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CircularPV

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<u>Deliverable D3.1:</u>

Extended life cycle assessment for optimal environmental footprint

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Executive summary

CIRCULAR-PV is a Clean Energy Transition (CET) Partnership project that targets to develop and test innovative circularity strategies combined with low environmental impact manufacturing of perovskite PV modules to achieve reliable, sustainable, recyclable, and potentially lower cost PV. The CIRCULAR-PV consortium comprises of five partners from four countries that bring their expertise together to address the ambitious objectives of this project, namely University of Cyprus (Cyprus), which is also the Coordinator, the University of Freiburg (Germany), the Forschungszentrum Jülich (Germany), Solaronix (Switzerland), and Dyenamo (Sweden). The CIRCULAR-PV partnership will strive to investigate eco-design modules outdoors in terms of their lifetime and stability studying links between material recovery and degradation pathways generated by real field operation. Moreover, it will aim to demonstrate successful material recovery without substantial quality loss and to study the feasibility of re-manufacturing eco-friendly PV. Ultimate target of the project is to achieve effective recycling of eco-friendly perovskite modules without sacrificing long-term stability and efficiency.

CIRCULAR-PV is expected to lead to minimisation of use of critical raw materials, to new circularity-by-design approaches, to the demonstration of the feasibility of scaling up perovskites using sustainable green approaches, circularity designs, and pre-industrial processes, as well as to the demonstration of the technology (in terms of stability and in terms of circularity effectiveness) in different climatic conditions in Cyprus and in Germany. The project's official launch date was January 2025, and it is scheduled to run for 36 months.

The report D3.1 ('Extended LCA and strategy for optimal environmental footprint') is a deliverable of Work package three of CIRCULAR-PV (WP3. Circularity strategy) and it deals with the environmental impact throughout the production and recycling phases of the modules.

Purpose of this document

This report was prepared with the purpose of examining the environmental impact associated with the manufacturing and recycling of perovskite solar modules. The report includes the results of an early-stage life cycle assessment, the estimated materials bound in 1TW of perovskite module scale-up, the LCAs conducted by metal associations, solvent selection guidelines by Chem21, and a lab-scale cost analysis. This report is aimed to be useful for selection of perovskite module manufacturing and recycling materials and solvents, with long-term supply and sustainability kept in mind.

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What is a life cycle assessment and how is it modelled

A life cycle assessment is an approach for assessing the impacts associated with a product within a set of boundaries. This project is focused on the environmental impacts associated with a perovskite solar module, where the boundary is from raw material extraction to the manufacture and then recycling of the module.

There are two commonly used terms in LCA development that may be beneficial to know for this document:

1. Functional unit: the unit that is being used to represent the product. In this project, it is 1m^2 of perovskite solar module.
2. Flow: another term for 'material' or 'energy' that is input into or output from the product.

The behind-the-scenes of a life cycle assessment are straight forward: it is simply adding up the material input and output flows for each of the individual components of a product. The life cycle assessment requires Life Cycle Inventories (LCIs), which is the 'ingredients list' to manufacture a component – what other materials, heat and electricity are required to create it. Most of the work in developing a life cycle assessment comes from the step of finding or producing these LCIs or ingredients lists.

There are three methods of finding these LCIs, in order of preference: using paid-for databases; referring to published papers; and estimating the values used in industry scale production. Conventional materials that are produced at industry scale and used frequently – such as solvents like methanol or metals like aluminium – are often found in already developed, paid-for databases such as Ecoinvent. For novel materials that aren't already in these databases, their LCIs can sometimes be found in published papers from research that is conducting life cycle assessments on a similar topic. For materials that do not have LCIs in databases or papers, the conventional approach is using lab-scale synthesis routes to estimate the material and energy requirements for industry scale production of that material. Each of these approaches, however, comes with a myriad of issues. A summary of these is provided in the next section.

Once the LCA has been modelled it results in, among other things, a list of all the input and output flows to create the product, and the impact categories. Given that there are many materials included in the output flows (up to 2500), the impact categories are a sum of these to simplify the interpretation of the results. Different lifecycle impact assessment methodologies (LCIA) sum these flows differently which result in different categories for environmental impact. Three examples are provided below. These impact categories are what are used to judge the environmental impacts of a product.

Table 1: Example of the impact categories that are used by different life cycle impact assessment methodologies.

LCIA method	Impact categories
ReCiPe	Particulate matter, tropospheric ozone formation, ionizing radiation, stratosphere ozone depletion, human toxicity (cancer), human toxicity (non-cancer), global warming, water use, freshwater ecotoxicity, freshwater eutrophication, troposphere ozone (eco) terrestrial ecotoxicity, terrestrial acidification, land use/transformation, marine ecotoxicity, mineral resources, fossil resources
CML	Global warming potential, acidification potential, eutrophication potential, human toxicity potential, photochemical ozone creation potential, ozone layer depletion potential, primary energy, terrestrial ecotoxicity potential, marine ecotoxicity potential
TRACI	Climate change, ozone depletion, acidification, eutrophication, smog formation, human health impacts (carcinogenic and non-carcinogenic), ecotoxicity

Justification for not providing a detailed LCA

One of the main requirements of this deliverable is the development of a complete, traditional life cycle assessment (LCA). Although this initially seemed feasible, it became clear as the project progressed that an LCA on these perovskite modules would produce few meaningful results.

