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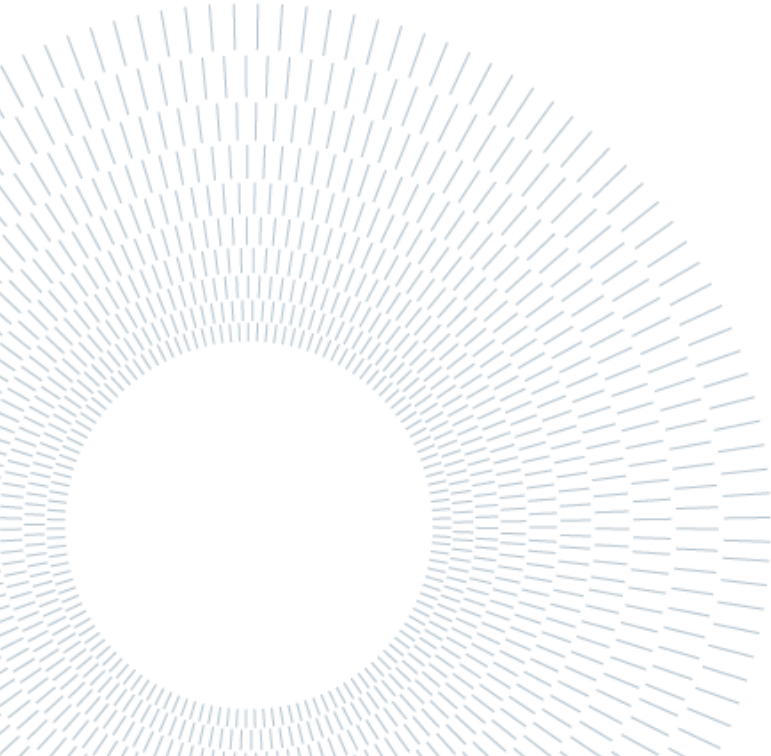
SCUOLA DI INGEGNERIA INDUSTRIALE
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Perovskite photovoltaic modules: a technoeconomic and life cycle analysis in an industrial setting, with alternative encapsulation and a responsible end of life approach

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Abstract

In a world fragmented by renewed and widespread tensions, the European energy market is going through a period of extreme uncertainty and rapid adaptation. An unstable balance, aimed at reconciling and smoothing over geopolitical divergences, ultimately affecting the end users. At the same time, crucial issues such as the socioeconomic impact and environmental sustainability in electricity generation are drawing a clear line for the future of this market. Efficient, stable, and clean technologies, capable of combining essential economic convenience with improved sustainability.

In this context, perovskites emerge as a promising alternative in the photovoltaic market. With excellent technological flexibility and a reduced impact, these materials could address emerging issues related to silicon, such as the current inconvenience in managing its end-of-life waste and the approaching technical efficiency limits.

In this thesis, through the evaluation of different impact categories in a life cycle analysis (LCA) approach and the study of techno-economic parameters such as production cost and levelized cost of energy (LCOE), a comparative analysis between perovskites and silicon in terms of environmental and socioeconomic sustainability has been performed.

After necessary ex-ante evaluations on materials and deposition methods aimed at studying alternatives with reduced impacts and mitigating supply chain pressures, this study highlights how, at the current state of the art, this technology proves to be environmentally sustainable but unable to ensure a sufficiently long lifespan to remain competitive in the market. The installation and system balancing costs significantly affect this conclusion.

At the same time, the effect of specific procedures chosen ad hoc to improve the overall profile of the technology was studied, with relevant conclusions regarding the cost-effectiveness of glass frit as an encapsulant substitute for more common thermoplastics, the viability of end-of-life regeneration processes, and the unforeseen deleterious contribution of clean solvents compared to alternatives with greater impact.

Key-words: perovskites; encapsulation; end of life; sustainability; levelized cost of electricity; life cycle analysis.

Abstract in italiano

In un mondo frammentato da rinnovate e dilaganti tensioni, il mercato europeo dell'energia vive un periodo di estrema incertezza e rapido adattamento. Un instabile equilibrio, mirato a bilanciare e appianare divergenze geopolitiche a discapito, di fatto, degli utenti finali. Al contempo, tematiche cruciali quali l'impatto socioeconomico e la sostenibilità ambientale nella produzione di energia elettrica, tracciano una linea ben delineata nel futuro di tale mercato. Tecnologie efficienti, stabili e pulite, che riescano a coniugare l'indispensabile convenienza economica con una migliorata sostenibilità.

In questo contesto, le perovskiti si candidano a valida alternativa nel mercato del fotovoltaico. Dotati di un'ottima flessibilità tecnologica e di un ridotto impatto, questi materiali potrebbero sopperire ai problemi emergenti legati al silicio, quali l'attuale sconvenienza nel gestirne gli scarti a fine vita e l'approssimarsi del limite tecnico in termini di efficienza. In questa tesi, tramite la valutazione di diverse categorie di impatto in un'ottica di analisi di ciclo di vita (LCA) e lo studio di parametri tecno-economici quali il costo di produzione e il costo livellato dell'energia (LCOE), si è performata un'analisi comparativa tra perovskite e silicio in termini di sostenibilità ambientale e socioeconomica.

Dopo necessarie valutazioni *ex-ante* su materiali e metodi di deposizione mirate a studiare alternative dai ridotti impatti e sollecitazione delle catene di approvvigionamento, questo studio sottolinea come, all'attuale stato dell'arte, questa tecnologia si dimostri sostenibile per l'ambiente ma incapace di garantire una vita utile sufficiente per risultare competitiva nel mercato. Su tale conclusione, i costi di installazione e bilanciamento del sistema inficiano in modo preponderante.

Al contempo, l'effetto di peculiari procedure scelte *ad-hoc* per migliorare il profilo generale della tecnologia è stato studiato, ottenendo conclusioni rilevanti in merito alle condizioni di convenienza della frittata di vetro come incapsulante sostitutivo alle più comuni termoplastiche, alla consistenza di processi di rigenerazione al fine vita, e all'imprevisto contributo deleterio portato da solventi puliti rispetto ad alternative dal maggiore impatto.

Parole chiave: perovskiti; incapsulamento; fine vita; sostenibilità; costo livellato dell'elettricità; analisi di ciclo vita

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Introduction

Present and future of European energy markets, the opportunity for renewables to rise

Following recent balance breaking events that threatened peace and economic stability, European energy market is struggling for taking back its old balance, making overall electricity price way higher than before; the consequences of Ukrainian war are reshaping relations with extra communitarian forces for the supply of natural gas, the main source for power production in Europe and whether it's for liquified gas from USA, for Arabian or for Russian gas from third parties, citizens and productive activities are paying themselves the burden of sanctions to Russia in terms of affordability and reliability.[1]

Electricity consumption in Europe will continuously rise in the next future, following the increasing automation of productivity and newborn highly intensive markets like artificial intelligence, calling for firm and decisive policies to stabilise electricity price and attract foreign investment. [2] [3]

Given many governments' reluctance in exploiting newborn and advanced nuclear solutions that could decrease electricity price and leverage security of supply, renewables could stand a chance for becoming a dominant main source of electricity in European future.

During 2022, the EU renewable electricity penetration (REP), accounting for the percentage of power consumption from green sources on the overall one, has reached the record value of 41.8%, surpassing the 40% threshold for the first time in history, while renewable energy share (RES), accounting for primary energy consumption, stands at 24.5%. Currently, the most up-to-date data available show a 44% of REP, confirming this positive trend.[5]

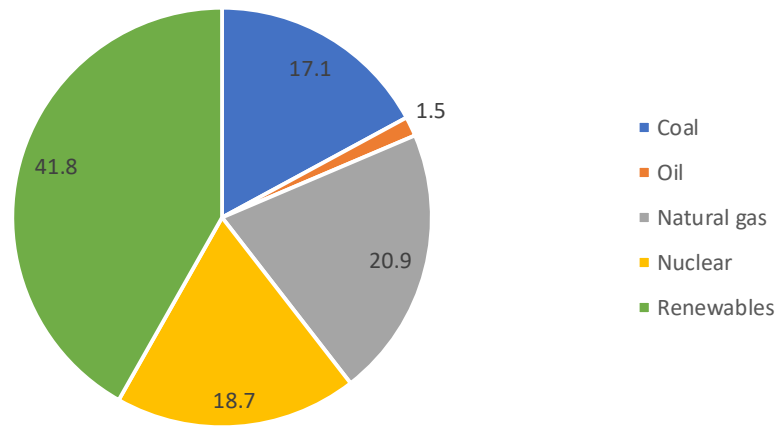


Figure 1: Electricity generation by sources, Europe, 2022, data from IEA

As shown in Figure 2, GHG emissions from fuel combustion in Europe have been decreasing since the late 2000s. However, despite these promising trends, the current trajectory remains far from the target of a 55% reduction in total emissions by 2030, a milestone essential for achieving climate neutrality by 2050 as outlined in the European Green Deal and the Fit for 55 framework. This underscores the urgent need to maintain and accelerate decarbonization efforts, even in the face of increasingly challenging external conditions.

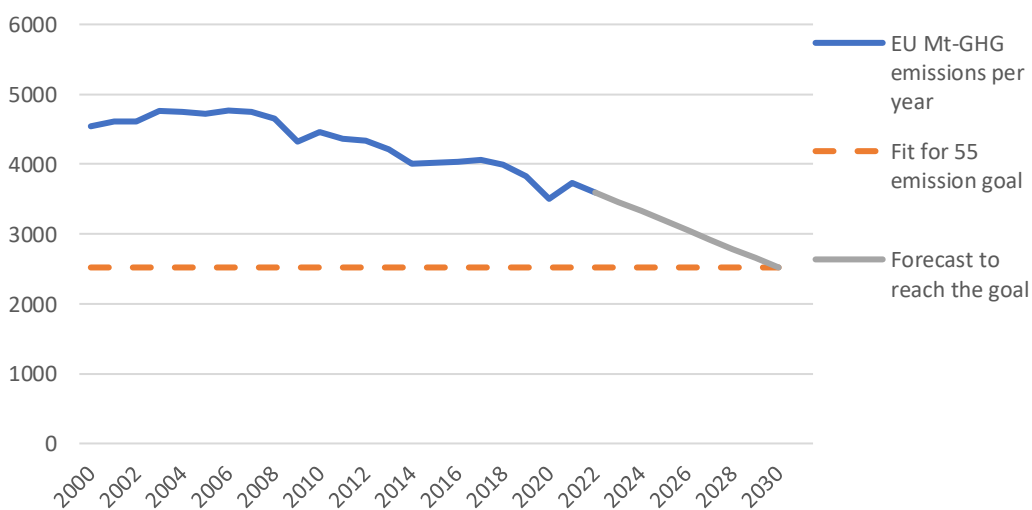


Figure 2: Green House Gas (GHG) Emissions from fuel combustion per year until 2022 and 2030 goal, data obtained from IEA

Despite private firms and national governments investing resources to stay on track, external constraints—such as rising geopolitical tensions and inward-looking policies adopted by many powerful market countries—could also impact Europe by exacerbating trade tariffs. The ongoing fragmentation of contractual exchange relations could significantly alter the economic profile of common goods, rendering profitable and affordable solutions unviable in the near future.

In this difficult scenario, innovation and research could help the future reshape of energy markets, bringing to life new technologies to boost resiliency in power production and decrease the environmental burden linked to fossil fuels abuse.

1 An overview of European photovoltaic market: silicon domain and the upcoming interest in perovskite

Concerning renewable power production, solar photovoltaic (PV) represents a grounded and flexible solution; the direct conversion of light into electricity is a versatile and user-friendly technique both for utility power production and residential applications. Starting from traditional applications such as rooftop or ground-mounted systems, new adaptations such as agrivoltaics, floating and vehicle-integrated systems are currently expanding the market, showing the adaptability of PV technology into diverse applications.

Nevertheless, the daylight dependency of this devices makes them less suitable for stand-alone systems and considering its unsuitable pairing to the “duck curve” that describe the common electricity consumption in a common day, it raises concerns about the overproduction during middle day hours and about the impossibility to meet the demand after sunset, calling for energy storing systems to collect excesses and cover shortcomings.

Even considering these limitations, it's clear that solar energy is stealing the spotlight: present estimates show that the 11 % of total European electricity production in 2024 was covered by photovoltaics, surpassing coal for the first time in history and reaching a total cumulative capacity installed of 325 GW. On global basis, a huge expansion is happening in terms of new power installed, that, with an 87 % increase from the previous year, showed a boost that never happened since the market exceed the gigawatt scale. This great expansion turned photovoltaics into the leader of its own sector: considering the new renewable capacity installed in 2023, it can be easily pointed out the difference between solar markets' scale and other renewable's one, with solar accounting for the 78 %. [4]

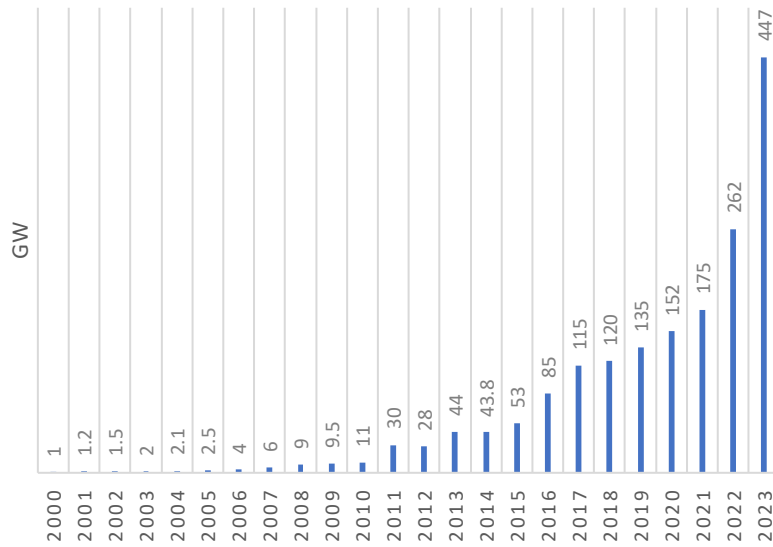


Figure 3: New installed PV capacity in Europe per year, reproduced from [5].

The incremental trend in newly installed capacity was observed over each of the last four years as a direct consequence of COVID-19 lockdowns. Due to the coronavirus crisis and the associated disruptions to supply and trade chains, market prices rose significantly in 2021 due to production unavailability. To mitigate this temporary phenomenon, an increase in production capacity was initiated, leading to a substantial overcapacity that doubled supply relative to demand. As a result, thanks to demand-side elasticity, prices dropped, making this technology far more attractive for both stand-alone consumers and utility-scale applications. Since then, technological advancements and public subsidies in manufacturing countries have further driven prices down, establishing it as the most cost-effective technology in the renewable power market.[5]

1.1. Silicon photovoltaics: a broad and perspective analysis of a market dominant technology

1.1.1. The reasons behind silicon domain in solar market

The photovoltaic sector is undergoing continuous advancements, with silicon wafer-based PV standing as the leader of the market with more than 97 % of total global production. Among its different variations, mono-crystalline silicon (mono-Si) technology has become the mainly exploited one, gradually replacing multi-crystalline configuration.

The dominance of this technology over other PV technologies is based on its techno-economic profile: comparing mono-Si to other configuration, it offers the best trade-off in terms of efficiency and cost. On the technical side, with their 27.3 % power conversion efficiency (PCE) and 25-years warranty, mono-Si modules are the most efficient and resilient single-junction configuration on the market, ensuring high energy conversion performance for many years. This also positively affects the economic aspects, resulting in a levelized cost of electricity (LCOE, a figure of merit that accounts for the total lifetime cost linked to the production of one kWh of electricity from a given technology) ranging between 3.1 and 5.7 ct€/kWh.

The low LCOE for mono-Si was also positively affected by the reduction of manufacturing costs, triggered by the reduction of material usage per Wp (from around 16 g/Wp (in 2004) to about 2.2 g/Wp in 2023) and well displayed by the experience or learning curve concept, whereby grown up and mature technologies decrease in price because of innovations regarding manufacturing and because of economies of scale [5].

1.1.2. Main concerns and limitations of silicon devices

Despite the superior techno-economic profile and maturity of silicon wafer-based photovoltaic (PV) technology, this study critically examines the potential for alternative technologies to emerge in the photovoltaic sector. Consequently, the possible factors that could lead to the decline of mono-Si's dominance in this field will be thoroughly evaluated.

- This technology has a maximum theoretical efficiency of nearly 32% known as Shockley-Queisser limit, which represents the highest efficiency value that could be ideally achieved given the physical constraints imposed by the absorption spectrum of silicon. By developing the technology to its full potential, the practical limit will be reached soon, a value even lower than the theoretical one due to technological constraints such as recombination, optical and electrical losses. This warns us about the possibility that, with the 27.3% efficiency reached by modern modules, this technology could be approaching its threshold, possibly resulting in a LCOE stagnation in the near future. [6]
- The energy embedded in the high temperature manufacturing of silicon wafer negatively affects the Energy Pay Back Time (EPBT) of this technology, increasing its relative environmental impact in terms of greenhouse gas emissions. New Technologies developed with lower temperature manufacturing methods could decrease this burden, reducing the EPBT and possibly, if good stability and long lifetime are achieved, also increasing the Energy Return On Investment (EROI) for novel solutions. [7]
- Given the ongoing trade conflict between the USA and China, the European Union must adopt a decisive stance within this dichotomy, which could influence trade rates for a wide range of products from either of the two powers. This may undermine the price competitiveness of silicon panels, which are predominantly manufactured in China. The prevailing Chinese dominance in the photovoltaic market, as in numerous other sectors, could spur the emergence of new technologies with local supply chains, facilitating their development and positioning them to take a leading role.
- The end-of-life management of silicon modules raises concerns about the sustainability of this technology. Given the low amount of expensive materials and the high costs of remanufacturing and recycling, the only economically viable solution for this stage of mono-Si life is landfill storage. To make matters worse, recycling has been

found to have an even greater environmental impact than landfill disposal itself, due to the high energy and solvent requirements. As a result, neither manufacturers nor users are willing to bear the burden of end-of-life management, leading to a waste of the material and energy invested in this technology which will eventually result in 60 to 70 million tons of waste from solar power production expected by 2050. Regulatory measures are crucial to avoid significant environmental and economic damage; injecting capital in the form of subsidies or fees to address the economic imbalance and promoting innovation in recycling and reuse are essential. [5],[8]

1.2. Perovskite photovoltaics: brief introduction of a concrete alternative for a sustainable future.

After the failure of many second and third generation technologies to take the lead, perovskite are nowadays the only viable technology to partially substitute silicon obtaining a relevant share of photovoltaics market. Since their first application in 2009, many steps have been done up to today, and progressively more and more firms are focusing their energy to take a seat in this new, fascinating sector.

1.2.1. The reasons behind the increasing interest in a future record-breaking technology

With mono-Si PV approaching its practical limit, interest in new materials for photovoltaic technologies has risen in recent years. Among these new solutions, perovskite solar cells (PSCs) have shown promising developments, achieving, in less than 20 years, efficiencies comparable to those of silicon. [9]

Given their different charge carrier dynamics and wider absorption spectrum, PSCs are expected to outperform silicon by surpassing it in PCE. Their tuneable bandgap makes them a viable solution for various applications, depending on the spectrum of the light source, ranging from the Internet of Things (IoT) to utility-scale power production. The possibility of manufacturing flexible modules using roll-to-roll production methods makes them a compact solution for building-integrated and vehicle-integrated power generation. [10]

On the production side, the lower temperatures and energy intensity of manufacturing methods result in an Energy Payback Time (EPBT) ranging

from 3 to 6 months, which is one-fourth to one-half that of mono-Si. The low energy consumption during this stage of the technology's lifetime positively affects both manufacturing costs and environmental impact. Additionally, the wide range of material choices in terms of cost leads to a raw material cost per unit area lower than that of mono-Si, further improving the Levelized Cost of Electricity (LCOE).

On the use side, the lower reflectance of the materials used in perovskite solar modules (PSMs) at higher incidence angles (0.08 compared to 0.2 for mono-Si) increases the devices' performance ratio, enhancing the overall performance of the module and positively affecting the LCOE. Furthermore, it results in less visual pollution in terms of reflected light, a commonly overlooked but potentially unpleasant phenomenon that can raise concerns among neighbouring users.

