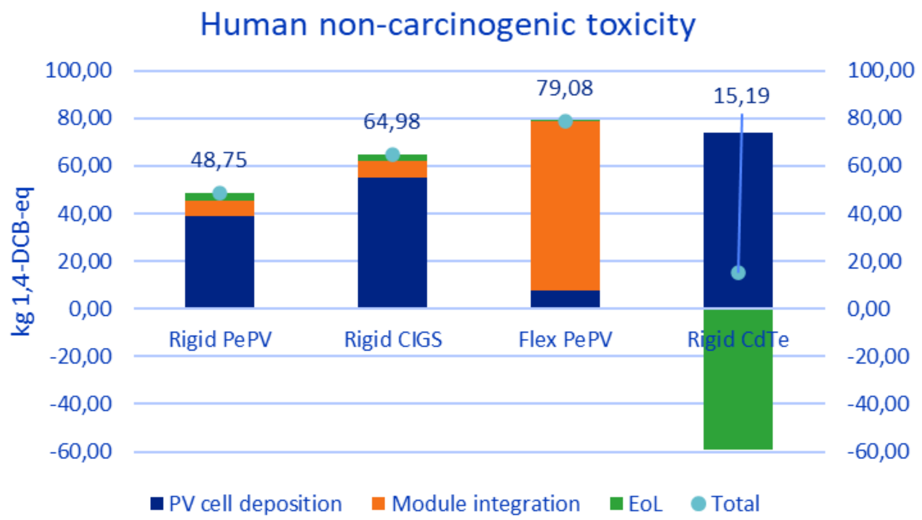


Figure 29: Human non-carcinogenic toxicity for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe.

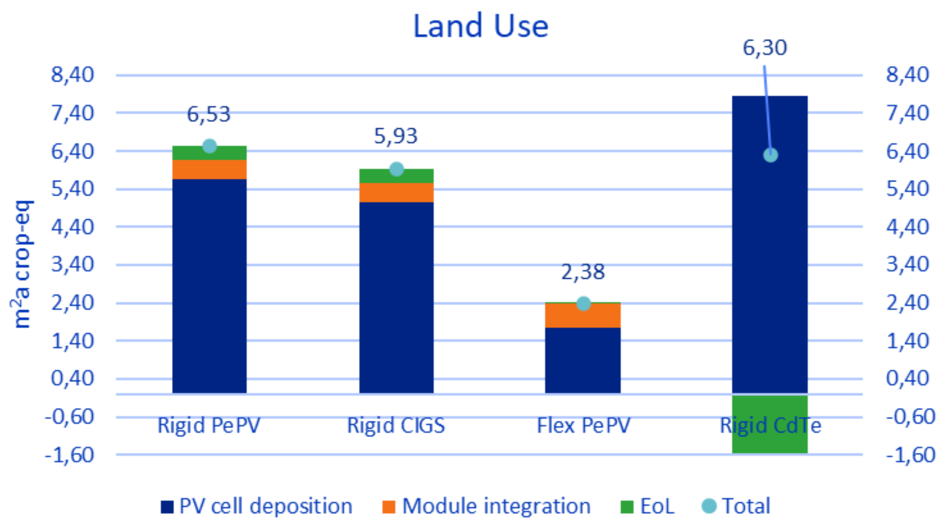


Figure 30: Land use for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe

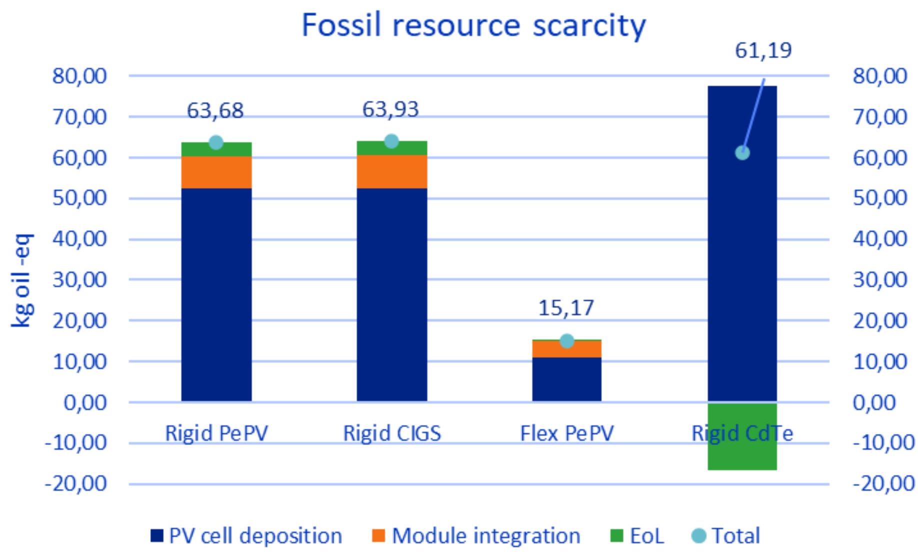


Figure 31: Fossil Resource scarcity for 1 kWp of Rigid PePV, Rigid CIGS, Flexible PePV and CdTe

It can be seen that the impacts of the Rigid PePV production are quite similar to the impacts of the rigid CIGS. In all midpoint categories considered here, the manufacturing process of the rigid PePV (and the rigid CIGS) deliver the largest contribution to the environmental impact. In all midpoint categories except human toxicity, the flexible PePV shows a much smaller impact than the Rigid counterpart. This is due to the avoided use of glass and reduced energy consumption during the manufacturing process. The high impact that the Flexible PePV shows in the Human toxicity category is due to the large amount of copper used in the original data set for the integration of PV cells in a module. This larger amount of copper arises from the fact that the original integration dataset refers to flexible CIGS cells that are integrated into roof tiles and therefore require more interconnecting cables per kWp than regular modules, due to their reduced size. While optimising the original benchmark dataset was outside the scope of this project, the building integrated application of flexible PV could still be potentially relevant for PePV applications, therefore this dataset was used in any case. Another important observations to keep in mind while reading these results is that the inventory of the rigid CdTe includes the benefits associated to the recovery of the materials during the EoL processes, (giving rise to the negative contributions in the rigid CdTe results) as these could not be separated in the original inventory. Furthermore the CdTe inventory could not be separated in "cell deposition" and "integration" for this reason the results are agglomerated in "cell deposition". Further details on the benchmark inventories are given in section 3.4.1.

4.3 Comparison of PeroCUBE OLED devices with benchmark

As in the previous cases, initially the Endpoint results were investigated. Figure 32 to Figure 35 display the endpoint results for the three PeLED devices and the reference OLED screen as described in (1). The most relevant impact categories in this case were global warming potential, fine particulate matter formation, terrestrial acidification, land use and fossil resource scarcity. Interestingly, in the case of the red PeLED, Mineral resource scarcity appears to be more relevant than fossil resource scarcity. This is due to the fact that the red PeLED ink used Caesium Iodide instead of Caesium Bromide. This difference is probably to be attributed on how the inventory for caesium bromide and iodide have been modelled: these are taken from two different sources that use different modelling approaches. Unfortunately, at the time of writing it was not possible to find two consistent inventory sources for these two materials.

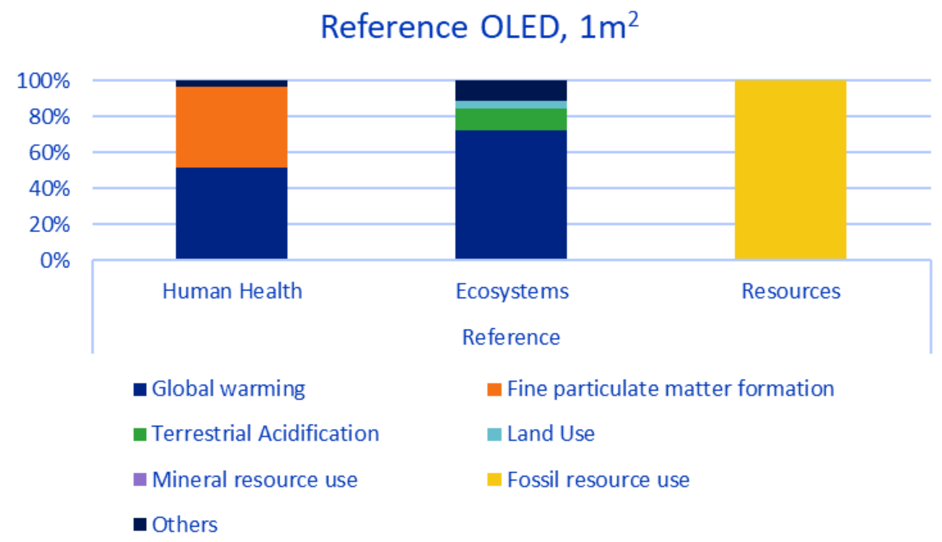


Figure 32: Endpoint results for 1m² of OLED reference device, as modelled according to the description in section 3.4.2

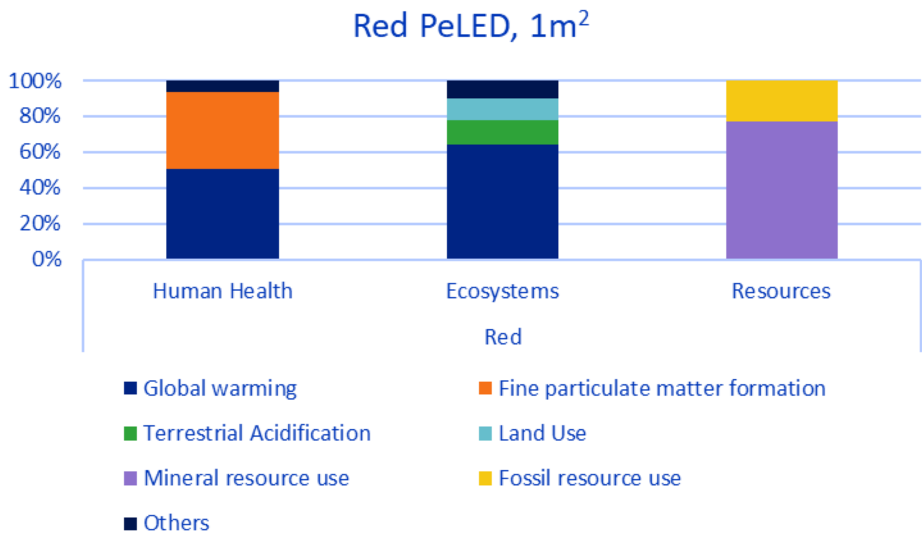


Figure 33: Endpoint results for 1m² of Red PeLED device.

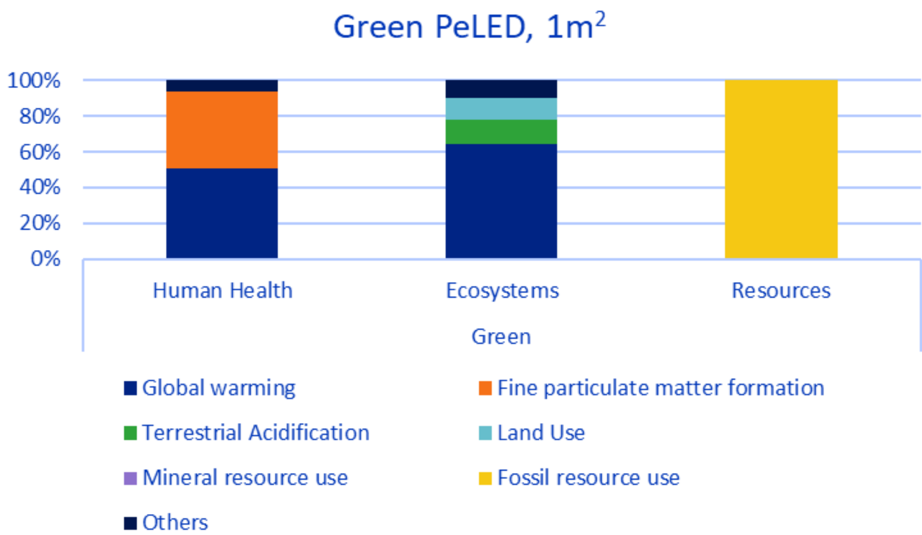


Figure 34: Endpoint results for 1m² of Green PeLED device.

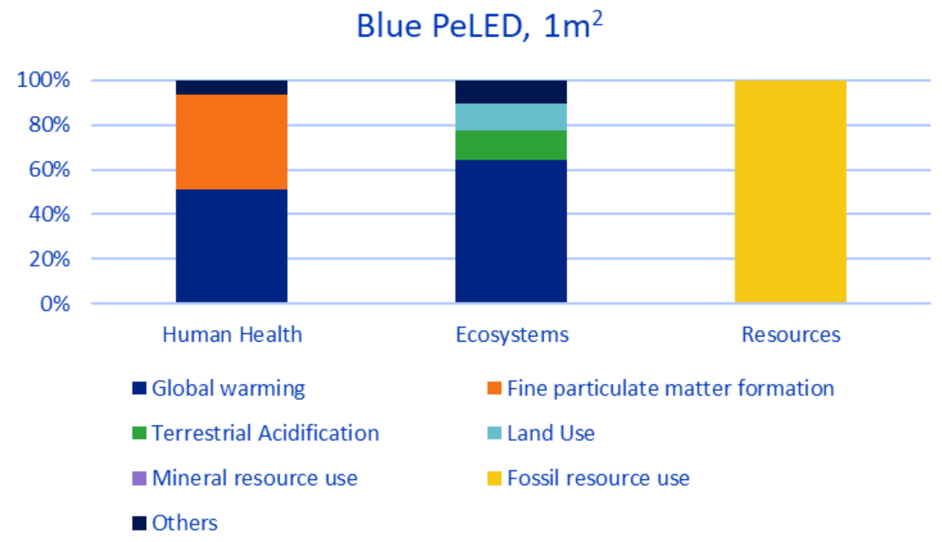


Figure 35: Endpoint results for 1m² of Blue PeLED device.