There were several challenges when assembling the life cycle assessment for this project. Most of which stem from the limited availability of reliable data on novel chemical production, as well as inconsistencies with the data that does exist:

1. Most novel materials are not available in Ecoinvent – a paid-for database that is designed for the development of an LCA. Of approximately 39 different materials used in the manufacturing of the project's modules, 23 of them are not listed in Ecoinvent.
2. The Ecoinvent database is limited, and in some cases even recommends against using their data.
3. Life cycle inventories (LCI) for novel materials are scarce: four materials had no available LCIs, most had only one LCI, some had two and a few had four.
4. Comparing LCIs of the same material is difficult: either the functional units differ significantly (e.g., 1cm^2 of FTO versus 1m^2 of FTO), or there is no agreement between different LCIs for the same material.
5. Scaling up requires exact knowledge on the synthesis route of a material - which is not always available – and requires too many simplifying assumptions. As a result, there are concerns that scale-up estimates may not accurately reflect real world processes.
6. The nature of LCAs makes them very difficult to compare results, and the reliability of the ISO 14040/44 standard is widely debated.
7. Different frameworks aggregate output flows differently, making their impact categories difficult to compare.

As a result of these limitations, an LCA was conducted for one of the modules to give a first indication of whether recycling the module would be beneficial. However, an in-depth analysis of the LCA results has not been provided, given the concerns that that the exact values for the flows and impact categories are not precise enough to draw meaningful conclusions from them. Additionally, only one module's LCA was complete to avoid the comparison of the two module manufacturing routes and material choices, since the available data was not considered reliable enough to make a fair comparison.

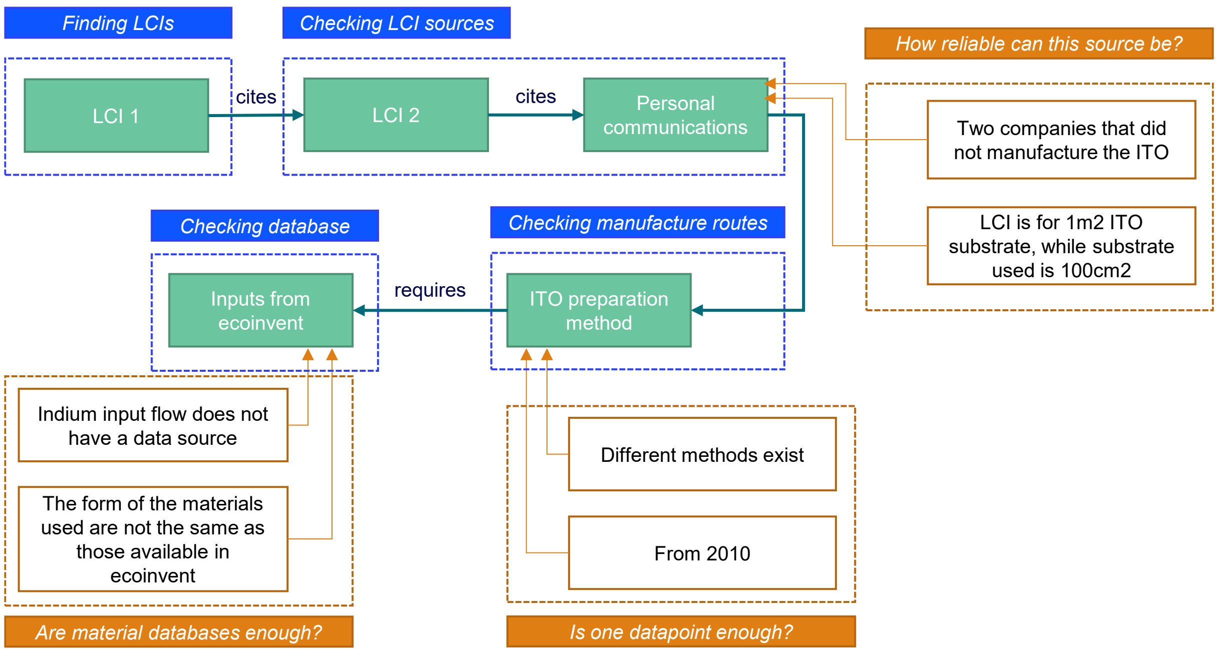

Figure 1: An example of how the LCI data is sourced, and where data-related uncertainties and discrepancies are introduced

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An exploratory LCA

An overview of the LCA

An exploratory LCA has been completed, with several considerations in mind: some novel materials could not be modelled; energy and material required for recycling were estimated; transport from the PV manufacturing site to the PV plant is included; and the CML methodology was used for impact assessment.