Additionally, the supply of materials for this technology may not be affected by the increasing trade rates from China, due to the wide variety of compatible materials, making it a suitable solution for local supply chains and community development.[11]

Finally, the most relevant and impactful enhancement of perovskite solar modules (PSMs) is linked to their end-of-life (EOL) management. Given the low value added by the active layers' materials to the overall value of the device, the recycling and reuse of long-lifetime components, such as cover glass and transparent conductive oxide, is not only environmentally recommended but also economically advantageous. This distinction regarding the convenience of responsible end-of-life procedures for perovskites, compared to silicon, may, along with the low LCOE, be the key to making this new technology dominant in the market in the near future, thereby avoiding millions of tons of highly valuable, highly impactful electronic waste.

1.2.2. Main concerns and possible drawbacks at current state of the art

Despite the many reasons for perovskite to overcome silicon as the future leader of silicon market, many issues are still to be addressed to make it a competitive technology.

- The main concerns are related to the stability of the devices. Like all other PV technologies, perovskite cells suffer from degradation mechanisms that lead to efficiency losses. The most significant factors include high-temperature operation, light exposure, ion migration,

electric field interactions, and reactions of the active layers with oxygen, air, and moisture. While effective encapsulation can act as a barrier to prevent interaction with the external environment, the other degradation mechanisms can only be mitigated by researching materials with improved stability, integrating passivants to reduce these effects, and enhancing the deposition of active layers to minimize degradation-triggering defects. Defining T80 as the time required for a cell to reach 80% of its initial efficiency, commonly used as the useful lifetime of photovoltaic technology, the average value for perovskite modules is around three months. Compared to the 25-year warranty of mono-Si panels, this highlights how far perovskite technology is from achieving competitiveness. [12],[13]

- This technology suffers from scaling up losses much more than others, losing up to 40% of its efficiency increasing the size from cell to module dimensions.[14],[15]
- Most configurations use lead-based active materials, a toxic substance that could raise concerns about human and environmental toxicity if released into the environment. Nevertheless, numerous studies have shown that lead leakage under normal operating conditions does not exceed threshold values that would harm the ecosystem.[16]
- Manufacturing methods designed to achieve high-performance devices may involve excessively high embedded energy and the extensive use of toxic solvents or substances with a significant environmental impact. This leads to an increase in EPBT and a deterioration of the overall environmental profile of the technology. Furthermore, these methods may be too complex for large-scale industrial implementation, significantly increasing the complexity of production lines and the manufacturing costs of the devices. Simple, linear, and cost-effective manufacturing methods are essential, ensuring high process repeatability and maintaining the quality of the manufactured products.[17],[18].

2 Model description and fundamental assumptions

2.1. The procedure: TEA and LCIA introduction

In this thesis, a combined techno-economic analysis (TEA) and life cycle analysis (LCA) of perovskite photovoltaic technology is performed.

Expanding on these concepts, TEA is a standard methodology used to evaluate the technical strengths and limitations that influence the economic viability of both emerging and market-ready technologies. By conducting a comprehensive yet precise comparison of the costs related to various PSM configurations, manufacturing processes, and end-of-life strategies, it is possible to determine the most economically competitive and market-ready option.

On the other hand, LCA provides a comprehensive and thorough assessment of the environmental burden associated with the target technology followed by a critical interpretation of results. By identifying the many interactions, a product has throughout its lifetime and considering the relative impact of each, various indicators are first generated and then critically evaluated to derive well-founded conclusions regarding impacts on human health, ecosystems, and resource availability. This approach helps uncover aspects of technological sustainability that might otherwise remain hidden or underestimated.

By combining these methodologies, a critical evaluation of the viability and overall sustainability of PSM will be conducted, resulting in an essential assessment of the economic and environmental implications of PSM entering and potentially sharing the PV market with silicon.

2.2. Goal and scope definition

The first step in building a grounded and robust assessment model is to define its functional unit: a quantified reference unit that describes the final function of the analysed system in terms of the service it provides and that is essential for final comparison of results across different studies.

Accordingly, the chosen functional unit is 1 kWh of.[19] The size of the perovskite solar panel considered is 800 cm² of effective area.

This choice provides easy quantification and exhaustiveness for comparative analysis, ensuring system dependent results and covering at the same time the function of the system itself considering also efficiency and stability. Various alternatives were considered, such as 1 m² or 1 kW of power from a market-ready module, but as suitable as these choices maybe, they lack exhaustiveness about the efficiency and stability of the module in the final application.

Once the functional unit is decided, the goal and scope of the analysis must be clarified.

The goal of this work is to evaluate the economic performance and lifecycle impact related to the production of 1 kWh of electricity from perovskite modules, manufactured using scalable methods, incorporating reliable long-term encapsulants, and considering responsible end-of-life (EOL) procedures. The time boundaries are defined by technology's lifetime, while the spatial ones are represented by an area that includes both the manufacturing plant, the usage application spot and the end of life related plant. A sustainability-oriented approach is adopted to identify the optimal configuration among several alternatives, excluding from the analysis those that have been extensively studied in previous works, showing shortcomings in terms of environmental awareness, economic competitiveness, or market viability.

To better understand this approach, a brief discussion about sustainability is essential. The term "sustainable" is often misused to describe low-impact and eco-friendly technologies, but this is insufficient when discussing power generation devices. In this context, a sustainable technology must demonstrate clear and established improvements over state-of-the-art systems, ensuring positive environmental impact and economic profitability when compared to existing solutions. Environmentally friendly devices cannot be considered sustainable if they lack efficiency, stability, or economic competitiveness, but rather they must guarantee high performances over long periods for a suitable cost. To adequately address this issue, the correct functional unit and appropriate figures of merit have been selected for the upcoming analysis, ensuring meaningful and self-explanatory results.

2.3. Model development fundamental hypothesis

Perovskite photovoltaics, like many emerging research fields, is characterized by a fragmented landscape. While a few core concepts have been firmly established, numerous debatable ideas and alternative approaches contribute to the uncertainty in the field. In the early stages of model development, it is essential to clearly articulate the principles guiding the decisions made to address these uncertainties.

Sustainability serves as the primary driving concept of this work—it is the cornerstone for critically evaluating power production systems from both economic and environmental perspectives. From this foundation, several fundamental principles emerge, including the reduction of energy consumption during device manufacturing, the selection of low-toxicity and low-impact materials and solvents, and the implementation of scalable, straightforward, and efficient deposition methods that avoid unnecessary complexity.

The following sections detail the assumptions made during the model development process.

2.3.1. Device's layout, the planar n-i-p single junction configuration

Despite the economic and environmental scope of this study, a quick presentation of the different configurations is conducted without exploring too much in details. For the chosen configuration, the different layers composing the device and their distinct functions are presented in the next section. [20]

- Regular n-i-p junction is the most common, largely studied configuration for perovskite cells, which shows higher efficiency and easier deposition methods when compared to the others. It is composed by a transparent conductive oxide (TCO) with subsequently deposited electron transport layer (ETL) perovskite layer (PL) and hole transport layer (HTL), and with a metal back electrode and a cover glass to complete the device. Despite the better performances in terms of efficiency, this configuration shows negative behaviours in terms of stability in the long term and hysteresis of the I-V curve.
- Mesoporous planar perovskite cells show enhanced performances in term of stability, with a negative trade off on the efficiency side. Additionally, replacing the ETL with dense and mesoporous TiO_2 , a material that needs high annealing temperature after the deposition,

the energy embedded increases, worsening the energy payback time for this configuration.

- Inverted p-i-n junction is a less common but recently highly investigated configuration characterised by a lower efficiency with respect to regular one, showing on the other hand improved behaviour in terms of stability and hysteresis. Regarding the structure, this configuration adopts the same functional layers as the regular one, but the position of ETL and HTL is inverted.

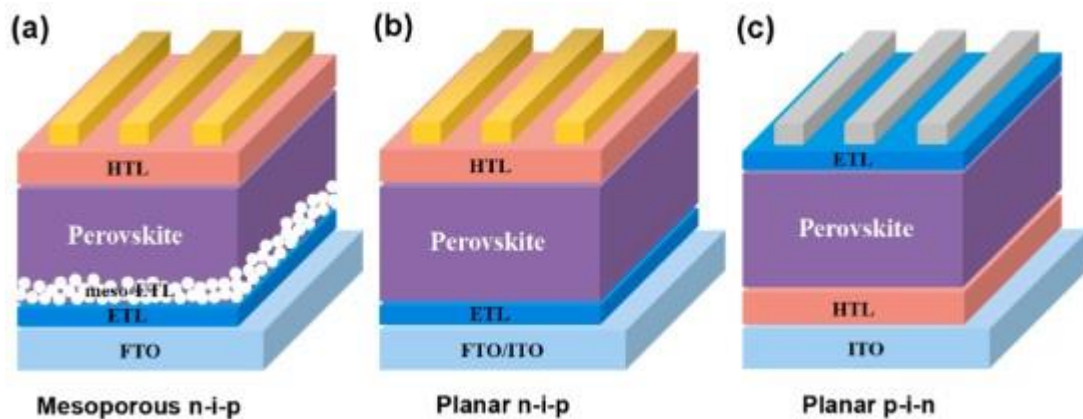


Figure 4: Schematic representation of (a) mesoporous n-i-p , (b) planar n-i-p and (c) planar p-i-n configurations, from [21]

Far more could be said about the pros and cons of each different configuration, but it would exceed the scope of this thesis. For this work's purposes, the choice of the configuration falls on the regular one, given the higher amount of data available upon this theme.

2.3.2. Deposition methods, the choice of slot die coating due to its scalability, reproducibility and cost effectivity

Many different methods are used to perform active layer deposition, and each of them offers different pros and cons. The standard techniques can be divided in two macro categories: the solution based, which offer good homogeneity and reproducibility of the results by the means of simple, easily scalable and cost cost-effective methods and machineries, and the vapour based ones, that guarantee enhanced homogeneity and quality of deposition, but losing elasticity in scaling up and bringing complexity and cost increment into the process. For these many reasons and considering the trade-off between costs, complexity, scalability and homogeneity, solution-based deposition methods are chosen in this model.

Among the various solution-based methods, screen printing for the back electrode and slot die coating for the other layers are chosen. Slot die coating, in particular, is chosen at the expenses of blade coating, dip coating and spray coating (spin coating is neglected as unscalable) because of its improved reproducibility and overall quality of the deposition. [22]

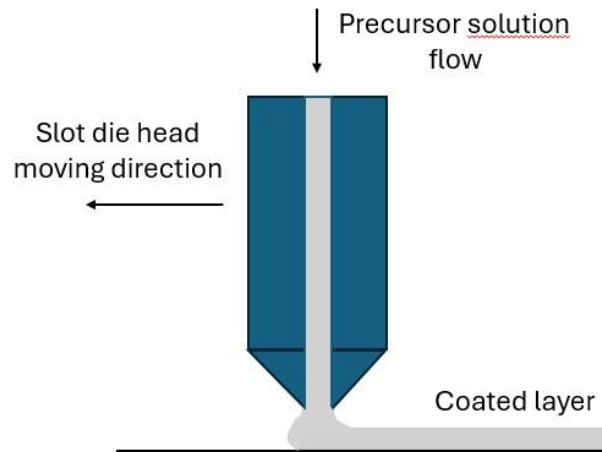


Figure 5: Slot die coating basic schematic representation.

In a conventional slot-die coating process, the coating head is positioned close to the substrate, while the ink is delivered using a syringe pump. The ink is then dispensed through a narrow slit along the length of the coating head, forming a uniform layer on the substrate. The thickness of deposited perovskite layer is determined by many different parameters, like the gap between the coating head and the substrate, the ink flow rate, and the substrate's moving speed. Additionally, surface tension, viscosity, and the ink's wettability properties play a crucial role in ensuring a defect-free coating.

2.3.3. Materials used for the manufacturing of PSM respecting sustainability

2.3.3.1. Transparent conductive oxide (TCO)

Transparent conductive oxide (TCO) is a key component of perovskite solar modules, ensuring the high transparency and conductivity required for the upper sheet to allow photons and electrons to flow. Concerning perovskite field, the most used TCOs are indium tin oxide (ITO), fluorine-doped tin oxide (FTO) and aluminium-doped zinc oxide (AZO). Due to the early stage of AZO's development in this field, an *ex-ante* qualitative analysis was performed

to discard this option and select the best alternative among the remaining ones.

In its current state, ITO represents the most efficient and homogeneous option for TCO, but on the other hand shows high cost and lacks sustainability: indium, in fact, is one of those critical raw materials whose availability is stressed for supplying modern markets such as drones, robotics and semiconductors. [23]

Consequently, in accordance with the previously mentioned sustainability-focused mindset, the material chosen as transparent conductive oxide in this context was FTO, despite its slightly lower efficiency due to reduced electrical conductivity, counterbalanced by better stability and lower cost. [24]

2.3.3.2. Electron transport layer (ETL), perovskite layer (PL) and hole transport layer (HTL)

Electron transport layer (ETL), perovskite layer (PL) and hole transport layer (HTL) are the fundamental active components guaranteeing the generation of voltage difference that combined with charge mobilization results in a positive power output.

While in the bulk of halide PL the photoelectric process itself is carried out, absorbing the energy of suitable wave-length photons to generate photo-excited electrons into the conduction band and a positive charge called hole into the valence band, the ETL and HTL are responsible for the extraction and mobilization of those charges. Their compatibility in terms of bandgap with the PL is the key for obtaining a functional device, while the chemical stability of common boundaries is the key for avoiding degradation processes at the interface between the many layers, resulting in long-term stability.

Many different strategies are suitable for enhancing these materials' positive behaviours, like surface passivation, composition engineering and additives insertion, making the future development of PSM realistic and foreseeable. Furthermore, a vast array of materials is suitable for these applications, but only a few effectively meet the technical standards required for market entry. In this context, the following materials are selected for the analysis, considering also their compatibility with slot-die coating.

- As ETL, a compact layer of TiO_2 combined with SnO_2 . This is a widely used and common option for this layer, providing good efficiency in the n-i-p junction configuration. Issues with TiO_2 must be underlined

considering its poor light stability, challenges related to titanium supply, high annealing temperature, and the need for different deposition methods, such as spray coating. Other suitable alternatives could include ZrO_2 [16], which was discarded due to its high economic burden, equally to other materials whose thermal evaporation method does not meet the required standards for simple, scalable, and low-energy consumption deposition methods.

- As PL, $\text{Cs}_{0.05}\text{FA}_{0.79}\text{MA}_{0.16}\text{Pb}(\text{Br}_{0.16}\text{I}_{0.84})_3$, a triple cation halide perovskite, is chosen. [25, 26] The typical composition of perovskite follows the formula ABX_3 , where the cation A is often methylamine (MA^+), which offers high efficiencies but low stability at high temperatures, formamidinium (FA^+), a highly stable but less efficient molecule, or alkali metal ions such as cesium (Cs^+), or rubidium (Rb^+). The cation B can be either lead (Pb^{2+}) or tin (Sn^{2+}), while the anions X_3 are halogen ions such as chlorine (Cl), bromine (Br), or iodine (I). The adoption of a triple A cation molecule ($\text{Cs}_{0.05}\text{FA}_{0.79}\text{MA}_{0.16}$) and a double anion ($\text{Br}_{0.16}\text{I}_{0.84}$) enhances the stability of the molecule by strongly bonding the atoms in a complex structure, making it more difficult to transition to a non-perovskite phase or other degradation pathways.

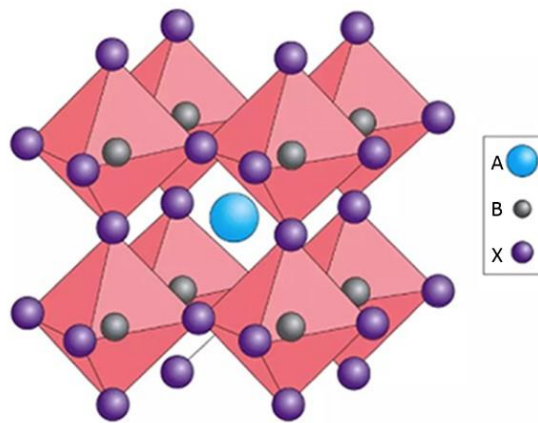


Figure 6: Perovskite crystal composition, from [27].

- Regarding HTL, a comparison between PTAA [28], P3HT [29], and CuSCN [30] is performed. This is typically the most expensive and technologically critical layer, often exhibiting the worst stability and higher complexity in terms of synthesis. For these reasons, comparative results of three different molecules, each with distinct strengths and weaknesses, are provided to determine which one could potentially

perform better in a sustainable environment, considering the ongoing debate about organic and inorganic materials.[31]

Considering slot-die coating solution-based deposition methods, further consideration is necessary regarding the solvents used in the coating process. The most commonly used solvents are dimethyl formamide (DMF) and dimethyl sulfoxide (DMSO), which ensure improved deposition homogeneity and overall quality. Similar solvents play a significant role in this analysis due to their high usage ratio per square meter of module, their complex synthesis, and their considerable environmental impact. For these reasons, green solvents are regarded as one of the key factors for reducing the environmental footprint of this technology.

The green solvents considered in the analysis are acetonitrile and ethanol. While acetonitrile cannot be classified as entirely eco-friendly, it presents a lower environmental impact compared to conventional alternatives and has demonstrated good compatibility with perovskites in previous studies [32]. Ethanol, by contrast, has not yet been fully validated for this process and still poses challenges in terms of the efficiency of the resulting devices. Nevertheless, it represents the most environmentally favourable scenario within the scope of this analysis, serving as the best-case scenario.

2.3.3.3. Back electrode

Screen-printed carbon was chosen as the back electrode material screen printing.[33]. Given the current collector function performed by this layer, high electrical conductivity is required, making metals the primary candidates. Gold, silver and carbon are widely adopted metals in the perovskite sector; however, due to silver's incompatibility with the n-i-p junction configuration and the well-documented economic and environmental drawbacks of gold, carbon emerges as the best option for future development. Nevertheless, carbon itself exhibits poor technical suitability in this field. Due to its lower conductivity, thin deposited layers are required to achieve low resistance, but the currently adopted deposition methods and carbon structures are not yet capable of delivering such high performance. For the scope of this work, the development of a screen-printing method for a thin carbon layer to meet technical standards for cell operation is assumed, as this remains one of the main concern of researchers aiming to obtain a sustainable configuration.

2.3.4. Encapsulation and balance of module

To effectively safeguard the integrity of the active layers and prevent direct interaction with the ambient atmosphere, an adequate encapsulation method is required. The reaction of the perovskite layer with oxygen and moisture is the most severe degradation phenomenon affecting active materials, leading to a progressive loss of efficiency that surpasses other sources of instability, such as light exposure and high temperatures. Furthermore, the lead content in perovskite materials raises concerns about potential toxic leakages, which could harm the surrounding environment. Therefore, a resilient sealing solution is essential to prevent such interactions and preserve both the internal stability of the module and the integrity of the external environment.

At this stage, the materials used as encapsulants for perovskite cells and modules are the same as those commonly employed in mono-Si technology, namely thermoplastics. These polymers perform well in silicon-based modules; however, their non-negligible oxygen and moisture transmission rate—directly proportional to the gas mass flow through the polymer—may be insufficient for reliable long-term sealing. Unfortunately, given the early stage of perovskite development, a definitive answer to this concern cannot yet be provided due to the lack of multi-year testing under real operating conditions. Consequently, an alternative sealing method, namely laser-assisted glass frit encapsulation, is comparatively evaluated in this context.

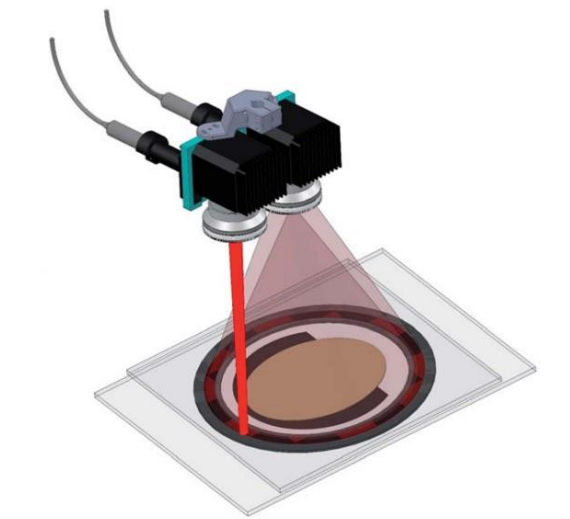


Figure 7: Laser assisted glass frit encapsulation machinery for lab scale, to be scaled up to fit an industrial environment

Glass frit is a compound of low-melting-point glass particles, ensuring enhanced hermeticity and zero transmission rate for long-term applications. The sintering of this material, performed using an external medium-power laser source, creates a strong bond between the FTO glass and the cover glass, creating a hermetic sealing with improved stability and resilience. On the other hand, considering that the higher cost of both the material and the sealing equipment could offset long-term benefits, a more comprehensive analysis must be conducted to evaluate the overall sustainability and profitability of this method. [34] [35]

Additionally, balance-of-module components, such as electrical wires and the junction box, are considered in the model to ensure a realistic evaluation of the devices.