Figure 36 to Figure 39 display the midpoint results of the PeLED devices and OLED reference device. As it can be seen, in both cases, the electricity use contributes the most to the environmental footprint in all categories, with the exception of the Mineral resource scarcity in the case of the Red PePV ink. This difference is due to the use of caesium iodide in the PeLED inks, instead of Caesium bromide. The large impact is caused by the use of pollucite ore, which is used for the production of the caesium iodide, but not in the production of caesium bromide, which in our case is modelled according to (14). In the case of the PeLED devices, the second largest contributor is the PET and in the case of the OLED reference device it is the glass.

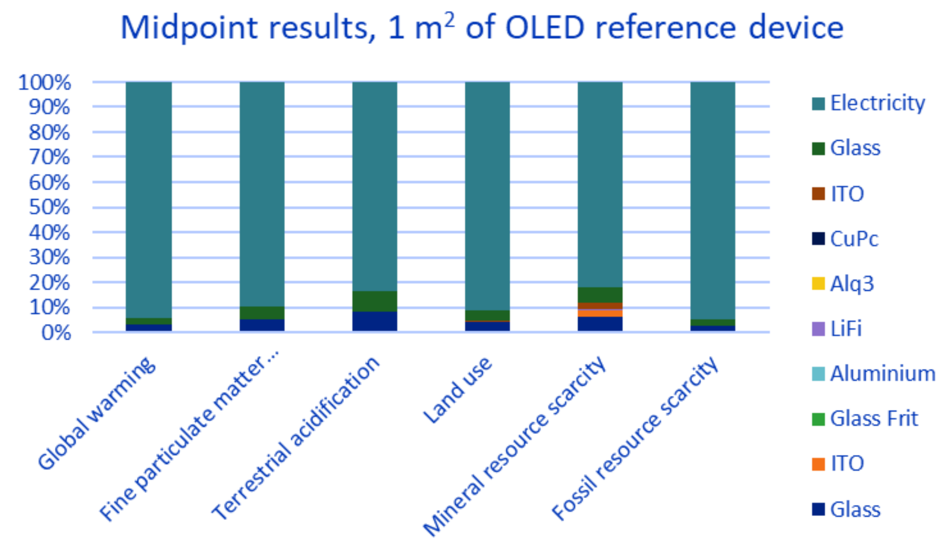


Figure 36: Midpoint results for 1 m² of OLED reference device.

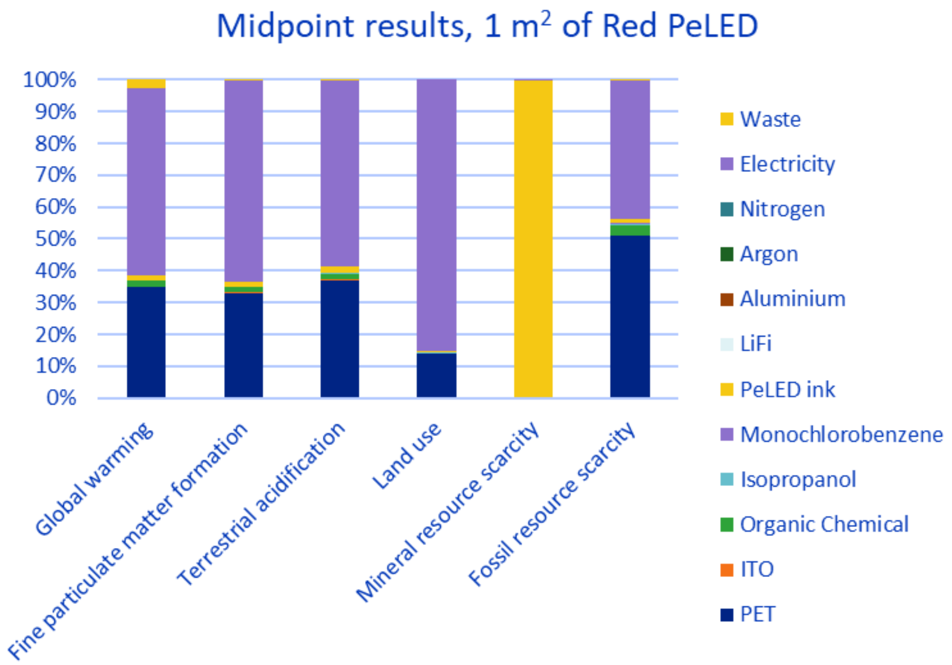


Figure 37: Midpoint results for 1 m2 of Red PeLED device.

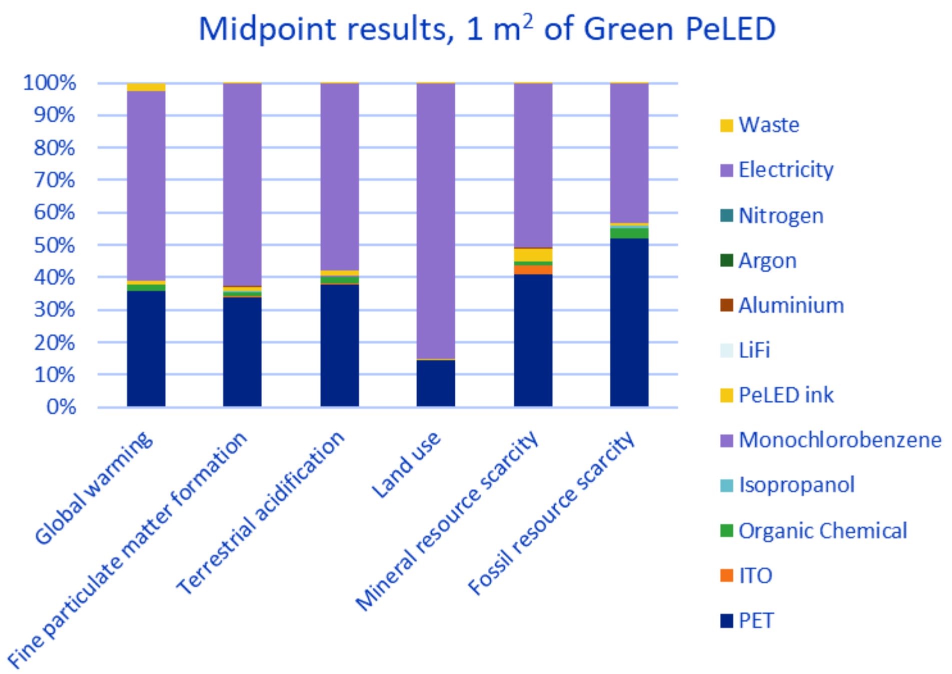


Figure 38: Midpoint results for 1 m2 of Green PeLED device.

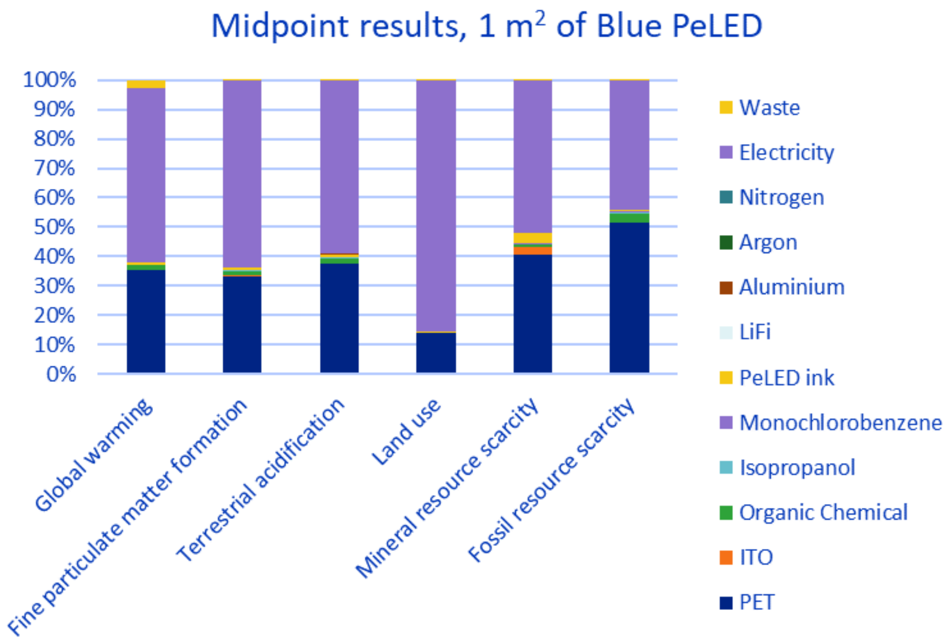


Figure 39: Midpoint results for 1 m2 of Blue PeLED device.

Looking at the absolute numbers for different impact categories, displayed in Figure 40, it can be seen that, per m^2, the impact of the Reference OLED device is several times higher than the impacts of the PeLED devices, except in the case of the Red PeLED (and the only in the case of mineral scarcity).

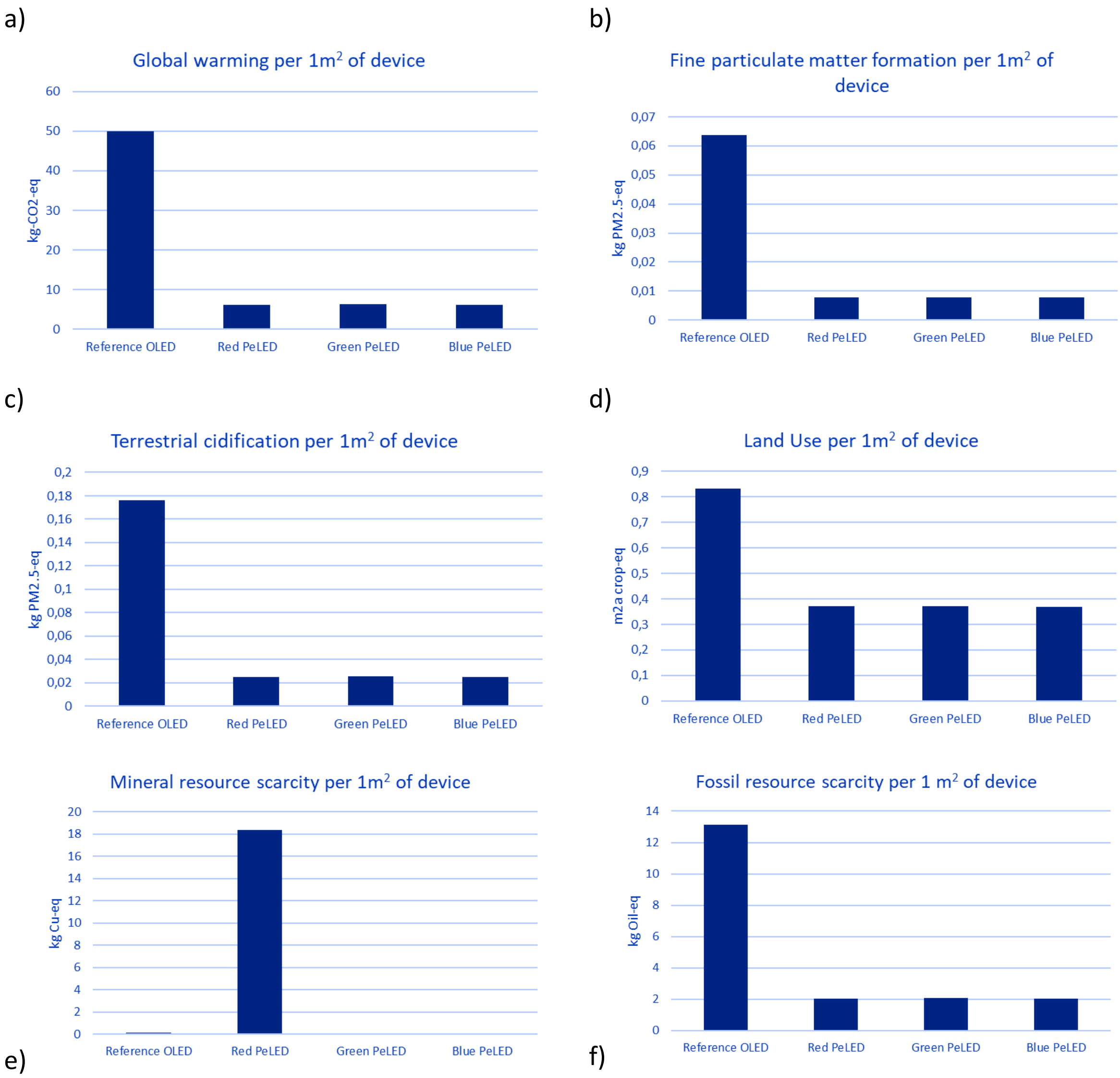


Figure 40: Results for the most relevant midpoint impact categories for the PeLED and OLED reference device. a) Global warming, b) fine particulate matter formation, c) Terrestrial Acidification, d)Land Use, e) Mineral resource scarcity and f) Fossil resource scarcity

When looking at these results some important considerations have to be kept in mind before drawing any conclusions. Firstly it is assumed that the reference OLED device is manufactured in South Korea, while the reference PeLED are manufactured in Finland. The electricity mix of the two countries is different as the South Korean mix relies heavily on coal (~37%) while the Finnish mix relies on more environmentally friendly sources. For this reason, it is better to keep in mind that the energy used for the production of the OLED reference device is ~67 kWh/m^2 and for the PeLED devices ~13 kWh/m^2, a significant difference. Secondly no lifetime of the device is taken into account, and while the reference OLED device is used as a screen in commercial smartphones, the PeLED has currently has a lifetime of only some minutes.

