Co-funded by the European Union

CircularPV

Project acronym	CIRCULAR-PV
Project full title	Towards long-lived and recyclable perovskite photovoltaics
Call identifier	CETP-FP-2023-00528
Instrument	Clean Energy Partnership Transition (CETP)
Call Module	CM2023-03B (IOA) Advanced renewable energy (RE) technologies for power production
Start date of project	01/01/2025
Duration	36 months
Coordinator	Dr. Maria Hadjipanayi, University of Cyprus

Deliverable D3.2:

Evaluating material criticality and supply chains for perovskite solar cells

Dissemination Level	**Public**
Nature	Report
Responsible partner	Dyenamo
Contributing partners	Forschungszentrum Jülich, University of Freiburg, Solaronix, University of Cyprus
Due date of deliverable	30/06/2025
Actual submission date	04/07/2025

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag

Co-funded by
the European Union

Contents

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Co-funded by the European Union

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 D3.2 ('Evaluating material criticality and supply chains for perovskite solar cells') is a deliverable of Work package three of CIRCULAR-PV (WP3. Circularity strategy) and it deals with the robustness of supply chains for the materials of the module technologies of the project.

1. Purpose of this document

This report was prepared with the purpose of examining material criticality and availability as concerns the manufacturing of the solar cell devices. This analysis is very useful in making decisions on materials to be avoided for the manufacturing or alternatives that could be sought for more sustainable devices. To achieve this, an inventory of all resources used in production including materials, processes and energy has been developed for the two manufacturing partners of the project, namely Solaronix and University of Freiburg.

2. Material Criticality and supply chains analysis

The project has selected two module technologies:

i) the mesoscopic n-i-p structure developed and manufactured by Solaronix, and
ii) the p-i-n structure developed and manufactured by University of Freiburg.

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

It is important to highlight that both these device technologies are under development in CIRCULAR-PV. The objective of this deliverable is thus to provide input for the development regarding potential materials to avoid.

2.1 The CIRCULAR-PV module technology from Solaronix

The Circular PV module technology from Solaronix is based upon a mesoscopic n-i-p structure, Figure 1. An overview of the process steps are shown in Figure 2. In short, three porous layers, TiO2, ZrO2 and carbon, are subsequently screen-printed on top of each other on a conducting glass substrate. After a sintering process, the perovskite precursor is introduced to the porous structure via inkjet-printing whereupon the perovskite layer is formed via a heating process. The device manufacturing is finalized by encapsulation and contacting. The advantage of the concept is a straightforward manufacturing route based upon screen- and inkjet-printing in combination with low material cost and high robustness. The disadvantage to date is reduced efficiency in relation to other concepts.

As input for the material criticality analysis, all materials in a 1 m2 of the present reference modules of Solaronix are summarized in Table 1. In addition, the solvents used in the various process steps for manufacturing 1 m2 are defined in Table 2.

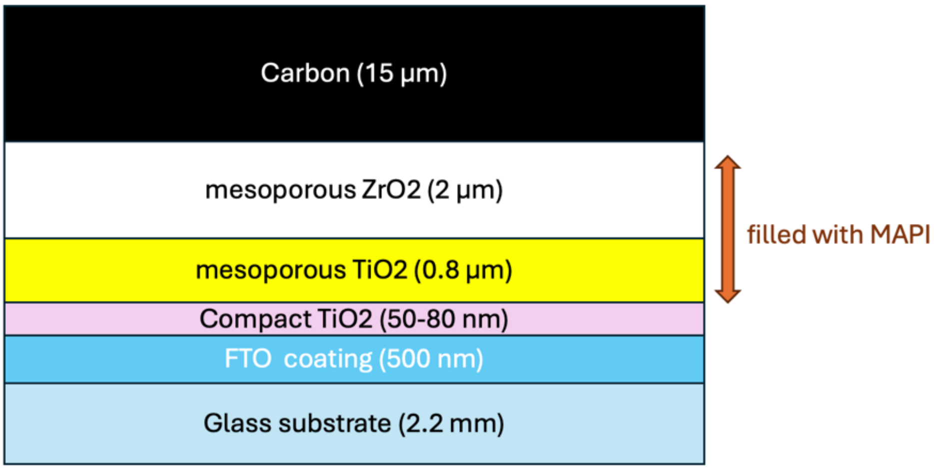

Figure 1. Cross-section of a cell used in the Circular PV device technology developed by Solaronix.