2.3.5. End of life

End of life (EOL) procedures could be the key for perovskite to surpass intense waste generating mono-Si as the market leader. In a highly polluting world, where many production activities result in tons of waste being sent to landfills or incinerated, the three Rs of sustainability and circularity- reduce, reuse, recycle- are essential for the long-term survival of ecosystems.

The order of these principles is not random, as it reflects their varying importance in terms of environmental benefits. In this context, the reducing route is not feasible, as the amount of material used for each layer is strictly tied to device optimization. Re-use, instead, is possible. However, reuse is a viable option. A thorough literature review has led to the identification of a scalable and flexible procedure for recovering many high-impact and costly components—particularly cover glass, FTO glass, and the TiO₂ layer—allowing them to be reused in the production of second-life modules with an efficiency approaching 90 % of new ones. [36]

A comprehensive analysis will be conducted to compare the overall environmental and economic benefits of responsible EOL procedures versus landfill storage and incineration.

3 Life cycle analysis (LCA) and technoeconomic analysis (TEA) model development

Deeping into the evaluation, the life cycle impact and techno economic models are developed on the hypothesis and *ex ante* considerations already provided.

After the goal and scope definition, Life Cycle Analysis (LCA) includes three more steps: Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and an ongoing interpretation of data and results provided by the subsequent step of the analysis

3.1. Life Cycle Inventory (LCI), definition of the system and cut-off model description

During the LCI step, all interactions between the system's components and both external and internal entities are analysed, resulting in a list of heterogeneous flows allocated to different products. The model's boundaries and components are represented in Figure 9.

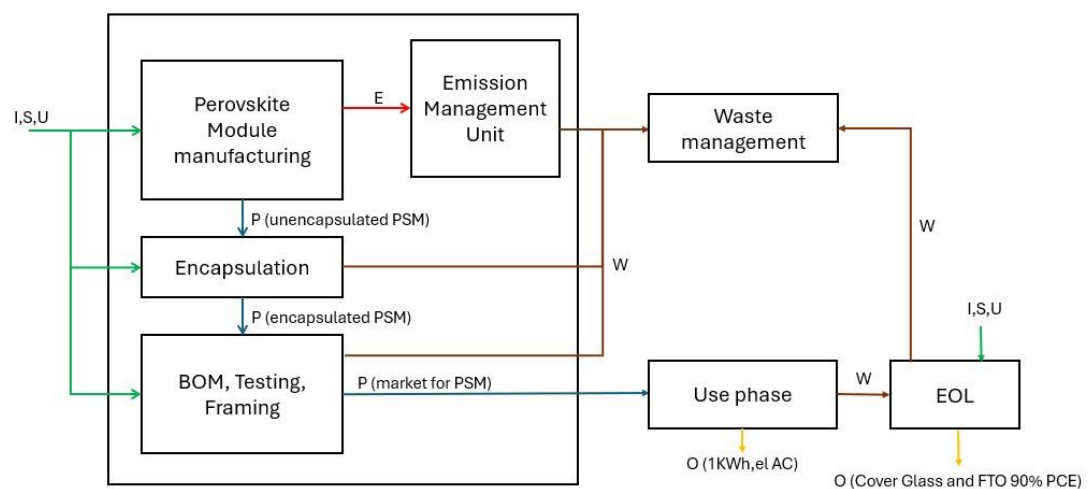


Figure 8: Product system analyzed by LCA

Compared to many literature reviews and specific studies focusing solely on module manufacturing, incorporating the use phase and end-of-life processes into the inventory yields more comprehensive results for this technology. This approach also accounts for module stability issues, mounting and balance-of-plant components, and waste management at the end of its lifecycle. [37],[38],[39].

The rules defining how to assess each flow's contribution to the final output's impact are established by the System Model (SM). Various models exist, each with different assumptions and accounting rules for evaluating the relative impact of each flow. In this context, the cut-off SM was chosen.

The main differences among system models concern the impact allocation of recyclable products and waste. Regarding the cut-off model, the impact of a good's primary production is allocated to its primary consumption. Secondary production (recycling) does not bear the burden of primary one but only that of the recycling process itself.

The decision to recycle does not influence the primary consumption. This system is particularly well-suited for studies on recycling and product re-use, as it assigns waste responsibility to the producer under the "polluter pays" principle. Additionally, recyclable products are considered burden-free (cut-off), incentivizing responsible recycling and re-use models.

The different flows considered, along with their respective units and balance signs, are shown in the table in the Appendix [A.1]. While many additional flows could be included, the level of detail provided in this analysis is deemed sufficient given its scope.

A detailed life cycle inventory for each phase of the manufacturing process—including chemical production, encapsulation, module balance, system balance, and solvent waste incineration—along with hypotheses regarding emissions and data sources, is clearly outlined in the Appendix [A.1].

Data collection was conducted through literature review, direct contact with manufacturers, and personal experience with laser-assisted glass frit sealing in the UPorto laboratories.

3.2. Life Cycle Impact Assessment (LCIA), impact categories and emissions accounting

During the LCIA step, the inward-streaming impacts are evaluated by multiplying the relative impact of each unit flow by its magnitude. These impacts are then allocated to the outward-streaming reference products using different allocation logics

3.2.1. Impact categories and Energy Pay Back Time (EPBT)

After an accurate literature review about this topic, little concerns about the legibility and interpretability of results were underlined. Many studies have highlighted a widespread difficulty in selecting an adequate number of impact categories from the vast array available. This challenge arises from the need to represent the analysis results in detail while avoiding the inclusion of measurements that may be superfluous. As a result, truly significant and relevant data, from which useful conclusions about the sustainability of the subject under analysis could be drawn, often end up being diluted.

To avoid this weakening of results, a smaller group of impact categories is chosen, mainly focusing on ecosystem damage, human health risks and global warming potential, supply risks for materials with a specific focus on critical raw materials, and overall energy intensity in the PSM lifecycle.

- Ecotoxicity: To obtain an accurate assessment of how a chemical substance released into a freshwater ecosystem can damage biodiversity, alter ecological functions, and compromise the health of organisms, freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP), and terrestrial ecotoxicity potential (TETP) are considered in this analysis. The values are calculated in kilograms of 1,4-dichlorobenzene-equivalent (1,4-DCB-eq.), a reference substance used to compare ecotoxicological damage. These impact categories are essential for critically evaluating the different end-of-life (EOL) procedures studied, as they allow for a comparison of ecological damage caused by the long-term release of PSM (Perovskite Solar Module) internal substances into landfills versus a remanufacturing scenario. In the remanufacturing case, the scenario is considered at the end of the second lifecycle, but the impact associated with landfill leakage of active layer materials and the additional use of solvents,

materials, and utilities is counterbalanced by a higher production output, which helps dilute the burden.

- **Human toxicity:** to gain a clear understanding of how prolonged exposure to a substance may cause irreversible damage to human health—both in terms of potential cancer development and overall physical and mental well-being—carcinogenic human toxicity potential (HTPc) and non-carcinogenic human toxicity potential (HTPnc) are considered. The analysis of these values highlights the importance of proper encapsulation to prevent hazardous leakage during the use phase, particularly near human environments. It also reinforces the positive impact of the remanufacturing option. Similar to Ecotoxicity, these values are measured in kilograms of 1,4-dichlorobenzene-equivalent (1,4-DCB-eq.).

- **Global warming:** to quantify the climatic impact associated with the lifecycle of the analyzed technology, the Global Warming Potential (GWP100) is selected as the most explanatory index. GWP100 evaluates the climatic effect of greenhouse gas emissions over a 100-year period, accounting for each gas's potential to absorb infrared radiation and its residence time in the atmosphere. The results are expressed relative to the impact of one kilogram of carbon dioxide (kg CO₂-Eq). This measure is crucial for understanding the climatic burden associated with the manufacturing and waste management processes, as these stages are typically the highest contributors to pollution during the PSM lifecycle.

- **Energy imbedded:** To evaluate the amount of primary energy required to obtain the desired functional unit, the Cumulative Energy Demand (CED) is considered. This is a measure of the total amount of primary energy needed, step by step, to achieve the final result, and considers energy in its various forms, such as electricity demand and fossil fuel consumption. This index, measured in equivalent Mega-joules (MJ-eq), is essential for evaluating the Energy Payback Time (EPBT) of PSM, a widely adopted figure of merit for power generation systems, that shows the time require for technology to produce the same amount of energy as the one consumed in the many steps of technology's manufacturing, lifetime and, in this context, end of life. It is obtained by dividing the total embedded energy in the technology as already

described by the power output of the device. In this analysis, the following equation was used considering 1 m² of module.

$$EPBT = \frac{CED \times \varepsilon}{I \times PCE \times PR \times CF}$$

where CED is the cumulative primary energy demand (MJ/m²), ε is a standard electrical to primary energy conversion factor equal to 0.35, PR is Performance Ratio of the module, PCE is solar module efficiency, I is insolation constant and CF is a conversion factor for MJ to kWh. [40]

A further key piece for sustainability, namely critical raw materials (CRMs) depletion, is not assessed by the LCA but regulated from the very beginning in the assumptions of the model. Materials with high CRMs consumption are excluded from the analysis.

The data gathering was performed using Eco-invent database as main source, but literature articles were highly used to obtain the inventory and impact related to unlisted complex chemicals. A deeper explanation of assumptions and individual impact is displayed into the appendix. [A.1]

3.2.2. Impact balances and allocations logics.

To better understand the logic behind impact allocation on products, the following impact balance equation is presented. It illustrates how the total impact associated with the various fluxes involved in the production of a given output is determined by summing the contributions of each process to obtain the final result.

$$\sum_{i=1}^{N_{input}} X_i \times \tilde{I}_i = \sum_{j=1}^{N_{output}} Y_j \times X_j \times \tilde{I}_j \quad (2)$$

Where the total impact is determined by summing the contributions of each i -th input, calculated as the specific impact (\tilde{I}_i) multiplied by the corresponding input quantity (X_i), each expressed in its respective unit of measurement. This sum equals the total impact of the outputs.

To properly allocate the impact among different outputs, the coefficient Y_j is introduced. This weighting factor distributes the impact of a production

activity among its various outputs. Depending on the nature of the process, three different assumptions about the outputs of processes distinguished:

- Single product, with the entirety of the impact allocated on a single useful output.
- Multi-product, when a process generates multiple useful outputs which can be further exploited and used inside or outside the system sharing the impact burden.
- By-product, when a process generates a primary useful output along with additional by-products that neither contribute to the system's functionality nor hold significant value but are inevitably produced. Usually if this is the case, only the useful product covers the impact of entire production, while the others are discarded or available burden-free.

When multiple products are generated, impact allocation can be performed either on an economic basis, where Y_j is related to the price per unit of the j-th product compared to the sum of all product unit prices, or on a mass basis, where allocation is determined by the relative magnitude of each output. The specific assumptions applied in each allocation process are detailed in the appendix. [A.1]

Once the nature of weighing coefficients is stated and unitarian impacts are gathered, the impact of one unit of j-th product can be obtained as it follows:

$$\tilde{I}_{goal} = \sum_{i=1}^{N_{input}} \frac{X_i \times \tilde{I}_i}{Y_i \times X_i} - \sum_{j=1}^{N_{output}-1} Y_j \times X_j \times \tilde{I}_j \quad (3)$$

Figure 10 shows the flows analysed in this phase and how are they accounted both in mass balances and in impact balances.

Wastes and services appear as positive contributions in the impact balance, increasing the overall impact of the output. As previously stated, wastes, including recyclable ones, are allocated to primary products as part of waste management services, primarily incineration. Given the energy-intensive and highly polluting nature of this process, its impact is far from negligible and significantly raises the relative impact of the output.

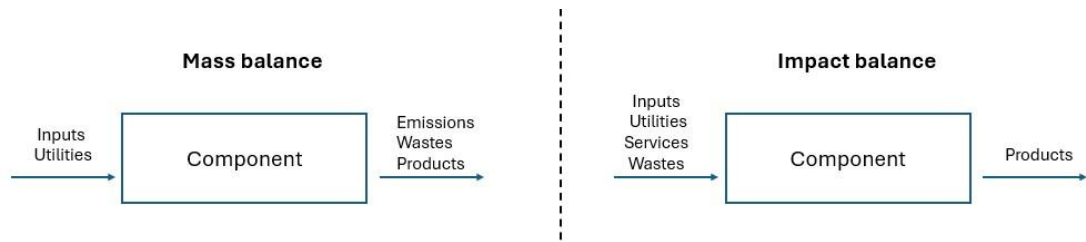


Figure 9: Flows analyses in mass and impact balances

Concerning emissions, their relative contribution to the overall impact is accounted for in the same way as waste, assuming proper confinement of manufacturing processes within atmosphere-controlled boxes equipped with emissions and pollution control units. This is a fundamental assumption in this model, necessary both from a technological perspective – since exposure to ambient air during deposition leads to severe efficiency losses in the device – and from an environmental perspective, given the harmful impact of toxic solvent releases. As a result, enclosing highly automated processes in controlled environments is considered a suitable and reasonable solution.

Depending on the toxicity of the materials used in each specific step, emissions contributing to the environmental burden are accounted for as hazardous waste management or specific solvent waste management. While this assumption reduces the flexibility and realism of the model, it enables a more straightforward yet accurate assessment of emissions' impact – an aspect often misjudged or neglected. Additionally, this consideration will be reflected in the economic analysis by incorporating increased equipment costs to account for controlled environments and emission management units.

3.2.3. Results comparison

Given the heterogeneity in terms of units of measurement and orders of magnitude among the various impact categories analysed, an absolute representation proves to be redundant and of limited significance. Considering the ultimate objective of this analysis – namely, a comparison between perovskite and silicon in terms of sustainability – a silicon module-based normalization of the results is frequently employed in the literature to enhance representability and comparability.

The "Normalized Impact" (NI) factor is obtained by dividing the impact value of perovskite by the corresponding value for silicon in each of the six evaluated categories. This factor indicates the relative impact of the analysed module within a specific category, showing whether it is greater ($NI > 1$) or lower ($NI < 1$) than that of standard mono-Si technology.

$$NI_i = \frac{I_{i,kWh_{el} \text{ from perovskite}}}{I_{i,kWh_{el} \text{ from mono-si}}} \quad (4)$$

To evaluate the overall sustainability of these technologies in relation to the market-dominant one, the average of the NI values can serve as a useful indicator. A lower average suggests a general environmental advantage for the analyzed devices.

3.3. Technoeconomic analysis (TEA)

The overall techno-economic profile of perovskite solar modules was evaluated through a detailed analysis of each step of their lifetime. The three parameters used to provide a clear picture of the competitiveness of this technology are further discussed.

3.3.1. Manufacturing cost (MC)

The manufacturing cost represents the total cost to be faced to manufacture a square meter of module. [41] [41] To evaluate it, a manufacturing plant model with a production capacity of 100MW with fixed operative conditions but different scale depending on the configuration studied was considered. Each of the many costs associated with materials, solvents, machineries, facilities, employers, plant's operation, transport of goods, waste management and many other cost items were listed. To have a better conceptual display of this concept, reference may be made to the following equation.

$$MC \left[\frac{USD}{m^2} \right] = \left(\sum_{i=1}^{Nstep} M_i + U_i + L_i + EM_i + MD_i \right) + FD \quad (5)$$

$$MC \left[\frac{USD}{W} \right] = \frac{A_{module}}{P_{module,DC}} * MC \left[\frac{USD}{m^2} \right] \quad (6)$$

Delving into the meaning of each cost item, M_i represents the cost of materials used in the i -th step of the manufacturing process, while U_i and L_i respectively account for utilities (water and electricity) and labor involved in each step.

The values for these three cost items are either obtained with a bottom-up approach, with data from lab scale cell manufacturing of perovskite cells and mini-modules scaled up to requested capacities and dimensions, or with a top-down approach, with values obtained from previous studies about industry scale manufacturing of perovskite module.

Furthermore, EM_i represents the cost of equipment maintenance, which, in line with similar studies on this subject, is assumed to be 20% of MD_i . Here, MD_i represents the share of the total cost of the i -th machinery to be allocated to the production unit flowing a linear depreciation logic. In this method, useful for allocating the cost of equipment across its output, the cost of each machine is initially distributed over its expected operational lifespan and subsequently allocated on annual production volumes. Costs are obtained from literature and direct contact with manufacturers. [42] [43]

At this stage, the differentiation among analysed configurations becomes evident. While the material cost per square meter of module doesn't depend on device performances, efficiency plays a pivotal role when costs are related to power. Modules of identical dimensions but differing efficiencies show a different watt power production per square meter, affecting the total manufactured module area to meet the annual production target of 100 MW. Consequently, higher-efficiency modules need lower manufactured area to meet the target capacity either resulting in higher amount or in bigger machineries needed, increasing plant's depreciation cost.

Furthermore, an important distinction through the different configuration of module studied is given by the maximum machineries' throughput. This parameter is affected by the deposition time needed by different materials, a value that, in this context, is mainly determined by the slot-die head maximum velocity to obtain homogenous layer. Once again, due to the fixed total capacity to be guaranteed, the higher the throughput a machinery can achieve, the lower the amount of machineries needed, the lower the depreciation cost attributed to the module.

Detailed tables with values for each layer, assumptions and sources are displayed in the appendix. [B.1]

In the end, FD accounts for facility depreciation, following the same logic just displayed, but considering building costs and plant operation related costs. As for machineries, also this cost items are module performance dependent, raising further differences among the different configurations considered.

To specifically determine the cost value, a thorough literature review on similar manufacturing plants has been carried out, leading to the majority of costs already being scaled to the required amount. The specific cost of materials and utilities depends on delivered quantities, with price reductions as order sizes increase. The specific price function, together with detailed tables with cost items for each layer, deposition features, assumptions and sources are displayed into the appendix. [B.1]

3.3.2. Minimum Sustainable Price (MSP)

Starting from MC, an additional step can be taken by considering the Minimum Sustainable Price (MSP). This is a widely adopted and stated technoeconomic figure of merit that is mainly useful for comparison with similar studies. and different technologies.

This represents the minimum price to be charged onto a technology to obtain an economic balance between cost of production and revenues from sale, additionally covering an expected profit for investors (WAAC), taxes (tx) and overhead costs (OH), accounting for research and development, administration costs, marketing and advertising costs, and many others cost items that are neglected in the manufacturing cost estimation.

$$MSP = \frac{1}{P_{module,DC}} \times (MC + OH + tx + WAAC) \quad (7)$$

To simplify the final evaluation, the WAAC and OH are assumed to be respectively 14% and 15% of the operating revenue, while taxes are assumed to be 28% of the operating profit. These values are typical for comparable industries in Europe. The final result is usually expressed in $\frac{USD}{W}$, but can easily be converted to $\frac{USD}{m^2}$ by using the module's power output.

A detailed table concerning the assumptions and key parameters for this analysis is available in the appendix [B.2]

3.3.3. Levelized cost of electricity (LCOE)

If MC gives a picture of production cost to be sustained by a firm to produce a good, and MSP displays the threshold selling price for the firm itself to make it profitable, a further figure of merit is required to evaluate the user convenience in adopting the analysed power generation system over others.

From user perspective, the convenience of an investment is not just related to the economic side, but also to the long-term functionality of the technology purchased. Two technologies with comparable purchasing price but with different yearly electricity production and long-term stability will result in different convenience for the buyer.

In this context, the perfect figure of merit for user affordability considerations is the levelized cost of electricity, that is generally defined as the ratio between the cost of a PV system throughout its lifetime to the total energy that that system can generate during the lifespan. It takes into consideration all the operation related costs, like inverter, electric wires and mounting systems, commonly referred as balance of system components, and yearly maintenance needed for cleaning the modules and solving potential technical issues.

$$LCOE = \frac{\sum_{i=0}^N \frac{C_i}{(1+D)^i}}{\sum_{i=0}^N \frac{E_i(1-d)^i}{(1+D)^i}} \quad (8)$$

Both the cost sustained during each year of PV system lifespan and yearly electricity production are actualized to purchasing moment using the discount rate, while the degradation rate accounts for efficiency losses in time.

This parameter considers the many key points for the overall convenience, taking into consideration both the purchasing cost for final user and the functionality of the module into an operative PV system. Given the importance of efficiency and lifetime in this context, a clear explanation of the assumptions considered is mandatory.

