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Large area perovskite solar cells and modules

LUMINOSITY

Large area uniform industry compatible perovskite solar cell technology

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= Deliverable D1.2 =

Guidelines for a sustainable life cycle

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Executive Summary

This document presents the guidelines developed within the LUMINOSITY project for the sustainable production and end-of-life of large area flexible perovskite modules, as a result of Task 1.2. The objectives of the present guidelines are to provide insights and recommendations based on life cycle assessment (LCA) and techno-economic assessment (TEA) studies related to flexible perovskite.

The deliverable focuses on the results from the literature review of studies on flexible PV systems. It includes the environmental hotspots from the LCA studies and the cost drivers from the TEA studies. It also highlights the impacts of material toxicity, material scarcity, manufacturing and upscaling, and end-of-life scenarios on the environmental sustainability and economic viability of flexible perovskite modules. Based on the findings from the literature, implications and areas for improvement are identified with their corresponding recommendations which provide strategies to reduce the environmental footprint and costs for upscaling flexible perovskite modules and serve as guidelines for subsequent LCA and TEA iterations.

For the next steps, the implementation of the requirements and recommendations provided in this document will be followed by a benchmark LCA and TEA analysis based on the blueprint describing process steps and cell architecture described in Deliverable 1.1 (First guidelines for a blueprint of a roll-to-roll (R2R) flexible perovskite PV processing line) and using actual production data from other technology partners. Additionally, the appropriate LCA approach (ex-ante or prospective) for scaling up projections of large area perovskite modules will be evaluated. A TEA would also be performed considering improvements in efficiency and stability (which will be developed concurrently with other work packages in the project) as key input parameters and their effect on manufacturing costs and levelized cost of energy (LCOE). These activities will be conducted under Work Package (WP) 7 and the results will be communicated in Deliverable 7.1 (Intermediate report on design strategies towards a sustainable perovskite PV module and its R2R production line based on intermediate TEA and LCA results) and Deliverable 7.2 (Final report on design strategies towards a sustainable perovskite PV module and its R2R production line based on final TEA and LCA results).

By addressing the challenges described in this paper, the LUMINOSITY project aims to position flexible perovskite solar modules as a competitive and sustainable alternative in the PV market. This deliverable serves as a foundation and starting point for further studies under WP7, and provides input to WP5 and WP6, supporting the transition to industrial-scale commercialization.

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List of Abbreviations

a-Si	Amorphous silicon
ADR	Annual degradation rate
APR	Annual progress rate
BIPV	Building-integrated photovoltaic
BOS	Balance-of-system
c-Si	Crystalline silicon
CAGR	Compound annual growth
CAPEX	Capital expenditure
CdTe	Cadmium telluride
CED	Cumulative energy demand
CFF	Circular Footprint Formula
CIGS	Copper indium gallium selenide
CIPV	Car-integrated photovoltaic
CRM	Critical raw material
DMF	Dimethylformamide
DMSO	Dimethyl sulfoxide
EoL	End-of-life
EPBT	Energy payback time
f-PSC	Flexible perovskite solar cell
GEF	Grid emission factor
GFF	Geometric fill factor
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
IPL	Intense pulsed light
ISO	International Organization for Standardization
ITO	Indium tin oxide
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCOE	Levelized cost of energy
LT	Lifetime
mc-Si	Multi-crystalline silicon
NZE	Net zero emissions
OPEX	Operational expenditure
OPV	Organic photovoltaic
PCE	Power conversion efficiency
PET	Polyethylene terephthalate
PR	Performance ratio
PSC	Perovskite solar cell
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
R2R	Roll-to-roll
S2S	Sheet-to-sheet
SJ	Single-junction
SVHC	Substance of very high concern
TCO	Transparent conducting oxide
TEA	Techno-economic assessment
TRL	Technology readiness level
VIPV	Vehicle-integrated photovoltaic
WEEE	Waste electrical and electronic equipment

1. Introduction

The transition towards renewable energy is crucial to reduce our reliance on fossil-based resources and to bring down CO_2 emissions, ultimately limiting global warming to 1.5°C (IEA, 2024a). However, we are currently off-track from our energy transition goals, prompting a need to ramp up the deployment of more efficient renewable energy technologies (IRENA, 2023). Among the renewable energy technologies, solar photovoltaic (PV) technology has the highest potential for growth and accounted for 78% of the added renewable energy capacity in 2023, bringing the global PV capacity to 1.6 TW and making up 5% of the global electricity mix. Its expansion plays an essential role in the energy transition, which is forecasted to account for 16% of the global electricity generation by 2030 to reach the targets in the Net Zero Emissions by 2050 (NZE) Scenario (IEA, 2024b; SolarPower Europe, 2024).

One of the most promising PV technologies to facilitate this expansion is perovskite solar cells (PSCs). Due to the solution-processability and the ability to be manufactured on flexible substrates of the perovskite layer, flexible PSCs are created (Kim et al., 2019). Flexible PSCs have already reached power conversion efficiencies (PCEs) of up to 26.1% and can be produced at a lower weight and cost (Skafi et al., 2023; NREL, 2024a). There is also a high potential for low-cost, low-energy manufacturing of flexible perovskite modules using large-scale production schemes such as roll-to-roll (R2R) manufacturing (Weerasinghe et al., 2024). The flexibility of these modules leads to more applications such as wearable devices and building integrated PVs (BIPVs) (Tian et al., 2024). PSCs also provide the EU an opportunity to diversify its PV manufacturing and reduce supply chain risks linked to traditional silicon technologies, especially as the demand for PV solutions increases (Martulli et al., 2024). Their inherent physical and optoelectronic characteristics, upscaling potential, wide range of applications and potential for diversifying the supply chain position PSCs as key drivers in the growth of the PV market. Despite this, flexible perovskite modules are not yet commercialized.

To facilitate this commercialization, the environmental and economic viability of flexible perovskite modules must be evaluated. This can be done using life cycle assessment (LCA) and techno-economic assessment (TEA). Currently, LCA and TEA on flexible perovskite are mostly based on lab-scale data, with a wide range of results due to differences in process energy consumption (Vidal et al., 2021; Martulli et al., 2022). The LUMINOSITY project aims to fill this gap by conducting the first LCA and TEA on industrial-scale R2R production of flexible perovskite modules. The results will support the project's main goal of promoting flexible PSC technology by upscaling its production at a commercial level using R2R processing methods and bridging the gap from a sheet-to-sheet (S2S) processed flexible PSC at TRL 5 to a stable and efficient R2R produced flexible perovskite module at TRL 7.

The purpose of this report, Deliverable 1.2 (D1.2), is to provide possible strategies to minimize the environmental impacts and production costs of upscaling flexible perovskite modules using R2R production. This document serves as an output of Task 1.2 (T1.2) regarding the sustainable production of flexible perovskite modules including their end-of-life management. T1.2 falls under the wider scope of the specifications and requirements of Work Package 1 (WP1).