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

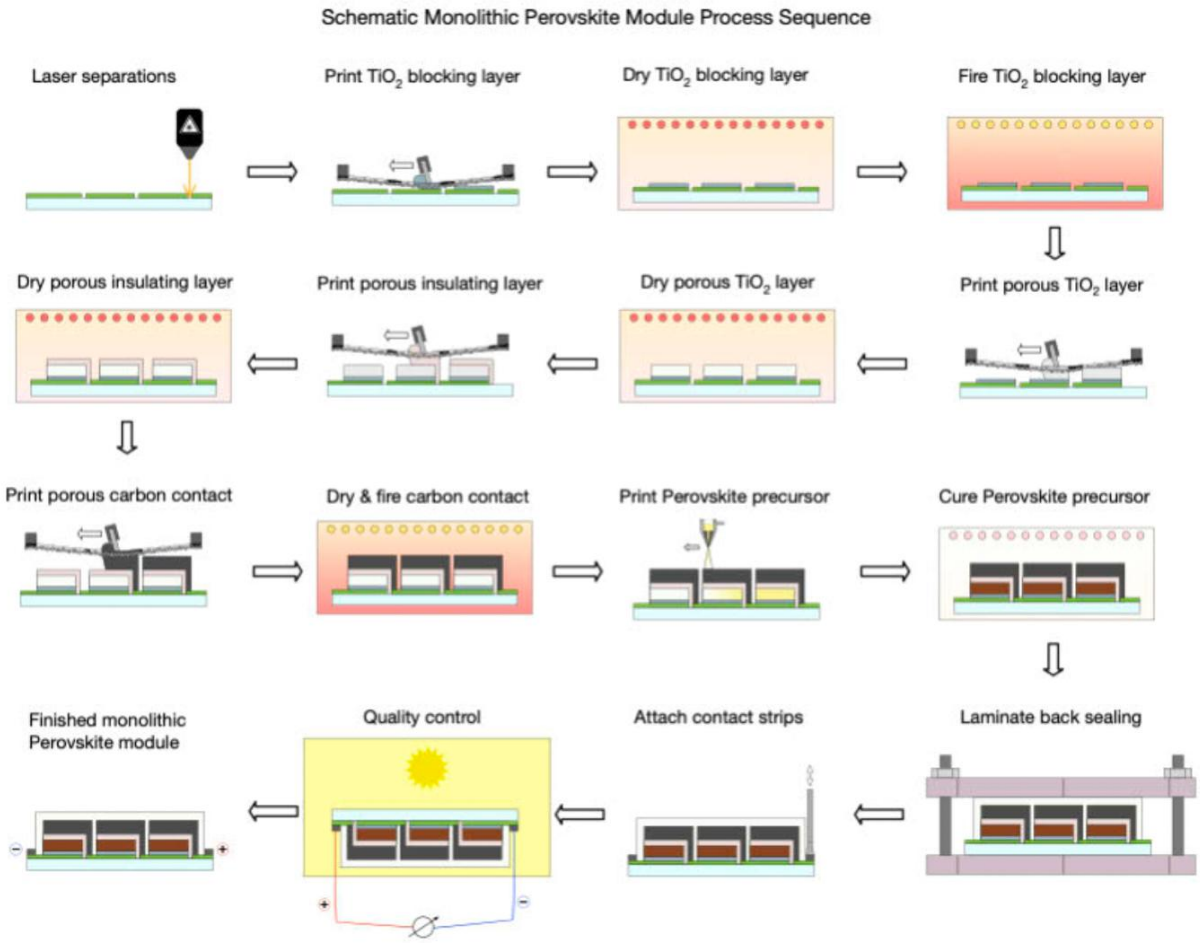

Figure 2. Overview of the process steps for manufacturing a Solaronix module.