5 Discussion

5.1 Flexible PePV devices

As displayed in the Results section 4.1, the largest environmental impact through the lifetime of the flexible PePV device arises during the manufacturing stage, both in the case of the gold back contact as in the case of the carbon back contact. As gold is used only for research and development purposes and its impact is a known issue (16), the focus of the remaining part of this discussion will rest on the results obtained analysing the device with the carbon back contact. In that case, the global warming potential (GWP) obtained amounts to 6.6 kg CO_2-eq/m^2 and the largest environmental impacts arise from the electricity consumption during the manufacturing phase and PET use in all midpoint categories. There is a vast amount of literature available on the LCA of perovskite solar cells (16–21). The reported results are comparable to other results reported in literature: a recent review (22), reported a global warming potential for single junction perovskite solar cells ranging from 10-1650 kg CO_2-eq/m^2. More specifically, (23) reports a GWP of 16 kg CO_2-eq/m^2 for a cell printed on PET substrate (with glass encapsulation), with the PET/glass encapsulation being the major contributor and (24) reported a GWP of approximately 10 kg CO_2-eq/kWp for a flexible Perovskite solar cell (PSC) with graphene back contact. The lower carbon footprint obtained in this study can be explained by the use of full PET encapsulation (no glass), the carbon back contact (no metals) and the use of the Finnish electricity mix.

Looking at future production, the impact of the flexible PePV cell could be further reduced by reducing the use of PET: currently three PET layers are used, one as a substrate and two as front and back encapsulation, in a more industrialised setting, these could be reduced to two layers, using the substrate directly as part of the encapsulant. Furthermore electricity consumption of the production method could be further optimised as discussed in (25,26)

5.1.1 EoL analysis

In this study three different EoL processes were considered: Standard EoL i.e. incineration with energy recovery, WEEE EoL i.e. assuming gold recovery through a pyrometallurgical process and Experimental EoL, i.e. assuming a separate step for PbI_2 recovery before shredding and incineration. The WEEE EoL scenario was specifically designed for the recovery of gold. This is unlikely to be relevant for an industrially mature device, as gold is used only for research and development purposes, the Experimental EoL.

Looking at Figure 11 and Figure 14, it can be seen that the end of life processes do not contribute significantly to the environmental impact of the Flexible PePV. The WEEE scenario delivers important environmental benefits due to the recovery of gold, see Figure 11. This is only relevant in the case of a solar cell with gold back contact, which, as already mentioned, is unlikely to reach industrial stage. The remaining two EoL scenarios (Standard EoL and Experimental EoL) are therefore more interesting to analyse in detail. Comparing Figure 18 and Figure 19, it can be seen that while the energy recovery derived from the incineration offsets the burdens associated with the incineration process itself, even delivering an environmental “benefit” in several categories, this is no longer true for the experimental scenario. The benefits attributed to the recovery of PbI_2 do not offset the burdens associated with the extra operations needed for the recovery process itself (i.e. heating, centrifuging and disposal of the contaminated water). Still, some more considerations have to be made before drawing a conclusion. In the case of the experimental scenario, a large burden arises from the disposal of the contaminated water used for dissolving the perovskite layer in the PePV device. The work reported in (5) mentioned that the water could probably be reused multiple times before being disposed of, but this was not further investigated in (6). In this study, the conservative assumption that the water could be used twice was made, as a worst case scenario. It could be possible to reuse the water for several cycles before having to dispose of it, thus considerably reducing the impact of the wastewater disposal per m^2. Furthermore, a temporal consideration needs to be made: while the PePV badge is produced in the present, its incineration and energy recovery would happen at a later point in time, which, according to the kind of application considered, could occur also several years after production. During the lifespan of the device it is expected that the environmental impact of the electricity mix would reduce and therefore the benefit obtained from the energy recovery would also reduce, making the recovery of PbI_2 more attractive.

Finally, a few general remarks on the EoL treatment of PePV should be added. As investigated in deliverable 7.2, accidental damage and exposure to weathering agents (e.g. hail and rain) might lead to lead emissions to the environment. This is also relevant for the EoL: the collected devices should be stored indoor, or at least stored under a roof, to prevent damage and leaching. Moreover the waste treatment processes are likely to include shredding or crushing: recovering separately the PbI_2 during this step, as modelled in the experimental scenario, would also avoid possible worker exposure and emissions associated with the disposal of incineration ashes.

5.1.2 Toxicity results

Analysing in more detail the human toxicity impact categories, the results show that the largest contribution of toxicity occurs during the manufacturing process, but that a leakage of perovskite crystals to the environment can significantly increase the toxicity impacts of the device (especially regarding the non-carcinogenic toxicity). This highlights the importance of a safe encapsulation process that will impede the leaking of the perovskite to the environment. A more detailed investigation of the emissions occurring during the R2R deposition process showed that the perovskite ink emissions to indoor air (thus in the working environment) have a very small impact on the overall toxicity and that the impact of indoor air emissions during the ink synthesis is negligible. Still, these results are not sufficient to say that the manufacturing process as it is, is safe for the workers. In order to draw this conclusion further studies are needed and an absolute quantification of worker exposure needs to be made.

When looking at the overall LCA results, it might seem that the toxicity impacts are negligible in comparison to the other impact categories and therefore not worrisome, in contrast to what has been investigated thus far in WP 7. This dichotomy arises from a fundamental difference between LCA and HHRA. While the LCA is a comparative tool, which assesses which products or processes give rise to “less” emissions and are therefore comparatively “better” for the environment, the HHRA takes an “absolute” quantitative stand from the prospective of the environment, i.e. looks at the actual emissions associated with a product or process and sets them against a maximum emission threshold that can be considered “acceptable” (i.e. with no damage) for the workers (27). Therefore, the LCA results alone do not provide a complete answer to the assessment of the sustainability of the product taken in consideration but have to be looked at together with the risk assessment results presented in D7.3 and compared with local regulation on emission of toxic substances into environmental compartments.

Toxicity impacts are both local impacts (i.e. the impacts that arise directly where the emission took place) and global impacts via the atmosphere (inhalation) or via exchange to other environmental compartments. The toxicity impact of electricity production (or gold extraction) occurs where the energy carriers (or metals) are sourced and refined and, in these locations, environmental safety measures and risk management measures are put in place to prevent exposure and contamination. Instead, the toxicity issues related to the leakage of the perovskites (in case of encapsulation damage) will arise where the leakage has taken place e.g. on the roof or façade of a building where there are currently no measures to prevent contact and contamination with the toxic materials.

Determining if the lead emissions arising from the potential breach of the PePV encapsulation pose a risk is no easy task. Existing literature has investigated this issue more in depth (28,29): the overall lead content used in PSCs is quite low and comparable to other existing technologies available on the market (e.g. Si PV). However, in the case of damaged encapsulation, the majority of lead in PSCs would be washed off into the environment by rain and pose a severe risk to human health and the environment (28) meaning that a safe encapsulation is essential to bring these products to the market. A recent publication (30) reported that the variability found in the levels of Pb causing toxicity is strikingly large: some studies found incipient toxicity at Pb levels approaching natural background concentrations whereas other studies failed to identify Pb-related effects at concentrations of >1000 mg Pb/kg. Parameters such the bioavailability of lead in soil, measuring conditions and soil properties can lead to different lead toxic thresholds being detected. A recent commentary paper (31) calculate the air, soil, groundwater, and surface water lead concentrations resulting from the landfilling of a hypothetical 5 MWp solar plant with flexible perovskite modules. The authors reported that the resulting contamination levels for air, soil, ground and surface water were below the maximum U.S. Environmental Protection Agency target levels for acceptable risks (0.2µg/m^3 for air, 100 mg/kg for soil and 15 µg/mL for groundwater).

In the case of the flexible PePV taken in consideration here, the emissions of perovskite crystals in case of complete loss due to encapsulation damage would be 1,32 g (to surface and ground water) and 0,19 g (to soil) for 1 m^2 of the flexible PePV (calculated according to the release mechanisms described in deliverable 7.2, section 3.2.1). Assuming that this would happen for a domestic roof installation of 5 kWp, and assuming that the efficiency of the PePV would reach 18%, the roof installation surface would reach 27,8 m^2. In the worst case scenario, 36.7 g of perovskite crystals would reach the water and 5.28 g would reach the soil, corresponding to 2.3 g of lead reaching the soil and 0.3 g of lead reaching the water. The current limits for lead in soil under the European directive 86/278/EEC vary between 50 and 300 mg Pb/kg dry weight of soil (30). Assuming that the emission of perovskite crystals would occur in a soil with a natural lead concentration of 40 mg/kg and on a surface size of 15 x 15 m (a plot of land suitable for a house in an urban context) and considering a depth of 0.3 m this would amount to 67.5 m^3 of ground. Assuming ground density of 1200 kg/m^3, this results in a mass of ground of 81000 kg. The emitted lead concentration would amount to 0.03 mg/kg, which would not significantly change the previous lead concentration in the soil and fall below the threshold of posed by the European directive. Still, this has to be considered just as an early indication because percolation of a metal like Pb into the soil depends on a lot of localised soil related factors (e.g. organic or inorganic matter content, moisture content, pH levels, redox conditions). A more thorough assessment of this aspects should be performed before placing the PeroCUBE devices on the market.

Furthermore, in Europe to prevent the distribution of potentially hazardous commercial electrical and electronic equipment (EEE) the RoHS Directive was put in place (31). The RoHS Directive requires that the concentration of restricted hazardous substances in EEE be evaluated on a per-weight basis, where the maximum tolerated weight concentration for lead in **homogeneous** materials according to the RoHS Directive is 0.1%, or 1,000 mg of lead per kg of total material. The question arises what should be considered the homogeneous material for the case of wearables: the perovskite itself or the Pe-enabled product? Another issue to consider is the layer thickness, it is suggested that layers thinner than 100 nm can be exempted from the directive (32), however it should be possible to separate the layer by physical means, which is not likely for the PeroCUBE devices. According to (31), the substrate material mass would make a fundamental difference if the PePV would meet or not the RoHS maximum lead content threshold (max. 0.1% of mass for homogeneous materials). In the case of the Flexible PePV reported here, the total mass for 1 m^2 is 0.65 kg, including 0.003 kg of PePV ink. This in turn contains 0.0002 kg of lead (contained in the lead iodide and lead bromide used in the ink formulation, amounting to 0.03 %. This is including the mass of three PET layers used in this experimental design and this percentage would increase to 0.04 % if the PET layers would be reduced to two (total mass of the device 0.476 kg/m^2). This seems a promising start for the devices produced within the PeroCUBE consortium but, considering the uncertainties mentioned in the application of the RoHS, this calculation is to be considered only as an initial rough estimation.

5.2 Rigid PePV devices

The in depth analysis of the Rigid PePV did not highlight particularly concerning environmental impacts. Figure 25 reports the values for the GWP of the 4 different technologies analysed here: 240 kg CO_2-eq/kWp for the rigid PePV, 237 kg CO_2-eq/kWp for rigid CIGS, 46 kg CO_2-eq/kWp for the flexible PePV and 217 kg CO_2-eq/kWp for the CdTe. The results obtained are in line with the values found in literature: a recent review (17) found GWP of different perovskite cells on rigid substrates ranging from 173 to 14 552 kg CO_2-eq/kWp (The latter value being an outlier related to an experimental tin based perovskite cell with an efficiency of 6%). This study included the earliest LCA studies on PSC which were based on lab scale data as well as more advanced production methods. The reviewed papers that considered more industrially mature production processes and stacks reported a GWP of 212-606 kg CO_2-eq/kWp. The same review (17) investigated the reported GWP for other market available technologies, such as CIGS (reporting values between 230 and 766 kg CO_2-eq/kWp for CIGS modules with efficiencies between 12-15 %), CdTe (reporting values of 358 and 518 kg CO_2-eq/kWp for modules with an efficiency of 11.9 % produced in China). Comparable results for CIGS and CdTe were reported by (23). The impact of the rigid PV is higher than the impact of the flexible PV. This is mostly due to the higher energy requirements during the manufacturing process (70 kWh/m^2 vs 10.8 kWh/m^2) and the use of glass instead of PET.

In the case considered here, there are no important differences in any impact categories between the ITO or Silver back contact.

When comparing the rigid PePV device with existing technologies, it is interesting to see that its environmental impact is comparable with the benchmarks in all the midpoint categories considered here. Considering that the energy use is a large contributor to most impact categories and that the estimate used for these calculations still relies on laboratory values, it is expected that further energy reductions could be achieved when upscaling the production to industrial level, thus reducing the environmental impact of rigid PePV even further. The EoL modelling of CdTe is not completely consistent with the Cut-off approach followed in the case of the EoL modelling of the PePV devices and rigid CIGS. Still, when looking at the different EoL analysis reported in section 4.1 and 4.1.2, it can be seen that the standard EoL and Experimental EoL do not change significantly the environmental profile of the PePV devices and therefore the results presented in section 4.2.1 are still meaningful also when compared when CdTe.