A decremental relative approach is used to evaluate the performances of the whole module given each layer's relative performances. For a better display of this context, equation 9 is presented. Overall efficiency is derived starting from a reference value for a partially slot die coated state of the state of the art mini module with similar perovskite absorber [44] equal to 17.62% for a 64 cm² aperture area (PCE_{LAB}). This value was further modified using an efficiency

factor to account for the relative difference in efficiency apported by each modification of initial structure, deposition methods (k_{dep}) and dimension (k_{scale}).

$$PCE_{TOT} = PCE_{LAB} \times k_{scale} \times k_{dep} \times \prod k_{layer,PCE} \quad (9)$$

The same was performed for lifetime and degradation rate. Considering state of the art, a lifetime close to 0.5 years is highlighted when many studies and previous work are compared [12]. Considering a cost increase equal to 5% of the manufacturing cost to include passivation layers, UV filter and other measures to increase the overall stability of the module, a lifetime value of 5 years is considered as reference value for the beginning of the analysis, to be modified translating same method adopted in performances evaluation for the PCE to the degradation rate (d_{TOT}). Technology's lifetime is equal to the T_{80} of the module, the timespan for the device to degrade until 80% of its initial efficiency.

$$d_{MOD} = d_{5years} \times \prod k_{layer,d} \quad (10)$$

This value will be further modified in a sensitivity analysis to understand its critical impact on levelized cost of electricity, while an additional goal function will be used to address the market readiness issue, obtaining the expected lifetime for this technology to be competitive against mono-Si devices.

A detailed table with reference values and relative factors for both efficiency and lifetime is showed in the appendix. [B.3]

4 Results

To provide a clear and meaningful assessment of the cost-effectiveness and sustainability of the studied modules, only the most significant results are presented, rather than a comprehensive analysis. A full representation would overly dilute the discussion, preventing a proper emphasis on the most relevant findings.

Based on the stated assumptions and the described methodology, a total of 36 different configurations result from the combination of the analyzed options (three HTL materials, three solvents for perovskite deposition, two end-of-life procedures, and two encapsulation techniques). Among these, only the most relevant configurations are critically examined, supported by graphs and tables to draw meaningful conclusions.

Following the analysis of the impact of choices related to solvents, encapsulation, and end-of-life on the configurations presented in Chapter 3, a further investigation will be carried out to exclusively assess the techno-economic implications of these choices on a hypothetical module, featuring enhanced technical characteristics and improved market competitiveness.

4.1. Manufacturing cost and impact for each layer and procedure

Tables 1 and 2 show the results of TEA and LCA for each layer and procedures regarding modules' lifecycle.

Starting from the economic analysis, it becomes evident that the most significant components in the manufacturing cost per unit area of a market-ready module are the transparent conductive oxide (FTO), the balance of module (BOM), and the encapsulant. In particular, the high cost of glass, which accounts for more than half of the total module cost, substantially increases the expenses associated with the first two components, underscoring the economic advantage of the remanufacturing process.

Regarding the encapsulant material, a clear distinction can be pointed out between glass frit and its plastic counterpart in terms of cost, that calls for an enhanced stability to balance the expenses in the long term. As for machinery

depreciation, the adoption of highly scalable deposition methods ensures that this expense remains a less significant factor in the overall cost structure.

These considerations will need to be further evaluated from a techno-economic perspective over the entire product lifecycle, shifting the focus from manufacturing cost to the Levelized Cost of Energy (LCOE).

Table 1 Manufacturing cost of modules' layers and procedures

	Materials USD/m ²	Utilities USD/m ²	Labour USD/m ²	Depreciation USD/m ²	Total USD/m ²
FTO	7.45	0.26	0.03	0.02	7.76
FTO 2nd life	1.05	0.35	0.17	0.02	1.57
ETL	0.11	0.17	0.43	0.29	1.00
PL	1.15	0.06	0.31	0.29	1.81
PL,green solvent	1.05	0.06	0.31	0.27	1.69
PTAA	1.95	0.05	0.30	0.19	2.49
CuSCn	0.01	0.06	0.12	0.16	0.35
P3HT	1.14	0.05	0.12	0.19	1.50
Carbon	1.82	0.04	0.03	0.15	2.03
EVA+PIB	3.50	0.14	0.10	0.32	4.06
Glass Frit	8.36	0.24	0.10	0.31	9.00
BOM	4.96	0.59	0.97	0.23	6.75
BOM 2nd life	0.97	0.06	0.97	0.07	2.08
Use phase	1.05	0.35	0.17	0.06	1.63
Incineration	0.00	0.00	0.00	0.00	0.00

The same considerations can also be applied from an environmental impact perspective, where the most significant contributions originate primarily from glass. The limited relevance of absolute values, as shown in the table, underscores the necessity of normalizing them relative to silicon values to enable a meaningful final comparison.

It is also important to note that, in the post-remanufacturing configuration, both the cost and environmental impact of FTO directly reflect the per-square-meter values of the remanufacturing process itself, in accordance with the cut-off logic applied in the analysis.

Table 2 Life cycle impact assessment for modules' layers and procedures

	GWP100 kg CO ₂ -Eq	FETP kg 1,4-DCB-Eq	METP kg 1,4-DCB-Eq	TETP kg 1,4-DCB-Eq	HTPc kg 1,4-DCB-Eq	HTPnc kg 1,4-DCB-Eq
FTO	8.37E+00	3.25E-03	3.26E-03	6.19E+00	8.56E-04	6.49E-02
FTO 2nd life	6.16E+00	2.00E-02	7.55E-03	4.77E+00	9.34E-04	7.01E-02
ETL	8.83E-02	4.68E-05	3.53E-05	4.27E-02	9.32E-06	6.39E-04
PL	1.10E-02	1.53E-05	8.23E-06	1.32E-02	1.57E-06	1.30E-04
PL,green solvent	1.67E-02	1.91E-05	1.14E-05	1.51E-02	2.43E-06	1.90E-04
PTAA	1.40E-02	9.54E-06	4.99E-06	4.05E-03	8.37E-07	8.56E-05
CuSCn	9.17E-01	2.68E-04	2.96E-04	4.25E-01	7.23E-05	5.28E-02
P3HT	7.23E-02	2.12E-05	2.94E-04	2.82E-02	6.03E-06	4.83E-04
Carbon	5.03E-01	2.63E-04	1.77E-04	2.46E-01	2.59E-04	8.52E-03
EVA+PIB	2.09E+00	1.15E-03	1.11E-03	1.78E+00	5.26E-04	3.51E-02
Glass Frit	2.32E-02	4.61E-04	2.21E-04	2.33E-01	1.55E-05	5.22E-03
BOM	1.06E+01	4.98E-03	5.38E-03	8.38E+00	1.36E-03	8.49E-02
	2.84E+00	3.47E-03	3.03E-03	3.46E+00	6.45E-04	3.19E-02
Use phase	6.16E-01	6.81E-04	6.76E-04	1.81E+00	3.68E-04	1.77E-02
Remanufacturing	6.16E+00	2.00E-02	7.55E-03	4.77E+00	9.34E-04	7.01E-02
Incineration	3.60E+00	2.47E-03	3.32E-03	5.92E+00	5.41E-04	5.45E-02

4.2. Hole transport layer (HTL) – materials comparison

This section presents a comparative analysis of the three different materials proposed for the Hole Transport Layer of the final module, aiming to determine which could serve as a viable solution for future industrial-scale development. This analysis is conducted using the so-called basic configuration, with a standard EVA+PIB encapsulant, no remanufacturing, and standard solvents for perovskite deposition. To represent the Levelized Cost of Energy (LCOE) for the various configurations, an initial lifetime value is set at five years. A sensitivity analysis on this parameter will subsequently be conducted to assess its impact on the final value and to gain insights into the overall competitiveness and sustainability of the product.

Figure 11 shows graphically the cost composition for basic configuration modules. This is useful to graphically catch the subdivision of costs in the many layers. From a purely economic perspective, the material that results in the lowest manufacturing cost per square meter is CuSCN.

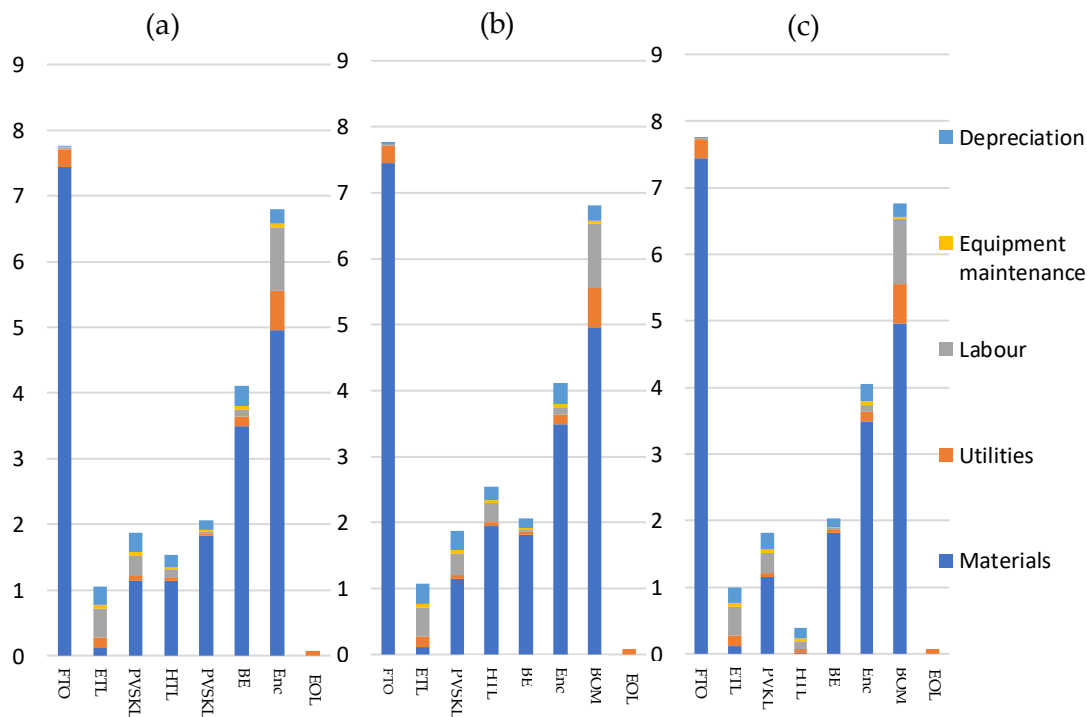


Figure 10: Manufacturing cost results per layer and per category, for a square meter of module with (a)P3HT(b)PTAA(c)CuSCn as HTL

However, when considering the technical aspects of the module, the lower efficiency of this inorganic material compared to its organic counterparts leads to a deterioration in terms of Minimum Selling Price (MSP) and Levelized Cost

of Energy (LCOE). In this regard, P3HT and PTAA exhibit a largely comparable economic profile, where the relatively higher cost of the latter is offset by an improvement in efficiency.

As displayed in Figure 12 These considerations can be fully applied to the analysis of the human-environmental impact of the different materials. Although CuSCN demonstrates greater overall sustainability, its higher impact stems from the lower energy production over which the impact is allocated.

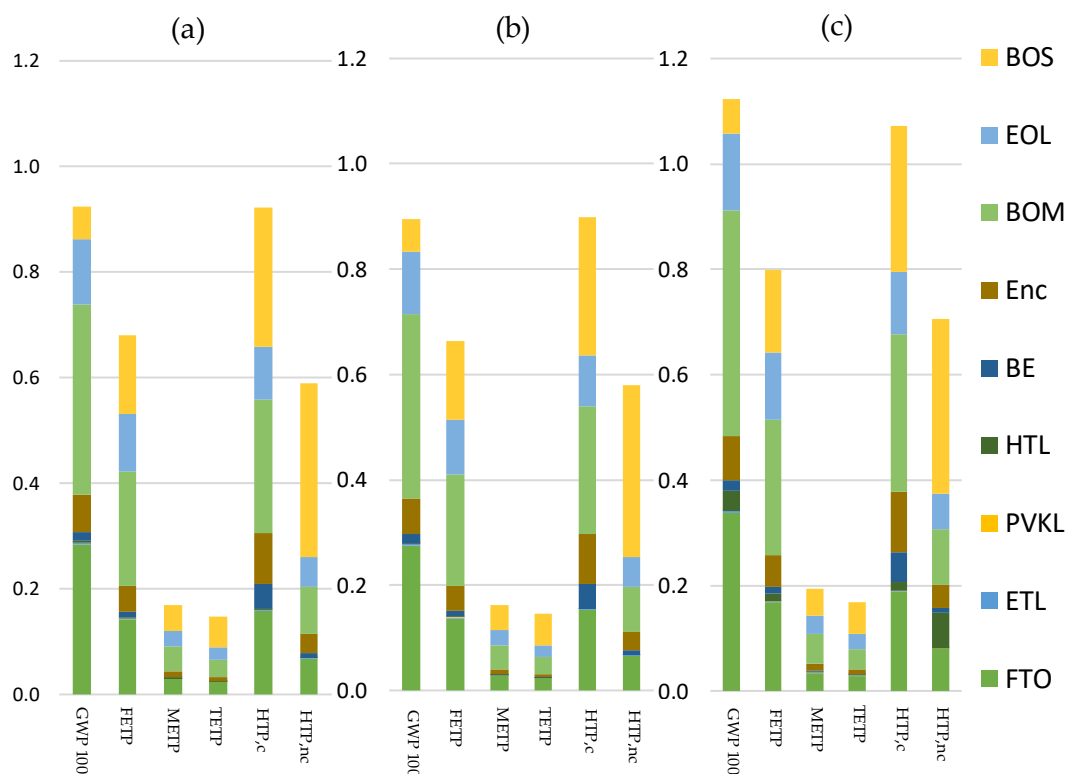


Figure 11: Impact results and composition per layer and per category, for a square meter of module with (a)P3HT(b)PTAA(c)CuSCn as HTL

Similarly, the Energy Payback Time (EPBT) of the inorganic material is higher than that of its organic counterparts, although, as previously noted, it remains significantly lower than that of silicon.

However, by analysing the sensitivity of these results in relation to the module's lifetime, key considerations arise when comparing the outcomes. As shown in Figure 13, the considerable uncertainty surrounding the stability of state-of-the-art technologies highlights a crucial factor that must be addressed to assess their competitiveness and sustainability accurately.

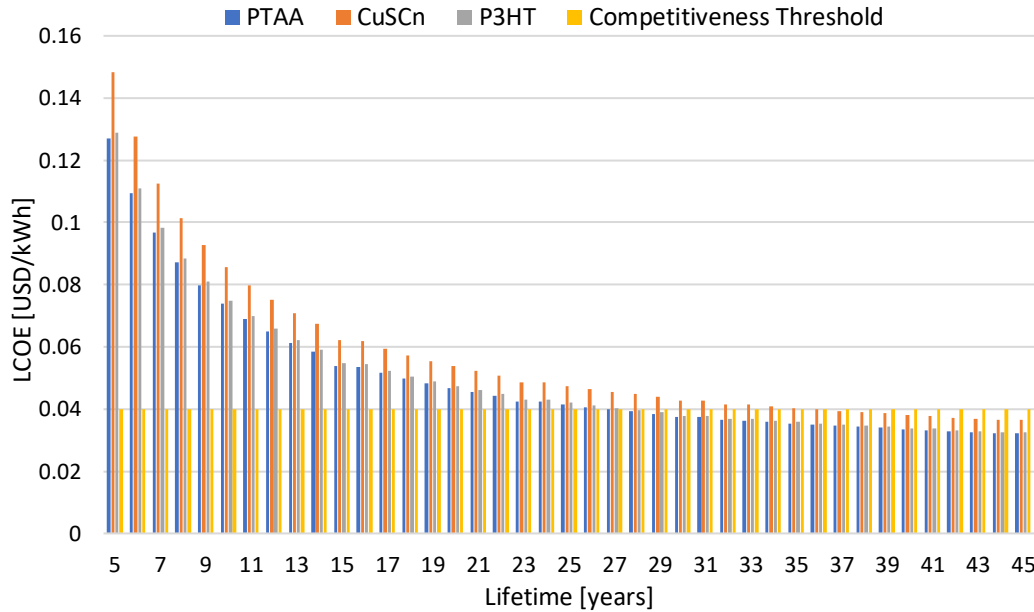


Figure 12: LCOE over lifespan of the three HTL in basic configuration, with competitiveness threshold set at 0.04 [USD/kWh. For improved readability of the graph, only lifetime values greater than 5 years are considered

To achieve an LCOE of 0.04 USD/kWh and establish real competitiveness in the photovoltaic market, the analysed modules should have a lifetime—defined as the time required for degradation to 80% of their initial efficiency—ranging between 26 and 36 years. This translates, in terms of degradation rate, to values of 0.80 %, 0.82 %, and 0.62 % PCE/year for P3HT, PTAA, and CuSCN, respectively.

Regrettably, these values are far from being realistic or attainable for the given configurations, which, as previously discussed, exhibit an average operational lifespan of merely 0.5 years.

Neither the layer under investigation nor the other constituent components of the device could provide the necessary stability to sustain such performance levels, thereby rendering these configurations inherently unsustainable.

To critically assess this outcome, it is important to first consider the low efficiency of the modules in question. In the pursuit of configurations with a reduced environmental impact and limited industrial complexity, the efficiency of the technology was compromised, resulting in a significant decrease in its economic competitiveness.

The manufacturing costs of the three configurations are considerably lower compared to more efficient alternatives found in the literature, which, from a

techno-economic perspective, should theoretically lead to a trade-off that would make the two options comparable.

However, the installation and balance of system (BOS) costs have a much more detrimental effect on less efficient technologies than on more expensive ones. This is primarily because a portion of these costs is linked to the surface area occupied by the module. In our case, the BOS accounts for over 50% of the total LCOE, effectively nullifying the efforts made to develop a competitive device despite its limited performance.

Table 3 TEA results for the three HTL in basic configuration

	P3HT	PTAA	CuSCn
Manufacturing Cost (MC) [USD/m ²]	25.43	26.47	24.02
Minimum sustainable price (MSP) [centUSD/W _{P,DC}]	26.48	26.72	29.71
Levelized Cost Of Electricity – 25 years LT [centUSD/kWh]	4.19	4.15	4.74
Minimum lifetime to achieve economic competitiveness [years]	27.53	26.84	35.73
Maximum degradation rate to achieve economic competitiveness [%PCE/year]	0.80	0.82	0.62

Conversely, to attain a total impact comparable to that of silicon, corresponding to a Mean Normalized Impact (MNI) of 1, the lifetime of perovskite modules would need to range between 2 and 3 years.

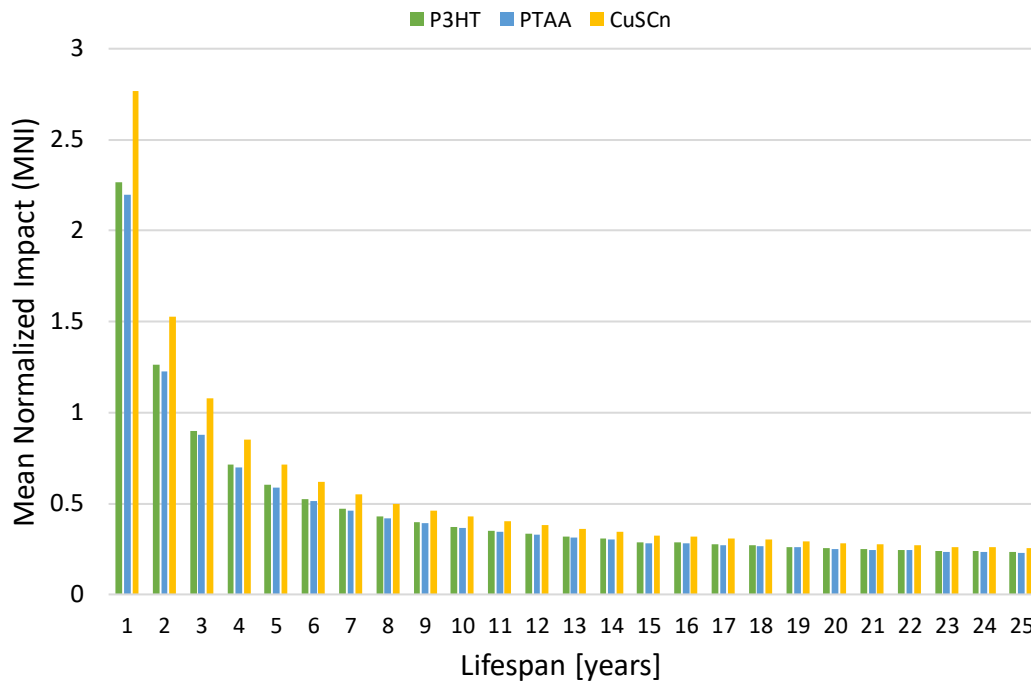


Figure 13: MNI over lifespan analysis of the three HTL in basic configuration

Table 4 shows that, although PTAA itself has an impact more than ten times higher than P3HT and CuSCN in terms of kg, its introduction into a complex system like a photovoltaic module results in an overall improved impact. This is due to its lower usage ratio per square meter of the product and its superior performance during the device's operation.