Co-funded by the European Union

Table 1. The materials in 1 m^2 of manufactured Solaronix modules

FTO glass 2,2 mm thick	Fluorine doped tin oxide glass (FTO)	5.94	kg
Contacts	Silver paste	0.00216	kg
Blocking layer, deposited by screen-printing)	BL-TiO2 whole paste	0.02	kg
	TiO2 (anatase) nanoparticles	0.00032	kg
Electron-transport layer (mesoporous TiO2), deposited by screen-printing	m-TiO2 whole paste	0.079	kg
	TiO2 (anatase) nanoparticles	0.0079	kg
Insulating layer deposition (mesoporous ZrO2), deposited by screen-printing	m-ZrO2 whole paste	0.0079	kg
	ZrO2 nanoparticles	0.0142	kg
Cathode (carbone), deposited by screen-printing	Carbon whole paste	0.285	kg
	Graphite	0.057	kg
	Carbon black	0.0142	kg
Perovskite layer, deposited by inkjet	Perovskite layer	0.0166	kg
	PbI2	0.0049	kg
	CH3NH3I	0.0017	kg
Encapsulation	tPO	0.552	kg
	Back glass without FTO	5	kg

Table 2. The solvents used in various process steps for manufacturing of 1 m^2 Solaronix module

Process step	**Solvent**	**Solvent amount**
Blocking layer cTiO2	Terpineol	0.0178 kg
Mesoporous mTiO2	Terpineol	0.0636 kg
Mesoporous mZrO2	Terpineol	0.0576 kg
Carbon	Terpineol	0.202 kg
Perovskite layer	g-butyrolactone	0.01 kg

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Co-funded by the European Union
CET Partnership

2.2 The CIRCULAR-PV module technology from University of Freiburg

The CIRCULAR-PV module technology from the University of Freiburg is based upon a p-i-n cell structure, Figure 3. An overview of the process steps is shown in Figure 4. In short, the process is adapted from a published module fabrication process from University of Freiburg in collaboration with Fraunhofer ISE1 and scaled to a functional unit area of 1 m². For this reason, blade coating processes with comparably high volumes of solution are the basis for calculations. For actual 1m² modules, more scalable and efficient slot-die coating processes would be employed, with optimized solution consumption. In addition, the layer stack investigated in this study was supplemented by a UV curable encapsulant and a cover glass (Figure 3), enabling sealed modules with glass-glass encapsulation as laid out in the project proposal.

As input for the material criticality analysis, all materials in a 1 m2 of the present reference modules of the University of Freiburg are summarized in Table 3. In addition, the solvents used in the various process steps for manufacturing 1 m2 are defined in Table 4.

Cover Glass	**1.1 mm**
Encapsulant	**100 µm**
Aluminum	**150 nm**
BCP	**10 nm**
PCBM	**30 nm**
$FA_{0.83}Cs_{0.17}PbI_3$	**600 nm**
MeO-2PACz	**5 nm**
Indium Tin Oxide (ITO)	**150 nm**
Glass substrate	**1.1 mm**

Figure 3. Cross-section of the Circular PV device technology developed by the University of Freiburg.

[1] Ernst, M., Herterich, J., Margenfeld, C., Kohlstädt, M. and Würfel, U. (2022), Multilayer Blade-Coating Fabrication of Methylammonium-Free Perovskite Photovoltaic Modules with 66 cm2 Active Area. Sol. RRL, 6: 2100535. https://doi.org/10.1002/solr.202100535