Another important remark needs to be added here: the lifetime of the devices is not taken in consideration here as the lifetime of the PePV devices is still uncertain at the time of writing. Commercial CIGS and Si devices have a commercial lifetime of 25 - 30 years. Recent publications (33,34) pointed out that a growing number of studies is performing lifetime tests under accelerating ageing conditions on the perovskite modules showing operational lifetime well above 1000 hours at temperatures between 85 and 95 ^{o}C, still at present perovskite modules are far from the 25 year target. Some manufacturers offer a lifetime warranty of 10 years, meaning that for a comparison including lifetime, the impacts of the perovskite modules showed in section 4.2.1 would need to be multiplied by a factor 2.5. This means that they would no longer be comparable with the analysed benchmarks. Still, this does not have to be taken as a conclusive remark: according to (34), most of the degradation processes that reduce the lifetime of devices are initiated by defects in the interfaces of the cell layers. This could be solved by improving manufacturing techniques which would not automatically imply that the environmental impact of the production process would increase by a factor 2.5.

5.3 PeLED considerations

Looking at the results presented in section 4.3, some general conclusions can be drawn regarding the manufacturing of the PeLED devices. The R2R manufacturing methods are clearly more advantageous than the vapour deposition methods used in the manufacturing of the OLED reference device, as they lead to a considerably lower energy use per m^2. Furthermore, the use of PET instead of glass leads also to important advantages in terms of environmental footprint. From this analysis moreover, no large differences can be seen in the impacts deriving from the use of the perovskite inks instead of the organometallic dye (Alq3) used in the OLED reference device. Still, this cannot be considered exhaustive on the subject as an in depth comparison of different types of emissive layers was out of scope for this LCA. Keeping in mind the differences related to lifespan and energy mixes used during the production process, the results obtained seem to indicate that the production of PeLED devices could be more sustainable than the commercial OLED counterparts.

At last it has to be iterated that this LCA did not include use phase and EoL phase where, potentially, emissions to the environment of perovskite inks could arise. Due to the similar composition in perovskite inks and manufacturing processes, the same observations as reported in the case of Flexible PePV still hold.

6 Conclusions

This extensive LCA study analysed several aspects of the manufacturing of PePV and PeLED devices and placed it in the context of existing commercial alternatives. It can be concluded that:

- The LCA with integrated HHRA for three PeroCUBE devices (Flexible PePV, Rigid PePV and PeLED) has been carried out and the results obtained for the flexible and rigid PePV are in line with the results published in literature so far. Not a lot of literature is available for perovskite LEDs at the time of writing. The PeLED has therefore been compared with a commercially available OLED. This is to be considered a screening LCA due to the limited data availability on the OLED manufacturing.
- The manufacturing of the devices has the largest environmental impact during the whole life cycle of the devices. It is expected that this impact would be further reduced when reaching more mature production. The use phase and EoL of the device do not contribute significantly to the environmental impact of the devices.
- The PePV devices (from an LCA prospective) perform equally or better than the current commercially available technologies, especially in the case of the PePV on flexible substrates. Device lifetime it is still an open issue, but it is reasonable to expect that this will improve in the near future.
- A thorough modelling of the potential emissions of perovskites during the use phase of the device highlighted the importance of developing fail safe encapsulation methods to avoid lead leakage into the environment.
- Leaching of perovskite during the use phase significantly increases (nearly doubles) the impact on human non-carcinogenic risks.
- Preliminary assessment of lead emissions and lead content of the PeroCUBE devices seems to be below the limits of the current regulations, still this cannot be considered as a conclusive assessment on this matter.

This is the conclusive deliverable of PeroCUBE's WP7 which followed a tiered approach to assess the human health risk and provide a lifecycle assessment of three PeroCUBE devices. The tiered approach started with a qualitative assessment (LICARA innovation scan, Deliverable 7.1), which required relatively few and qualitative inputs, followed by the hotspot scan (Deliverable 7.2), which provided a scan of the potentially toxic materials used in the manufacturing process and assessed their expected emissions during each of the life cycle stages of a device, followed by the quantitative human health risk assessment (Deliverable 7.3), which derived characterisation factors for the materials used and emissions arising during the life cycle of the devices and finished with the life cycle assessment which included the inputs from the previous deliverables and performed the environmental assessment of three PeroCUBE devices.

The tiered approach followed here allowed a more complete assessment of the devices taken in consideration: the LCA without the HHRA would have not been able to capture the impacts on human health as it is described in sections 4.1.1and 5.1.2. This could only be done thanks to the characterisation factors calculated in the HHRA. Similarly, the HHRA cannot give an overview of the complete environmental impact of the device under study. In turn, the HHRA (and consequently the LCA) needed the information derived from the hotspot scan, such as the screening of the toxic materials used and the emission routes and quantification during the lifecycle. In this way this tiered approach has to be seen like an organic method for a through combined HHRA and LCA.

35. Van der hulst M et al, "Comparing environmental impacts of single-junction silicon and silicon/perovskite tandem photovoltaics – a prospective life cycle assessment", submitted to ACS Sustainable Chemistry & Engineering, currently under revision.

7 References

1. Amasawa E, Ihara T, Ohta T, Hanaki K. Life cycle assessment of organic light emitting diode display as emerging materials and technology. J Clean Prod [Internet]. 2016;135:1340–50. Available from: http://dx.doi.org/10.1016/j.jclepro.2016.07.025

2. Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assessment, [online] [Internet]. 2016;(21(9)):pp.1218–1230. Available from: http://link.springer.com/10.1007/s11367-016-1087-8

3. Huijbregts M, Steinmann ZJN, Elshout PMFM, Stam G, Verones F, Vieira MDM, et al. ReCiPe 2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. Natl Inst Public Heal Environ [Internet]. 2016;194. Available from: https://www.rivm.nl/bibliotheek/rapporten/2016-0104.pdf

4. Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, et al. USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess. 2008 Oct;13(7):532–46.

5. Beynon D, Parvazian E, Hooper K, McGettrick J, Patidar R, Dunlop T, et al. All-Printed Roll-to-Roll Perovskite Photovoltaics Enabled by Solution-Processed Carbon Electrode. Adv Mater. 2023;35(16).

6. Schmidt F, Amrein M, Hedwig S, Kober-Czerny M, Paracchino A, Holappa V, et al. Organic solvent free PbI2 recycling from perovskite solar cells using hot water. J Hazard Mater. 2023;447(November 2022).

7. Doka G. Life Cycle Inventories of Waste Treatment Services. ecoinvent report No. 13 Part II Waste Incineration [Internet]. 2003 [cited 2023 Sep 21]. Available from: https://doka.ch/13_II_WasteIncineration.pdf

8. Doka G. LCI calculation tools for regionalised waste treatment-General introduction. 2017 [cited 2023 Mar 9]; Available from: https://doka.ch/publications.htm

9. Classen M, Althaus H-J, Blaser S, Scharnhorst W, Tuchschmid M, Jungbluth N, et al. Life Cycle Inventories of Metals. Final Rep ecoinvent data v21 No 10. 2009;(10):1–926.

10. NREL. Best research-cell Efficiency chart [Internet]. 2023. Available from: https://www.nrel.gov/pv/cell-efficiency.html

11. Fthenakis V, Leccisi E, Frischknecht R, Stolz P, Krebs L, de Wild-Scholten M, et al. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems 2020 Task 12 PV Sustainability [Internet]. 2021 [cited 2023 Aug 10]. Available from: www.iea-pvps.org

12. Bansal A. A Prospective Life Cycle Assessment for CdTe Thin Film PV panels using background scenarios Master ' s Graduation Report A Prospective Life Cycle Assessment for CdTe Thin Film PV panels using background scenarios [Internet]. Eindhoven University of Technology; 2023. Available from:

https://pure.tue.nl/ws/portalfiles/portal/304239923/060723_1671561_Final_Graduation_Thesis_A_Prospective_Life_Cycle_Assessment_for_CdTe_Thin_Film_PV_panels_using_background_scenarios_Aaradhya.docx.pdf

13. van der Hulst MK, Huijbregts MAJ, van Loon N, Theelen M, Kootstra L, Bergesen JD, et al. A systematic approach to assess the environmental impact of emerging technologies: A case study for the GHG footprint of CIGS solar photovoltaic laminate. J Ind Ecol [Internet]. 2020 Dec 1 [cited 2023 Aug 10];24(6):1234–49. Available from: https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.13027

14. Borowski P, Grömmer F, Karg F. Carbon Footprint Analysis of CIGS Thin-Film PV Modules with Focus on Building-Integrated Applications. In 2021. p. 901–6. Available from: https://userarea.eupvsec.org/proceedings/EU-PVSEC-2021/4DV.2.19/

15. Müller A, Friedrich L, Reichel C, Herceg S, Mittag M, Neuhaus DH. A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory. Sol Energy Mater Sol Cells. 2021 Sep 15;230:111277.

16. Zhang J, Gao X, Deng Y, Zha Y, Yuan C. Comparison of life cycle environmental impacts of different perovskite solar cell systems. Sol Energy Mater Sol Cells. 2017 Jul 1;166:9–17.

17. Vidal R, Alberola-Borràs JA, Sánchez-Pantoja N, Mora-Seró I. Comparison of Perovskite Solar Cells with other Photovoltaics Technologies from the Point of View of Life Cycle Assessment. Adv Energy Sustain Res. 2021;2(5).

18. Alberola-BorràsBorràs J-A, Rosario Vidal ab, Mora-SeróSer I. Evaluation of multiple cation/anion perovskite solar cells through life cycle assessment †. 2018;

19. Celik I, Song Z, Cimaroli AJ, Yan Y, Heben MJ, Apul D. Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab. Sol Energy Mater Sol Cells [Internet]. 2016;156:157–69. Available from: http://dx.doi.org/10.1016/j.solmat.2016.04.037

20. Ramamurthy Rao HK, Gemechu E, Thakur U, Shankar K, Kumar A. Life cycle assessment of high-performance monocrystalline titanium dioxide nanorod-based perovskite solar cells. Sol Energy Mater Sol Cells. 2021 Sep 15;230:111288.

21. Gong J, Darling SB, You F. Perovskite Photovoltaics: Life cycle assessment of Energy and Environmental impacts. Energy Environ Sci. 2015;

22. Maalouf A, Okoroafor T, Jehl Z, Babu V, Resalati S. A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems. Renew Sustain Energy Rev [Internet]. 2023;186(July):113652. Available from: https://doi.org/10.1016/j.rser.2023.113652

23. Leccisi E, Fthenakis V. Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV. Prog Photovoltaics Res Appl. 2021;29(10):1078–92.

24. Li Q, Monticelli C, Zanelli A. Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. Renew Energy [Internet]. 2022;195:906–17. Available from: https://doi.org/10.1016/j.renene.2022.06.075

25. Sokka L, Välimäki M, Väisänen KL, Keskinen J, Hakola E, Mäntysalo M, et al. Life cycle assessment of a new smart label for intelligent packaging. Flex Print Electron. 2024;9(1).

26. Naji Nassajfar M, Välimäki M, Hakola L, Eiroma K, Immonen K, Abdulkareem M, et al. The effect of conductive ink alternation on the sustainability and functioning of printed electronics. Flex Print Electron. 2023;8(2).

27. Muazu RI, Rothman R, Maltby L. Integrating life cycle assessment and environmental risk assessment: A critical review. J Clean Prod [Internet]. 2021;293:126120. Available from: https://doi.org/10.1016/j.jclepro.2021.126120

28. Ren M, Qian X, Chen Y, Wang T, Zhao Y. Potential lead toxicity and leakage issues on lead halide perovskite photovoltaics. J Hazard Mater [Internet]. 2022;426(August 2021):127848. Available from: https://doi.org/10.1016/j.jhazmat.2021.127848

29. Kim GY, Kim K, Kim HJ, Jung HS, Jeon I, Lee JW. Sustainable and environmentally viable perovskite solar cells. EcoMat. 2023 Apr 1;5(4).

30. Oorts K, Smolders E, Lanno R, Chowdhury MJ. Bioavailability and Ecotoxicity of Lead in Soil: Implications for Setting Ecological Soil Quality Standards. Environ Toxicol Chem. 2021;40(7):1950–63.

31. Moody N, Sesena S, deQuilettes DW, Dou BD, Swartwout R, Buchman JT, et al. Assessing the Regulatory Requirements of Lead-Based Perovskite Photovoltaics. Joule. 2020;4(5):970–4.

32. European Commission. RoHS 2 FAQ. Vol. 2. 2012. p. 1–28.

33. Zhu P, Chen C, Dai J, Zhang Y, Mao R, Chen S, et al. Toward the Commercialization of Perovskite Solar Modules. Adv Mater. 2024;

34. Le TH, Driscoll H, Hou CH, Montgomery A, Li W, Stein JS, et al. Perovskite Solar Module: Promise and Challenges in Efficiency, Meta-Stability, and Operational Lifetime. Adv Electron Mater. 2023;9(10).

35. Van Kalkeren HA, Blom AL, Rutjes FPJT, Huijbregts MAJ. On the usefulness of life cycle assessment in early chemical methodology development: the case of organophosphorus-catalyzed Appel and Wittig reactions †. 2013 [cited 2023 Sep 26]; Available from: www.rsc.org/greenchem

36. Kumar P, Agrawal N, Pandey VK, Gautam AK, Sharma SK, Chaudhary SD. Highly-efficient OLED with cesium fluoride electron injection layer. Solid State Electron [Internet]. 2021;183(May):108031. Available from: https://doi.org/10.1016/j.sse.2021.108031

37. Van der hulst M et al, "Comparing environmental impacts of single-junction silicon and silicon/perovskite tandem photovoltaics – a prospective life cycle assessment", submitted to ACS Sustainable Chemistry & Engineering, currently under revision.