The report focuses on the results from the literature review of the LCA and TEA studies on flexible PV systems. It includes the environmental hotspots from the LCA studies and the cost drivers from the TEA studies. Based on these results, implications and areas for improvement are identified with their corresponding recommendations which would serve as guidelines for the subsequent LCA and TEA iteration in D7.1 (Intermediate report on design strategies towards a sustainable perovskite PV module and its R2R production line based on intermediate TEA and LCA results) and D7.2 (Final report on design strategies towards a sustainable perovskite PV module and its R2R production line based on final TEA and LCA results) under WP7.

2. Literature Review

2.1. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a methodology to evaluate the potential environmental impacts of a product, process or activity at every stage or the entirety of its life cycle. Conducting an LCA provides insights into the environmental flows that may arise at each step of a product or process, from raw materials extraction to the end-of-life (EoL). The choice of which stages to include in the analysis establishes the system boundaries of the LCA, which vary for each study, such as cradle-to-gate, cradle-to-grave, gate-to-gate and cradle-to-cradle. The framework for conducting an LCA is governed by the ISO 14040 and 14044 standards and is conducted in 4 phases: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation (ISO, 2006a; ISO, 2006b). Despite being standardized, this framework still provides various options, such as setting the scope of the system and choosing the impact assessment method, which can impact the outcomes and findings of LCA studies and make the results incomparable.

For LCA studies on PV systems, efforts have been made to develop best practices to ensure the consistency and reliability of the results. The International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) provided the first set of methodology guidelines in 2009, which includes PV-specific parameters, assumptions in the LCI analysis and the implementation of the modeling approaches (Alsem et al., 2009). Subsequent editions have been released, with the fourth edition published in 2020 (Frischknecht et al., 2020).

2.1.1. LCA of flexible PV systems

PV systems can be classified into two categories depending on their capacity to be bent or shaped without deforming: rigid or flexible. Rigid systems have been dominating the PV market, with crystalline silicon (c-Si) based technology accounting for 97% of the total production in 2023. The remaining market share is occupied by thin-film technologies such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) (Fraunhofer ISE, 2024). Perovskite solar cells (PSCs) are another promising technology that has shown a rapid increase in its power conversion efficiency (PCE) in the last decade, reaching up to 26.1% in 2023 (Liang et al., 2023; NREL, 2024a). Despite reaching PCEs comparable to that of other rigid PVs (c-Si at 26.7%, CdTe at 22.6% and CIGS at 23.4%), PSCs have only reached high efficiencies at small module areas under laboratory conditions (Zhu, 2024). Because of this, they have not been fully commercialized yet.

There currently is a growing need for more lightweight, ultrathin and flexible PV systems not only for traditional PV purposes (e.g., residential and industrial use) but for other niche applications, such as wearable electronic devices, vehicle-integrated PV (VIPV) (e.g., car-integrated PV (CIPV))and building-integrated PV (BIPV) (Zhu et al., 2024). As a result, more research has been directed towards developing flexible PV modules in recent years (Kim et al., 2020). Flexible perovskite solar cells (f-PSCs) are shown to be the most promising among the flexible PV technologies due to the intrinsic mechanical flexibility of perovskite and its ability to be roll-to-roll (R2R) processed at low temperatures (Li, et al., 2023; Tian et al., 2024). R2R manufacturing consists of continuously processing a flexible substrate as it moves along a roller-based processing line. The products are rolls of the finished material produced cost-effectively and efficiently. This method is used in multiple applications ranging from textiles and printed media to flexible electronic devices (NREL, 2024b). R2R manufacturing has already been identified as a promising method for upscaling f-PSCs due to their high throughput (Jung et al., 2018; Wang et al., 2018; Yang et al., 2021). However, technical difficulties, such as finding layer deposition techniques that are compatible with an R2R line and avoiding vacuum-processing steps to reduce energy consumption and cost, have hindered its implementation on a larger scale.

Most LCA studies on PV technologies focus on two impact categories: cumulative energy demand (CED) and global warming potential (GWP) (Vidal et al., 2021). The CED, expressed in MJ, quantifies the primary energy consumed from renewable and non-renewable energy source across the life cycle of the product or process. It not only considers the direct energy used but also the indirect energy consumed for the extraction and preparation of the raw materials (e.g., energy used in mining and refining ores). On the other hand, GWP quantifies the greenhouse gas (GHG) emissions produced within the system boundaries in kg of CO_2-equivalent. In terms of LCA interpretation, the energy payback time (EPBT) is the most common metric reported for PVs. It is the time required for an energy system to provide an equivalent amount of energy that was used to produce the system across its whole lifecycle (Leccisi & Fthenakis, 2020; Vidal et al., 2021).

Since the goal of developing and promoting PV technologies is to increase our share of renewable energy usage and decarbonize the energy grid to mitigate climate change, LCA literature focuses on these three metrics as a means to quantify these benefits. While this emphasis is justified, these indicators do not reflect other sustainability issues, such as material scarcity, ecotoxicity, and human toxicity. It is then essential to assess other impact categories to make sure that efforts made to optimize CED, GWP and CED do not transfer the environmental burdens to other areas, undermining the broader sustainability goals of PV technologies (Resalati et al., 2022). Evaluating these additional impact categories will provide a more comprehensive view of the environmental footprint of emerging PV technologies, helping guide decisions as the technology advances that balance climate benefits with environmental and human health impacts.

To advance the commercialization of flexible PSCs, it is crucial to address several key challenges: the lower efficiencies observed in larger modules, the lack of established R2R manufacturing processes, and the limited LCA studies. The LUMINOSITY project will contribute to filling these gaps by upscaling the production of large area flexible perovskite modules using R2R manufacturing maintaining high efficiencies and low manufacturing costs, transitioning the technology from lab scale (TRL 5) to industrial scale (TRL 7). To ensure the sustainable growth of the technology, the project also aims to conduct an LCA study, considering the EoL scenarios. As a starting point, a review of flexible PVs was done to serve as a benchmark and gain insight into the best practices for conducting the LCA. Although multiple LCA studies have been done on rigid PV configurations (Leccisi & Fthenakis, 2020; Vidal et al., 2021), not much has been reported on their flexible counterparts.

The studies reviewed below were identified in three iterations, by expanding the search scope. For all iterations, Google Scholar and the Scopus database were used for the research. In the first iteration, only LCA studies regarding flexible perovskite were considered. However, only two papers on flexible perovskite were identified. The second iteration expanded the search criteria towards other flexible PV modules, such as organic PVs (OPVs) and CIGS. For the third iteration, LCA studies for the prominent rigid PV modules (c-Si, CdTe and CIGS) and perovskite were identified. Data for rigid PV systems were included for comparison and because specific functional materials may be reused regardless of the substrate. To show the recent values and for brevity, only the latest values for each rigid PV type were listed. Since LUMINOSITY aims to develop a flexible single-junction (SJ) perovskite PV module, LCA studies on tandem perovskite configurations were excluded (Tian et al., 2020). Since there is inadequate data related to the end-of-life scenarios of PV panels (e.g., recycling), most LCA studies limit the scope only up to the use phase. For this reason, only studies with a cradle-to-gate boundary were included. Table 1 lists the relevant LCA studies conducted on rigid and flexible systems sorted by technology. The device configuration, deposition methods used and other relevant information in the LCA studies are shown in detail in Table 4 and the LCIA results are shown in Table 5 and Table 6 in Annex 9.1.