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

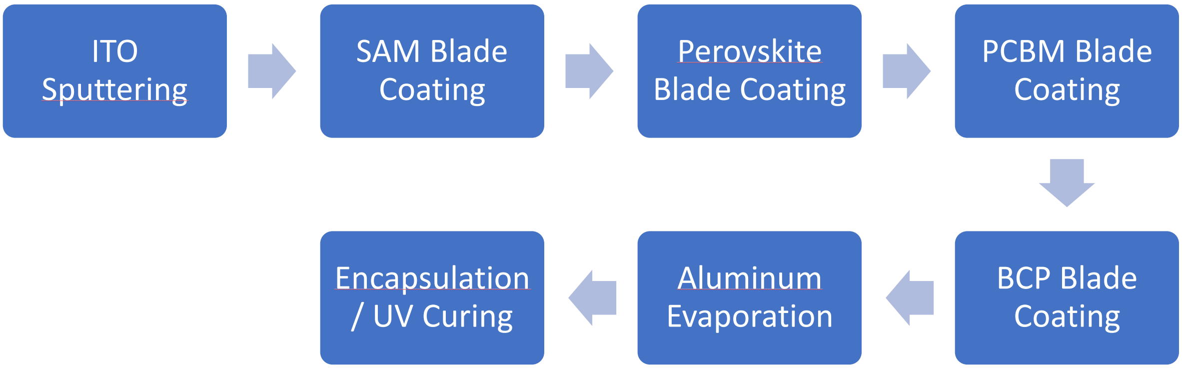

Figure 4. Overview of the process steps for manufacturing the module.

Table 3. The materials in 1 m^2 of manufactured modules by the University of Freiburg

Material	**Amount in 1 m^2 module**	**Comment**
Glass	2 750 g	Float Glass
ITO	1.071 g	Commercial supply of ITO glass
SAM (MeO-2PACz)	0.007 g	Density value for calculation approximated by taking into account literature value for derivative material 2PACz
Perovskite (FA0.83Cs0.17PbI3)	2.700 g	Density estimated; Thickness and thus material amount could be higher for final product
PC61BM	0.045 g	
Bathocuproine (BCP)	0.013 g	
Aluminum	0.405 g	
Encapsulant	121 g	UV-curable encapsulant, mixture of acrylate resin. Composition based on material safety datasheet: Calcium oxide, 30-35% Isobornyl methacrylate, 15-20% Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide, <1%
Cover Glass	2750 g	Float Glass

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

Table 4. The solvents used in various process steps for manufacturing of 1 m^2 module by the University of Freiburg

Process step	Solvent	Solvent amount
SAM Blade Coating	Ethanol	70 mL
Perovskite Blade Coating	Dimethylformamide: N-Methyl-2-pyrrolidone 91:9	DMF: 2.10 mL NMP: 0.21 mL (Total: 2.31 mL)
PC61BM Blade Coating	Chlorobenzene	3 mL
BCP Blade Coating	2-Propanol	25 mL

2.3 Evaluation of material criticality

The main parameters that are used to determine the criticality of a material are financial importance and supply risk. Numerous countries and groups have developed their own critical raw mineral (CRM) lists. These include, but are not limited to, those from Canada, the United Kingdom, the OECD, the EU, and the USGS. Even though there is considerable overlap between these lists, there are also a few differences. Table 5 (found in Appendix) summarises the materials that are considered critical by either the EU or the US that are used in solar cells produced by Solaronix and the University of Freiburg (Table 1-4). Moreover, Table 5 includes the most recent 5-year price changes according to the United States Geological Survey, as well as the main import sources of these materials to the EU as reported by European Commission.

The three CIRCULAR-PV materials relevant that are considered critical by both the EU and USGS are titanium, natural graphite and aluminium. Moreover, phosphorous is merely considered critical by the EU; whereas tin, zirconium, indium, and caesium are considered critical merely by the US.

For materials not currently on the EU's CRM list, the 5-year price change and the primary import sources were considered (Table 5). This, alongside the comparison to the US list, was done to assess their potential future criticality. The 5-year price increase ranges from 11.5% to 68.1% - with the exception of indium, which experienced a 33% price decrease. Nearly all of the materials are imported from outside of the EU, with many of them coming from Indonesia, South Africa, Australia and China.

3. *Delay / Deviation from plan*

This deliverable is delayed only by a few days.