A. Data tables for inventories of PeroCUBE devices

Table 13: Inventory table for the Flexible PePV ink precursors

Output	**Amount**	**Unit**	**Comment**
PePV_ink_VTT	1	kg	
Inputs			
Formamidinium iodide (FAI)	0,4717	kg	Inventory taken from supporting documentation to (16)
Cesium iodide (CsI)	0,0146	kg	Inventory according supporting info (37)

Lead iodide	0,1372	kg	Inventory according supporting info (18)
Lead Bromide	0,0121	kg	Inventory taken from supporting documentation to (16)
Dimethyl sulfoxide (DMSO)	0,3517	kg	ecoinvent
Methylammonium Chloride	0,0021	kg	This inventory is based on (18) for methylammonium Bromide. The mass of methylamine and hydrogen Chloride have been adjusted according to the stochiometric proportions of the reaction between methylamine and hydrogen chloride. The other material inputs have remained the same as in the case of the hydrogen bromide.
Maize starch {GLO}| market for maize starch | Cut-off, U	0,0106	kg	ecoinvent
Emissions to air (indoor)			
Dimethyl sulfoxide	3,52E-05	kg	ecoinvent
Emissions to water			
Dimethyl sulfoxide	0,007034	kg	ecoinvent

Table 14: Inventory table for the Rigid PePV ink precursors

Output	**Amount**	**Unit**	**Comment**
PePV_ink_CSEM	1	kg	
Inputs			
N,N-dimethylformamide (DMF)	0,5670	kg	ecoinvent
Lead (II) Iodide (PbI2)	0,2344	kg	Inventory according supporting info (18)
Formamidinium Iodide (FAI)	0,0720	kg	Inventory taken from supporting documentation to (16)
Cesium Iodide (CsI)	0,0232	kg	Inventory according supporting info (37)
Lead (II) Bromide (PbBr2)	0,0329	kg	Inventory taken from supporting documentation to (16)
Methylammonium Bromide (MABr)	0,0100	kg	This inventory is based on (18) for methylammonium Bromide.
Methylammonium Chloride (MACl)	0,0061	kg	This inventory is based on (18) for methylammonium Bromide. The mass of methylamine and hydrogen Chloride have been adjusted according to the stochiometric proportions of the reaction between methylamine and

			hydrogen chloride. The other material inputs have remained the same as in the case of the hydrogen bromide.
Additive A	0,0083		Inventory based on (16)
Additive B	0,0433	kg	Proxy used: Urea {RER}| market for urea | Cut-off, U
Additive C	0,0001		Chemical, organic {GLO}| market for chemical, organic | Cut-off, U
Additive D	0,0027	kg	Proxy used: Ethylene glycol diethyl ether {GLO}| market for ethylene glycol diethyl ether | Cut-off, U
Emissions to air (indoor)			
Dimethyl sulfoxide	3,52E-05	kg	Available in database
Emissions to water			
Dimethyl sulfoxide	0,007034	kg	Available in database

Table 15: Carbon screen paste inventory

Output	**Amount**	**Unit**	**Comment**
Carbon screen paste	1	kg	Inventory based on (5)
Inputs			
Carbon black {GLO}| market for Cut-off -U	0,06	kg	
Graphite {GLO}| market for graphite Cut-off -U	0,16	kg	
Xylene {RER}| market for xylene Cut-off -U	0,69	kg	Proxy for 2-Methoxytoluene or 2-Methylanisole. Choice based on internal discussion with VTT
Carboxymethyl cellulose, powder {RER}| carboxymethyl cellulose production, powder | Cut-off, U	0,09	kg	Proxy for ethyl cellulose. Also non-toxic. Choice based on internal discussion with VTT.
Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	0,333	kWh	Based on (35)
Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas | Cut-off, U	2 MJ		Based on (35)

Table 16: Inventory table for R2R Flexible PePV deposition

Output	Amount	Unit	Comment
PePV R2R deposition_VTT_FI	1	m2	
Inputs			
Polyethylene terephthalate, granulate, bottle grade {GLO}| market for polyethylene terephthalate, granulate, bottle grade | Cut-off, U	0,178	kg	PET substrate film
Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, U	0,178	kg	PET substrate film
Indium tin oxide powder, nanoscale, for sputtering target {RER}| market for indium tin oxide powder, nanoscale, for sputtering target | Cut-off, U	0,000919	kg	ITO coating
Chemical, organic {GLO}| market for chemical, organic | Cut-off, U	0,0368	kg	Etching paste proxy
Argon, liquid {RER}| market for argon, liquid | Cut-off, U	0,0002	kg	plasma cleaning
Nitrogen, liquid {RER}| market for nitrogen, liquid | Cut-off, U	0,0007	kg	plasma cleaning
Isopropanol {GLO}| market for | Cut-off, U	0,04716	kg	isopropyl alcohol for cleaning the etching paste.
Stannic oxide (SnO2) ink VTT	0,0018	kg	Tin dioxide
PePV_ink_VTT	0,00288	kg	Perovskite
Chemical, organic {GLO}| market for chemical, organic | Cut-off, U	0,0016	kg	Proxy for the P3HT ink
Gold {GLO}| market for gold | Cut-off, U	0,00155	kg	Back contact
Polyethylene terephthalate, granulate, bottle grade {GLO}| market for polyethylene terephthalate, granulate, bottle grade | Cut-off, U	0,42	kg	Encapsulant.
Polymethyl methacrylate, sheet {GLO}| market for polymethyl methacrylate, sheet | Cut-off, U	0,1236	kg	Proxy for edge seal
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	10,83	kWh	
Emissions to air			
PePV ink	0,000000144	kg	From the HSS, we assume that 0,05kg of PePV ink are emitted

			every 1000 kg for the fabrication of PePV
Waste to treatment			
Waste PePV badge {RER}| treatment of, incineration | Cut-off, U	0,0179	kg	Plastic waste from cutting contaminated with PePV ink
Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration, with energy recovery | Cut-off, U	0,0471	kg	Waste isopropanol

Table 17: Inventory table for Rigid PePV deposition

Output	**Amount**	**Unit**	**Comment**
PePV_rigid_deposition	1	m2	
Inputs			
Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	5,04E+00	kg	
Indium tin oxide powder, nanoscale, for sputtering target {GLO}| market for | Cut-off, U	1,07E-03	kg	
Nickel concentrate, 16% Ni {GLO}| market for nickel concentrate, 16% Ni | Cut-off, U	1,33E-07	kg	Proxy for Nickel Oxide
PePV_ink_CSEM	9,35E-03	kg	
Graphite {GLO}| market for graphite | Cut-off, U	3,30E-08	kg	Proxy for C60
Stannic oxide (SnO2) ink VTT	6,95E-08	kg	Buffer
Indium tin oxide powder, nanoscale, for sputtering target {GLO}| market for | Cut-off, U	1,07E-03	kg	Back contact (for transparent PV, only one option to be selected)
Silver {GLO}| market for silver | Cut-off, U	3,73E-07	kg	Back contact (For opaque PV, only one option to be selected)
Polyethylene terephthalate, granulate, bottle grade {GLO}| market for polyethylene terephthalate, granulate, bottle grade | Cut-off, U	5,52E-01	kg	Lamination layer
Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, U	5,52E-01	Kg	
Flat glass, uncoated {RER}| market for flat glass, uncoated | Cut-off, U	5,04E+00	kg	

Argon, liquid {RER}| market for argon, liquid | Cut-off, U	4,59E-02	kg	Consumables for sputtering process
Electricity, medium voltage {RER}| market for electricity, medium voltage | Cut-off, U	70,169	kWh	

Table 18: Inventory for the Green PeLED ink

Output	**Amount**	**Unit**	**Comment**
PeLED_Green_ink_VTT	1	kg	
Inputs			
Butylamine Bromide	0,1519	kg	Proxy for butylammonium bromide, see inventory reported in Table 22
Cesium Bromide	0,2950	kg	Inventory taken from supporting documentation to (16)
Lead (II) Bromide (PbBr2)	0,5071	kg	Inventory taken from supporting documentation to (16)
Ethylene oxide {RER}| market for ethylene oxide | Cut-off, U	0,0360	kg	Proxy for crown ethers
Dimethyl sulfoxide (DMSO)	0,0099	kg	Inventory taken from supplementary information to (20)

Table 19: Inventory for the Blue PeLED ink

Output	**Amount**	**Unit**	**Comment**
PeLED_Blue_ink_VTT	1	kg	
Inputs			
Butylamine Bromide	0,1417	kg	Proxy for butylammonium bromide, see inventory reported in Table 22
Cesium Bromide	0,2993	kg	Inventory taken from supporting documentation to (16)
Lead (II) Bromide (PbBr2)	0,5155	kg	Inventory taken from supporting documentation to (16)
Ethylene oxide {RER}| market for ethylene oxide | Cut-off, U	0,0340	kg	Proxy for crown ethers
Dimethyl sulfoxide (DMSO)	0,0094	kg	Inventory taken from supplementary information to (20)

Table 20: Inventory for the Red PeLED ink

Output	**Amount**	**Unit**	**Comment**
PeLED_Red_ink_VTT	1	kg	
Inputs			
Butylamine Bromide	0,1711	kg	Proxy for butylammonium bromide, see inventory reported in Table 22
Cesium Iodide	0,5045	kg	
Lead (II) Iodide	0,2856	kg	Inventory according supporting info (18)
Ethylene oxide {RER}| market for ethylene oxide | Cut-off, U	0,0305	kg	Proxy for crown ethers
Dimethyl sulfoxide (DMSO)	0,0084	kg	Inventory taken from supplementary information to (20)

Table 21: Inventory for the deposition of 1m2 of PeLED

Output	Amount	Unit	Comment
PeLED_green_deposition	1	m2	
Materials/fuels			
Polyethylene terephthalate, granulate, bottle grade {GLO}| market for	1,78E-01	kg	PET substrate film
Extrusion, plastic film {RER}| extrusion	1,78E-01	kg	PET substrate film
Indium tin oxide powder, nanoscale, for sputtering target	3,68E-04	kg	ITO coating
Chemical, organic {GLO}| market for	3,68E-02	kg	Etching paste proxy
Chemical, organic {GLO}| market for	2,04E-03	kg	Proxy for PDOT:PSS
Isopropanol {RER}| market for	6,14E-03	kg	Solvent for PDOT:PSS ink
Chemical, organic {GLO}| market for	2,30E-03	kg	Proxy for polyvinylcarbazole PVK (2.61 E-03 for blue LED and red LED)
Monochlorobenzene {RER}| market for	1,28E-03	kg	Chlorobenzene solvent in PVK ink for green and blue LED (9.58E-04 for blue LED)
PeLED_Green_ink	2,86E-03	kg	Perovskite (Blue ink for Blue LED and red ink for red LED)

Polyethylene terephthalate, granulate, bottle grade {GLO}|	2,07E-02	kg	Protective tape (Only for Greed LED)
Extrusion, plastic film {RER}|	2,07E-02	kg	Protective tape (Only for Greed LED)
Chemical, organic {GLO}| market for	4,30E-05	kg	Proxy for the TPbI ink
Lithium fluoride {GLO}| market for	2,00E-06	kg	Lithium fluoride
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for	2,03E-04	kg	
Polyethylene terephthalate, granulate, bottle grade {GLO}| market for	3,45E-01	kg	Encapsulant
Extrusion, plastic film {RER}| extrusion	3,45E-01	kg	Encapsulant
Polymethyl methacrylate, sheet {GLO}| market for	1,20E-01	kg	Proxy for adhesive.
Argon, liquid {RER}| market for	2,00E-04	kg	plasma cleaning
Nitrogen, liquid {RER}| market for	7,00E-04	kg	plasma cleaning
Electricity/heat			
Electricity, medium voltage {FI}| market for	1,34E+01	kWh	
Emissions to air			
PePV ink	1,44E-07	kg	From the HSS, we assume that 0,05kg of PePV ink are emitted every 1000 kg for the fabrication of PePV
Waste to treatment			
waste PePV badge {RER}| treatment of, incineration | Cut-off, U	1,79E-02	kg	Plastic waste from cutting
Spent solvent mixture {Europe without Switzerland}| treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | Cut-off, U	4,71E-02	kg	Waste isopropanol

Table 22: Inventory for Butylamine Bromide

Output	Amount	Unit	Comment
Butylamine Bromide	1	kg	Materials proxies available in ecoinvent were used to model the reaction reported on Wikipedia: "tetrabutylammonium bromide can be prepared by the alkylation of tributylamine with 1-bromobutane". Since no stoichiometry was available and assumption of equal parts was made.
Inputs			
Tert-butyl amine {GLO}| market for tert-butyl amine | Cut-off, U	0,5	kg	
Bromopropane {RER}| bromopropane production | Cut-off, U	0,5	kg	Proxy for bromobutane
Chemical factory, organics {GLO}| market for chemical factory, organics | Cut-off, U	4,0E-10	kg	
Electricity, low voltage {RER}| market group for electricity, low voltage | Cut-off, U	143,05	kWh	Same energy used for methylammonium bromide

Table 23: Inventory table for the disposal of 1m2 of PePV badge with lead iodide recovery as based on (6)

Output	Amount	Unit	Comment
PePV experimental EoL	1	m2	
Avoided products			
Lead iodide	0,384	g	96% of the original lead iodide is recovered
Heat, district or industrial, natural gas {FI}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	3,28192865	MJ	
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	1,8234216	MJ	
Inputs			