Earlier LCA studies on flexible PVs primarily focused on organic photovoltaics (OPVs). Despite this emphasis, it is essential to evaluate these findings, as OPVs utilize the same processes and techniques as PSCs, with the main difference being the materials used in the active layer. The methods and identified hotspots in the LCA studies for OPVs can provide valuable insights for enhancing PSCs, as demonstrated by LCA studies on flexible PSCs.

One of the first LCA studies on flexible solar cells was conducted by Roes et al. (2009) on the environmental and economic assessment of OPVs. The study evaluated the environmental impacts of OPV modules with a glass substrate and PET substrate and compared the results with that of multi-crystalline silicon (mc-Si) PV. The results showed that the modules with a flexible substrate can achieve a significant reduction in the environmental impact compared to the rigid counterparts, with reductions in the range of 80-95%. The study however shows many gaps, as the environmental impact is based on energy-focused indicators, without addressing the scarcity issue that derives from the indium usage and without taking into account the toxicity of some compounds. Moreover, the data used comes from lab-scale studies, and is not representative for large scale systems.

Table 1: Overview of LCA studies of rigid and flexible single-junction PV systems including the system boundary, lifetime (LT), power conversion efficiency (PCE), performance ratio (PR), active area (AA), energy payback time (EPBT) and global warming potential (GWP)

Source	System	System boundary	LT	PCE (%)	PR (%)	AA (%)	EPBT (years)	GWP (g CO_2 eq./kWh)
RIGID								
Fthenakis and Leccisi (2021)	c-Si	Cradle to gate	30	20.5	85	-	0.75	23
Leccisi et al. (2016)	CdTe	Cradle to gate	30	15.6	80	-	0.60	16
Leccisi et al. (2016)	CIGS	Cradle to gate	30	14	80	-	1.10	26
Ravilla et al. (2024)	Perovskite	Cradle to gate	25	19	75	-	0.33	6.01
FLEXIBLE								
Resalati et al. (2022)	CIGS	Cradle to gate	30	20	80	-	-	27.08
Roes et al. (2009)	Organic	Cradle to gate	25	5	75	-	0.19	4.14
Espinosa et al. (2010)	Organic	Cradle to gate	15	(a) 2 (b) 3	80	67	(a) 2.02 (b) 1.35	(a) 56.65 (b) 37.77
Espinosa et al. (2011)	Organic	Cradle to gate	15	(a) 1 (b) 3 (c) 5	80	37	(a) 9.45 (b) 3.15 (c) 1.89	(a) 137.68 (b) 91.79 (c) 55.07
Li et al. (2022)	Organic	Cradle to gate	5	1.57	80	70	1.60	89.97
Sarialtin et al. (2020)	Perovskite	Cradle to gate	5	14	80	75	1.98	243
Li et al. (2022)	Perovskite	Cradle to gate	2	11.50	80	70	0.15	30.54

This study was followed by Espinosa et al. (2010), which investigated the environmental impact of the production of flexible polymer solar cells produced using an R2R method called ProcessOne. It showed that the process achieved an EPBT of 2.02 years for modules with 2% efficiency, which could be reduced to 1.35 years at 3% efficiency. The study also assessed the GWP of the polymer solar cell modules and found that it varied depending on the efficiency. For a 2% efficient module, the GWP was 56.65 g CO_2-eq/kWh, while for a 3% efficient module, it was reduced to 37.77 g CO_2-eq/kWh. The use of ITO as the electrode was identified to have the highest contribution to the embedded energy, comprising 87% of the total. Because of this, the use of ITO was discouraged not only for being energy-intensive but also due to its scarcity, which can pose a problem in the long term.

The next study done by Espinosa et al. (2011) followed up on their previous concern on indium scarcity and conducted an LCA analysis on ITO-free OPV modules with a PET substrate produced through R2R coating and printing. The main goal of the study was to evaluate the environmental impact of using a sputtered aluminum/chromium electrode, which was produced using the Hiflex process, versus the indium tin oxide (ITO) electrode. The results showed an EPBT of 9.5 years due to the high energy consumption of the R2R sputtering and the low efficiency of the resulting modules at about 1%. This is a very high EPBT value compared to other PV technologies such as c-Si (1.7-2.7 years), CdTe (0.6-1.4 years) and CIGS (1.0-2.4 years) (Bhandari et al., 2015). The relatively high EPBT compared to other PV technologies indicates that the technology presents a less positive impact in climate change mitigation, but shows a trade-off with a different impact category thanks to the substitution of indium with less scarce metals.

This example demonstrates why including other environmental impact categories is crucial in showing a complete picture of the sustainability of a PV technology. The same study also investigated the effect of increasing the efficiency and the active area of the EPBT, showing that increasing the efficiency from 1% to 10% decreases the EPBT from 9.45 to 0.94 years. Meanwhile, increasing the active area from 36.78% to 68.10% also decreases the EPBT from 9.45 to 5.31 years. Besides removing indium to lower the environmental impacts, the study also emphasized avoiding vacuum processing steps for future developments.

With the issue of indium scarcity already identified in OPVs, LCA studies on flexible PSCs by Sarialtin et al. (2020) and Li et al. (2022) used alternative materials for the transparent conducting oxide (TCO) layer, using Ag/PH1000 for the former and graphene for the latter. Both studies identified the perovskite layer deposition as the most energy-intensive process, given that both used the same deposition process (spin coating). However, Sarialtin et al. (2020) found that the perovskite layer contributed the most in all impact categories while Li et al. (2022) identified that graphene was the most impactful since its production utilized large amounts of copper, which is used to transfer the graphene layer onto the PET substrate. The mining and refining operations of copper consume a large amount of energy and produce toxic by-products which is why using it during the graphene transfer has high environmental impacts associated with it. Although not a critical material, copper is considered a strategic material since it is essential in the electrification of all strategic technologies (e.g., PV) and is difficult to replace with another material due to its superior electrical performance (European Commission, 2023). The values for the EPBT and GWP in the study by Sarialtin et al. (2020) were also significantly higher than in the study by Li et al. (2022). This shows that even for the same PV type, the values from the LCA studies would still differ due to the variations in material, process and methodological choices made in the study.

For flexible PVs, the diverse variety of cell configurations leads to significant differences in material input and output flows, as well as the energy consumed across various processes. Additionally, it is crucial to recognize that many studies focus on lab scale findings, which can distort the results of the analysis. Compared to flexible PVs, rigid PVs have considerably lower EPBTs. Since they are already more established and have been commercialized, rigid PVs have already been developed to have higher efficiencies and longer operational lifespans. Despite this, rigid PVs do not necessarily have lower GWPs since they use more energy-intensive processes and more materials, whereas flexible PVs are thinner and use less material than their rigid counterparts.