Table 4 LCA for the three HTL in basic configuration

	P3HT	PTAA	CuSCn
Energy Pay Back Time (EPBT) [years] - [days]	0.23 - 85	0.22 - 82	0.29 - 106
Mean Normalized Impact – 25 years LT [-]	0.23	0.23	0.25
Minimum lifetime to have a comparable to mono-Si impact [years]	2.73	2.64	3.35
Maximum degradation rate to have a comparable to mono-Si impact [%PCE/year]	7.85	8.11	6.64

A critical analysis of all the displayed results allows us to conclude that, given the significant instability repeatedly demonstrated by these devices, such low values of degradation rate are not realistically achievable [32][12]. On the other hand, inorganic materials like CuSCn have consistently shown improved

thermal, electrical and light-stability, making it, at the very least, plausible to achieve a higher lifetime than organic counterparts.

Therefore, CuSCn, or other similar inorganic materials, is considered the best alternative for a resilient technology. Consequently, in order to reproduce the results in a meaningful and linear manner, subsequent analyses will be conducted based on this initial result. All evaluations performed from this point onward are similarly replicated for organic HTLs within the corresponding section in the appendix.

In summary, while the configurations analyzed thus far demonstrate excellent performance in terms of environmental impact and human health, they do not constitute a realistically competitive alternative to silicon-based modules. Further investigations into the profitability of the CuSCN-based configuration will be conducted to evaluate the impact of advanced encapsulation techniques and enhanced end-of-life management strategies on both its techno-economic viability and overall performance.

However, it is essential to underscore that, in accordance with the definition outlined in Chapter 2.2, this configuration cannot be classified as sustainable, given its inability to achieve competitiveness within the market.

4.3. Perovskite Layer (PVKL) – standard vs green solvents

This section examines the actual impact differences between the solvents traditionally used for depositing the perovskite precursor (DMF and DMSO) and the potential adoption of alternatives that are less harmful and more environmentally sustainable. As outlined in the following discussion, assessing the environmental impact alone is sufficient to derive meaningful conclusions, rendering a detailed economic analysis unnecessary.

Table 5 and 6 illustrate the results of this analysis, with negative values signifying an improvement associated with the adoption of cleaner solvents, reflecting a percentage reduction in the respective impact category. Conversely, positive values indicate a deterioration, resulting from an increase in the same impact category.

Table 5 Percentual difference in adopting Acetonitrile instead of DMF:DMSO

	GWP100 kg CO ₂ -Eq	FETP kg 1,4-DCB-Eq	METP kg 1,4-DCB-Eq	TETP kg 1,4-DCB-Eq	HTPc kg 1,4-DCB-Eq	HTPnc kg 1,4-DCB-Eq
%Impact/m²	-1.67	-4.05	-0.18	-5.66	-1.58	-6.19
%Impact/W_{P,DC}	6.57	5.68	5.13	4.47	5.34	3.18

Table 6 Percentual difference in adopting Ethanol instead of DMF:DMSO

	GWP100 kg CO ₂ -Eq	FETP kg 1,4-DCB-Eq	METP kg 1,4-DCB-Eq	TETP kg 1,4-DCB-Eq	HTPc kg 1,4-DCB-Eq	HTPnc kg 1,4-DCB-Eq
%Impact/m²	-1.68	-4.06	-0.18	-5.66	-1.58	-6.19
%Impact/W_{P,DC}	5.30	2.98	2.22	1.59	2.47	0.84

Although the overall sustainability of the module per square meter improves with the adoption of clean solvents, this is no longer the case when transitioning to an analysis based on $W_{P,DC}$. This occurs because such solvents induce a slight reduction in the module's performance, negatively affecting all other layers. As a result, the relative impact contribution of these layers increases due to the decrease in the functional unit to which they are allocated. In other words, the enhancement observed in the perovskite layer does not offset the corresponding deterioration in the other layers caused by the reduction in PCE.

The results presented were obtained by applying a 6% efficiency reduction for acetonitrile, consistent with findings from existing studies in the field [ref], and a 9% reduction for ethanol—though the latter is a very small value, likely unrealistic, it serves as a plausible best-case scenario.

This analysis underscores the point that improving the overall environmental impact of the module can only be achieved through holistic measures that aim to enhance the product's sustainability, while ensuring that its technical characteristics remain largely unchanged.

4.4. Encapsulation, sealant comparison

Building upon the previous evaluations, the analysis continues with an examination of the configuration featuring CuSCn as HTL and standard solvents.

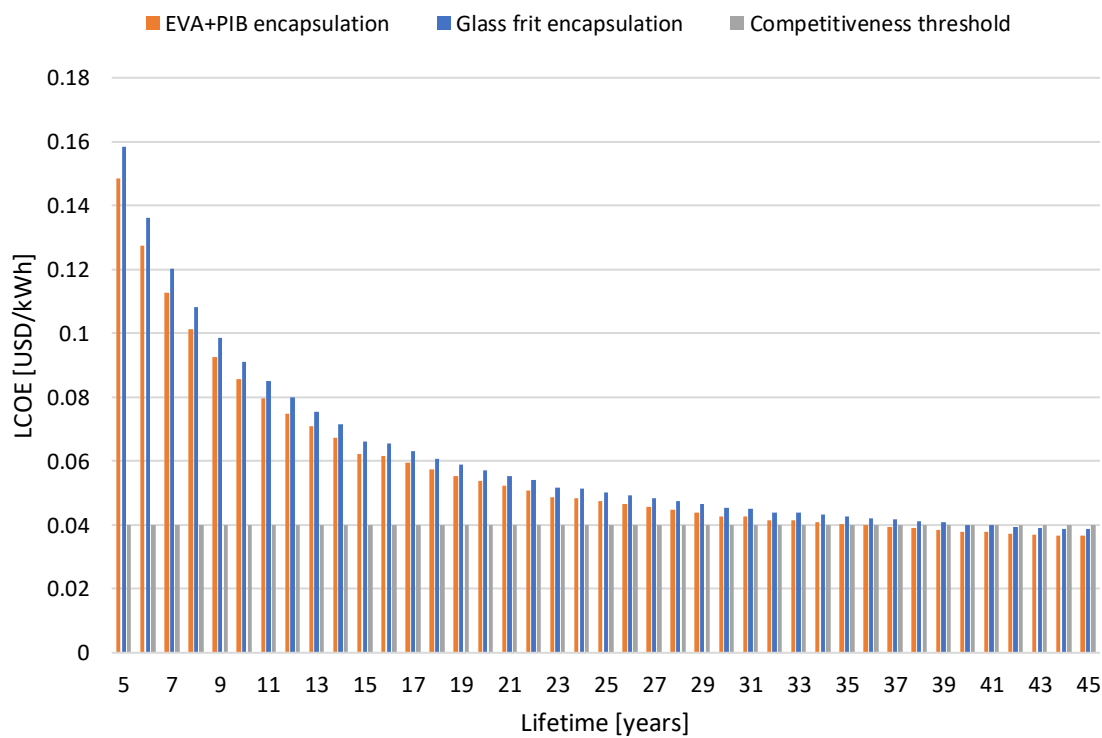


Figure 14: LCOE over lifespan analysis of CuSCn HTL configuration with DMS:DMF solvent for perovskite deposition using different encapsulants. For improved readability of the graph, only lifetime values greater than 5 years are considered

Table 7 shows the economic threshold values for this analysis. Although, as previously noted, achieving similar lifetime and degradation rate values is unattainable for this configuration, it is still possible to derive meaningful conclusions regarding the differences between the two solutions analyzed.

Even if the degradation rate is unrealistic, insights about their ratio are particularly relevant for evaluating the practical profitability of glass frit: should either of these criteria be met, it would undoubtedly prove more cost-effective than the plastic alternative.

In order for the glass frit encapsulant to be considered economically competitive with its plastic counterpart, it must demonstrate a long-term

degradation rate that is no more than 87% of the degradation rate associated with EVA, resulting in a lifetime 1.15 times longer.

Table 7 Economic impact of different encapsulation

	EVA+PIB	Glass Frit	Ratio GF/EVA
Minimum lifetime to achieve economic competitiveness [years]	35.74	41.03	1.15
Maximum degradation rate to achieve economic competitiveness [%PCE/year]	0.62	0.54	0.87

Nonetheless, an additional clarification is necessary. The difference in stability between the two configurations is solely related to oxygen and humidity triggered degradation processes of the active layers. These substances permeate the module through the plastic barrier, leading to a significant loss of efficiency, which, in the case of glass frit, would be almost entirely prevented. The issue lies in the fact that the process by which external air infiltrates the module is not linear, and therefore, it is difficult to approximate at any given point using a linear degradation coefficient.

Qualitatively, this function will display very low values during the early stages of the module's lifespan, when external substances must flow through the edge sealant, after which it will gradually increase, approaching an asymptotic upper limit towards the end of life. In essence, describing this function with a linear coefficient, such as the degradation rate, is only valid when the exact point on the curve is known, or, in other words, when the precise lifetime of the technology is clear.

Consequently, to assess the profitability of glass frit in a real configuration, this study should be replicated in a similar manner once actual lifetime is determined. At that point a verification through the provided ratio can assess the profitability.

On the other hand, the improved impact profile of glass frit is easily displayed by Figure16 and Table8.

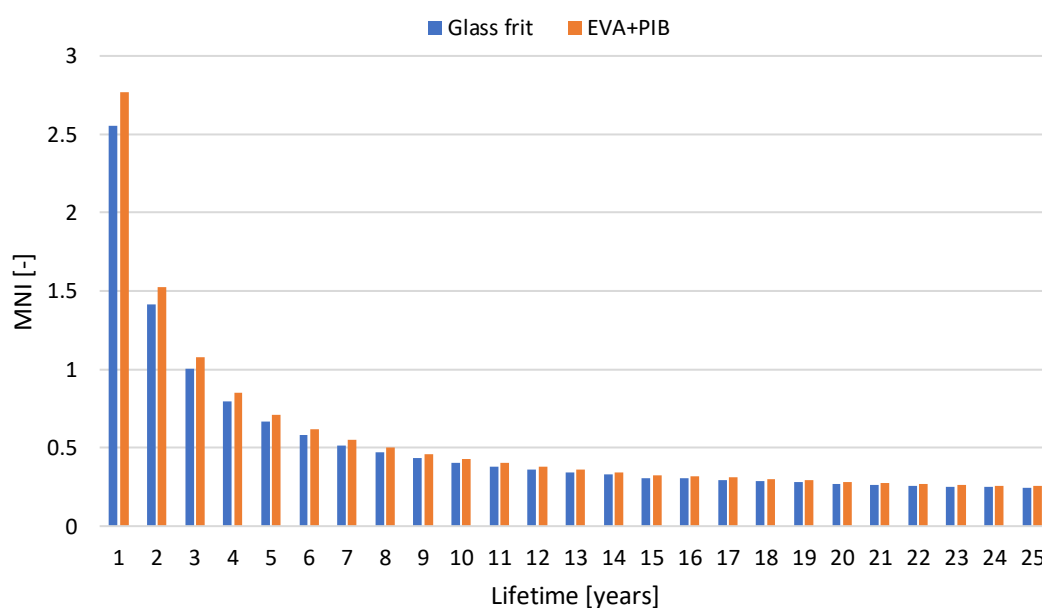


Figure 16: MNI over lifespan analysis of CuSCn HTL configuration with DMS:DMF solvent for perovskite deposition using different encapsulants,

Avoiding the employment of a large surface encapsulant like EVA, but focusing just on the edge sealing, Glass frit shows improved outcomes both in terms of Energy payback time and environmental-human health impact.

Table 8 LCA results of different encapsulation

	Glass Frit	EVA+PIB
Energy Pay Back Time (EPBT) [years - days]	0.26 - 95	0.29 - 106
Minimum lifetime to have a comparable to mono-Si impact [years]	3.01	3.35
Maximum degradation rate to have a comparable to mono-Si impact [%PCE/year]	7.15	6.44

4.5. End of life processes comparison

After assessing the conditions under which an alternative encapsulant may be advantageous, we revert to the baseline configuration to examine the benefits of a potential remanufacturing process at the module's end of life.

From an environmental impact perspective, the remanufactured module exhibits an overall improvement across all impact categories, with the sole exception of freshwater ecotoxicity (FETP), where the impact is found to triple. When evaluating the total environmental footprint of the remanufactured configuration in comparison to the mono-Si module using the MNI, a clear improvement emerges, with an average reduction of 2.5% relative to that of a new module. This translates into a decreased minimum service life required to achieve parity with the mono-Si module (Table 9).

Furthermore, a significant reduction in the module's Energy Payback Time (EPBT) is observed in the remanufactured version.

In essence, from a strictly environmental standpoint, the remanufacturing process for an end-of-life module proves to be a better alternative, impact wise, than its replacement with a new module.

Table 9 LCA results of different EOL

	New	Remanufactured
Energy Pay Back Time (EPBT) [years - days]	0.27 - 101	0.18 - 67
Minimum lifetime to have a comparable to mono-Si impact [years]	0.65	0.54

In conducting a techno-economic analysis to assess the profitability of such an end-of-life process, the evaluation timeframe must be extended to encompass the contributions of both the initial and remanufactured modules within the same analysis and levelized cost of electricity (LCOE) assessment.

At the conclusion of the first module's operational life, the acquisition cost of the second—along with the expenses associated with the balance of system and reinstallation—will be incorporated and discounted to present value. As a result, the scope of the analysis shifts from considering a single module throughout its lifecycle to a more comprehensive system perspective, spanning from the deployment of the first module to the end of life of the second, with the remanufacturing process serving as a pivotal transitional phase.

The considerable extension of the evaluation period will substantially reduce the impact of the later years on the final outcome, as a result of the discounting of future costs at the time of the initial investment. In essence, given that the remanufacturing process occurs after many years, the variation in terms of LCOE will be minimal. However, even a slight improvement in this parameter would underscore the substantial economic feasibility of the process under consideration.

In this context, Table 10 well displays the positivity of such a procedure, where it's shown how the same technology, with the same basic efficiency and degradation rate, achieves improved results if a remanufacturing process is taking place.

Table 10 Economic results of different EOL

	New	Remanufactured
LCOE with degradation rate equal to 0.6 [USD/kWh]	3.987	3.945
Maximum degradation rate to achieve economic competitiveness [%PCE/year]	0.62	0.618

This further substantiates the effectiveness of the remanufacturing process, highlighting how perovskite technologies may be less susceptible to the challenges associated with waste generation, a critical issue for silicon-based counterparts.

While, in the case of the market-dominant technology, module recycling poses significant drawbacks in terms of both economic and environmental sustainability, for perovskites, the remanufacturing process proves to be advantageous on all fronts. This could represent a compelling argument in favor of this emerging technology, potentially strengthening its position in the renewable energy landscape.

5 Conclusions

5.1. Overall sustainability

The work presented in this thesis aims to assess the environmental and techno-economic sustainability of a perovskite solar module with an enhanced impact profile. Through a careful selection of materials and manufacturing methodologies, a range of configurations with a reduced impact on human health and a compelling environmental performance has been analysed.

Furthermore, these configurations ensure a responsible use of resources, preventing excessive strain on the supply chains of critical raw materials while simultaneously avoiding an increase in greenhouse gas emissions into the atmosphere.

The findings of this investigation indicate that the materials and processes selected to meet these requirements are, at the current stage of research, unable to achieve the critical level of cost-effectiveness required for power production systems.

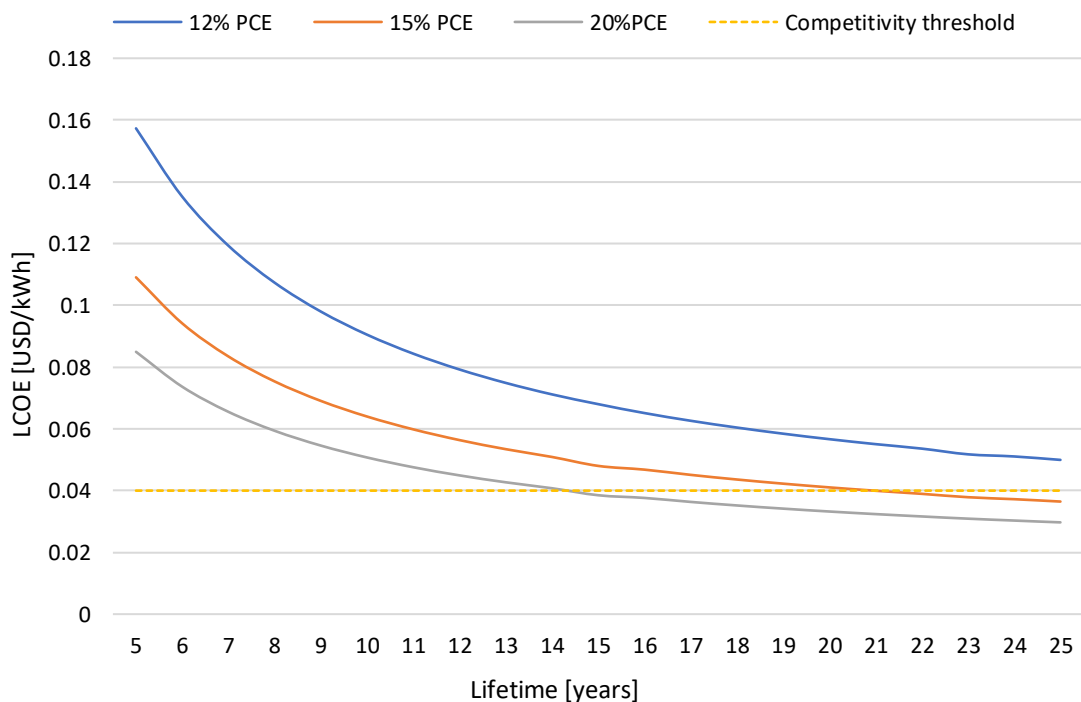


Figure 17 LCOE as function of lifetime and efficiency of the module, basic configuration

Building on the previously mentioned combination of low-impact materials and processes, the technical performance of the studied devices was determined through a thorough literature review and reasonable assumptions. The resulting system exhibits an average efficiency of approximately 12%. As illustrated in Figure 17, this efficiency is insufficient to achieve economic competitiveness, given the extremely limited lifespan of this technology, which currently stands at around 0.5 years.

Critically analyzing this result, it is essential to note how the viability of this technology is worsened by the balance of system (BOS) contribution. The installation and BOS costs have a much more detrimental effect on less efficient technologies than on more expensive ones, mainly because a relevant portion of these costs is associated with the surface area occupied by the module.

Consequently, although logically, the low costs should offset the poor performance, this trade-off is precariously unbalanced by external costs that have a much more significant impact on low-performance technologies.

A significant development in terms of both stability and efficiency of these materials is necessary for these configurations to be competitive in the market. For efficiency values between 15% and 20%, technologies with a lifespan exceeding 15 years are required. Unfortunately, such improvements may be unattainable while maintaining the environmentally sustainable materials and processes we have considered so far.

5.2. Other relevant conclusions

Despite the likely impossibility of making this configuration economically viable, the analysis conducted on the adoption of green solvents, glass frit as an encapsulation, and responsible end-of-life procedures has yielded results that could be of interest.

Green solvents adoption for perovskite deposition

About the use of greener solvents for perovskite deposition, considering the industrial setting needed for this layer deposition, with null release of substances due to the necessary adoption of controlled environments to ensure product quality, results in an overall worsening of the impact profile.

This is because such adoption leads to a performance loss which, although limited, exacerbates the impact of the other layers that make up this technology. In other words, the perovskite layer's enhancement fails to counterbalance the deterioration in other layers due to reduced efficiency. This

analysis shows how Improving the module's environmental impact requires holistic measures that boost sustainability without compromising technical performance.

Glass Frit

This is an alternative encapsulant that ensures improved hermeticity leading to a reduction of oxygen and moisture related degradation in the module. It could guarantee both an improved impact profile and a longer lifespan for the analysed technologies.

Given the higher cost for the glass frit encapsulant, to make the configurations that adopt this material competitive with the plastic counterpart, they must demonstrate a long-term degradation rate that is no more than 87% of the degradation rate associated with EVA, resulting in a lifetime 1.15 times longer.

Remanufacturing route at the end of life

While module recycling presents significant economic and environmental challenges for the market-dominant technology, a remanufacturing process that ensures the re-use of FTO and cover glass components proves to be highly advantageous for perovskites across all aspects.