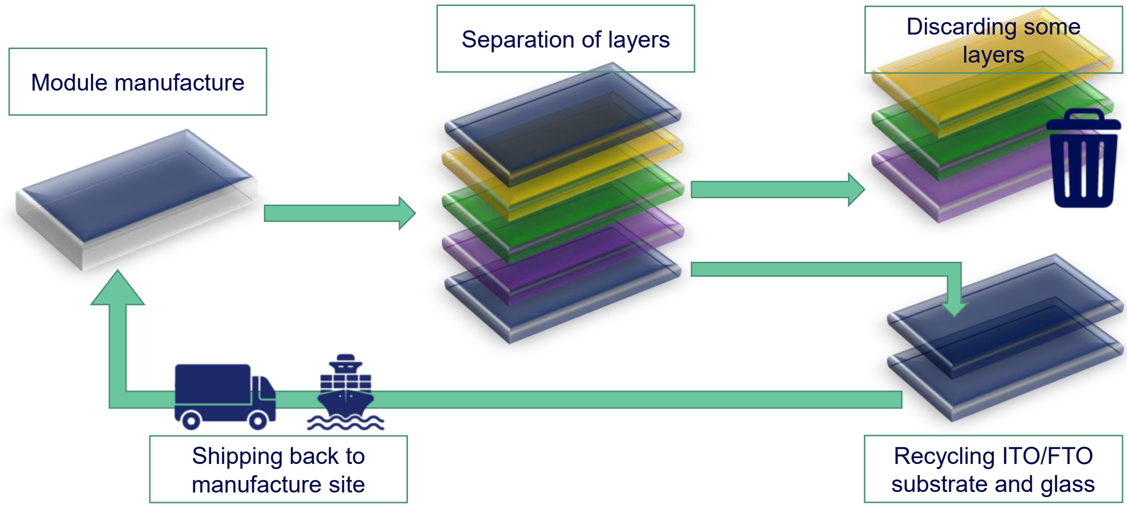

Figure 2: Overview of recycling route used to model the life cycle assessment.

The LCIs of most novel materials are not considered
Most novel materials were represented with a 'generic chemical' from Ecoinvent, which is the material and energy flows of an 'unweighted average of 20 inorganic substances'. This approach is likely more reliable than relying on single, conflicting, outdated, or estimated scaled-up datapoints from publications.

The recycling energy and material consumption is estimated
The recycling route is similar to that of the production route, except that recycling does not require new substrates (both front and back glass), it includes the electricity required for recycling, the use of two solvents (toluene and GBL), and the transport from the PV plant back to the manufacturing site.

WP-5 demonstrated that the use of heat and a few solvents can indeed recycle the glass substrate, however, the exact quantities of each are yet to be finalised. For this deliverable, it is assumed that 1kWh of electricity and that 0.5kg of toluene and GBL are used to remove the layers from the glass and ITO substrate. This is considered conservative when compared to both WP-5's preliminary results, as well as the results of Tian 2021, who reported the use of 0.22kWh electricity and 0.0006902kg of solvent.

Transport is included
Transport impacts were included using conservative distances. It is assumed that the modules are produced in central China and are shipped via container ship and 32-tonne trucks to central Brazil. Two distances were compared and the shipping does not seem to have a significant effect on the environmental impacts.

Impact categories are considered, as are input and output flows
In line with a conventional LCA, the impact categories are presented. Additionally, some key input and output material flows are included too. These may allow for easier comparisons to future work.

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University of Freiburg module LCA results

Impact categories

The results for this exploratory LCA suggest that the recycling of the substrate front and glass back may indeed reduce the overall environmental impact of the module. The table below shows that, with the exception of eutrophication, all the impact categories saw a decrease if the ITO substrate is recycled.

Table 2: The production versus recycling impact categories using the CML methodology.

Impact category	Unit	Fresh materials	Recycled materials	Percent difference
Climate change	kg CO2-Eq	14.7	7.9	**46.5**
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	8.3	3.4	**59.7**
Ecotoxicity: marine	kg 1,4-DCB-Eq	22414	6941	**69**
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	0.059	0.045	**24.5**
Energy resources: non-renewable	MJ	176	125	**29**
Eutrophication	kg PO4-Eq	0.045	0.17	**-290**
Human toxicity	kg 1,4-DCB-Eq	12	7	**41.9**
Material resources: metals/minerals	kg Sb-Eq	0.00015	2.50E-05	**83.1**
Ozone depletion	kg CFC-11-Eq	2.30E-07	1.30E-07	**45.4**
Photochemical oxidant formation	kg ethylene-Eq	0.005	0.0041	**17.5**

The results also indicate that most of the environmental impacts arise from the production of the ITO substrate. It is important, however, to keep in mind the source of the ITO LCI: it is based on a single datapoint, sourced through personal communications from multiple manufacturers, and does not correspond to the specific manufacturer supplying the ITO used in the paper that published the LCI. For these reasons, this report does not provide an in-depth discussion of the results, as the exact values are unlikely to be reliable.