Water, deionised {Europe without Switzerland}| water production, deionised | Cut-off, U	0,4	kg	The amount of freshwater that is initially used. This water can be reused multiple times, until the concentration of the other soluble compounds is too high. Assumed it will be reused twice.
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	0,0458	kWh	Shredding
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	0,0183	kWh	Electricity used for centrifuging assuming 1,1 kW power for 1 minute
Heat, district or industrial, other than natural gas {RER}| market group for heat, district or industrial, other than natural gas | Cut-off, U	0,0371	kWh	Assuming that the input water is 10C, has to be warmed up to 50C. The heating capacity of water per kg in kWh is 0,00116. The heating and precipitation process should be done twice.
Waste to treatment			
Spent solvent mixture {Europe without Switzerland}| treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | Cut-off, U	0,2	kg	The remaining of the water is incinerated once it is used. Assumed the water can be used at least twice
waste PePV badge {RER}| treatment of, incineration | Cut-off, U	0,455	kg	The remaining of the plastic badge is incinerated

Table 24: Inventory for the WEEE EoL process

Output	**Amount**	**Unit**	**Comment**
WEEE EoL	1	m^2	
Avoided products			
Gold {GLO}| market for gold | Cut-off, U	0.406	g	
Electricity, medium voltage {FI}| market for electricity, medium voltage | Cut-off, U	0,0458	kWh	
Gold {SE}| treatment of precious metal from electronics scrap, in anode slime, precious metal extraction | Cut-off, U	1.16	g	

Table 25: Inventory for the deposition of a CIGS cell on rigid substrate, 1 kWp

This inventory is confidential

Table 26: Inventory for the integration of a rigid CIGS module, 1 kWp

This inventory is confidential

Table 27: Inventory for EoL processes of 1kWp of rigid CIGS

This inventory is confidential

Table 28: Inventory for the integration of 1 kWp of rigid PePV

Output	Unit	Quantity
PePV, PV module integration	kWp	1
Resources		
Water, cooling, unspecified natural origin, NL	m3	0,233
Solar glass, low-iron {GLO}| market for solar glass, low-iron | Cut-off, U	kg	0
1-propanol {GLO}| market for 1-propanol | Cut-off, U	kg	0.112
Copper, anode {GLO}| market for copper, anode | Cut-off, U	kg	0.01
Diode, auxilliaries and energy use {GLO}| market for diode, auxilliaries and energy use | Cut-off, U	kg	0.00611
Ethylvinylacetate, foil {GLO}| market for ethylvinylacetate, foil | Cut-off, U	kg	1.72
Polybutadiene {RER}| polybutadiene production | Cut-off, U	kg	0.0192
Polymethyl methacrylate, sheet {GLO}| market for polymethyl methacrylate, sheet | Cut-off, U	kg	0.351
Flat glass, uncoated {RER}| market for flat glass, uncoated | Cut-off, U	kg	0
Tempering, flat glass {GLO}| market for tempering, flat glass | Cut-off, U	kg	0
Tin {GLO}| market for tin | Cut-off, U	kg	0.0338
Electricity/heat		
Electricity, medium voltage {NL}| market for electricity, medium voltage | Cut-off, U	kWh	19.52
Emissions to air		
Carbon dioxide, fossil	kg	0,142
Heat, waste	MJ	87,1
NMVOC, non-methane volatile organic compounds	kg	0,0524
Water/m3	m3	0,181
Waste to treatment		
Waste glass sheet {Europe without Switzerland}| market for waste glass sheet | Cut-off, U	kg	452.539

Municipal solid waste {RER}| market group for municipal solid waste | Cut-off, U	kg	0.63
Waste plastic, mixture {RER}| market group for waste plastic, mixture | Cut-off, U	kg	0.161
Waste polyvinylfluoride {RoW}| market for waste polyvinylfluoride | Cut-off, U	kg	0.00195

Table 29: Inventory for the EoL processes on 1 kWp of rigid PePV

Output	Unit	Quantity
Takeback and recycling, PePV rigid module_EU_PeroCUBE	kWp	1
Inputs		
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U	tkm	5,9
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO4 | Cut-off, U	tkm	23,6
Electricity/heat		
Electricity, medium voltage {RER}| market group for electricity, medium voltage | Cut-off, U	kWh	6,549
Diesel, burned in building machine {GLO}| market for diesel, burned in building machine | Cut-off, U	MJ	3,8232
Waste to treatment		
Waste plastic, mixture {Europe without Switzerland}| treatment of waste plastic, mixture, municipal incineration | Cut-off, U	kg	2,55
Waste plastic, mixture {Europe without Switzerland}| treatment of waste plastic, mixture, sanitary landfill | Cut-off, U	kg	0,45

B. OLED reference device

Table 30: Inventory of the reference OLED device as derived from (1) *for 1 m² of device*

Function	ecoinvent	Thickness [m]	Density [kg/m3]	Mass kg/m2	Comment
Cover glass	Solar glass, low-iron {GLO}| | Cut-off, U	5,00E-04	2,52E+03	1,26E+00	
ITO coating	Indium tin oxide powder, nanoscale, for sputtering target {RER}| | Cut-off, U	1,50E-07	7,14E+03	1,07E-03	
Sealant (Glass frit)	Flat glass, uncoated {RER}| market for | Cut-off, U	9,50E-06	2,52E+03	2,39E-02	
Cathode	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| Cut-off, U	1,25E-07	2,71E+03	3,39E-04	Assumed based on (36)
Electron injection layer (EIL)	Lithium fluoride {GLO}|| Cut-off, U	1,00E-07	2,64E+03	2,64E-04	Assumed the same material as in PeLED devices
n-doped Electron transport layer (ETL)	Alq3	2,50E-08	1,71E+03	4,28E-05	Density estimated based on the atomic weights of the Alq3 composition.
Emissive layer (EML)	Alq3	6,50E-08	1,71E+03	1,11E-04	Assumed only one layer of emissive material, as PeLED devices are single colour
p-doped Hole transport layer (HTL) 100e150 Organometallic dyes/Oligomers	CuPc	1,25E-07	1,75E+03	2,19E-04	
Anode 100e200	Indium tin oxide powder, nanoscale, for	1,50E-07	7,14E+03	1,07E-03	

ITO Sputtering	sputtering target {RER}| market for | Cut-off, U				
Glass	Solar glass, low-iron {GLO}| market for | Cut-off, U	5,00E-04	2,52E+03	1,26E+00	
Electricity				2,40E+02 MJ/m2	based on the values reported in (1)

C. Data tables of results

Table 31: Total Endpoint results for all leaching scenarios for the complete life cycle of a Flexible PePV device with Carbon back contact (CB) or gold back contact (GB)

Impact category	Unit	100% to EoL CB	95% to EoL CB	50% to EoL CB	0% to EoL CB	100% to EoL GB	95% to EoL GB	50% to EoL GB	0% to EoL BG
Global warming, Human health	DALY	6,09E-06	6,09E-06	6,09E-06	6,09E-06	5,57E-05	5,57E-05	5,57E-05	5,57E-05
Stratospheric ozone depletion	DALY	6,89E-09	6,89E-09	6,89E-09	6,89E-09	2,41E-08	2,41E-08	2,41E-08	2,41E-08
Ionizing radiation	DALY	2,79E-09	2,79E-09	2,79E-09	2,79E-09	6,63E-09	6,63E-09	6,63E-09	6,63E-09
Ozone formation, Human health	DALY	1,00E-08	1,00E-08	1,00E-08	1,00E-08	2,70E-07	2,70E-07	2,70E-07	2,70E-07
Fine particulate matter formation	DALY	4,38E-06	4,38E-06	4,38E-06	4,38E-06	8,82E-05	8,82E-05	8,82E-05	8,82E-05
Human carcinogenic toxicity	DALY	1,83E-07	1,84E-07	1,85E-07	1,86E-07	5,65E-06	5,65E-06	5,66E-06	5,66E-06
Human non-carcinogenic toxicity	DALY	3,23E-07	3,35E-07	4,43E-07	5,64E-07	4,29E-05	4,29E-05	4,30E-05	4,31E-05
Water consumption, Human health	DALY	1,20E-07	1,20E-07	1,20E-07	1,20E-07	6,29E-07	6,29E-07	6,29E-07	6,29E-07
Global warming, Terrestrial ecosystems	species.yr	1,84E-08	1,84E-08	1,84E-08	1,84E-08	1,68E-07	1,68E-07	1,68E-07	1,68E-07
Global warming, Freshwater ecosystems	species.yr	5,02E-13	5,02E-13	5,02E-13	5,02E-13	4,59E-12	4,59E-12	4,59E-12	4,59E-12
Ozone formation, Terrestrial ecosystems	species.yr	1,51E-09	1,51E-09	1,51E-09	1,51E-09	3,91E-08	3,91E-08	3,91E-08	3,91E-08
Terrestrial acidification	species.yr	3,42E-09	3,42E-09	3,42E-09	3,42E-09	6,72E-08	6,72E-08	6,72E-08	6,72E-08
Freshwater eutrophication	species.yr	1,46E-10	1,46E-10	1,46E-10	1,46E-10	1,39E-08	1,39E-08	1,39E-08	1,39E-08
Marine eutrophication	species.yr	2,00E-13	2,00E-13	1,95E-13	1,90E-13	2,48E-12	2,48E-12	2,47E-12	2,47E-12
Terrestrial ecotoxicity	species.yr	1,84E-10	1,84E-10	1,84E-10	1,84E-10	3,32E-09	3,32E-09	3,32E-09	3,32E-09
Freshwater ecotoxicity	species.yr	4,37E-12	4,37E-12	4,37E-12	4,37E-12	1,13E-09	1,13E-09	1,13E-09	1,13E-09
Marine ecotoxicity	species.yr	1,51E-12	1,51E-12	1,51E-12	1,51E-12	8,11E-10	8,11E-10	8,11E-10	8,11E-10

Land use	species.yr	2,67E-09	2,67E-09	2,67E-09	2,67E-09	3,39E-08	3,39E-08	3,39E-08	3,39E-08
Water consumption, Terrestrial ecosystem	species.yr	7,41E-10	7,41E-10	7,41E-10	7,40E-10	4,54E-09	4,54E-09	4,54E-09	4,54E-09
Water consumption, Aquatic ecosystems	species.yr	3,56E-14	3,56E-14	3,56E-14	3,56E-14	5,61E-13	5,61E-13	5,61E-13	5,61E-13
Mineral resource scarcity	USD2013	6,89E-02	6,89E-02	6,89E-02	6,89E-02	1,32E+00	1,32E+00	1,32E+00	1,32E+00
Fossil resource scarcity	USD2013	6,16E-01	6,16E-01	6,16E-01	6,16E-01	3,55E+00	3,55E+00	3,55E+00	3,55E+00

Table 32: Midpoint results for 1m2 of Flexible PePV with gold back contact, WEEE EoL and assuming 100% perovskite leaching to the environment

Impact category	Unit	PePV R2R deposition	PePV use phase	PePV badge WEEE EoL
Global warming	kg CO2 eq	8,49E+01	0,00E+00	-2,48E+01
Stratospheric ozone depletion	kg CFC11 eq	6,18E-05	0,00E+00	-1,65E-05
Ionizing radiation	kBq Co-60 eq	1,01E+00	0,00E+00	-2,27E-01
Ozone formation, Human health	kg NOx eq	4,46E-01	0,00E+00	-1,49E-01
Fine particulate matter formation	kg PM2.5 eq	2,10E-01	0,00E+00	-6,93E-02
Ozone formation, Terrestrial ecosystems	kg NOx eq	4,55E-01	0,00E+00	-1,52E-01
Terrestrial acidification	kg SO2 eq	4,73E-01	0,00E+00	-1,56E-01
Freshwater eutrophication	kg P eq	3,17E-02	0,00E+00	-1,10E-02
Marine eutrophication	kg N eq	2,15E-03	0,00E+00	-6,97E-04
Terrestrial ecotoxicity	kg 1,4-DCB	4,26E+02	0,00E+00	-1,35E+02
Freshwater ecotoxicity	kg 1,4-DCB	2,42E+00	0,00E+00	-7,88E-01
Marine ecotoxicity	kg 1,4-DCB	1,17E+01	0,00E+00	-4,02E+00
Human carcinogenic toxicity	kg 1,4-DCB	1,56E+00	8,81E-04	1,48E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1,30E+02	1,06E+00	5,80E+01
Land use	m2a crop eq	5,68E+00	0,00E+00	-1,85E+00
Mineral resource scarcity	kg Cu eq	8,59E+00	0,00E+00	-2,90E+00
Fossil resource scarcity	kg oil eq	2,22E+01	0,00E+00	-6,81E+00
Water consumption	m3	8,27E-01	0,00E+00	-2,47E-01

Table 33: ReCiPe midpoint results for the deposition of 1 m2 of Flexible PePV with gold back contact