This advantage could serve as a strong argument in favor of this emerging technology, potentially enhancing its position within the renewable energy landscape, where the dominant technology is still linked with million tons of wastes production.

Thanks to the beneficial contribution of the second-life module to the original one this process would help make competitive those technologies that fall just short of the required lifetime.

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A Appendix A- Life cycle analysis

A.1. Life Cycle Inventory

The flow categories considered in the analysis are further explained

Category	Flows	Sign in mass balance	Sign in impact assessment balance
Input (I)	Material [Kg]	+	+
	Solvent [Kg]		
Utility(U)	Electricity [KWh]	+	+
	Water [Kg]		
Service (S)	Labour [employee*hour]	*	+
	Transport [Ton*Kg]		
Waste (W)	Solid waste [Kg]	-	+
	Liquid waste [Kg]		
	Gasues waste [Kg]		
Emission(E)	Liquid emission [Kg]	-	**
	Gaseous emission [Kg]		
Product (P)	Primary Product [unit]	+/-	+/-
	By- product [unit]		
Output (O)	Output [unit]	-	-

*unconsidered into the analysis

**considered as waste to be managed

A.1.1. Chemicals inventory

TiO₂ related chemicals

Ammonium fluoride production

Category	Process	Amount	Unit	Source
O	Ammonium fluoride	1	kg	[36]
I	Ammonia, liquid {RER} market for	0.46	kg	[36]
U	Heat, heavy fuel oil, at industrial furnace 1MW/RER S	0.57	MJ	[36]
I	Hydrogen fluoride {RER} market for hydrogen fluoride	0.54	kg	[36]
U	Chemical factory, organics {GLO} market for	4E-10	unit	[36]
W	Waste heat	0.57	MJ	[36]

Tin tetrachloride production

Category	Process	Amount	Unit	Source
O	Tin tetrachloride	1	kg	[36]
I	Tin {GLO} market for	0.48	kg	[36]
I	Chlorine, liquid {RER} market for chlorine, liquid	0.57	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW {Europe without Switzerland}	0.13	MJ	[36]
U	Chemical factory, organics {GLO} market for	4E-10	unit	[36]
W	Waste heat	0.57	MJ	[36]

TTIP (Titanium (IV) isopropoxide)

Category	Process	Amount	Unit	Source
O	TTIP	1.00	kg	[36]
O	Ammonium chloride {GLO} market for	0.94	kg	[36]
I	Titanium tetrachloride {GLO} market for	0.83	kg	[36]
I	Isopropanol {RER} market for	1.06	kg	[36]
I	Ammonia, liquid {RER} market for	0.62	kg	[36]
I	Benzene {RER} market for	1.60	kg	[36]
U	Electricity, medium voltage {RER} market for	0.01	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Isopropanol waste incineration	0.21	kg	[36]
W	Benzene incineration	1.60	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.17	kg	[36]

Ketene production

Category	Process	Amount	Unit	Source
O	Ketene*	1.00	kg	[36]
O	Methane, 96% by volume {RoW} market for	0.58	m3	[36]
I	Acetone, liquid {RER} market for acetone, liquid	1.54	kg	[36]
U	Electricity, medium voltage {RER} market for	0.00	kWh	[36]
U	Heat, natural gas, at industrial furnace >100kW {RER}	2.99	MJ	[36]
U	Chemical factory, organics {GLO} market for	4E-10	unit	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.15	kg	[36]

*Allocated considering known impact co-products

Acetylacetonate (from rearranging isopropenyl acetate)

Category	Process	Amount	Unit	Source
O	Acetylacetonate	1.00	kg	[36]
I	Isopropenyl acetate	1.22	kg	[36]
U	Natural gas, high pressure {RoE} market for	0.08	m3	[36]
U	Electricity, medium voltage {DE} market for	0.57	kWh	[36]
U	Steam, in chemical industry {RER} market for	0.09	kg	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Heat	2.06	MJ	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.18	kg	[36]

Isopropenyl acetate

Category	Process	Amount	Unit	Source
O	Isopropenyl acetate	1.00	kg	[36]
O	Acetic anhydride {RER} production, ketene route	0.11	kg	[36]
I	Ketene	0.47	kg	[36]
I	Acetone, liquid {RER} market for acetone, liquid	0.62	kg	[36]
I	Acetic acid, without water, in 98% solution state {GLO} market for	0.07	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW {RER}	0.60	MJ	[36]
U	Steam, in chemical industry {RER} market for	1.67	kg	[36]
U	Electricity, medium voltage {DE} market for	1.05E-05	kWh	[36]

U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Acetone waste incineration	0.04	kg	[36]

Titanium Diisopropoxide bis Acetylacetonate (TAA)

Category	Process	Amount	Unit	Source
O	Titanium diisopropoxide bis Acetylacetonate solution (25 wt% isopropanol)	1.00	kg	[36]
I	TTIP	0.44	kg	[36]
I	Acetylacetonate	0.31	kg	[36]
I	Isopropanol	0.25	kg	[36]
U	Electricity, medium voltage {RER} market for	2.46E-05	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Heat	4.71E-05	MJ	[36]

Perovskite related chemicals

Potassium iodide

Category	Process	Amount	Unit	Source
O	Potassium iodide*	1.00	kg	[36]
O	Potassium iodate*	0.23	kg	[36]
I	Potassium hydroxide {GLO} market for	0.41	kg	[36]
I	Iodine {GLO} market for	1.02	kg	[36]
U	Tap water {Europe without Switzerland} market for	1.01	kg	[36]
U	Natural gas, burned in industrial furnace >100kW/RER S	3.31	MJ	[36]
U	Electricity, medium voltage {RER} market for	1.23E-02	kWh	[36]

U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.13	kg	[36]

*mass based allocation

Lead nitrate

Category	Process	Amount	Unit	Source
O	Lead nitrate	1.00	kg	[36]
I	Lead {GLO} market for	0.70	kg	[36]
I	Nitric acid, without water, in 50% solution state {RER} market for	1.13	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	0.20	kg	[36]
U	Electricity, medium voltage {RER} market for	3.09E-05	kWh	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	0.24	MJ	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.96	kg	[36]

Hydroiodic acid (57% in water)

Category	Process	Amount	Unit	Source
O	Hydriodic acid production	1.00E+00	kg	[36]
O	Sulfur	1.43E-01	kg	[36]
I	Hydrogen sulfide {RER} market for	1.69E-01	kg	[36]

I	Iodine	6.28E-01	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	7.85E-01	kg	[36]
U	Electricity, medium voltage {RER} market for	8.03E-05	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
U	Natural gas, burned in industrial furnace >100kW/RER S	0.49	MJ	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.44	kg	[36]

Methylamonium iodide

Category	Process	Amount	Unit	Source
O	Methylammonium iodide	1.00	kg	[36]
I	Hydroiodic acid (57% in water){RER} market for	1.46	kg	[36]
I	Methylamine {RER} market for	0.20	kg	[36]
I	Ethanol, without water, in 99.7% solution state, from ethylene {RER} market for ethanol, without water, in 99.7% solution state, from ethylene	0.41	kg	[36]
I	Diethyl ether, without water, in 99.95% solution state {RER} market for	3.57	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	0.56	MJ	[36]
U	Electricity, medium voltage {RER} market for	3.02	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

W	Ethanol incineration	0.41	kg	[36]
W	Diethyl ether incineration	3.56	kg	[36]
W	Hazardous waste incineration	0.66	kg	[36]

Potassium bromide

Category	Process	Amount	Unit	Source
O	Potassium bromide*	1.00	kg	[36]
O	Potassium bromate*	0.28	kg	[36]
I	Potassium hydroxide {GLO} market for	0.57	kg	[36]
I	Bromine {GLO} market for	0.81	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	1.72	MJ	[36]
U	Electricity, medium voltage {RER} market for	0.01	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

*mass based allocation

Triethyl orthoformate

Category	Process	Amount	Unit	Source
O	Triethyl orthoformate	1.00	kg	[36]
I	Hydrogen cyanide {RER} market for hydrogen cyanide	0.23	kg	[36]
I	Ethanol, without water, in 99.7% solution state, from ethylene {RER} market for ethanol, without water, in 99.7% solution state, from ethylene	1.44	kg	[36]
I	Hydrobromic acid	0.85	kg	[36]

U	Electricity, medium voltage {RER} market for	7.45E-05	kWh	[36]
U	Natural gas, burned in industrial furnace >100kW/RER S	1.50	MJ	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Ethanol waste incineration	0.51	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.05	kg	[36]

Formamidine acetate

Category	Process	Amount	Unit	Source
O	Formamidine acetate	1.00	kg	[36]
I	Triethyl orthoformate	1.71	kg	[36]
I	Acetic acid, without water, in 98% solution state {GLO} market for	0.41	kg	[36]
I	Ammonia, liquid {RER} market for	0.42	kg	[36]
U	Electricity, medium voltage {RER} market for	1.90E-04	kWh	[36]
U	Natural gas, burned in industrial furnace >100kW/RER S	1.09	MJ	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Ethanol incineration	0.62	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.91	kg	[36]

Lead iodide

Category	Process	Amount	Unit	Source
O	Lead iodide*	1.00	kg	[36]
O	Potassium nitrate {RER} production*	0.44	kg	[36]
I	Potassium iodide	0.76	kg	[36]
I	Lead nitrate	0.72	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	256.74	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	120.39	MJ	[36]
U	Electricity, medium voltage {RER} market for	1.06	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	Unit	[36]

*allocation based on known data for potassium nitrate

Lead chloride

Category	Process	Amount	Unit	Source
O	Lead chloride*	1.00	kg	[36]
O	Sodium nitrate*	0.61	kg	[36]
I	Lead nitrate	1.19	kg	[36]
I	Sodium chloride, powder {GLO} market for	0.44	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	31.52	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	15.80	MJ	[36]
U	Electricity, medium voltage {RER} market for	1.13	kWh	[36]

U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
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*allocated on mass and then modified for economic value economical value (lead chloride 99,999% 183,92\$ 10g, Sodium nitrate 115\$ 10g [53])

Lead chloride

Category	Process	Amount	Unit	Source
O	Lead bromide*	1.00	kg	[36]
O	Potassium nitrate*	0.55	kg	[36]
I	Lead nitrate	0.90	kg	[36]
I	Potassium bromide	0.68	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	25.20	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	12.08	MJ	[36]
U	Electricity, medium voltage {RER} market for	1.13	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

* allocated on cost basis plus mass (potassium nitrate 50\$ 10 g, lead bromide 350 10g [53])

Methylammonium bromide

Category	Process	Amount	Unit	Source
O	Methylammonium bromide	1.00	kg	[36]
I	Hydroboromic acid (48% in water)	1.55	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	0.81	kg	[36]

I	Hydrobromic acid	0.74	kg	[36]
I	Methylamine {RER} market for	0.29	kg	[36]
I	Methanol {RER} market for	0.42	kg	[36]
I	Diethyl ether, without water, in 99.95% solution state {GLO} diethyl ether production, from ethanol dehydration	3.57	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	0.58	MJ	[36]
U	Electricity, medium voltage {RER} market for	3.02	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Diethyl ether wastse incineration	3.56	kg	[36]
W	Methanol incineration	0.42	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.84	kg	[36]

Formamidinium iodide

Category	Process	Amount	Unit	Source
O	Formamidinium iodide	1.00	kg	[36]
I	Hydroiodic acid (57%)	1.75	kg	[36]
I	Formamidine acetate	0.62	kg	[36]
I	Ethanol, without water, in 99.7% solution state, from ethylene {RER} market for ethanol, without water, in 99.7% solution state, from ethylene	0.83	kg	[36]
I	Diethyl ether, without water, in 99.95% solution state {RER} market for diethyl ether, without water, in 99.95% solution state	3.57	kg	[36]

U	Heat, natural gas, at industrial furnace >100kW/RER S	0.66	MJ	[36]
U	Electricity, medium voltage {RER} market for	3.08	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Ethanol incineration	0.83	kg	[36]
W	Diethyl ether wastse incineration	3.56	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	1.37	kg	[36]

Caesium iodide

Category	Process	Amount	Unit	Source
O	Caesium iodide	1.00	kg	[36]
O	Aluminium hydroxide {IAI Area, EU27 & EFTA} aluminium hydroxide production	0.39	kg	[36]
O	Gypsum, mineral {RER} market for gypsum, mineral	2.77	kg	[36]
O	Barium sulfide {GLO} barium sulfide production	0.10	kg	[36]
I	Spodumene {GLO} market for	2.98	kg	[36]
I	Sulfuric acid {RER} market for sulfuric acid	3.81	kg	[36]
I	Water, deionised {Europe without Switzerland} water production, deionised APOS, S	28.68	kg	[36]
I	Quicklime, milled, packed {RER} market for quicklime, milled, packed	1.16	kg	[36]
I	Hydroiodic acid (57%)	1.13	kg	[36]

I	Barium hydroxide {GLO} market for barium hydroxide	0.07	kg	[36]
I	Crushing, rock {RER}	2.98	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	31.09	MJ	[36]
U	Electricity, medium voltage {RER} market for	0.41	kWh	[36]
U	Chemical factory, organics {GLO} market for	1.20E-09	unit	[36]
W	Waste gypsum {Europe without Switzerland} market for waste gypsum	2.03	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	2.85	kg	[36]

*allocation based on known data for co-products

Carbon electrode related chemicals

Benzyl bromide synthesis

Category	Process	Amount	Unit	Source
O	Benzyl bromide	1.00	kg	[36]
I	Toluene, liquid {RER} market for toluene, liquid	0.54	kg	[36]
I	Bromine {GLO} market for	0.47	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	2.76	MJ	[36]
U	Electricity, low voltage {RER} market for	0.57	kWh	[36]
U	Steam, in chemical industry {RER} market for steam, in chemical industry	0.07	kg	[36]
U	Chemical factory, organics {GLO} market for	4.10E-10	unit	[36]

Hydrobromic acid synthesis

Category	Process	Amount	Unit	Source
O	Hydrobromic acid	1.00	Kg	[36]
I	Hydrogen, liquid {RER} market for	8.77E-03	l	[36]
I	Bromine {GLO} market for	1.04	kg	[36]
U	Electricity, medium voltage {RER} market for	0.33	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	kWh	[36]

n-butyl bromide (bromobutane)

Category	Process	Amount	Unit	Source
O	n-butyl bromide	1.00	kg	[36]
I	n-butanol {RER} market for	0.55	kg	[36]
I	Hydrobromic acid	0.61	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	0.44	MJ	[36]
U	Electricity, medium voltage {RER} market for	0.07	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

n-butyl-lithium

Category	Process	Amount	Unit	Source
O	n-butyl-lithium*	1.00	kg	[36]
O	Lithiumbromide*	0.95	kg	[36]
I	n-butyl bromide	1.79	kg	[36]

I	Diethyl ether, without water, in 99.95% solution state {RER} market for diethyl ether, without water, in 99.95% solution state	1.86	kg	[36]
I	Lithium {GLO} market for	0.18	kg	[36]
U	Electricity, medium voltage {RER} market for	0.03	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.32	kg	[36]
W	diethyl ether waste incineration (electricity)	1.86	kg	[36]

*just mass allocation cause difficult finding cost of pure n-butyl-lithium

Pentylbenzene production

Category	Process	Amount	Unit	Source
O	Pentylbenzene*	1.00	kg	[36]
O	Lithium bromide*	0.62	kg	[36]
I	Benzyl bromide	1.21	kg	[36]
I	n-Buthyllithium	0.45	kg	[36]
U	Electricity, medium voltage {RER} market for	2.55E-05	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

*Allocation on mass and cost basis (pentylbenzene 49\$ 10g, lithium bromide 8\$ 10g)

2-Ethoxyethanol

Category	Process	Amount	Unit	Source
O	2-ethoxyethanol	1.00	kg	[36]
I	Ethylene oxide {RER} market for ethylene oxide	0.51	kg	[36]
I	Ethanol, without water, in 99.7% solution state, from ethylene {RER} market for ethanol, without water, in 99.7% solution state, from ethylene	0.54	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	3.00	MJ	[36]
U	Electricity, medium voltage {RER} market for	0.57	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Ethanol waste incineration	0.03	kg	[36]

2-(2-ethoxyethoxy)ethyl acetate

Category	Process	Amount	Unit	Source
O	2-(2-ethoxyethoxy)ethyl acetate	1.00	kg	[36]
I	Ethylene oxide	0.28	kg	[36]
I	2-ethoxyethanol	0.57	kg	[36]
I	Acetic acid, without water, in 98% solution state {GLO} market for	0.36	kg	[36]
U	Heat, natural gas, at industrial furnace >100kW/RER S	5.52	MJ	[36]
U	Electricity, medium voltage {RER} market for	1.15	kWh	[36]
U	Steam, in chemical industry {RER} market for steam, in chemical industry	0.17	kg	[36]

U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
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Carbon paste

Category	Process	Amount	Unit	Source
O	Carbon paste	1.00	kg	[36]
I	Carbon black {GLO} market for	0.04	kg	[36]
I	Graphite {GLO} market for	0.11	kg	[36]
I	2-(2-ethoxyethoxy)ethyl acetate	0.37	kg	[36]
I	Coal tar {GLO} market for	0.24	kg	[36]
I	Pentyl benzene	0.24	kg	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.51	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.09	tkm	[36]

Nitrocellulose

Category	Process	Amount	Unit	Source
O	Nitrocellulose	1.00	kg	[36]
I	Cellulose fibre, inclusive blowing in {GLO} market for	0.64	kg	[36]
I	Nitric acid, without water, in 50% solution state {RER} market for nitric acid, without water, in 50% solution state	0.75	kg	[36]
U	Natural gas, burned in industrial furnace >100kW/RER S	0.26	MJ	[36]
U	Electricity, medium voltage {RER} market for	2.12E-05	kWh	[36]

U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.39	kg	[36]

a-Terpineol production

Category	Process	Amount	Unit	Source
O	a-Terpineol	1.00	kg	[36]
I	Water, deionised {Europe without Switzerland} water production, deionised	0.12	kg	[36]
I	Dichloromethane {RER} market for dichloromethane	0.55	kg	[36]
I	Hydrogen, liquid {RER} market for	0.03	kg	[36]
I	Acetone, liquid {RER} market for acetone, liquid	0.75	kg	[36]
I	Acetylene {RER} market for acetylene	0.34	kg	[36]
U	Electricity, medium voltage {RER} market for	0.42	kWh	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

Hole transport layer related chemicals

PTAA

PTAA (modelled as Spiro-OMeTAD because of impact similarities)

Category	Process	Amount	Unit	Source
O	Spiro-OMeTAD*	1.00	kg	[37]
O	2-Chloronitrobenzene*	0.57	kg	[37]
O	Hydrogen bromide*	0.43	kg	[37]

I	Phenol {RER}, market for	0.72	kg	[37]
I	Sodium hydroxide, without water, in 50% solution state {RER}	1.63	kg	[37]
I	Dimethyl sulfate {RER}, market for	0.49	kg	[37]
I	Potassium iodide	0.84	kg	[37]
I	Potassium iodate	0.41	kg	[37]
I	Methanol {RER} market for	2.47	kg	[37]
I	Hydrochloric acid, without water, in 30% solution state {RER} production, from the reaction of hydrogen with chlorine	5.04	kg	[37]
I	Hydrogen, liquid {RER} market for	0.17	kg	[37]
I	Chlorine, liquid {RER} market for	4.90	kg	[37]
I	Bromine {GLO} market for	0.60	kg	[37]
I	Coal tar {GLO} market for	0.30	kg	[37]
I	Ethylene glycol {RER} market for	1.06	kg	[37]
I	Aniline {RER} market for	0.94	kg	[37]
I	Sodium nitrite {RER} market for	0.22	kg	[37]
I	Sulfur dioxide {RER} market for	0.41	kg	[37]
I	Magnesium {RER} market for	0.03	kg	[37]
i	Sodium methoxide {GLO} market for	0.28	kg	[37]
I	Monochlorobenzene {GLO} market for	0.97	kg	[37]
I	Nitric acid, without water, in 50% solution state {RER} market for nitric acid, without water, in 50% solution state	1.08	kg	[37]
I	Sulfuric acid {RER} market for sulfuric acid	1.62	kg	[37]
U	Heat	272.00	MJ	[37]
U	Electricity	24.30	kWh	[37]

U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[37]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	81.90	kg	[37]

*Fully allocated on spiro, cause economic value is incomparable

P3HT

Thiophene

Category	Process	Amount	Unit	Source
O	Thiophene	1.00	kg	[37]
I	Aluminium, cast alloy {GLO} market for	0.40	kg	[37]
I	Butane {GLO} market for	0.69	kg	[37]
I	Chromium trioxide {RER} market for	0.80	kg	[37]
I	Hydrogen sulfide {RER} market for	1.22	kg	[37]
I	Sulfur {RER} market for	1.52	kg	[37]
U	Electricity, medium voltage {RER} market for	1.81	kWh	[37]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[37]