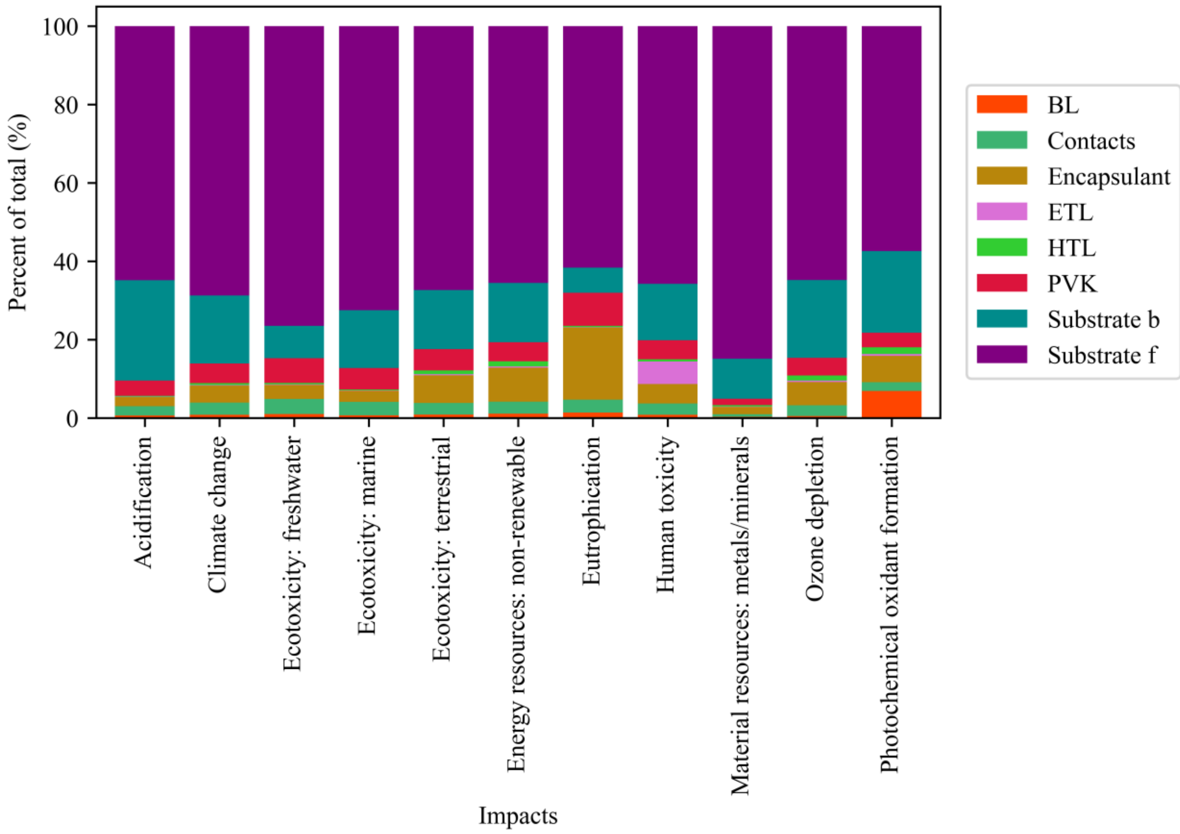

Figure 3: Demonstrating how much each layer contributes to each impact category.

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Input and output flows
As with the impact categories, an in-depth discussion of the input and output flows is not provided. The plots below are intended only to illustrate the potential for reduced material consumption and waste creation if the module is recycled.