2.1.2. Material toxicity

In earlier LCA studies of flexible PV systems, more emphasis was put on which materials require the most energy to process and produce the most GHG emissions. The results varied depending on various factors, such as the deposition methods used and the cell efficiency. However, these metrics do not take into account other issues that may have a deleterious effect on human health and the environment. For perovskites, toxicity is a major concern because of one key component — lead (Prince et al., 2024).

The upscaling of perovskite modules, either rigid or flexible, raises concerns regarding accidental releases of lead from the perovskite layer into the environment (Leccisi & Fthenakis, 2020). The toxicity of a material is already reflected in LCA using, for example, the leading USEtox model under the impact categories human toxicity (cancer and non-cancer) and ecotoxicity (Fantke et al., 2017).

LCA studies on PSCs have recognized the possible risk of using lead but concluded that it had a minimal effect on the environmental impacts compared to other materials present, only contribute

ng <1% of the human toxicity impacts (Zhang et al., 2017; Li et al., 2022), and that it was still a better active material than its possible alternatives, such as tin (Sarialtin et al., 2020). Serrano-Lujan et al. (2015) reported that besides being more costly, tin-based PSCs had higher environmental impacts than lead-based PSCs. Other possible alternatives to lead, such as gallium, bismuth and antimony, are considered to be critical raw materials (CRMs) and can be a barrier to upscaling PSC production when used since they pose a risk to the supply chain. Because of these factors, lead is still the more rational choice when it comes to perovskites and more efforts are focused on identifying and developing robust encapsulation techniques and materials to prevent its leakage and eliminate the environmental risk (Charles et al., 2023).

Besides lead, the solvents used also have a significant effect on the toxicity. The most commonly used solvent for perovskite layer deposition, dimethylformamide (DMF), is recognized as a substance of very high concern (SVHC) by the European Chemical Agency due to its toxic effect on human reproduction systems (Vidal et al., 2020). LCA studies on PSCs have shown that DMF and other solvent mixtures containing DMF had high contributions to the environmental impacts, especially in the toxicity impact categories (Gong et al., 2015; Zhang et al., 2017). While the exposure and risk of using DMF can be mitigated in a lab-scale setting, it would be challenging to take similar safety measures if PSCs are mass-produced. For upscaling flexible perovskite modules, other "greener" solvents must be considered. Of all the alternative solvents, dimethyl sulfoxide (DMSO) had the lowest total impact in terms of its effect on the environment and human health (Vidal et al., 2020).

2.1.3. Material scarcity

Another material-related issue is scarcity, especially for the metallic components. The wide use of indium across PV systems as a transparent conductive oxide (TCO) on substrates is problematic in the long term as it is a scarce material, with the demand possibly exceeding the global reserves. In the EU, indium has been considered critical since the European Commission's first communication on raw materials was released in 2011 (European Commission, 2011) until the present (European Commission, 2023). The criticality of indium has already been recognized as a bottleneck for emerging PV technologies for more than a decade, which is reflected in the LCA studies of using ITO-free substrates, replacing indium with either fluorine, aluminum/chromium, silver or graphene, for OPVs and PSCs (Espinosa et al., 2011; Sarialtin et al., 2020; Li et al., 2022). It is important to keep in mind that direct substitution of the scarce material with other materials would not be beneficial in the long term as it would only shift the material dependency to the alternatives. In the case of indium, using aluminum as a possible replacement could pose a problem when upscaling PSCs since it has also been considered a CRM since 2023 (European Commission, 2023).

Compared to toxicity, scarcity was not very well represented in previous LCA studies. Although the scarcity of materials used in the process (e.g., indium) was recognized by conducting LCA studies on the alternatives, an indicator for measuring this scarcity was not evaluated and embedded in the LCA.

2.1.4. Manufacturing and upscaling

For manufacturing flexible PSC, the chosen deposition method for the perovskite active layer in the LCA study not only affects the quality of the perovskite film but also has a huge impact on the overall environmental viability of the production (Leccisi & Fthenakis, 2020; Ravilla et al., 2024). The study by Sarialtin et al. (2020) showed that the spin coating deposition process of the perovskite active layer had the highest share in all impact categories. These results are consistent with the findings by Leccisi and Fthenakis (2020), where despite being the most common method used for perovskite deposition at the lab scale, spin coating has low throughput, high energy demand, highest material waste produced compared to other techniques and can only accommodate small-scale substrates. Because of this, spin coating is not suitable for industrial-scale production. This presents an opportunity to consider other solution-based deposition methods for upscaling flexible perovskite modules such as blade coating, slot die coating, bar coating, spray coating, inkjet printing and screen printing (Li et al., 2020).

To evaluate the scalability of deposition methods, the toxicity of the materials used and the wastes produced should be taken into account. Leccisi & Fthenakis (2020) assessed the potential scalability of solution-based techniques based on the solvents used, the amount of material waste produced and the throughput. They found that slot die coating, spray coating and inkjet coating have a high potential for scalability due to low material wastes (as low as 1-5%) and high throughput. Although DMF is usually used as the solvent in these processes, it can be replaced by DMSO. Perovskite films can also be deposited using vapor-based techniques, usually operated at sub-atmospheric pressures. These vapor-based methods, commonly used in solar cell production for technologies like CIGS and CdTe, offer the added advantage of being solvent-free, which reduces the environmental impact associated with chemical solvents. A significant factor in the LCA of these manufacturing techniques is the electricity used, which can substantially influence GWP. Across studies, electricity consumption for these processes accounts for 75–96% of the GWP, vastly outweighing material contributions (Leccisi & Fthenakis, 2020).

However, considerable differences in energy consumption values are reported between studies for the same processes. For example, a comparison of findings using spin coating as the deposition method shows that electricity use in the study by Espinosa et al. (2015) was about two magnitudes higher than in Gong et al. (2015). This disparity may be due to measurements taken from lab scale equipment, where energy efficiency is not optimized, suggesting potential overestimation in non-industrial settings. Thus, it is anticipated that energy consumption will decrease in industrial-scale production, highlighting the variability and uncertainty in reported energy use values across studies.

2.1.5. End-of-life scenarios

Direct landfilling or incineration of PV panels in the EU is not an option: according to the waste electrical and electronic equipment (WEEE) directive, PV panels that have reached their EoL must be treated, valuable metals must be recovered and 65% of the components recycled, and the hazardous materials must be safely disposed of. In addition, recent amendments to the WEEE directive have also allocated the costs of the management and disposal of the PV modules sold after August 13, 2012 to the producer (Directive 2024/884). This directive emphasizes the importance of considering the EoL scenarios of current and emerging PV technologies even before they are released to the market.

The EoL can be an opportunity to recover hazardous substances and other inert components, thus possibly reducing the toxicity risks of the PV modules. Several studies have already been done to recover lead from rigid PSCs such as using dissolution by eutectic solvents and electrodeposition (Poll et al., 2016) and by water extraction and DMF dissolution (Binek et al., 2016). Nonetheless, these studies were conducted at lab scale and such techniques might be challenging to implement for PV modules at production scales. Caution should also be exercised when employing extraction methods that use potentially toxic solvents, which might cause more harm than good. In this case, the environmental impacts of possible extraction processes should be assessed first using LCA to confirm their sustainability.