P3HT

Category	Process	Amount	Unit	Source
O	P3HT	1.00	kg	[37]
I	Bromine {GLO} market for	8.97	kg	[37]
I	Hexane {GLO} market for	2.58	kg	[37]

I	Thiophene	7.81	kg	[37]
I	Tap water {Europe without Switzerland} market for	11136.15	kg	[37]
U	Heat	1.15	GJ	[37]
U	Electricity, medium voltage {RER} market for	36.41	kWh	[37]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[37]

CuSCn

CuSCn

Category	Process	Amount	Unit	Source
O	CuSCn	2.40E-03	kg	[38]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[38]
I	Copper {GLO} market for	1.25E-03	kg	[38]
I	Carbon dioxide, liquid {RER} market for	4.34E-04	kg	[38]
I	Ammonium thiocyanate {GLO} market for	11.97	kg	[38]
I	Potassium hydroxide {GLO} market for	2.58	kg	[38]
I	Hydrochloric acid, from the reaction of hydrogen with chlorine {RER}	7.81	kg	[38]
I	Monochlorobenzene	36.41	kWh	[38]

Encapsulation related chemicals

Vanadium pentoxide

Category	Process	Amount	Unit	Source
O	Vanadium pentoxide	1.00	kg	*
I	Ammonium sulfate {RER} market for	0.31	kg	*

I	Soda ash, dense {RER} market for	0.37	kg	*
I	Oxygen, liquid {RER} market for	0.56	kg	*
I	Petrol, unleaded {RER} market for	0.69	kg	*
I	Ilmenite, 54% titanium dioxide	5.07	kg	*
I	Quicklime ,milled packed {RER} market for	0.61	kg	*
I	Iron ore, crude ore 63% Fe {RER market for	11.90	kg	*
U	Electricity, low voltage {RER} market for	10.94	kWh	*
U	Heat, natural gas, at industrial furnace >100kW {Europe without Switzerland}	1.51	MJ	*
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	*

*direct experience + [34],[35]

Isobutylene production

Category	Process	Amount	Unit	Source
O*	Isobutylene	1.00	kg	[36]
O*	Acetone, liquid {RER} production	0.03	kg	[36]
I	Propylene oxide, liquid {RER} market for propylene oxide, liquid	0.30	kg	[36]
I	Zeolite, powder {GLO} market for	0.07	kg	[36]
I	Phosphoric acid, industrial grade, without water, in 85% solution state {GLO} market for	0.42	kg	[36]
U	Steam, in chemical industry {RER} market for	14.21	MJ	[36]
U	Electricity, medium voltage {RER} market for	0.06	kWh	[36]

U	Tap water {Europe without Switzerland} market for	173.50	kg	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]

*allocation from known impact of co-products

PIB with desiccant production

Category	Process	Amount	Unit	Source
O	PIB with desiccant	1.00	kg	[36]
I	Isobutylene	0.78	kg	[36]
I	Quicklime, milled, packed {RER} market for quicklime, milled, packed	0.23	kg	[36]
P	Electricity, medium voltage {RER} market for	0.03	kWh	[36]

A.1.2. Manufacturing and end-of-life inventory

FTO inventory

FTO glass production

Category	Process	Amount	Unit	Source
O	FTO glass	1.00	m ²	[36]
I	Flat glass, uncoated {RER} market for flat glass, uncoated	7.50	kg	[36]
I	Hydrogen fluoride {RER} market for hydrogen fluoride	1.21E-03	kg	[36]
I	Tin tetrachloride	0.08	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	0.01	kg	[36]
I	Nitrogen, liquid {RER} market for nitrogen, liquid	0.05	kg	[36]
U	Electricity, medium voltage {RER} market for	1.40	kWh	[36]
W	Municipal solid waste {ROW} treatment of, incineration	0.07	kg	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.09	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	7.57E-03	tkm	[36]

FTO glass cutting

Category	Process	Amount	Unit	Source
O	FTO glass (cut)*	1.00	m ²	[36]
O	Glass cullet, sorted {GLO} market for*	0.29	kg	[36]
I	FTO glass	1.00	m ²	[36]

U	Electricity, medium voltage {RER} market for	0.03	kWh	[36]
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*allocation based on known data for co-products

FTO Glass Washing and scribing

Category	Process	Amount	Unit	Source
O	FTO glass, washed	1.00	m2	[36]
I	FTO glass (cut)	1.00	m2	[36]
I	Acetic acid, without water, in 98% solution state {GLO} market for	1.10E-03	kg	[36]
I	Acetone{RER} market for	0.09	kg	[36]
I	Isopropanol {RER} market for	0.09	kg	[36]
U	Electricity, medium voltage {RER} market for	0.20	kWh	[36]
U	Water, ultrapure {RER} market for	3.51	kg	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.10	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.10	Tkm	[36]

ETL inventory

c-TiO₂ (Spray pyrolysis)

Category	Process	Amount	Unit	Source
O	c-TiO ₂ layer	1.00	m2	[36]
I	TAA (in isopropanol, 25 wt%)	1.64E-03	kg	[36]
I	Ethanol {GLO}, market for	0.02	kg	[36]
U	Tap water {Europe without Switzerland} market for	10.76	kg	[36]

U	Electricity, medium voltage {RER} market for	0.89	kWh	[36]*
W	Isopropanol waste incineration	1.23E-03	kg	[36]
W	Ethanol waste incineration	0.02	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	1.20E-03	kg	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.01	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	1.77E-03	tkm	[36]

*For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

SnO2 (Slot die coating)

Category	Process	Amount	Unit	Source
O	SnO2 layer	1.00	m2	[36]
I	Tin oxide {GLO} market for	5.92E-06	kg	[36]
U	Water, deionised {Europe without Switzerland} market for	2.57E-04	kg	[36]
U	Tap water {Europe without Switzerland} market for	3.95E-05	kg	[36]
U	Electricity, medium voltage {RER} market for	0.36	kWh	[36]*
T	Transport, freight train {RER} market group for transport, freight train	1.58E-04	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	2.63E-05	tkm	[36]

*For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

Perovskite layer inventory

Standard DMSO:DMF solvents

Perovskite precursor solution in DMF:DMSO

Category	Process	Amount	Unit	Source
O	Cs _{0.05} FA _{0.79} MA _{0.16} Pb(Br _{0.16} I _{0.84}) ₃ precursor solution (industrial) in DMF	1.00	kg	[25]
I	Formamidinium iodide	0.09	kg	[25]
I	Methylammonium bromide	0.01	kg	[25]
I	Lead iodide	0.25	kg	[25]
I	Caesium iodide	5.13E-03	kg	[25]
I	Lead bromide	0.02	kg	[25]
I	Dimethylformamide {RER} market for	0.48	kg	[25]
I	Dimethyl sulfoxide {RER} market for	0.14	kg	[25]
U	Electricity, low voltage {RER} market for	8.85E-03	kWh	[36]*
T	Transport, freight train {RER} market group for transport, freight train	0.60	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.10	tkm	[36]

*For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

Perovskite layer, DMF:DMSO (slot die coated)

Category	Process	Amount	Unit	Source
O	Perovskite layer, HI (slot die coated)	1.00	m ²	[25]
I	Cs _{0.05} FA _{0.79} MA _{0.16} Pb(Br _{0.16} I _{0.84}) ₃ precursor solution (industrial) in DMF	8.69E-04	kg	[25]

U	Electricity, medium voltage {RER} market for	0.54	kWh	*
W	DMF:DMSO- Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	5.44E-04	kg	[25]

*The electricity consumptions accounts for slot die coating and annealing. Slot die coating electricity consumption is obtained from direct contact with FOM technologies, while the one related to conveyor oven is further modelled at the end of the chapter.

Green solvents

Perovskite precursor solution in Acetonitrile

Category	Process	Amount	Unit	Source
O	Cs _{0.05} FA _{0.79} MA _{0.16} Pb(Br _{0.16} I _{0.84}) ₃ precursor solution (industrial) in Acetonitrile	1.00	kg	[25]
I	Formamidinium iodide	0.09	kg	[25]
I	Methylammonium bromide	0.01	kg	[25]
I	Lead iodide	0.25	kg	[25]
I	Caesium iodide	5.13E-03	kg	[25]
I	Lead bromide	0.02	kg	[25]
I	Acetonitrile {GLO} market for	0.62	kg	[32]*
U	Electricity, low voltage {RER} market for	8.85E-03	kWh	[36]**
T	Transport, freight train {RER} market group for transport, freight train	0.60	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.10	tkm	[36]

*In the reference [32], a mixture of Acetonitrile and 2-methoxyethanol (C₃H₈O₂) are used as solvent in the deposition of perovskite. For sake of simplicity, given the complexity of the second solvent to me modelled, just

acetonitrile was considered. In the ethanol version, accounting for the best-case scenario, the same amount of acetonitrile was replaced by ethanol.

**For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

Perovskite layer, Acetonitrile (slot die coated)

Category	Process	Amount	Unit	Source
O	Perovskite layer, HI (slot die coated)	1.00	m ²	[32]
I	Cs _{0.05} FA _{0.79} MA _{0.16} Pb(Br _{0.16} I _{0.84}) ₃ precursor solution (industrial) in DMF	8.80E-04	kg	[32]
U	Tap water {Europe without Switzerland} market for	14.55	kg	[36]
U	Electricity, medium voltage {RER} market for	0.46	kWh	*
W	Acetonitrile- Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	5.46E-04	E	[32]

*The electricity consumptions accounts for slot die coating and annealing. Slot die coating electricity consumption is obtained from direct contact with FOM technologies, while the one related to conveyor oven is further modelled at the end of the chapter.

HTL inventory

PTAA

PTAA, precursor solution

Category	Process	Amount	Unit	Source
O	PTAA, precursor solution	1.00	kg	[31]
I	PTAA	2.70E-03	kg	[31]
I	Monochlorobenzene {GLO} market for	1.00	kg	[31]
U	Electricity, low voltage {RER} market for	8.85E-03	kWh	[36]*

T	Transport, freight train {RER} market group for transport, freight train	0.60	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.10	tkm	[36]

*For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

PTAA layer (slot die coating)

Category	Process	Amount	Unit	Source
O	PTAA layer	1.00	m ²	[31]
I	PTAA, precursor solution	2.70E-03	kg	[31]
U	Electricity, medium voltage {RER} market for	0.33	kWh	*
W	Chlorobenzene- Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	2.69E-03	kg	[31]

*The electricity consumptions accounts for slot die coating and annealing. Slot die coating electricity consumption is obtained from direct contact with FOM technologies, while the one related to conveyor oven is further modelled at the end of the chapter.

P3HT

P3HT, precursor solution

Category	Process	Amount	Unit	Source
O	P3HT, precursor solution	1.00	kg	[37]
I	P3HT	0.01	kg	[37]
I	Monochlorobenzene {GLO} market for	0.99	kg	[37]
U	Electricity, low voltage {RER} market for	8.85E-03	kWh	[36]*

T	Transport, freight train {RER} market group for transport, freight train	0.60	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.10	tkm	[36]

*For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

P3HT layer (slot die coating)

Category	Process	Amount	Unit	Source
O	P3HT layer	1.00	m2	[37]
I	P3HT, precursor solution	0.01	kg	[37]
U	Electricity, medium voltage {RER} market for	0.33	kWh	*
W	Chlorobenzene- Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	0.01	kg	[37]

*The electricity consumptions accounts for slot die coating and annealing. Slot die coating electricity consumption is obtained from direct contact with FOM technologies, while the one related to conveyor oven is further modelled at the end of the chapter.

CuSCn

CuSCn, precursor solution

Category	Process	Amount	Unit	Source
O	CuSCn, precursor solution	1.00	kg	[30]
I	CuSCn	0.07	kg	[30]
I	DES	0.70	kg	[30]
I	MES	0.23	kg	[30]
U	Electricity, low voltage {RER} market for	8.85E-03	kWh	[36]*
T	Transport, freight train {RER} market group for transport, freight train	0.60	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.10	tkm	[36]

*For stirring and precursor preparation, the same value is applied to all the solvents in the analysis.

CuSCn layer (slot die coating)

Category	Process	Amount	Unit	Source
O	CuSCn layer	1.00	m ²	[30]
I	CuSCn, precursor solution	0.07	kg	[30]
U	Electricity, medium voltage {RER} market for	0.43	kWh	*
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.05	kg	[30]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.02	kg	[30]

*The electricity consumptions accounts for slot die coating and annealing. Slot die coating electricity consumption is obtained from direct contact with FOM technologies, while the one related to conveyor oven is further modelled at the end of the chapter.

Carbon electrode inventory

Carbon electrode (screen-printed)

Category	Process	Amount	Unit	Source
O	Carbon electrode layer*	1.00	m ²	[36]
I	Monochlorobenzene {GLO} market for	5.47E-03	kg	[36]
I	Graphite {GLO} market for	0.02	kg	[36]
I	Terpineol	0.06	kg	[36]
I	Nitrocellulose	0.02	kg	[36]
I	Fibre, polyester {GLO} market for fibre, polyester	2.14E-04	kg	[36]
U	Tap water {Europe without Switzerland} market for	14.55	kg	[36]

U	Electricity, medium voltage {RER} market for	0.25	kWh	[36]
W	Terpineol- Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	0.06	kg	[36]
W	Nitrocellulose- Municipal solid waste {ROW} treatment of, incineration	0.02	kg	[36]
W	Municipal solid waste {ROW} treatment of, incineration	2.14E-04	kg	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.07	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.01	tkm	[36]

*The same receipt used for the kind of carbon used in the source is applied, even if the deposition method is different.

Encapsulation inventory

EVA+PIB

EVA+PIB Encapsulation

Category	Process	Amount	Unit	Source
O	Encapsulated PSM	1.00	m2	[36]
I	Ethylvinylacetate, foil {GLO} market for	0.48	kg	[36]
I	Polyisobutylene with desiccant	0.04	kg	[36]
U	Electricity, medium voltage {RER} market for	0.99	kWh	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.10	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.05	tkm	[36]

Glass frit

Glass frit Encapsulation

Category	Process	Amount	Unit	Source
O	Encapsulated PSM	1.00	m2	*
I	Lead {GLO} market for	5.11E-03	kg	*
I	Boric Oxide {GLO} market for	6.18E-04	kg	*
I	Silica sand {GLO} market for	4.94E-04	kg	*
I	Aluminium oxide {IAI Area, EU27 & EFTA} market for	4.94E-04	kg	*
I	Epoxy resin, liquid {RER} market for	2.47E-04	kg	*
I	Vanadium pentoxide	6.31E-04	kg	*
I	Tellurium, semiconductor-grade {GLO} market for	5.74E-04	kg	*
I	Zirconium oxide {GLO} market for	5.74E-04	kg	*
I	Copper oxide {RER} market for	2.87E-05	kg	*
I	Barium oxide(99,5%) {GLO} market for	1.72E-04	kg	*
I	Zinc oxide(99,999%) {GLO} market for	1.72E-04	kg	*
U	Electricity, medium voltage {RER} market for	1.66	kWh	*
T	Transport, freight train {RER} market group for transport, freight train	1.82E-03	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	9.11E-04	tkm	[36]

*From direct experience with Seyedali Emami and his teams in the UPTEC labs.

Balance of module components inventory

Back sheet glass

Category	Process	Amount	Unit	Source
O	Back sheet glass	1.00	m2	[36]
O	Glass cullet, sorted {GLO} market for	0.39	kg	[36]
I	Solar glass, low-iron {RER} market for	7.89	kg	[36]
U	Water, ultrapure {RER} market for water, ultrapure	3.51	kg	[36]
U	Electricity, medium voltage {RER} market for	0.34	kWh	[36]
I	Tempering, flat glass {RER} processing	7.89	kg	[36]

*allocated considered known co-product impact

Bus bar and junction box attachment

Category	Process	Amount	Unit	Source
O	Bus bar and junction box (attached)	1.00	m2	[36]
I	Solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry {GLO} market for	3.75E-04	kg	[36]
I	Indium {GLO} market for	7.05E-04	kg	[36]
I	Copper {GLO} market for	8.88E-03	kg	[36]
I	Glass fibre reinforced plastic, polyamide, injection moulded {GLO} market for	0.11	kg	[36]
I	Silicone product {RER} market for silicone product	2.97E-03	kg	[36]
U	Electricity, medium voltage {RER} market for	0.79	kWh	[36]

Testing

Category	Process	Amount	Unit	Source
O	Tested PSM	1.00	m2	[36]

I	Electricity, medium voltage {RER} market for	0.20	kWh	[36]
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Use Phase inventory

Use phase

Category	Process	Amount	Unit	Source
T	Transport, freight train {RER} market group for transport, freight train	9.00	tkm	*
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	1.50	tkm	*

*Assumed with standard distance values from [36].

Remanufacturing procedure inventory

Remanufacturing

Category	Process	Amount	Unit	Source
O	Remanufacturing procedure	1.00	m2	[36]
I	Acetone, liquid {RER} market for acetone, liquid	0.75	kg	[36]
I	Methylamine {RER} market for	0.12	kg	[36]
I	Ethanol, without water, in 99.7% solution state, from fermentation {GLO} market for	0.24	kg	[36]
U	Electricity, medium voltage {RER} market for	2.09	kWh	[36]
U	Water, deionised {Europe without Switzerland} water production, deionised	0.62	kg	[36]
U	Chemical factory, organics {GLO} market for	4.00E-10	unit	[36]
U	Tap water {Europe without Switzerland} market for	14.55	kg	[36]

W	Treatment of cake from sorting of waste plastic, sanitary landfill {RER}	0.15	kg	[36]
W	Waste polyethylene {CH} treatment of, sanitary landfill	0.73	kg	[36]
W	Acetone waste incineration	0.75	kg	[36]
W	Ethanol waste incineration	0.24	kg	[36]
T	Transport, freight train {RER} market group for transport, freight train	0.32	tkm	[36]
T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	1.28	tkm	[36]

Incineration procedure inventory

Incineration

Category	Process	Amount	Unit	Source
O	Incineration	1.00	m2	[36]
W	Waste glass {GLO} treatment of, municipal incineration	15.00	kg	[36]
W	Waste polyethylene {CH} treatment of, municipal incineration	0.73	kg	[36]
W	Waste rubber, unspecified {Europe without Switzerland} treatment of waste rubber, unspecified, municipal incineration	0.04	kg	[36]
W	Waste, treatment of plastic industr. electronic, to municipal incineration {GLO}	0.11	kg	[36]
W	Waste copper {Europe without Switzerland} treatment of waste copper, municipal incineration	8.88E-03	kg	[36]
W	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration	0.06	kg	[36]

T	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	1.60	tkm	[36]
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A.1.3. Chemicals waste incineration inventory

Heat produced is accounted as burden free.