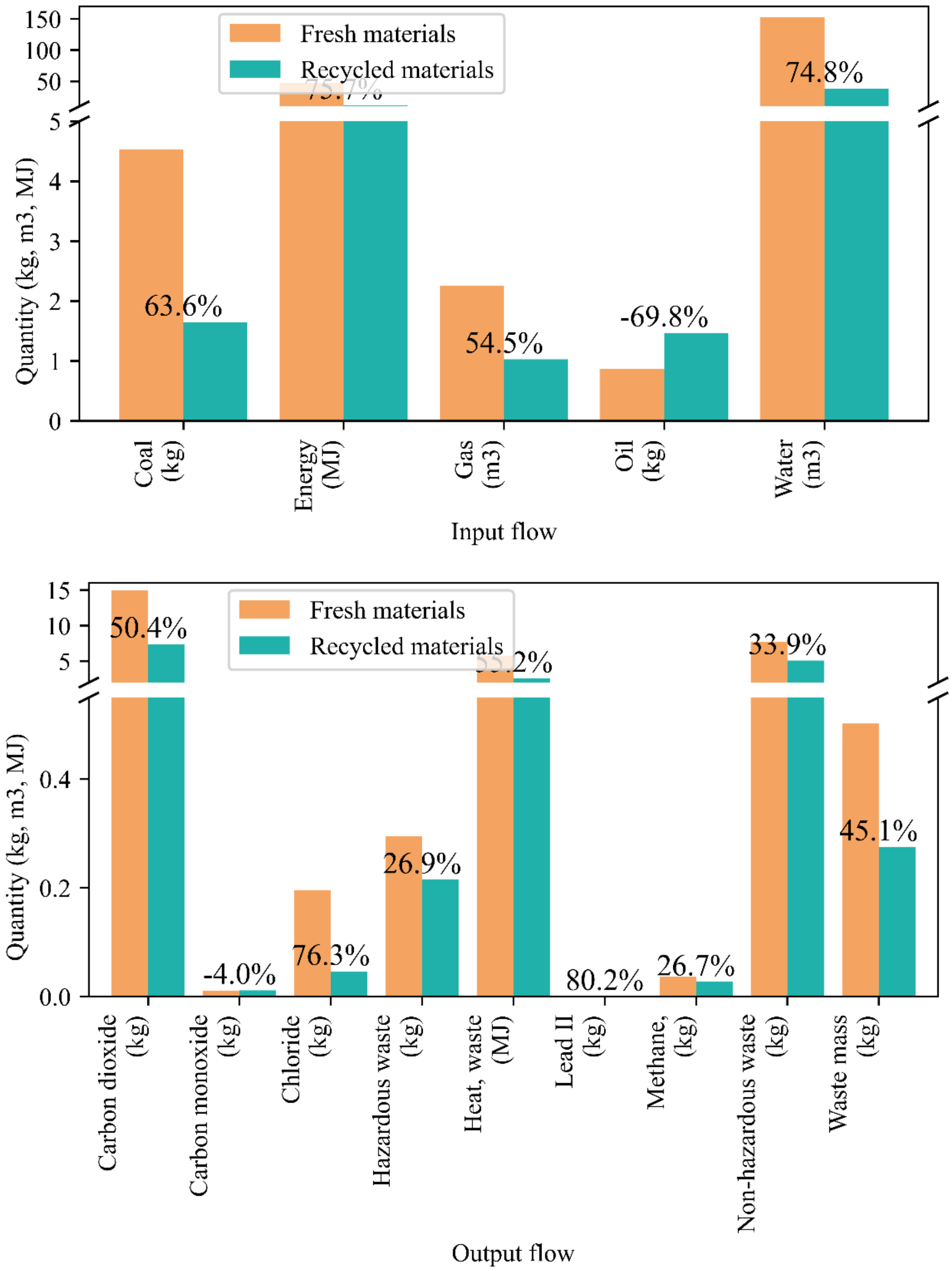

Figure 4: Visualising the difference between a selection of the input and output flows for the production versus recycling of the module.

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Alternative metrics for measuring sustainability

Given the lack of reliable data to develop a traditional LCA, other metrics were explored to determine the sustainability of the modules. These included:

1. Estimating the percentage of global material reserves required for a 1TW scale-up of these perovskite modules - similar to the approach taken by Wagner 2024.
2. Using the LCAs published by associations that represent a particular industry to obtain a more reliable estimate of energy and water consumption, and carbon footprint associated with the metals used in these modules.
3. Comparing solvents using the Chem21 Guidelines to identify which solvents are recommended and which are classified as problematic, hazardous, or highly hazardous (Prat 2016).

Materials bound in a 1TW perovskite module scale-up

World reserve estimates were taken primarily from the United States Geological Survey. The exception was indium for which there is no official data, but the NREL 2015 has suggested a value of 15,000 tonnes. The USGS data is sometimes reported directly as quantities of the material of interest (e.g., tin), and sometimes it is reported in ore quantities, thus requiring calculation based on the average percent of the material of interest present in that ore (e.g., calculating the titanium content in ilmenite ore).

The total area required to scale up to 1TW is calculated assuming a power to area ratio of the Oxford silicon perovskite tandem modules which produced 421 watts on an area of $1.68m^2$. Thus, the total area required for a 1TW scale up would be $4x10^9$ m^2.

Table 3: Estimated world reserves and world production of the metals used in the project's modules, alongside the quantity used in a 1TW scale-up. Metals highlighted red should be avoided, while metals highlighted orange should have alternatives investigated.

	Layer	Material	World reserves (tonnes)	World production (tonnes/ annum)	1TW scale-up (tonnes)	Percent embedded in 1TW scale-up
			Substrate			
F	ITO substrate	Indium	15000	1080	3181	**21.2**
F		Tin	4200000	300000	337	**8.15E-03**
S	FTO substrate	Fluorine	35000000	9500000	214	**6.11E-04**
S		Tin	4200000	300000	3198	**7.61E-02**
			Hole transport, electron transport, blocking, insulating layers			
F	HTL/SAM	Phosphorus	3870000000	240000000		**6.95E-08**
S	Insulating layer	Zirconium	51800000	1500000	12585	**1.38**
S	Blocking layer, ETL	Titanium	178000000	4880000	359000	**3.08E-01**
			Perovskite			
F	Perovskite	Caesium	35000	2200	384	**2.4**
F		Lead	96000000	4300000	3514	**3.70E-02**
S	Perovskite	Lead	96000000	4300000	8790	**9.15E-03**
			Contacts			
F	Contacts	Aluminum	8730000000	78400000	1616	**1.85E-05**
S	Contacts	Silver	560000	27000	6460	**1.15**
			Cathode			
S	Cathode	Graphite	800000000	930000	526000	**6.57E-02**