Impact category	Unit	Total	PET	Extrusion	ITO	Chemical, organic	Argon,	Nitrogen,	Isopropanol	Stannic oxide	PePV_ink	Chemical, organic	Gold	PET	Extrusion	Polymethyl methacrylate	Electricity	PePV badge incineration	Spent solvent
Global warming	kg CO2 eq	8,49E+01	5,45E-01	6,68E-02	6,17E-03	7,74E-02	2,54E-04	1,44E-04	1,12E-01	1,21E-03	5,80E-02	3,37E-03	7,91E+01	1,06E+00	1,29E-01	1,13E+00	2,46E+00	3,87E-02	9,38E-02
Stratospheric ozone depletion	kg CFC 11 eq	6,18E-05	3,48E-06	2,74E-08	3,37E-09	1,32E-08	1,17E-10	6,57E-11	1,25E-08	2,77E-10	2,78E-08	5,76E-10	4,92E-05	6,74E-06	5,30E-08	7,37E-09	2,26E-06	1,66E-08	2,33E-08
Ionizing radiation	kBq Co-60 eq	1,01E+00	1,63E-03	1,73E-03	1,19E-04	1,63E-04	1,01E-05	5,65E-06	1,48E-04	4,98E-06	7,99E-04	7,10E-06	6,65E-01	3,16E-03	3,35E-03	2,59E-05	3,32E-01	5,37E-07	3,35E-05
Ozone formation, Human health	kg NOx eq	4,46E-01	1,19E-03	1,18E-04	2,80E-05	1,65E-04	4,49E-07	2,66E-07	2,36E-04	3,20E-06	1,44E-04	7,17E-06	4,35E-01	2,30E-03	2,29E-04	2,23E-03	4,39E-03	8,69E-06	3,91E-05
Fine particulate matter formation	kg PM2.5 eq	2,10E-01	6,46E-04	7,73E-05	1,23E-05	8,99E-05	3,41E-07	1,94E-07	1,25E-04	2,80E-06	6,86E-05	3,91E-06	2,02E-01	1,25E-03	1,50E-04	1,34E-03	3,31E-03	1,22E-06	1,47E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	4,55E-01	1,26E-03	1,24E-04	2,94E-05	1,80E-04	4,65E-07	2,75E-07	2,67E-04	3,35E-06	1,58E-04	7,81E-06	4,43E-01	2,44E-03	2,40E-04	2,44E-03	4,59E-03	8,74E-06	4,05E-05
Terrestrial acidification	kg SO2 eq	4,73E-01	1,48E-03	1,93E-04	3,28E-05	2,16E-04	8,60E-07	4,86E-07	3,49E-04	4,04E-06	1,83E-04	9,39E-06	4,57E-01	2,86E-03	3,75E-04	4,31E-03	6,27E-03	3,58E-06	3,25E-05
Freshwater eutrophication	kg P eq	3,17E-02	1,81E-05	5,27E-06	5,70E-07	3,37E-06	2,43E-08	1,36E-08	9,97E-06	4,85E-08	3,88E-06	1,47E-07	3,15E-02	3,50E-05	1,02E-05	3,11E-05	1,04E-04	5,72E-09	1,01E-06

Marine eutrophication	kg N eq	2,15E-03	7,12E-06	9,84E-07	1,16E-07	4,86E-07	1,40E-09	8,35E-10	4,03E-07	5,22E-09	2,21E-06	2,11E-08	2,04E-03	1,38E-05	1,91E-06	6,25E-05	1,97E-05	3,10E-07	6,01E-07
Terrestrial ecotoxicity	kg 1,4-DCB	4,26E+02	2,37E+00	1,24E-01	1,77E-01	1,76E-01	3,62E-04	2,35E-04	4,46E-01	4,20E-03	3,14E-01	7,67E-03	4,12E+02	4,59E+00	2,40E-01	1,94E-01	4,98E+00	9,91E-02	2,19E-02
Freshwater ecotoxicity	kg 1,4-DCB	2,42E+00	7,23E-04	6,11E-05	1,66E-04	4,94E-05	1,75E-07	1,04E-07	7,05E-05	1,07E-06	9,37E-04	2,15E-06	2,41E+00	1,40E-03	1,18E-04	4,77E-04	2,21E-03	5,50E-06	1,93E-05
Marine ecotoxicity	kg 1,4-DCB	1,17E+01	2,12E-03	1,23E-04	3,16E-04	1,48E-04	3,27E-07	2,10E-07	3,15E-04	3,43E-06	2,24E-04	6,44E-06	1,17E+01	4,11E-03	2,38E-04	7,40E-04	3,89E-03	8,29E-05	4,05E-05
Human carcinogenic toxicity	kg 1,4-DCB	1,56E+00	7,47E-03	9,33E-04	1,28E-03	6,48E-04	2,02E-06	1,18E-06	9,22E-04	1,40E-05	6,31E-04	2,82E-05	1,50E+00	1,45E-02	1,81E-03	6,21E-03	2,16E-02	1,67E-05	1,63E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1,30E+02	2,09E-01	1,28E-02	2,22E-02	1,16E-02	5,38E-05	3,07E-05	2,74E-02	4,55E-04	2,06E-02	5,05E-04	1,29E+02	4,05E-01	2,48E-02	1,77E-02	6,43E-01	1,53E-03	2,84E-03
Land use	m2a crop eq	5,68E+00	7,52E-03	9,87E-03	2,64E-04	8,49E-04	7,64E-06	4,40E-06	9,64E-04	2,15E-05	1,22E-03	3,69E-05	5,36E+00	1,46E-02	1,91E-02	5,71E-04	2,56E-01	5,49E-06	1,47E-04
Mineral resource scarcity	kg Cu eq	8,59E+00	2,11E-03	1,73E-04	4,50E-04	1,47E-04	4,41E-07	2,56E-07	2,85E-04	9,67E-05	2,83E-01	6,40E-06	8,29E+00	4,08E-03	3,36E-04	1,49E-04	6,95E-03	3,48E-06	3,21E-05
Fossil resource scarcity	kg oil eq	2,22E+01	2,77E-01	1,77E-02	1,66E-03	4,82E-02	6,99E-05	3,91E-05	6,52E-02	5,95E-04	2,33E-02	2,10E-03	2,03E+01	5,37E-01	3,42E-02	3,59E-01	6,02E-01	1,37E-04	3,05E-03
Water consumption	m3	8,27E-01	5,64E-03	3,90E-03	1,58E-04	1,19E-03	1,47E-05	8,28E-06	7,31E-04	1,30E-05	1,54E-03	5,18E-05	7,19E-01	1,09E-02	7,56E-03	4,16E-03	7,20E-02	9,77E-06	1,19E-04

Table 34: ReCiPe midpoint results for the deposition of 1 m2 of Flexible PePV with carbon back contact

Impact category	Unit	Total	PET	Extrusion	ITO	Chemical, organic	Argon,	Nitrogen,	Isopropanol	SnO2	PePV_ink	Chemical, organic	PET	Extrusion,	Polymethyl methacrylate, sheet	Carbon screen paste	Electricity	waste PePV incineration	Spent sovent
Global warming	kg CO2 eq	5,78E+00	5,45E-01	6,68E-02	6,17E-03	7,74E-02	2,54E-04	1,44E-04	1,12E-01	1,21E-03	5,32E-02	3,37E-03	1,06E+00	1,29E-01	1,13E+00	2,32E-03	2,46E+00	3,87E-02	9,38E-02
Stratospheric ozone depletion	kg CFC 11 eq	1,27E-05	3,48E-06	2,74E-08	3,37E-09	1,32E-08	1,17E-10	6,57E-11	1,25E-08	2,77E-10	2,80E-08	5,76E-10	6,74E-06	5,30E-08	7,37E-09	2,66E-10	2,26E-06	1,66E-08	2,33E-08
Ionizing radiation	kBq Co-60 eq	3,43E-01	1,63E-03	1,73E-03	1,19E-04	1,63E-04	1,01E-05	5,65E-06	1,48E-04	4,98E-06	8,21E-04	7,10E-06	3,16E-03	3,35E-03	2,59E-05	9,83E-06	3,32E-01	5,37E-07	3,35E-05
Ozone formation, Human health	kg NOx eq	1,11E-02	1,19E-03	1,18E-04	2,80E-05	1,65E-04	4,49E-07	2,66E-07	2,36E-04	3,20E-06	1,08E-04	7,17E-06	2,30E-03	2,29E-04	2,23E-03	3,96E-06	4,39E-03	8,69E-06	3,91E-05
Fine particulate matter formation	kg PM 2.5 eq	7,09E-03	6,46E-04	7,73E-05	1,23E-05	8,99E-05	3,41E-07	1,94E-07	1,25E-04	2,80E-06	6,54E-05	3,91E-06	1,25E-03	1,50E-04	1,34E-03	1,98E-06	3,31E-03	1,22E-06	1,47E-05
Ozone formation, Terrestrial	kg NOx eq	1,18E-02	1,26E-03	1,24E-04	2,94E-05	1,80E-04	4,65E-07	2,75E-07	2,67E-04	3,35E-06	1,21E-04	7,81E-06	2,44E-03	2,40E-04	2,44E-03	4,28E-06	4,59E-03	8,74E-06	4,05E-05

ecosystems																			
Terrestrial acidification	kg SO2 eq	1,63E-02	1,48E-03	1,93E-04	3,28E-05	2,16E-04	8,60E-07	4,86E-07	3,49E-04	4,04E-06	1,71E-04	9,39E-06	2,86E-03	3,75E-04	4,31E-03	5,31E-06	6,27E-03	3,58E-06	3,25E-05
Freshwater eutrophication	kg P eq	2,23E-04	1,81E-05	5,27E-06	5,70E-07	3,37E-06	2,43E-08	1,36E-08	9,97E-06	4,85E-08	3,87E-06	1,47E-07	3,50E-05	1,02E-05	3,11E-05	4,13E-08	1,04E-04	5,72E-09	1,01E-06
Marine eutrophication	kg N eq	1,10E-04	7,12E-06	9,84E-07	1,16E-07	4,86E-07	1,40E-09	8,35E-10	4,03E-07	5,22E-09	2,07E-06	2,11E-08	1,38E-05	1,91E-06	6,25E-05	1,46E-08	1,97E-05	3,10E-07	6,01E-07
Terrestrial ecotoxicity	kg 1,4-DCB	1,37E+01	2,37E+00	1,24E-01	1,77E-01	1,76E-01	3,62E-04	2,35E-04	4,46E-01	4,20E-03	3,09E-01	7,67E-03	4,59E+00	2,40E-01	1,94E-01	4,10E-03	4,98E+00	9,91E-02	2,19E-02
Freshwater ecotoxicity	kg 1,4-DCB	6,24E-03	7,23E-04	6,11E-05	1,66E-04	4,94E-05	1,75E-07	1,04E-07	7,05E-05	1,07E-06	9,34E-04	2,15E-06	1,40E-03	1,18E-04	4,77E-04	1,13E-06	2,21E-03	5,50E-06	1,93E-05
Marine ecotoxicity	kg 1,4-DCB	1,23E-02	2,12E-03	1,23E-04	3,16E-04	1,48E-04	3,27E-07	2,10E-07	3,15E-04	3,43E-06	2,12E-04	6,44E-06	4,11E-03	2,38E-04	7,40E-04	3,78E-06	3,89E-03	8,29E-05	4,05E-05
Human carcinogenic toxicity	kg 1,4-DCB	5,62E-02	7,47E-03	9,33E-04	1,28E-03	6,48E-04	2,02E-06	1,18E-06	9,22E-04	1,40E-05	6,65E-04	2,82E-05	1,45E-02	1,81E-03	6,21E-03	1,55E-05	2,16E-02	1,67E-05	1,63E-04
Human non-carcinoge	kg 1,4-DCB	1,40E+00	2,09E-01	1,28E-02	2,22E-02	1,16E-02	5,38E-05	3,07E-05	2,74E-02	4,55E-04	1,95E-02	5,05E-04	4,05E-01	2,48E-02	1,77E-02	1,75E-04	6,43E-01	1,53E-03	2,84E-03

nic toxicity																			
Land use	m2a crop eq	3,12E-01	7,52E-03	9,87E-03	2,64E-04	8,49E-04	7,64E-06	4,40E-06	9,64E-04	2,15E-05	1,20E-03	3,69E-05	1,46E-02	1,91E-02	5,71E-04	9,25E-05	2,56E-01	5,49E-06	1,47E-04
Mineral resource scarcity	kg Cu eq	2,98E-01	2,11E-03	1,73E-04	4,50E-04	1,47E-04	4,41E-07	2,56E-07	2,85E-04	9,67E-05	2,83E-01	6,40E-06	4,08E-03	3,36E-04	1,49E-04	4,04E-05	6,95E-03	3,48E-06	3,21E-05
Fossil resource scarcity	kg oil eq	1,97E+00	2,77E-01	1,77E-02	1,66E-03	4,82E-02	6,99E-05	3,91E-05	6,52E-02	5,95E-04	2,18E-02	2,10E-03	5,37E-01	3,42E-02	3,59E-01	1,49E-03	6,02E-01	1,37E-04	3,05E-03
Water consumption	m3	1,09E-01	5,64E-03	3,90E-03	1,58E-04	1,19E-03	1,47E-05	8,28E-06	7,31E-04	1,30E-05	2,29E-03	5,18E-05	1,09E-02	7,56E-03	4,16E-03	3,10E-05	7,20E-02	9,77E-06	1,19E-04

Table 35: ReciPe midpoint results for the Standard EoL treatment of 1m2 of PePV

Impact category	Electricity, Shredding	Electricity, recovered	Heat, recovered	Incineration
Global warming	1,04E-02	-1,15E-01	-1,10E-01	9,90E-01
Stratospheric ozone depletion	9,57E-09	-1,05E-07	-2,56E-08	4,26E-07
Ionizing radiation	1,40E-03	-1,54E-02	-2,51E-05	1,37E-05
Ozone formation, Human health	1,86E-05	-2,04E-04	-1,26E-04	2,22E-04
Fine particulate matter formation	1,40E-05	-1,54E-04	-2,20E-05	3,13E-05
Ozone formation, Terrestrial ecosystems	1,94E-05	-2,14E-04	-1,46E-04	2,24E-04
Terrestrial acidification	2,65E-05	-2,92E-04	-5,47E-05	9,15E-05
Freshwater eutrophication	4,41E-07	-4,86E-06	-3,80E-07	1,46E-07
Marine eutrophication	8,34E-08	-9,18E-07	-9,40E-08	7,92E-06
Terrestrial ecotoxicity	2,11E-02	-2,32E-01	-3,56E-02	2,54E+00
Freshwater ecotoxicity	9,35E-06	-1,03E-04	-1,61E-05	1,41E-04
Marine ecotoxicity	1,64E-05	-1,81E-04	-4,68E-05	2,12E-03
Human carcinogenic toxicity	9,12E-05	-1,00E-03	-5,35E-04	4,26E-04
Human non-carcinogenic toxicity	2,72E-03	-2,99E-02	-2,76E-03	3,91E-02
Land use	1,08E-03	-1,19E-02	-3,58E-04	1,40E-04
Mineral resource scarcity	2,94E-05	-3,24E-04	-1,07E-04	8,90E-05
Fossil resource scarcity	2,55E-03	-2,81E-02	-3,76E-02	3,50E-03