Ethanol waste incineration

Category	Process	Amount	Unit	Source
O	Ethanol incinerated	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	3	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

Diethyl ether waste incineration

Category	Process	Amount	Unit	Source
O	Diethyl ether incinerated	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	7.30	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]

P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]
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Isopropanol waste incineration

Category	Process	Amount	Unit	Source
O	Isopropanol incineration	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	5.25	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

Methanol waste incineration

Category	Process	Amount	Unit	Source
O	Methanol incinerated	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	-0.36	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration, with energy recovery	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

Ethyl acetate incineration

Category	Process	Amount	Unit	Source
O	Ethyl acetate	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	-0.22	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration, with energy recovery	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

DMF waste incineration

Category	Process	Amount	Unit	Source
O	DMF incinerated	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	1.23	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

DMSO waste incineration

Category	Process	Amount	Unit	Source
O	DMSO incinerated	1	kg	[36]

O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	0.64	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

Benzene waste incineration

Category	Process	Amount	Unit	Source
O	Butanol incineration	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	7.62	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

Benzene waste incineration

Category	Process	Amount	Unit	Source
O	Acetone incineration	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	4.11	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]

P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]
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Chlorobenzene waste incineration

Category	Process	Amount	Unit	Source
O	Chlorobenzene incineration	1	kg	[36]
O	Heat, from steam, in chemical industry {RER} steam production, as energy carrier, in chemical industry	3.56	MJ	[36]
W	Spent solvent mixture {Europe without Switzerland} treatment of spent solvent mixture, hazardous waste incineration	1	kg	[36]
P	Transport, freight, lorry 16-32 metric ton, euro6 {RER} market for transport, freight, lorry 16-32 metric ton, EURO6	0.1	t*km	[36]

A.1.4. Balance of system components inventory

Balance of system

Category	Process	Amount	Unit	Source
O	Balance of system, utility scale (500kWp)	1.00	unit	[36]
I	Inverter 500 kW	1.00	unit	[36]
I	Photovoltaic mounting system	0.23	Kg	[36]

A.1.1. Conveyor oven electricity consumption and cost

Power [kW]	Temperature [°C]	Conveyor length [m]	Time [min]	Throughput [m ² /hour]	Source
20	100	14.1	10	132.27	[36]
35	850	30	30	88.2	[36]

Layer	Power [kW]	Temperature [°C]	Conveyor length [m]	Time [min]	Throughput [m ² /hour]	Eel [kWh/m ²]
TiO ₂	28.00	500.00	14.10	10.00	132.27	0.21
SnO ₂	20.80	140.00	30.00	30.00	88.20	0.24

PL,DM						
F	20.00	100.00	30.00	30.00	88.20	0.23
Pl,green	21.00	150.00	18.08	15.00	121.25	0.17
PTAA	20.00	100.00	14.10	10.00	132.27	0.15
CuSCn	20.80	140.00	14.10	10.00	132.27	0.16
P3HT	20.80	140.00	14.10	10.00	132.27	0.16
Carbon	20.40	120.00	18.08	15.00	121.25	0.17

LAYER	Investment cost [USD/machinery]
TiO2	350000
SnO2	2000000
PL,DMF	2000000
Pl,green	762500
PTAA	350000
CuSCn	350000
P3HT	350000
Carbon	762500

From source [36] the power consumption for each layer is obtained by linear interpolation. The same was applied for costs, that were obtained from direct contact with manufacturers or from literature. [42][43]

B Appendix B- Technoeconomic analysis

B.1. Manufacturing cost (MC)

FTO glass

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
FTO coated solar glass	1.00E+00	m2	-	6.92E+00	[43]
Industrial detergent (acetic acid)	1.00E+00	g	[45]	7.78E-03	[50]
Tap water	3.51E+03	g	[45]	3.20E-06	[52]
Acetone	1.11E+02	g	[45]	3.29E-03	[50]
Isopropanol	1.09E+02	g	[45]	1.30E-03	[50]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Electricity cleaning	2.00E-03	KW/ tool	[43]	1.42E-01	[42]
Labour cleaning	4.72E-03	Emp l/too l	[43]	1.81E+01	[46]
Electricity laser scribing	2.89E-02	kWh	[36]	1.42E-01	[42]
Labour laser scribing	4.99E-03	Emp l/too l	[43]	1.81E+01	[46]

TiO2 blocking layer

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
TAA (in isopropanol, 25 wt%)	1.71E+00	ml	[36]	2.40E-02	[53]
Ethanol	1.61E-02	kg	[36]	4.34E+00	[50]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	1.06E-02	Tones *km	[36]	9.68E-03	***
Transport, freight, lorry	1.77E-03	Tones *km	[36]	3.87E-02	****
Electricity spray pyrolysis	5.88E-01	kWh	[36]	1.42E-01	[42]
Labour spray pyrolysis	6.86E-03	Empl/ tool	[43]*	1.81E+01	[46]
Electricity anealing	2.12E-01	kWh	[A.1.1]	1.42E-01	[42]
Labour annealing	3.43E-03	Empl/ tool	[43]	1.81E+01	[46]
Cooling water	1.08E+01	liter	[36]	4.00E-06	[52]
Hazardous waste management	1.20E-03	kg	**	1.61E-01	[48]
Solvents waste management	1.73E-02	kg	**	3.21E-03	[48]

*considered equal to slot die coating

**all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

***european mean value

****TRANSPORT MODEL, at the end of appendix B.1

SnO₂, water

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
SnO ₂	5.92E-03	g	[47]	1.16E-01	[42]
DI water	2.57E-01	ml	[47]	1.44E-03	[51]
Water	3.95E-02	ml	[47]	4.00E-06	[52]
Others	Specific Amount	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	3.71E-03	tkm	[36]	9.68E-03	*
Transport, freight, lorry	6.18E-04	tkm	[36]	3.87E-02	****
Electricity slot die coating	1.22E+01	KW/ tool	[36]	1.42E-01	[42]
Labour slot die coating	6.50E-01	Empl/ tool	[43]	1.81E+01	[46]
Electricity annealing	2.36E-01	kWh/ m ²	[A.1.1]	1.42E-01	[42]
Labour annealing	3.25E-01	Empl /tool	[43]	1.81E+01	[46]
Cooling water	5.06E+00	liter	[36]	4.00E-06	[42]

*european mean value

****TRANSPORT MODEL, at the end of appendix B.1

DMF/DMSO Perovskite

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
FAI(CH ₅ IN ₂)	7.49E-02	g	[25]	1.29E+00	[42]
MABr(CH ₃ NH ₃ Br)	9.87E-03	g	[25]	1.53E+01	[50]***

PbI2	2.13E-01	g	[25]	3.50E+00	[42]
CsI	4.40E-03	g	[25]	4.20E-01	[43]
PbBr2	1.83E-02	g	[25]	1.59E+00	[43]
MAcI	1.10E-02	g	[25]	1.43E-01	[50]***
DMF	4.16E-01	g	[25]	1.81E-01	[43]
DMSO ((CH3)2SO)	1.21E-01	g	[25]	3.74E-01	[43]
Others	Specific Amount [Unit/m²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	5.21E-04	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	8.69E-05	Tones *km	[36]	3.87E-02	****
Electricity slot die coating	2.14E-01	kWh/m ²	[42]	1.42E-01	[42]
Labour slot die coating	1.14E-02	Empl/tool	[46]	1.81E+01	[46]
Electricity annealing	2.27E-01	kWh	[A.1.1]	1.42E-01	[42]
Labour annealing	5.70E-03	Empl/tool	[46]	1.81E+01	[46]
Cooling water	5.06E+00	liter/m ²	[36]	4.00E-06	[42]
Solvents waste management	5.44E-04	Kg/m ²	*	3.21E-03	[48]

*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

**european mean value

***COST MODEL, at the end of the appendix B1

****TRANSPORT MODEL, at the end of appendix B.1

DMF/DMSO Perovskite

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
FAI(CH ₅ IN ₂)	7.49E-02	g	[49]	1.29E+00	[42]
MABr(CH ₃ NH ₃ Br)	9.87E-03	g	[49]	1.53E+01	[50]***
PbI ₂	2.13E-01	g	[49]	3.50E+00	[42]
CsI	4.40E-03	g	[49]	4.20E-01	[43]
PbBr ₂	1.83E-02	g	[49]	1.59E+00	[43]
MAcI	1.10E-02	g	[49]	1.43E-01	[50]***
DMF	4.16E-01	g	[49]	1.81E-01	[43]
DMSO ((CH ₃) ₂ SO)	1.21E-01	g	[49]	3.74E-01	[43]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	5.21E-04	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	8.69E-05	Tones *km	[36]	3.87E-02	****
Electricity slot die coating	2.14E-01	kWh/ m ²	[42]	1.42E-01	[42]
Labour slot die coating	1.14E-02	Empl/ tool	[46]	1.81E+01	[46]
Electricity annealing	2.27E-01	kWh	[A.1.1]]	1.42E-01	[42]
Labour annealing	5.70E-03	Empl/ tool	[46]	1.81E+01	[46]
Cooling water	5.06E+00	l/m ²	[36]	4.00E-06	[52]

Solvents waste management	5.44E-04	Kg/m ²	*	3.21E-03	[48]
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*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

**european mean value

***COST MODEL, at the end of the appendix B1

****TRANSPORT MODEL, at the end of appendix B.1

Green solvents perovskite layer

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
FAI(CH ₅ IN ₂)	7.49E-02	g	[49]	1.29E+00	[42]
MABr(CH ₃ NH ₃ Br)	9.87E-03	g	[49]	1.53E+01	[50]***
PbI ₂	2.13E-01	g	[49]	3.50E+00	[42]
CsI	4.40E-03	g	[49]	4.20E-01	[43]
PbBr ₂	1.83E-02	g	[49]	1.59E+00	[43]
MACl	1.10E-02	g	[49]	1.43E-01	[50]***
Acetonitrile (C ₂ H ₃ N)	2.53E-01	ml	[32]	2.00E-02	[50]***
2-methoxyethanol (C ₃ H ₈ O ₂)	2.39E-01	g	[32]	6.80E-02	[50]***
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	5.21E-04	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	8.69E-05	Tones *km	[36]	3.87E-02	****
Electricity slot die coating	2.14E-01	kWh/m ²	[42]	1.42E-01	[42]

Labour slot die coating	1.14E-02	Empl/ tool	[46]	1.81E+01	[46]
Electricity annealing	1.73E-01	kWh	[A.1.1]	1.42E-01	[42]
Labour annealing	5.70E-03	Empl/ tool	[46]	1.81E+01	[46]
Cooling water	5.06E+00	liter/ m ²	[42]	4.00E-06	[52]
Solvents waste management	5.46E-04	Kg/m ²	*	3.21E-03	[48]

*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

**european mean value

****TRANSPORT MODEL, at the end of appendix B.1

PTAA

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
PTAA	1.18E-03	g	[31]	1.65E+03	[31]
chlorobenzene	3.94E-01	ml	[31]	1.42E-02	[53]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	1.62E-03	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	2.70E-04	Tones *km	[36]	3.87E-02	****
Electricity slot die coating	1.47E-01	kWh/ m ²	[36]	1.42E-01	[42]

Labour slot die coating	7.82E-03	Empl	[43]	1.81E+01	[46]
Electricity annealing	1.51E-01	kWh/ m ²	[A.1.1]	1.42E-01	[42]
Labour annealing	3.91E-03	Empl	[43]	1.81E+01	[46]
Cooling water	5.06E+00	liter	[36]	4.00E-06	[52]
Electricity laser scribing	2.89E-02	kWh/ m ²	[36]	1.42E-01	[42]
Labour laser scribing	4.99E-03	Empl	[43]	1.81E+01	[46]
Solvents waste management	2.69E-03	kg	*	3.21E-03	[48]

*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

**european mean value

****TRANSPORT MODEL, at the end of appendix B.1

CuSCn

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
CuSCN	2.75E-03	g	[30]	2.39E+00	[31]
DES	2.95E-02	ml	[30]	1.80E-01	*
MES	9.84E-03	ml	[30]	6.00E-02	*
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	3.93E-02	Tones *km	[36]	9.68E-03	***
Transport, freight, lorry	6.54E-03	Tones *km	[36]	3.87E-02	****
Electricity slot die coating	2.45E-01	kWh/ m ²	[36]	1.42E-01	[42]

Labour slot die coating	1.04E-03	Empl oyees	[43]	1.81E+01	[46]
Electricity annealing	1.57E-01	kWh/ m ²	[A.1.1]	1.42E-01	[42]
Labour annealing	5.21E-04	Empl oyees	[43]	1.81E+01	[46]
Cooling water	5.06E+00	liter	[36]	4.00E-06	[52]
Electricity laser scribing	2.89E-02	kWh/ m ²	[36]	1.42E-01	[42]
Labour laser scribing	4.99E-03	empl	[43]	1.81E+01	[46]
Solvents waste management	6.11E-02	kg	**	3.21E-03	[48]

*as chlorobenzene

**all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

***european mean value

****TRANSPORT MODEL, at the end of appendix B.1

P3HT

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
P3HT	4.72E-03	g	[37]	2.41E+02	[50]***
chlorobenzene	3.94E-01	ml	[37]	1.42E-02	[53]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	7.20E-03	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	1.20E-03	Tones *km	[36]	3.87E-02	****

Electricity slot die coating	1.47E-01	kWh	[36]	1.42E-01	[42]
Labour slot die coating	3.23E-03	Empl oyees	[43]	1.81E+01	[46]
Electricity annealing	1.57E-01	kWh	[A.1.1]	1.42E-01	[42]
Labour annealing	3.91E-03	Empl oyees	[43]	1.81E+01	[46]
Cooling water	5.06E+00	liter	[36]	4.00E-06	[52]
Electricity laser scribing	2.89E-02	kWh	[36]	1.42E-01	[42]
Labour laser scribing	4.99E-03	empl	[43]	1.81E+01	[46]
Solvents waste management	1.19E-02	kg	*	3.21E-03	[48]

*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

**european mean value

****TRANSPORT MODEL, at the end of appendix B.1

Carbon electrode

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Carbon back electrode	1.00E+00	m2	[-]	1.82E+00	[11]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	6.58E-02	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	1.10E-02	Tones *km	[36]	3.87E-02	****
Electricity screen printing	5.04E-02	kWh	[42]	1.42E-01	[42]
Labour screen printing	5.37E-03	empl	[42]	1.81E+01	[46]

Electricity annealing	1.68E-01	kWh	[A.1.1]]	1.42E-01	[42]
Labour annealing	2.69E-03	Empl oyees	[43]	1.81E+01	[46]
Electricity laser scribing	2.89E-02	kWh	[36]	1.42E-01	[42]
Labour laser scribing	4.99E-03	empl	[43]	1.81E+01	[42]
Cooling water	1.45E+01	liter	[36]	4.00E-06	[52]
Solid mixture waste management	2.07E-02	kg	[36]	3.21E-04	[48]
Solvents waste management	6.16E-02	kg	*	3.21E-03	[48]

*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

**european mean value

***TRANSPORT MODEL, at the end of appendix B.1

Glass frit

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Glass frit	9.29E+00	g	[-]	9.00E-01	*****
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	1.82E-03	Tones *km	[36]	9.68E-03	**
Transport, freight, lorry	9.11E-04	Tones *km	[36]	3.87E-02	****
Electricity, laser sealing	7.79E-01	kWh	[42]	1.42E-01	[42]
Electricity hot plate	8.84E-01	kWh	[42]	1.42E-01	[42]
Labour, laser sealing	5.37E-03	empl	*	1.81E+01	[46]

*given the high automation of the production, it's assumed equal to screen printing

**european mean value

****TRANSPORT MODEL, at the end of appendix B.1

*****direct contact and quotations from YEKglasses

EVA+PIB

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Ethylvinylacetate, foil	9.29E+00	g	[-]	9.00E-01	[42],[43]
PIB with desiccant	-	-	-	9.08E-01	[53]
Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	1.05E-01	Tones *km	[36]	9.68E-03	*
Transport, freight, lorry	5.25E-02	Tones *km	[36]	3.87E-02	****
Electricity lamination	9.86E-01	kWh	[42]	1.42E-01	[42]
Labour lamination	5.37E-03	empl	[42]	1.81E+01	[42]

*european mean value

****TRANSPORT MODEL, at the end of appendix B.1

Balance of module

Material	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Adhesive	4.17E+00	m	[42]	6.00E-02	[42]
Glue	1.40E-01	g	[42]	1.67E+00	[42]
Tape	5.28E+00	m	[42]	5.80E-02	[42]

Cover glass	1.00E+00	m2	[42]	3.99E+00	[42]
Junction box	1.00E+00	piece	[42]	1.80E-01	[42]
Others	Specific Amount [Unit/m²]	Unit	Source	Specific cost [\$/Unit]	Source
Electricity tot	3.91E-01	kWh	[42]	1.42E-01	[42]
Labour tot	5.37E-02	empl	[42]	1.81E+01	[42]

Overhead

Others	Specific Amount [Unit/m²]	Unit	Source	Specific cost [\$/Unit]	Source
Electricity tot	3.78E+00	kWh	[36]	1.42E-01	[42]

Remanufacturing

Material	Specific Amount [Unit/m²]	Unit	Source	Specific cost [\$/Unit]	Source
Acetone	7.46E-01	kg	[25]	3.29E-03	[50]
Methylamine	1.18E-01	kg	[25]	3.29E-03	*
Ethanol	2.40E-01	kg	[25]	4.34E+00	[50]
Water, deionised	6.22E-01	kg	[25]	1.44E-03	[51]
Tap water	1.45E+01	kg	[25]	4.00E-06	[52]
Others	Specific Amount [Unit/m²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight train	3.20E-01	Tones *km	[36]	9.68E-03	***
Transport, freight, lorry	1.28E+00	Tones *km	[36]	3.87E-02	****

Electricity tot	2.09E+00	kWh/ m ²	[42]	1.42E-01	[42]
Labour tot	9.45E-03	Empl/ tool	[46]	1.81E+01	[42]
Solid mixture waste management	8.87E-01	kWh	[42]	3.21E-04	[48]
Solvents waste management	1.11E+00	Empl/ tool	*	3.21E-03	[48]

*assumed as acetone price wise

**all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

***european mean value

****TRANSPORT MODEL, at the end of appendix B.1

Incineration

Others	Specific Amount [Unit/m ²]	Unit	Source	Specific cost [\$/Unit]	Source
Transport, freight lorry	1.60E+00	Tones *km	[36]	3.87E-02	****
Solid mixture waste management	1.59E+01	kg	[42]	3.21E-04	[48]
Hazardous waste management	5.95E-02	kg	*	1.61E-01	[48]

*all the evaporated amount of solvent is considered as recollected and managed as solvent waste management if not toxic, as hazardous waste if toxic

****TRANSPORT MODEL, at the end of appendix B.1

***COST MODEL

Knowing the price per unit (P_1 and P_R) of a good for two different delivered quantities (Q_1 and Q_R), the price per unit for a third delivery size can be obtained as it follows.

$$P_2 = P_1 * \frac{Q_2^{\frac{\log(\frac{P_1}{P_R})}{\log(\frac{Q_1}{Q_R})}}}{Q_1}$$

This was particularly useful for evaluating costs of chemicals and materials from online suppliers' databases like Fisher scientific [53] or Sigmaaldrich[50].

The cost of machineries is displayed into the next table. It is the cost of machineries for the basic configuration. To obtain the specific cost for each configuration, some considerations must be considered. The scale coefficient is obtained as the ratio of the target throughput and the throughput at obtained from source cost. Each percentual values is assumed, the others are obtained by literature. [42] [43]

**** TRANSPORT MODEL

Costs for the transport model

Category	Cost Item	Cost	Unit	Source
Vehicle	Tractor	113000	USD	[54]
	Track	50000	USD	[54]
	Total km lifetime	1500000	km	*
Pilot	Pilot salary	15	USD/working hour	[46]
	Working hours per day	9	working hours/day	[55]
	Working days per year	240	working days /year	[55]
	Vehicle lifetime	10	years	[54]
Fuel	Fuel consumption	0.3	l/km	[54]
	Fuel price	1.5	USD/l	*
Vehicle	Higway price	0.2	USD/km	*
	Higway percentage	80	%	*

*coherent hypothesis at the present moment

Weights and results of the models

	Value	Unit
Gross vehicle weight	44	Ton
Tractor weight	8	Ton
Maximum tranported weight	36	Ton
Mean transported weight	20	Ton

	Value	Unit
TOT tonkm	30000000	Ton*km
TOT cost lifetime	1162000.16	USD
USD/tonkm	0.038733339	USD/ton*km

Total gross manufacturing area	4382
Extra space	1972
Total building area	6354

from [36], considering 1000\$/m² for the subsequent cost analysis.[41]

B.3. Levelized cost of electricity (LCOE)

LCOE assumptions

LCOE cost item	Values
O&M annual cost	\$7/(kW·yr)
Performance ratio	80 [%]
Insolation	1850 [kWh/m ²]
Installation and balance of plant	55 [USD/m ²]
O&M	0.007 [USD/m ²]
Inverter cost	0.0606 [USD/W _{DC}]
Inverter lifetime	15 [years]
Discount rate	0.037

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List of symbols

AZO	Aluminum-doped Zinc Oxide
BOM	Balance of Module
BOS	Balance of System
DC	Direct current
EOL	End of life
EPBT	Energy Payback Time
EROI	Energy Return on Investment
ETL	Electron Transport Layer
EU	European union
EVA	Ethylene-vinyl acetate
FETP	Freshwater Ecotoxicity Potential
FTO	Fluorine-doped Tin Oxide
GHG	Greenhouse Gas
HTL	Hole Transport Layer
IEA	International energy agency
ITO	Indium Tin Oxide
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
MC	Manufacturing Cost
METP	Marine Ecotoxicity Potential
MSP	Minimum Sustainable Price
OH	Overhead
PCE	Power Conversion Efficiency
PL	Perovskite Layer
PSM	Perovskite Solar Module
PT	Full name not found
PV	Photovoltaic
PVKL	Perovskite layer
REP	Renewable Electricity Penetration
RES	Renewable Energy Share
SM	System Model
TCO	Transparent Conductive Oxide
TEA	Techno-Economic Analysis

TETP Terrestrial Ecotoxicity Potential

WAAC Weighted Average Cost of Capital

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DIAMOND

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