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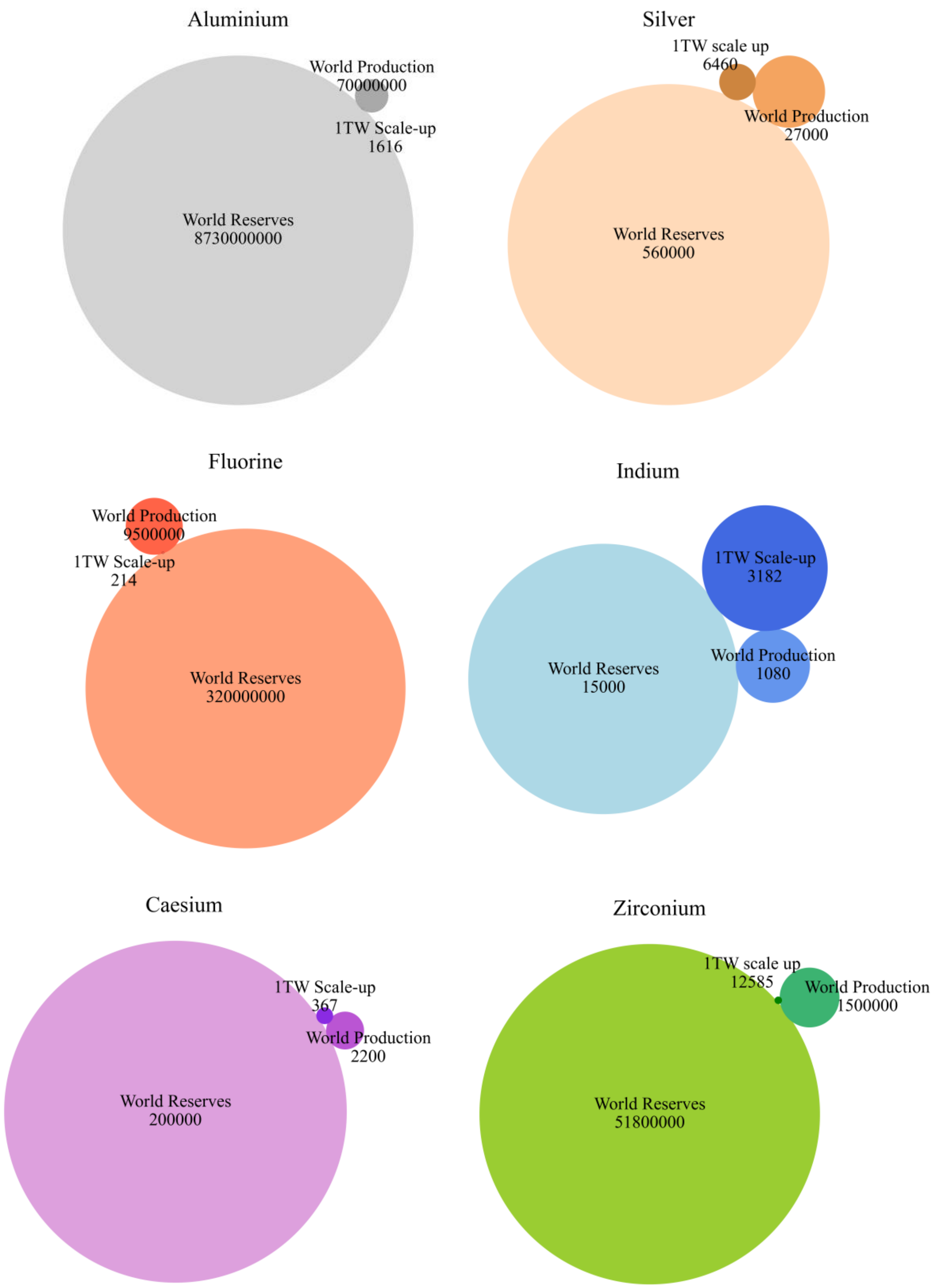

Figure 5: The image above is a visual representation of some of the values from the table. Fluorine's and aluminium's 1TW scale-up bubble is small in comparison to the estimated world reserves, thus the bubble is too small to see. All values are in metric tonnes.

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LCAs conducted by material associations and companies

Several industry associations represent significant portions of the global mining and refining sectors for specific metals. Some of these associations have compiled life cycle assessments for the metal they represent. Because these consider the average of multiple mines and refineries, they might offer a more reliable indication of sustainability than data provided in published papers or by paid-for databases. However, this approach is still incomplete: two metals (titanium and zirconium) did not have an association that has conducted an LCA on them; while three metals (silver, graphite and gold) only had company-specific LCAs.

There are a few limitations of this approach. One is that it does not account for the steps to transform 1kg of refined metal to the form that is required for module manufacture (e.g., powder or small ingots). As a result, the material and energy demands associated with these steps are not captured.

Differences in how each association collects its data introduce uncertainties and inconsistencies when comparing results. Each association also chooses their own life cycle impact assessment methodology and thus, have different impact categories. This means that even these results are not directly comparable. However, for the three main impact categories (energy consumption, water consumption and carbon footprint), it is assumed that these are calculated similarly enough to make a fair comparison.

Lastly, associations have also used paid-for databases to create their LCAs, so the issues mentioned above will be present in their results. However, it is assumed that these issues in data reliability are at least equal across all the LCAs.

Table 4: Energy consumption, water consumption and carbon footprint of metals commonly used in perovskite solar cell manufacturing.

Energy consumption (MJ)		Water consumption (m^3)		Carbon dioxide output (kg CO_2 eq)	
Platinum	494563	Gold	26000	Platinum	36828
Gold	209000	Platinum	297	Gold	15500
Silver	1869	Silver	190	Silver	158
Nickel	267	Tin	152	Nickel	13.1
Aluminum	161	Graphite	60.4	Graphite	9.5
Tin	105	Nickel	135	Tin	6.632
Copper	40.5	Copper	6.09	Copper	3.62
Lead	23.1	Lead	1.29	Lead	1.82
Graphite	-	Aluminium	0.775	Aluminum	0.0168

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Table 5: The results of the life cycle assessments conducted by metal associations or companies.