Water consumption	3,04E-04	-3,35E-03	-1,69E-04	2,50E-04

Table 36 ReciPe midpoint results for the Experimental EoL treatment of 1m2 of PePV

Impact category	Unit	Water, deionised	Shredding electricity	Centrifuging electricity	Heat, other than natural gas	Lead iodide (recovered)	Heat, (recovered)	Electricity, (recovered)	Disposal of solvent	Incineration of remaining material
Global warming	kg CO2 eq	1,80E-04	1,04E-02	4,17E-03	9,52E-03	-1,80E-02	-1,10E-01	-1,15E-01	3,98E-01	9,83E-01
Stratospheric ozone depletion	kg CFC11 eq	1,65E-10	9,57E-09	3,83E-09	2,18E-09	-1,69E-08	-2,57E-08	-1,06E-07	9,88E-08	4,23E-07
Ionizing radiation	kBq Co-60 eq	1,23E-06	1,40E-03	5,61E-04	8,52E-06	-6,33E-04	-2,52E-05	-1,55E-02	1,42E-04	1,36E-05
Ozone formation, Human health	kg NOx eq	3,77E-07	1,86E-05	7,43E-06	2,22E-05	-3,33E-05	-1,27E-04	-2,05E-04	1,66E-04	2,21E-04
Fine particulate matter formation	kg PM2.5 eq	5,06E-07	1,40E-05	5,60E-06	1,67E-05	-2,77E-05	-2,21E-05	-1,55E-04	6,24E-05	3,11E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	3,91E-07	1,94E-05	7,77E-06	2,27E-05	-3,45E-05	-1,47E-04	-2,15E-04	1,72E-04	2,22E-04
Terrestrial acidification	kg SO2 eq	1,36E-06	2,65E-05	1,06E-05	5,06E-05	-7,17E-05	-5,49E-05	-2,93E-04	1,38E-04	9,09E-05
Freshwater eutrophication	kg P eq	8,50E-09	4,41E-07	1,77E-07	4,90E-07	-1,62E-06	-3,82E-07	-4,88E-06	4,27E-06	1,45E-07
Marine eutrophication	kg N eq	2,31E-09	8,34E-08	3,34E-08	7,34E-08	-1,18E-07	-9,43E-08	-9,22E-07	2,55E-06	7,87E-06

Terrestrial ecotoxicity	kg 1,4-DCB	1,21E-03	2,11E-02	8,43E-03	1,60E-02	-1,10E-01	-3,58E-02	-2,33E-01	9,31E-02	2,52E+00
Freshwater ecotoxicity	kg 1,4-DCB	6,81E-07	9,35E-06	3,74E-06	3,14E-06	-2,46E-05	-1,62E-05	-1,03E-04	8,19E-05	1,40E-04
Marine ecotoxicity	kg 1,4-DCB	1,58E-06	1,64E-05	6,58E-06	1,51E-05	-7,86E-05	-4,70E-05	-1,82E-04	1,72E-04	2,11E-03
Human carcinogenic toxicity	kg 1,4-DCB	5,16E-06	9,12E-05	3,65E-05	3,98E-05	-2,60E-04	-5,37E-04	-1,01E-03	6,91E-04	4,23E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1,11E-04	2,72E-03	1,09E-03	1,98E-03	-1,26E-02	-2,78E-03	-3,01E-02	1,21E-02	3,88E-02
Land use	m2a crop eq	4,04E-06	1,08E-03	4,34E-04	6,28E-04	-5,67E-04	-3,60E-04	-1,20E-02	6,23E-04	1,40E-04
Mineral resource scarcity	kg Cu eq	1,27E-06	2,94E-05	1,18E-05	3,02E-06	-1,61E-03	-1,08E-04	-3,25E-04	1,36E-04	8,84E-05
Fossil resource scarcity	kg oil eq	4,27E-05	2,55E-03	1,02E-03	2,07E-03	-4,82E-03	-3,78E-02	-2,82E-02	1,30E-02	3,47E-03
Water consumption	m3	3,87E-04	3,04E-04	1,22E-04	5,99E-05	-3,00E-04	-1,69E-04	-3,37E-03	5,06E-04	2,48E-04

Table 37: Midpoint results for 1 kWp of Rigid PePV with ITO back contact

Impact category	Unit	Total	Solar glass	ITO	Nickel	PePV ink CSEM	Graphite	Stannic oxide	ITO	Flat glass	Argon	Electricity
Global warming	kg CO2 eq	2,01E+02	3,20E+01	1,15E-01	4,98E-07	8,49E-01	1,34E-08	2,59E-07	1,15E-01	2,88E+01	3,25E-01	1,39E+02

Stratospheric ozone depletion	kg CFC11 eq	7,14E-05	3,50E-06	5,74E-08	7,10E-13	6,81E-07	4,87E-15	5,94E-14	5,74E-08	2,80E-06	1,49E-07	6,41E-05
Ionizing radiation	kBq Co-60 eq	5,73E+00	4,72E-02	1,65E-03	3,77E-09	2,29E-02	6,21E-11	1,07E-09	1,65E-03	6,64E-02	1,29E-02	5,58E+00
Ozone formation, Human health	kg NOx eq	5,01E-01	1,34E-01	4,95E-04	2,85E-09	1,63E-03	7,04E-11	6,88E-10	4,95E-04	1,19E-01	5,73E-04	2,44E-01
Fine particulate matter formation	kg PM2.5 eq	3,22E-01	6,96E-02	2,38E-04	9,21E-10	1,20E-03	2,78E-11	6,02E-10	2,38E-04	6,32E-02	4,36E-04	1,87E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	5,15E-01	1,38E-01	5,19E-04	2,93E-09	1,74E-03	7,24E-11	7,20E-10	5,19E-04	1,22E-01	5,93E-04	2,53E-01
Terrestrial acidification	kg SO2 eq	8,69E-01	2,02E-01	5,78E-04	2,12E-09	3,06E-03	6,10E-11	8,67E-10	5,78E-04	1,91E-01	1,10E-03	4,71E-01
Freshwater eutrophication	kg P eq	1,46E-02	5,59E-04	9,37E-06	1,05E-10	7,32E-05	3,96E-13	1,04E-11	9,37E-06	5,00E-04	3,10E-05	1,34E-02
Marine eutrophication	kg N eq	1,56E-03	3,59E-04	1,88E-06	3,66E-11	1,00E-04	1,93E-13	1,12E-12	1,88E-06	3,33E-04	1,79E-06	7,60E-04
Terrestrial ecotoxicity	kg 1,4-DCB	3,72E+02	1,02E+02	2,87E+00	5,73E-06	4,82E+00	8,52E-08	9,01E-07	2,87E+00	6,96E+01	4,62E-01	1,89E+02
Freshwater ecotoxicity	kg 1,4-DCB	1,42E-01	2,53E-02	2,69E-03	3,42E-09	3,57E-03	2,58E-11	2,29E-10	2,69E-03	1,34E-02	2,24E-04	9,44E-02

Marine ecotoxicity	kg 1,4-DCB	3,24E-01	8,43E-02	5,12E-03	6,87E-09	3,47E-03	7,24E-11	7,37E-10	5,12E-03	5,50E-02	4,18E-04	1,71E-01
Human carcinogenic toxicity	kg 1,4-DCB	1,52E+00	2,26E-01	2,08E-02	7,18E-09	1,16E-02	1,98E-10	3,00E-09	2,08E-02	1,68E-01	2,58E-03	1,07E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	3,90E+01	4,81E+00	3,62E-01	2,25E-07	4,95E-01	3,08E-09	9,76E-08	3,62E-01	3,75E+00	6,86E-02	2,92E+01
Land use	m2a crop eq	5,65E+00	7,76E-01	4,36E-03	4,46E-08	2,37E-02	4,97E-10	4,62E-09	4,36E-03	6,54E-01	9,75E-03	4,18E+00
Mineral resource scarcity	kg Cu eq	8,13E+00	7,64E-02	7,28E-03	5,15E-07	7,74E+00	3,71E-08	2,08E-08	7,28E-03	6,42E-02	5,62E-04	2,33E-01
Fossil resource scarcity	kg oil eq	5,25E+01	7,62E+00	2,97E-02	1,21E-07	2,69E-01	3,64E-09	1,28E-07	2,97E-02	6,70E+00	8,92E-02	3,77E+01
Water consumption	m3	2,83E+00	1,72E-01	2,34E-03	1,94E-08	1,70E-02	5,96E-11	2,80E-09	2,34E-03	1,75E-01	1,88E-02	2,44E+00

Table 38: Midpoint results for 1 kWp of Rigid PePV with silver back contact

Impact category	Unit	Total	Solar glass	ITO	Nickel	PePV ink CSEM	Graphite	Stannic oxide	Silver	Flat glass	Argon	Electricity
Global warming	kg CO2 eq	2,01E+02	3,20E+01	1,15E-01	4,98E-07	8,49E-01	1,34E-08	2,59E-07	9,69E-04	2,88E+01	3,25E-01	1,39E+02

Stratospheric ozone depletion	kg CFC11 eq	7,13E-05	3,50E-06	5,74E-08	7,10E-13	6,81E-07	4,87E-15	5,94E-14	7,64E-10	2,80E-06	1,49E-07	6,41E-05
Ionizing radiation	kBq Co-60 eq	5,73E+00	4,72E-02	1,65E-03	3,77E-09	2,29E-02	6,21E-11	1,07E-09	7,58E-06	6,64E-02	1,29E-02	5,58E+00
Ozone formation, Human health	kg NOx eq	5,00E-01	1,34E-01	4,95E-04	2,85E-09	1,63E-03	7,04E-11	6,88E-10	8,06E-06	1,19E-01	5,73E-04	2,44E-01
Fine particulate matter formation	kg PM2.5 eq	3,21E-01	6,96E-02	2,38E-04	9,21E-10	1,20E-03	2,78E-11	6,02E-10	2,91E-06	6,32E-02	4,36E-04	1,87E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	5,15E-01	1,38E-01	5,19E-04	2,93E-09	1,74E-03	7,24E-11	7,20E-10	8,22E-06	1,22E-01	5,93E-04	2,53E-01
Terrestrial acidification	kg SO2 eq	8,68E-01	2,02E-01	5,78E-04	2,12E-09	3,06E-03	6,10E-11	8,67E-10	6,67E-06	1,91E-01	1,10E-03	4,71E-01
Freshwater eutrophication	kg P eq	1,46E-02	5,59E-04	9,37E-06	1,05E-10	7,32E-05	3,96E-13	1,04E-11	2,84E-07	5,00E-04	3,10E-05	1,34E-02
Marine eutrophication	kg N eq	1,56E-03	3,59E-04	1,88E-06	3,66E-11	1,00E-04	1,93E-13	1,12E-12	3,06E-08	3,33E-04	1,79E-06	7,60E-04
Terrestrial ecotoxicity	kg 1,4-DCB	3,69E+02	1,02E+02	2,87E+00	5,73E-06	4,82E+00	8,52E-08	9,01E-07	1,20E-02	6,96E+01	4,62E-01	1,89E+02
Freshwater ecotoxicity	kg 1,4-DCB	1,40E-01	2,53E-02	2,69E-03	3,42E-09	3,57E-03	2,58E-11	2,29E-10	1,19E-05	1,34E-02	2,24E-04	9,44E-02

Marine ecotoxicity	kg 1,4-DCB	3,20E-01	8,43E-02	5,12E-03	6,87E-09	3,47E-03	7,24E-11	7,37E-10	5,84E-04	5,50E-02	4,18E-04	1,71E-01
Human carcinogenic toxicity	kg 1,4-DCB	1,50E+00	2,26E-01	2,08E-02	7,18E-09	1,16E-02	1,98E-10	3,00E-09	4,43E-05	1,68E-01	2,58E-03	1,07E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	3,87E+01	4,81E+00	3,62E-01	2,25E-07	4,95E-01	3,08E-09	9,76E-08	1,82E-03	3,75E+00	6,86E-02	2,92E+01
Land use	m2a crop eq	5,65E+00	7,76E-01	4,36E-03	4,46E-08	2,37E-02	4,97E-10	4,62E-09	8,34E-05	6,54E-01	9,75E-03	4,18E+00
Mineral resource scarcity	kg Cu eq	8,13E+00	7,64E-02	7,28E-03	5,15E-07	7,74E+00	3,71E-08	2,08E-08	1,68E-04	6,42E-02	5,62E-04	2,33E-01
Fossil resource scarcity	kg oil eq	5,24E+01	7,62E+00	2,97E-02	1,21E-07	2,69E-01	3,64E-09	1,28E-07	2,51E-04	6,70E+00	8,92E-02	3,77E+01
Water consumption	m3	2,83E+00	1,72E-01	2,34E-03	1,94E-08	1,70E-02	5,96E-11	2,80E-09	8,33E-06	1,75E-01	1,88E-02	2,44E+00