LCA studies considering EoL scenarios have only been investigated for rigid PSCs, but not for flexible PSCs. Tian et al. (2021) conducted a cradle-to-grave LCA of rigid PSCs considering landfill and recycling scenarios. Their findings indicated that implementing recycling strategies could reduce the EPBT by 72.6%, while also decreasing GHG emissions by 71.2%. This highlights the potential of recycling to substantially lessen both the environmental impact and resource demands of PSCs, supporting a more sustainable lifecycle for PV technologies. Martulli et al. (2022) also considered recycling and refurbishment as the EoL for the LCA of rigid carbon-based perovskite modules. They found that there were reductions in the EPBT by 23% and grid emission factor (GEF) by 13%, assuming full recovery of materials and no performance reduction. Due to inconsistencies in modeling recycling in life cycle assessments (LCA), Wang et al. (2024) evaluated the effects of six EoL modeling approaches on the LCA results for rigid silicon/perovskite tandem modules. They found that the Circular Footprint Formula (CFF) approach best represents the characteristics of recycled materials. Additionally, van der Hulst et al. (2024) conducted a cradle-to-gate prospective LCA for rigid silicon and silicon/perovskite modules considering the recovery of silicon and silver, building on first-generation recycling schemes outlined by the IEA PVPS (Stolz et al., 2017) and explored in previous studies (de Wild-Scholten, 2019). Their assessment showed that recycling had a more considerable contribution to the climate change impact results (10-13%) than previously reported (2-3%), highlighting the importance of including recycling scenarios in LCAs to give a more accurate assessment of the effects of the EoL. The inclusion of recycling is crucial, even though these technologies are not yet mature, to promote the development of design strategies that facilitate easier recovery of materials.

2.2. Techno-economic Assessment (TEA)

Besides environmental sustainability, the economic viability of upscaling emerging technologies should also be evaluated. To achieve this goal, a TEA should be conducted on the defined f-PSC to validate the economic feasibility of the upscaling of such a technology. The aim of this review is to scope out cost studies conducted specifically on flexible PSC. The values would serve as a baseline and a point of comparison for cost indicators obtained in the following sections.

To quantify the economic feasibility of PVs, two important parameters are calculated: manufacturing costs and levelized cost of energy (LCOE). Manufacturing costs are usually reported as the cost per unit area (US$ per m^2) and refer to the sum of the costs of each process step including the material, equipment, operational (utilities, insurance and labor) and, repair and maintenance costs (Chang et al., 2017; Martulli et al., 2024). Meanwhile, the LCOE is the sum of the total costs incurred, with capital costs typically discounted, divided by the total energy produced over the lifetime of the PV system (Holzhey et al., 2022).

2.2.1. TEA of flexible perovskite modules

The literature review of TEA studies was conducted using Google Scholar and the Scopus database. Only cost studies on f-PSC from 2015 to the present were considered. Rigid and/or tandem perovskite configurations were also excluded to align with the aim of the project on the upscaling of flexible single-junction PSCs.

There have been five studies done on the economic feasibility of single-junction f-PSCs. All of the TEA studies assumed R2R manufacturing as the processing technique, with variations in the sequences, and used PET as substrate. Table 2 shows a summary of these studies with their corresponding cost parameters, manufacturing cost, LCOE assumptions and values.

The paper by Chang et al. (2017) is the first study that analyzed the economic feasibility of f-PSCs produced using R2R manufacturing. It assessed the manufacturing costs for three existing R2R production methods and explored possible cost savings through two improved approaches. Key findings suggested that to lower costs, it would be beneficial to avoid expensive materials like P3HT and PCBM, use affordable screen-printing for the rear metal layer, and replace costly transparent conductors like ITO with cheaper alternatives. These changes could potentially cut manufacturing costs to about $37 per m^2, making flexible perovskite modules more competitive if they achieve a PCE of 10%, a 68% geometric fill factor (GFF), and a 3-year lifetime. To compete with established PV technologies (e.g., c-Si and CdTe) would require even higher efficiencies (15% or more) and longer lifetimes (over 15 years). The study assumed that lab-based methods could be scaled for commercial use but noted that achieving this would require significant advancements in the efficiency and stability of the PSC. Specifically, R2R processes must scale up to produce large-area modules with interconnected cells, rather than the current single-cell designs under 1 cm^2. Achieving high GFF is essential to ensure competitive power-to-weight and power-to-area ratios. Additionally, the technology needs encapsulation materials that can protect modules while maintaining high efficiency, as well as rapid testing methods for quality control.

Mathews et al. (2020) investigated the feasibility of sustainable growth of R2R manufacturing of PSCs by calculating the production costs for flexible perovskite modules which ranged from $3.30 per watt for small-scale facilities (0.3 MW/year) to $0.53 per watt for larger, industrial-scale operations (1 GW/year). They also identified the key areas impacting economic viability, including the cost of barrier foils and the ITO-coated substrate, and the efficiency of perovskite cell encapsulation. Reductions in these costs, as well as improvements in perovskite stability and efficiency, emerged as critical to achieving lower per-watt production costs and sustainable scaling.

The results of the paper by Martin et al. (2022) highlighted that intense pulsed light (IPL) annealing significantly reduced costs in perovskite PV manufacturing compared to traditional thermal ovens, especially through decreased energy and equipment expenses. The cost drivers were material costs (specifically, the ITO-coated PET), which dominated over 90% of the total production cost, followed by equipment and utilities. The reduction in energy usage by IPL annealing (0.113 kWh per m^2) compared to traditional thermal ovens (0.607 kWh per m^2) provided energy savings of over 80%, reducing operating expenditures. Additionally, IPL shortened web lengths in the annealing step, reducing the potential for defects and associated downtime. They also evaluated the use of IPL annealing in three production capacities and found that increasing the production capacity resulted to a reduction in manufacturing costs.

The study by Holzhey et al. (2022) explored the potential for lightweight, f-PSCs to become commercially viable for residential photovoltaics. They found that the largest cost savings would come from reducing balance-of-system (BOS) costs, which include installation, transportation, and mounting infrastructure. This indicates that the PV module itself does not dominate the system cost. Flexible perovskite modules, being lighter and easier to handle, could be directly attached to roofs, eliminating the need for heavy racking systems. This would significantly lower both labor and material costs, making PSCs more competitive compared to traditional silicon panels, which require more complex and costly installations. The key cost factors identified in the study include BOS costs, which are the biggest contributor to the overall price of the system. By using lightweight and flexible modules, installation and transportation costs can be drastically reduced. Additionally, manufacturing costs play an important role, as perovskite modules could be produced more cheaply than silicon-based panels. The study also considered the efficiency and lifespan of the modules, with target efficiencies of 15-17% and lifetimes of 13 to 34 years, which could make PSCs competitive with silicon if these modules maintain lower BOS and production costs. When considering the LCOE, PSCs could achieve a cost range of $0.055 to $0.063 per kWh by 2030, significantly lower than the LCOE of traditional silicon-based systems, which is expected to range from $0.119 to $0.136 per kWh.