		International Aluminium Association	Aurubis EFD	Northern Graphite	International Tin Association	International Lead Association	Nickel Institute	International Copper Association	Aurubis	International PGM Association
Metal		**Aluminium**	**Silver**	**Graphite**	**Tin**	**Lead**	**Nickel**	**Copper**	**Gold**	**Platinum**
Percent industry representation		±7-89%			73%	85%[d]	50%	25%[a]		95%
Number of companies		>200	1	1					1	
Impact category	**Units**	**LCA results**								
Depletion of fossil energy resources / Primary energy demand	**MJ**	**161**	**1869**	**-**	**105**	**23.1**	**267**	**40.5**	**209000**	**494563**
Fresh water consumption	**m^3**	**0.775**	**190**	**60.4**	**152**	**1.29**[b]	**135**	**6.09**	**26000**	**297**
Climate change / Global warming potential	**kg CO_2 eq**	**0.0168**	**158**	**9.5**	**6.632**	**1.82**	**13.1**	**3.62**	**15500**	**36828**
Photochemical Ozone Creation Potential (POCP)	kg Ethene eq / kg NMVON eq / kg C_2H_2	0.006	1.02	-	0.035[c]	0.000718	0.1	17	76.6	258
Acidification Potential	kg SO2 eq / mol H+ eq	161	1.52	-	0.0334	0.0149	1.3	39.4	118	1687
Eutrophication Potential	kg P eq / mol N eq / kg N eq / kg PO_4^{3-} eq	0.006	4.371	-	0.035	0.000998	0.2	0.0675	324	687

a – Data excludes China.
b - Summed manually from input/output flows, as not included in impact categories.
c - Photochemical Ozone Depletion impact category
d – Only represents EU and US tin production

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Solvent choice using CHEM21 Guidelines

No attempt was made to conduct a full, comparative LCA on the different solvent options for this project's modules. It was assumed that these materials would face the same data limitations described earlier for the solutes and metals.

Instead, the '*CHEM21 selection guide of classical- and less-classical solvents*' (Prat 2016) was used to determine which solvents employed by this project are recommended and which are considered problematic or hazardous. This guide evaluates solvents based on Safety, Health and Environment criteria that are aligned with the Global Harmonised System and European Regulations. The guide has been developed collaboratively by six pharmaceutical companies, ten universities, and five small to medium sized enterprises, and is therefore deemed a reliable guide for solvent selection.

It is important to note that how a solvent is judged on sustainability is dependent on the research group and approach. For example, Cyrene is considered environmentally problematic by Chem21, but it is made from cellulose, it is considered bio-renewable, and is generally sold as a suitable replacement to DMF and NMP.

Additionally, the European Chemicals Agency (ECHA) has developed a list of restricted chemicals under the REACH framework. Of the commonly used perovskite solvents, NMP, DMF and 2-methoxyethanol are listed as they are toxic for reproduction. Thus, for this project, NMP and DMF should be replaced.

Table 6: A segment of the Chem21 Guidelines on solvent selection. The 'M' and 'R' are solvents used in manufacturing and recycling of the solar cells in this project, respectively.

Family	Solvent	Safety score	Health score	Env. score	Ranking
Water	Water[M]	1	1	1	Recommended
Alcohols	MeOH (methanol)	4	3	3	Recommended
	EtOH[M] (ethanol)	4	3	3	Recommended
	i-PrOH[M] (2-propanol)	4	3	3	Recommended
	n-BuOH	3	4	3	Recommended
	Terpineol[M]	1	2	7	Problematic
Ketones	Acetone[R]	4	2	3	Recommended
Esters	Ethyl acetate	4	2	3	Recommended
	i-PrOAc	4	2	3	Recommended
	γ-Valerolactone	1	5	7	Problematic
	γ-Butyrolactone[M]	1	4	7	Problematic
Ethers	Diethyl ether	10	3	7	Highly hazardous
Hydrocarbons	Anisole[R]	4	3	3	Recommended
	Toluene[R]	5	2	3	Problematic
	Xylene	5	2	3	Problematic
Halogenated	Chloroform	3	7	5	Highly hazardous
	Chlorobenzene[M]	8	2	5	Problematic
Aprotic polar	Acetonitrile	4	3	3	Problematic
	DMF[M]	10	8	3	Hazardous
	DMAc	9	8	3	Hazardous
	NMP[M]	9	8	3	Hazardous
	DMSO	1	1	3	Recommended

	Cyrene	1	2	7	Problematic
Miscellaneous	Methoxyethanol	10	6	3	Hazardous

Lab-scale cost analysis

The lab-scale production cost of a module is estimated using lab-scale cost of materials. Although material costs are expected to decrease at industrial scale, this cost per square metre provides an initial assessment of the hotspot materials of each layer in each stack. This approach enables a clear comparison between the two module designs developed in this project and helps identify materials that may require cautious use from a cost perspective. The current and historical cost of silicon-PV modules is provided to act as a comparison.

The total lab-cost of the two modules is 269€/m^2 and 182€/m^2 for the Solaronix and University of Freiburg and modules, respectively. Assuming a cell efficiency of 19% and using a 1 sun standard testing condition of 1000W/m^2, this would be equivalent to 1.36€/W and 0.9€/W, respectively. This is significantly better than the earliest silicon PV of 300$/W in 1956, followed by 77$/W around 1980, and finally 1$/W by 1988 (NRL 2026). The tables below show that the use of the titanium, zirconium and carbon pastes greatly increase the cost of the blocking, electron transport, insulating and cathode layers. Although the SAM, PCBM and BCP materials are the most expensive per gram produced (1133€/g, 1988€/g, 1820€/g, respectively), a small quantity is used so the cost per layer remains low.

The use of terpineol as a solvent also increases the cost of the Solaronix module as it is the most expensive solvent of choice at 0.0739€/mL versus the 0.00676-0.0298€/mL of ethanol, isopropanol, DMF and NMP.