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

4. Conclusions

Based on this investigation, the conclusions and recommendations for the solar cell manufacturing in CIRCULAR-PV are as follows:

Four of the materials used by Solaronix and University of Freiburg (Tabel 1-4) are currently considered critical by the EU. Additionally, five materials are considered critical by the USGS. Most of these have experienced a significant price increase over the past five years and are largely imported from outside of the EU.

For CIRCULAR-PV, it is recommended to begin identifying alternative materials to those that are already on the EU CRM list. The materials that are only considered critical by USGS should also be monitored closely, as they too might become critical in the near future. It should, however, be mentioned that finding alternatives will be challenging as the CRM lists are made up of about 50 minerals (including platinum group metals and rare earths).

Funding acknowledgment

This research was funded by CETPartnership, the Clean Energy Transition Partnership under the 2023 joint call for research proposals, co-funded by the European Commission (GA N°101069750) and with the funding organizations detailed on https://cetpartnership.eu/funding-agencies-and-call-modules. CIRCULAR-PV project is also co-funded by the EU within the framework of the Cohesion Policy Programme "THALIA 2021-2027, through the Research & Innovation Foundation (EP/CETP/0923/0009).

Co-funded by the European Union

Republic of Cyprus

RESEARCH & INNOVATION FOUNDATION

Co-financed by Swedish Energy Agency

SOLARONIX

Supported by: Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag

Appendix

Republic of Cyprus

RESEARCH & INNOVATION FOUNDATION

Co-financed by Swedish Energy Agency

SOLARONIX

Supported by: Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Table 5 Overview of the materials that are considered critical by either the EU or the US that are used in solar cells produced by Solaronix and the University of Freiburg

Elements	Component / layer in module	Qty used for 1m^2 (±g) *	EU CRM list 2023	US CRM list 2022	Main source to EU**	Year 0 price*** ($/t)	Year 5 price ($/t)	% increase 5 years
				Solaronix				
Tin	FTO coated glass	-	No	Yes	Indonesia 46% Belgium 18% Peru 10%	20700	34800	68.1%
Titanium+	Blocking layer	87.22	Yes	Yes	Kazakhstan 36% Russia 34% China 9% Switzerland 5%	11100	11500	3.6%
Zirconium	Insulating layer	22.1	No	Yes	S. Africa 38% Australia 30% Senegal 11%	1010	1450	43.6%
Graphite	Electrode	57.0	Yes	Yes	China 40% Brazil 13% Mozambique 12% Norway 8% Ukraine 7%	913	2090	128.9%
				University Freiburg				
Indium	ITO coated glass	1.071	No	Yes	China 66% S. Korea 18% Japan 8%	375000	250000	-33%
Tin	FTO coated glass	-	No	Yes	Indonesia 46% Belgium 18% Peru 10%	20700	34800	68.1%
Phosphorous	Hole transport layer & Encapsulant	0.007	Yes	No	Kazakhstan 65% Vietnam 22% China 13%	69.6	102.6	47.4%
Caesium	Perovskite	2.7	No	Yes	-	70600000	7870000	11.5%
Aluminium	Frame	0.405	Yes	Yes	Guinea 62% Brazil 12% Greece 10%	2170	3050	40.6%

Co-funded by the European Union
Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

***Quantity used in module:** using the value of the entire material or solution, not that particular element. For example, 0.00007kg of perovskite (SAM MeO-2PACz - $C_{16}H_{18}NO_5P$) was used, not 0.000007kg of P. So in reality there will be less P used.

****EU sourcing:** this depends on the source of the data as well as the state of the material (refined versus ore, etc). All EU CRM import source values are from the EU CRM 2023 final report. If the mineral is not considered critical, then the import value % is from the Europa.eu website.

*****5 year price changes:** All data from USGS database. The most recent available data was used, however, it is not necessarily from the last five years - for example, 2016-2020 or 2020-2024. In addition, the timeframe considered highly affects the price change. For example, the % change for tin varies from 0.29-108.38%.

Republic of Cyprus
RESEARCH & INNOVATION FOUNDATION
Co-financed by Swedish Energy Agency
SOLARONIX
Supported by: Federal Ministry for Economic Affairs and Climate Action on the basis of a decision by the German Bundestag