Table 2: Overview of TEA literature on flexible single-junction perovskite PV

Source	Study	Cost parameters	Manufacturing cost (US$/m²)	LCOE assumptions	LCOE (US$ cents/kWh)
Chang et al. (2017)	Calculation of the manufacturing costs of five R2R processing sequences: A: High-efficiency module on ITO coated PET substrate (CSIRO process) B: DUT 1-step process, screen printed rear metal C: DUT 2-step process, screen printed rear metal D: Combination of low cost active layers from Sequence A and low cost rear metal from Sequences B and C (optimized sequence) E: Similar to D, Flextrode substrate replacing ITO	Materials, labor, capital depreciation, operational expenses	A: 65 B: 60 C: 74 D: 53 E: 37	-	-
Mathews et al. (2020)	Investigation on the impacts of economies of scale and average selling price on profitability for flexible SJ perovskite and perovskite-silicon tandem Flexible SJ sequence based on structure D from Chang et al. (2017) and evaluated under two production capacities: A: 3 MW/year B: 1 GW/year	Materials, labor, investment, operational expenses	A: 120 B: 76	-	-
Martin et al. (2022)	Study on the effect of using intense pulsed light (IPL) as the annealing step on the cost of flexible perovskite on ITO-coated PET substrate Evaluated under three production capacities: A: 1 GW/year B: 2 GW/year C: 4 GW/year	Materials, labor, equipment, utilities, depreciation	A: 14 B: 13 C: 11	-	-
Holzhey et al. (2022)	Comparison of the PCE and LT of rigid and flexible PSCs to reach the same LCOE of c-Si PVs for residential applications	Materials, labor, overhead	35	PCE: 14% LT: 25 years	11.9
McGovern et al. (2023)	Comparison on manufacturing costs of flexible and rigid SJ perovskite modules based on literature Calculation of the LCOE from four module cost scenarios and extension of the LCOE equation to lightweight R2R-produced flexible perovskite using three scenarios with set values for module costs and PCEs and different compound annual growth rate (CAGR), annual progress rate (APR) and annual degradation rate (ADR) to project LCOE from 2025 to 2050: A: Conservative (20% CAGR, 0.2% APR) B: Baseline (25% CAGR, 0.3% APR) C: Optimistic (30% CAGR, 0.4% APR)	Materials, labor. CAPEX, OPEX	Corresponding initial costs: A: 108 B: 97 C: 76	PR: 85% LT: 25 years Irradiation: 1200 kWh/m²yr Discount rate: 5% Initial capacity: 1 GW/year ADR: A: 3% B: 2% C: 1% 2025 / 2050 PCE scenarios: A: 12.5% / 17.5% B: 15.0% / 22.5% C: 17.5% / 27.5%	2025 / 2050 values: A: 16 / 9.7 B: 11 / 5.6 C: 7 / 3.0

Lastly, McGovern et al. (2023) compared the manufacturing costs of rigid and flexible single-junction perovskite modules taken from literature and found that there was a wide spread of values which could be due to different assumptions made for each study. Flexible modules were found to have higher manufacturing costs at a production capacity of 100 MWp per year, at an average of 70 € per m^2, than the rigid modules, at an average of 40 € per m^2. However, no differentiation was made for the manufacturing cost based on the deposition method assumed for each study. The higher costs could be due to additional costs for the flexible substrate and the encapsulation method assumed in the previous studies. They also investigated the effect of increasing production capacity to manufacturing costs and found that a higher production capacity at 1 GWp per year has lower manufacturing costs of about 22 € per m^2 compared to a 100 MWp per year production capacity at 55 € per m^2. The reduced manufacturing costs at higher capacities could be due to a productivity increase, associated with the learning rate set at 25%, where module costs are reduced at higher throughput, and economy-of-scale, where the material costs decrease with increasing production capacity.

For the next part of the study, they examined how the efficiency, in terms of PCE, and stability, quantified by the annual degradation rate (ADR), affected the LCOE in four different module cost scenarios (12.5, 25, 50 and 100 € per m^2) and in which conditions would make the rigid and flexible perovskite modules cost-competitive to c-Si PV modules at utility scale. Flexible perovskite modules would have similar or lower LCOE values to c-Si PV (0.063 € per kWh) at a module cost of 25 € per m^2 and an ADR of 1% given that the PCE would exceed 12%. They also projected the LCOE up to 2050 based on three different scenarios (conservative, baseline and optimistic), each having initial values for the manufacturing cost and PCEs with corresponding compound annual growth rates (CAGR) and annual progress rate (APR), to determine how advances in the technology and increasing learning rate would affect the LCOE. It was shown that the LCOE would decrease for all scenarios as the technological learning rate and capacities increase over time. The LCOE of flexible perovskite modules would be similar to the LCOE of c-Si modules in 2039 for the baseline scenario and 2026 for the optimistic scenario. The cost-competitiveness of flexible perovskites could be reached even earlier if the module weight is reduced (10 times decrease in the weight-dependent term of the CAPEX for BOS-related costs), reaching LCOE parity in 2035 for the baseline scenario and 2025 in the optimistic scenario.

2.2.2. Materials used

Based on the TEA studies, the cost of materials has the highest share in the manufacturing costs of flexible perovskite modules, comprising about 53-93% of the total value. The usual cost drivers in the materials cost are the front substrate, materials used in the encapsulation and the junction box (McGovern et al., 2023). However, each study has different process sequences, materials used for each layer and assumptions which makes comparison of TEA results more challenging.

For most studies listed in this report, the ITO-coated PET substrate had a considerable contribution to the manufacturing cost (Chang et al., 2017; Mathews et al., 2020; Martin et al., 2022). Other high-cost materials mentioned are P3HT and PCBM (Chang et al., 2017) and the barrier foils in the encapsulation (Mathews et al., 2020), both of which were recommended to be avoided or minimized in the upscaling of flexible perovskite modules.

Besides finding alternatives for high-cost materials, the reduction in the amount of materials used to produce low-weight modules was also mentioned to bring down costs. Low-weight perovskite modules can have an effect in bringing down the CAPEX costs related to the BOS and consequently, in lowering the LCOE (McGovern et al., 2023).

2.2.3. Manufacturing and upscaling

Similar to the materials used, the manufacturing costs and LCOE differ for each study due to the differences in the process steps. The differences in the processes used also corresponds to differences in the process energy consumption, with one study showing the reduction of manufacturing costs using an alternative process for the annealing step (Martin et al., 2022). The TEA studies have also identified different processes with the highest contribution to the manufacturing costs, such as the evaporation step for the rear metal deposition (Chang et al., 2017) and the encapsulation step (Mathews et al., 2020).