Module costs were estimated at 2TW scale-up using Wright's learning law and a silicon-module-cost learning rate of 20%. The learning rate was applied to all the materials except the glass, as this is an already established industry. The Solaronix module is projected to cost 21.6€/m^2, while the university of Freiburg module is expected to cost 20.4€/m^2 – comparable to silicon modules today at 33€/m^2 (Trina Solar). If using standard testing conditions and a power conversion efficiency of 19%, the predicted cost of the Solaronix and Freiburg module would be 0.114€/W and 0.107€/W, respectively. This is comparable to a current silicon solar module cost of approximately 0.13€/W (pvXchange 2026).

Table 7: Lab-scale cost analysis of Solaronix materials.

Layer	Material	Percent of total cost (%)
Substrate	FTO glass, 2.2mm	**3.7%**
Blocking layer	TiO_2 (anatase) nanoparticles *Terpineol*	**1.1%**
ETL deposition	TiO_2 (anatase) nanoparticles *Terpineol*	**15%**
Insulating layer	ZrO_2 nanoparticles *Terpineol*	**54%**
Cathode	Graphite Carbon black *Terpineol*	**14%**
Perovskite	PbI_2 CH_3NH_3I *g-butyrolactane*	**4.2%**
Encapsulation	tPO (thermoplastic polyolefin) Back glass without FTO	**1.4%**
Contacts	Silver paste	**5.8%**

*Sale volume and price are from Sigma, Great Cell Solar, Carl Roth and Solaronix. a) from Liu 2025 b) PV-Magazine. c) Cost for POE. Percent values are rounded, thus may not sum to exactly 100%.

Table 8: Lab-scale cost analysis of University of Freiburg's materials.

Layer	Material	Percent of total cost (%)
Substrate	Glass ITO	**11%**
HTL layer	SAM (MeO-2PACz) *Ethanol*	**4.6%**
Perovskite	($FA_{0.83}Cs_{0.17}PbI_3$) FAI PbI_2 CsI *Dimethylformamide* *N-Methyl-2-pyrrolidone*	**31%**
ETL layer	PC61BM *Chlorobenzene*	**49%**
Hole-blocking layer	Bathocuproine (BCP) *2-Propanol*	**3%**
Contacts	Aluminum	**0.006%**
Encapsulant	Mixture of acrylate resin Glass	**2.1%**

*Sale volume and price are from Sigma, Great Cell Solar, Carl Roth and Solaronix. a) from PV-Magazine b) cost for POE. Percent values are rounded, thus may not sum to exactly 100%.

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Conclusions

Although the modelling of a full, traditional LCA is possible, this project has determined that it would not yield an honest and reliable representation of reality. This is primarily due to the absence of data, or the data that does exist is often inconsistent, unreliable, or outdated. Consequently, other metrics to judge sustainability were explored. These included using the estimated global reserves to determine the quantity of material bound in a 1 TW perovskite module deployment; analysing LCAs conducted by industry associations representing significant portions of their respective sectors; and the use of the Chem21 Guidelines for sustainable solvent selection.

Although a full LCA was not considered reliable at this stage, an exploratory assessment was conducted for one module. The results indicate that recycling modules reduces environmental impacts across most categories, including CO_2 emissions, water and energy use, and ozone depletion. While exact values were not analysed in detail, the overall trends support further investigation into recycling as a key sustainability pathway.

Only four materials exceed 1% of global reserves under a 1 TW deployment: indium (21.2%), caesium (2.4%), zirconium (1.38%), and silver (1.15%). All other materials consume between 6.95×10^{-8} % and 3.08×10^{-1} % of estimated reserves and are therefore considered suitable for large-scale deployment.

Comparison of transparent conducting substrates highlights FTO as a more sustainable alternative to ITO, given fluorine's abundance and indium's limited and uncertain availability. Similarly, aluminium contacts are strongly favoured over silver due to substantially higher global reserves ($8.73\text{x}10^{9}$ tonnes versus $5.6\text{x}10^{5}$ tonnes) and significantly lower energy use (11x less), water consumption (245x less), and carbon emissions (9000x less) during production.

Solvent assessment using the CHEM21 Guideline identifies water, ethanol, propanol, and anisole as recommended solvents; while toluene, chlorobenzene, gamma-butyrolactone and gamma-valerolactone are considered problematic; and DMF and NMP are considered hazardous and are both on ECHA's restricted chemical list. Reducing or eliminating the use of DMF and NMP should be prioritised, followed by exploring alternatives to the solvents regarded as problematic. Adopting the recommendations provided by CHEM21 offers a good starting point for the implementation of green solvents.

Finally, lab-scale cost analysis reveals that the perovskite modules today cost 182€/m^2 and 269€/m^2 for the University of Freiburg and Solaronix modules respectively. This is driven mainly by the use of titanium, zirconium, and carbon pastes and, although some organic materials (SAM, BCP, PCBM) are costly per gram, their low usage limits their cost impact. Solvent choice also affects costs, with terpineol emerging as a significant contributor. These results identify key materials and solvents that should be targeted for cost and sustainability optimisation during scale-up.

Using Wright's law with a learning rate of 20%, module costs are predicted to be0.114€/W and 0.107€/W at 2TW of deployment. When comparing to the historical and current costs of silicon solar modules – 300 $/W in 1956 and now 0.13$/W in 2026 – the current and predicted costs of perovskite modules are already better and become competitive to silicon modules. These results demonstrate the benefit to further investigating the development of perovskite-based solar modules.

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