In general, solution-based processes have lower manufacturing costs than vapor-based processes, which highlights the importance of the choice of deposition method for the economic feasibility of upscaling flexible perovskite modules (Roy et al., 2022). Since vacuum-based processes are more energy-intensive and require more complex systems, solution-based processes, such as slot-die coating, were used as the deposition process in the reviewed TEA studies (Chang et al., 2017; Mathews et al., 2020; Martin et al., 2022). Some of the TEA studies evaluated the effect of upscaling the production capacity of flexible perovskite modules and showed a reduction in the manufacturing costs (Mathews et al., 2020; Martin et al., 2022), however, these scenarios were set up assuming that the stability and efficiency of the flexible perovskite systems would be the same in the large-scale as in the lab-scale.

3. Implications and recommendations

The LCA and TEA studies reviewed in the previous sections have identified and presented areas for improvement in conducting environmental and economic assessments for flexible perovskite modules. A summary of the implications derived from the review of the LCA and TEA studies and the corresponding recommendations is shown in Table 3.

The issues related to material scarcity can be alleviated by conducting an alternatives assessment of the current materials used (Llanos et al., 2020) and employing eco-design to determine how different material choices and combinations can affect the probable EoL solutions of the PV system (Miettunen & Santasalo-Aarnio, 2021). Recovering scarce and/or critical materials from spent PV modules can be used for the production of new ones, also reducing the impact relative to resource depletion and addressing the issue of scarcity. The recovery of indium from spent PVs poses a challenge since they are only present in such small quantities and the payoff of extracting them for reuse is low compared to using primary sources (Charles et al., 2023). But, reusing the ITO-coated substrate seems to be more feasible. Augustine et al. (2019) used a potassium hydroxide (KOH) solution to separate and recover ITO-patterned glass substrates from the other layers in a rigid PSC. The recovered ITO substrate showed similar properties as the reference samples without using multiple and complex solvents, providing a possible scalable recovery option for industrial applications. Similar to techniques for lead recovery, the effects of using these processes must be analyzed to optimize the materials and conditions and ensure that they do not add to the total environmental impacts of the PV system.

Designing with recovery in mind and assessing the effect of scaling up the materials and solvents used on the environmental impacts even at lower TRLs and before commercialization would also be beneficial to ensure the sustainability of the flexible perovskite technology throughout its development. For PVs, the choice of materials and design of the cell architecture have huge impacts on the effectiveness and feasibility of recovering components. For example, Miettunen & Santasalo-Aarnio (2021) assessed that changing the substrate of dye-sensitized solar cells (DSSC) from thick glass to thin and flexible materials changes the weight percentage of the silver current collector grids making silver recovery more economically attractive. Li et al. (2017) investigated the use of a recyclable substrate template with a NiO/Au electrode and demonstrated a process of reloading the perovskite active layer. The study showed that the PCEs of the renewed PSCs using the recycled template (8.17% for the first round and 7.72% for the second round) were comparable to that of the original PSC (8.52%). These results illustrate the importance of integrating eco-design approaches to improve the recoverability of the materials at its EoL and how the design of the cell architecture also influences the possible EoL scenarios. This is something that should also be considered in upscaling flexible perovskite modules.

Table 3: Summary of possible bottlenecks and recommendations based on LCA and TEA studies

Possible bottlenecks/areas for improvement	Recommendations
LCA	
Toxicity of lead	● Improve encapsulation techniques to ensure safety during the use phase ● Employ lead recovery at the EoL ● Assess the effect of using Pb alternatives on the environmental impacts
Toxicity of solvents	● Seek alternatives for DMF and assess the effect of using the alternatives on the environmental impacts ● Use LCA methodologies that include the USEtox model to quantify the effect of using different solvents
Scarcity of indium and criticality of other metals used	● Use alternatives assessment/eco-design approach which integrates the scarcity of the materials ● Use the Material Criticality model for the LCA
High environmental impacts of materials (e.g., metals, solvents) and processes	● Consider using secondary raw materials as input (e.g., recycled aluminum, silver) ● Avoid energy-intensive processes (e.g., vacuum-based techniques) ● Assess the effect on the environmental impacts of scaling up the usage of possible materials and solvents
Exclusion of end-of-life scenarios	● Conduct cradle-to-grave LCA by setting up different EoL scenarios for each component ● Design with recovery approach
LCA based only on lab scale data	● Use primary data from manufacturers ● Update data (e.g., pilot scale data) in the LCA as the technology progresses
TEA	
High manufacturing costs and LCOE	● Investigate the effect of integrating parameters such as efficiency, stability and module degradation ● Use less energy-intensive processes (e.g., processes at ambient conditions)
High cost of ITO-coated substrates	● Use indium-free TCOs and evaluate the cost-benefit of using these alternatives

Recently, an LCA model based on the studies by Zapp & Schreiber (2021) and Bargiacchi et al. (2022) has been released related to material criticality and circularity (Cilleruelo, 2024). This model could be integrated into subsequent LCAs.

4. Future research and next steps

Compared to the studies reviewed in this report which used lab scale data, the LUMINOSITY project has the advantage of providing pilot-scale data for the LCA and TEA. With the collaboration of other technology partners in acquiring actual production data, the next steps are as follows:

a. Conducting a benchmark LCA and TEA based on the process steps and cell architecture described in D1.1 First guidelines for a blueprint of a R2R flexible perovskite PV processing line

b. Evaluating the LCA approach (ex-ante or prospective) to be used for scaling-up projections of large area perovskite modules

c. Performing a TEA where efficiency (PCE) and stability (ADR) will be used as input parameters, similar to the approach by McGovern et al. (2023), which will be varied to estimate the effect it would have on the manufacturing costs and LCOE

5. Conclusions

This report aims to establish guidelines for the sustainable production and end-of-life of large area flexible perovskite modules based on important findings and recommendations from relevant LCA and TEA studies. Based on the literature review, there are only two LCA studies related to flexible PSCs but the results from OPVs can be used since they have similar processing techniques. All the LCA studies on flexible PV systems are based on lab scale data, which can be improved by using pilot scale data. Toxicity, scarcity and exclusion of EoL scenarios were identified to be the main issues for conducting LCA, all of which will be addressed for the next LCA iterations. For the TEA, the cost of materials, specifically the ITO-coated substrate, was identified as the main cost driver.

A benchmark analysis will be conducted based on the blueprint described in D1.1. The results of this report will be used as the basis for the next tasks and deliverables and the work will be continued under WP7.

6. Degree of Progress

The deliverable is 100% fulfilled.

7. Dissemination level

The deliverable D1.2 is public.

8. References

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9. Annexes

9.1. Recent developments in LCA studies of flexible PV systems

Table 4: Overview of cell architecture and deposition methods used in LCA studies of single-junction flexible systems

Source	PV type	Cell structure	Active layer deposition	Functional unit	Data sources	LCIA methodology	Software	Irradiation (kWh/m^2yr)	Electricity mix	Impact categories*	Environmental hotspots
Resalati et al. (2022)	CIGS	Stainless steel/SiO2/Mo/CIGS/CdS/ITO	Selenisation	1 kWh	Primary data from manufacturers	CML For sensitivity analyses: IMPACT and ILCD	GaBi 9.2	850	EU (EU-28)	CED, AD, ADFF, GWP, OLD, HT, FAE, MAE, TE, PO, AC, EU, PENRT, PERT	Electricity consumption had the highest impact in most categories ***MATERIAL*** CIGS layer had the highest impact ***PROCESS*** Deposition of the absorber layer (CIGS) had the highest impact
Roes et al. (2009)	Organic	PET/ITO/PEDOT:PSS/P3HT:PCBM/Al	Gravure printing	1 W_p	Primary data from manufacturers, lab scale data, literature, Ecoinvent, BUWAL 250	CML	SimaPro 7	1700	EU (medium voltage)	non-renewable energy use (NREU), GWP, AD, OLD, PO, AC, EU	***MATERIAL*** The PCBM layer contributed the most to the total impacts due to high electricity use of the plasma generator High photochemical oxidant formation due to toluene evaporation during gravure printing ***PROCESS*** Environmental impacts mostly from sputtering and lamination
Espinosa et al. (2010)	Organic	PET/ITO/ZnO/P3HT:PCBM/PEDOT:PSS/Ag	Slot die coating	1 m^2	Primary data from industry sources, lab scale data, literature	-	-	1700	Denmark	Equivalent primary energy (EPE), EPBT, GHG	***MATERIAL*** ITO electrode accounted for 87% of the energy embedded in the input materials ***PROCESS*** PEDOT:PSS deposition

Source	PV type	Cell structure	Active layer deposition	Functional unit	Data sources	LCIA methodology	Software	Irradiation (kWh/m^{2}yr)	Electricity mix	Impact categories*	Environmental hotspots
											was the most energy-intensive step comprising 35% of the total energy consumption
Espinosa et al. (2011)	Organic	PET/Al/Cr/P3HT:PCBM/PEDOT:PSS/Ag	Slot die coating	1 m^2	Primary data from industry sources, literature	-	-	1700	Denmark	Embodied energy, EPBT, GHG	***MATERIAL*** Al/Cr on PET substrate accounted for 94% of the total embodied energy (no energy reduction from the substitution of indium) ***PROCESS*** PEDOT:PSS deposition was the most energy-intensive step comprising 51% of the total energy consumption
Li et al. (2022)	Organic	PET/Graphene/PEDOT:PSS/P3HT:PCBM/Al	Spin coating	1 m^2	Ecoinvent, literature, stoichiometric calculations	CML, ReCiPe	-	1700	EU (medium voltage)	AD, ADFF, GWP, OLD, HT, FAE, MAE, TE, PO, AC, EU	***MATERIAL*** Graphene contributed the most since its production uses a large amount of copper foils ***PROCESS*** PEDOT:PSS deposition was the most impactful (43% of the CED) due to the long drying process
Sarialtin et al. (2020)	Perovskite	PET/Ag/PH1000 mesh/PEDOT:PSS/$CH_3NH_3PbI_3$/PCBM/Al	Spin coating	1 m^2 1 kWh	Ecoinvent, literature	ILCD	GaBi 8.1	1700	-	ACD, GWP, ET, EP, HTCE, HTNE, POF, PED	Electricity consumption accounts for 90% of the environmental impact values ***MATERIAL*** The perovskite layer contributed the most in all impact categories ***PROCESS*** Perovskite layer deposition was the most impactful due to

Source	PV type	Cell structure	Active layer deposition	Functional unit	Data sources	LCIA methodology	Software	Irradiation (kWh/m^2yr)	Electricity mix	Impact categories*	Environmental hotspots
											the long stirring process
Li et al. (2022)	Perovskite	PET/Graphene/P3HT/$CH_3NH_3PbI_3$/PCBM/Ag	Spin coating	1 m^2	Ecoinvent, literature, stoichiometric calculations	CML, ReCiPe	-	1700	EU (medium voltage)	AD, ADFF, GWP, OLD, HT, FAE, MAE, TE, PO, AC, EU	***MATERIAL*** Graphene contributed the most since its production uses a large amount of copper foils ***PROCESS*** Perovskite layer deposition was the most impactful (37% of the CED), followed by PH3T and PCBM deposition (26% of the CED)

*For CML: AD – Abiotic depletion, ADFF – Abiotic depletion (fossil fuels), GWP – Global warming potential, OLD – Ozone later depletion, HT – Human toxicity, FAE – Freshwater aquatic ecotoxicity, MAE – Marine aquatic ecotoxicity, TE – Terrestrial ecotoxicity, PO – Photochemical oxidation, AC – Acidification, EU – eutrophication; For ILCD: ACD – Acidification, GWP – Global warming potential, ET – Ecotoxicity, EP – Eutrophication, HTCE – Human toxicity cancer effects, HTNE – Human toxicity non-cancer effects, POF – Photochemical ozone formation; For energy indicators: PENRT – Primary energy non-renewable resource, PERT – Primary energy renewable resource, PED – Primary energy demand

Table 5: Life cycle impact assessment results of single-junction flexible PV systems using the CML methodology (per kWh)

Source	Abiotic depletion (kg Sb eq)	Abiotic depletion fossil fuels (MJ)	Global warming potential (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Human toxicity (kg 1,4-DB eq)	Freshwater aquatic ecotoxcity (kg 1,4-DB eq)	Marine aquatic ecotoxicity (kg 1,4-DB eq)	Terrestrial ecotoxicity (kg 1,4-DB eq)	Photochemical oxidation (kg C_2H_4 eq)	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4 eq)	Primary energy non-renewable resource (MJ)	Primary energy renewable resource (MJ)
Resalati et al. (2022) *CIGS*	2.60E-07	3.06E-01	2.71E-02	2.64E-14	7.27E-03	7.23E-05	3.23E+00	3.40E-05	3.92E-06	5.12E-05	6.27E-06	5.14E-01	2.22E-01
Roes at al. (2009) *Organic*	3.11E-05	-	4.14E-03	1.71E-10	-	-	-	-	1.02E-05	3.04E-05	1.82E-06	-	-
Li et al. (2022) *Organic*	6.78E-06	7.92E-01	9.00E-02	4.65E-09	2.17E+00	1.21E+00	1.48E+03	1.16E-03	1.62E-04	2.00E-03	9.65E-04	-	-
Li et al. (2022) *Perovskite*	2.63E-06	2.53E-01	3.05E-02	1.50E-09	7.36E-01	4.13E-01	5.06E+02	4.11E-04	5.50E-05	6.88E-04	3.31E-04	-	-

Table 6: Life cycle impact assessment results of single-junction flexible PV systems using the ILCD methodology (per kWh)

Source	**Acidification (mol H+ eq)**	**Global warming potential (kg CO_2 eq)**	**Ecotoxicity (CTUe)**	**Eutrophication (kg N eq)**	**Human toxicity cancer effects (CTUh)**	**Human toxicity non-cancer effects (CTUh)**	**Photochemical ozone formation (kg NMVOC eq)**	**Primary energy demand (MJ)**
Sarialtin et al. (2020) *Perovskite*	1.22E-03	2.43E-01	7.39E-01	1.25E-04	8.21E-09	2.95E-08	4.10E-04	2.45E+00