The Material Use of Perovskite Solar Cells

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Abstract

This work quantifies, through material flow analysis, the demand and discard of lead and indium in a scenario of future adoption of perovskite solar cells, considering four aspects for the construction of scenarios. The first aspect was the type of perovskite solar, which was considered either as single junction or as tandem with silicon solar cell. The second aspect considered was the future market share, with assumptions of 20% and 80% in 2050. The third aspect was lifetime of the modules, considered to be either 5 years or 30 years. Finally, scenarios with and without recycling were evaluated. The results show that the demand for lead might not be significant compared to the current supply. On the other hand, the use of indium in a high market share might go beyond the current supply of this material. The use of tandem technologies might decrease the use of materials because of higher power conversion efficiency. Finally, a longer lifetime and the recycling at the end of life might decrease considerably the amount of materials that are dispersed into the environment.

1 Introduction

Zero and low-carbon energy supplies, including renewable energy, have been acknowledged as a main part of the strategy to mitigate climate change and limit the increase of temperature in the surface of the Earth because of anthropogenic greenhouse gas emissions [1]. Among the renewable energy technologies, photovoltaic devices can supply the required electricity and at the same time diminish the emissions per unit of energy produced compared to conventional conversion using fossil fuels [2]. Multiple photovoltaic technologies have been developed to increase the energy conversion and minimize the costs, making photovoltaic technologies competitive regarding conventional fossil fuels. Perovskite Solar Cells (PSC) have been acknowledged as a photovoltaic technology with a high potential, with an increase in power conversion efficiency (PCE) from 3.8% in 2009 to 22.7% in 2017 [3]. Such PCE is now comparable to the best research efficiencies for commercial technologies such as cadmium telluride (CdTe), cupper-indium-gallium-selenide (CIGS), and the most common technology polycrystalline silicon (p-Si) and close to the performance of single crystalline silicon (s-Si) and silicon heterojunction (SHJ) [3]. Besides PCE, multiple techniques have been developed to produce the cells using liquid solutions to deposit the absorbing materials or gas phase deposition, allowing the possibility of having devices at lower costs [4, 5].

Perovskite refers to the material used in the absorber of photovoltaic cells. These are materials with the chemical formula ABX_3, named after the Russian mineralogist Lev Perov. For photovoltaic purposes A is usually an organic cation, B is commonly lead and X is a halide anion. Perovskites have been produced in research laboratories in configurations denominated single junction or in combination with other absorbing materials, to produce what has been called tandems. In the first case, the efficiency is constrained to around 33% by the Shockley-Queisser limit , while in the latter case the combination offers the possibility of increasing the efficiency beyond 40% [6].

Although one of the advantages of perovskite technologies has been the use of abundant materials in their absorber, a complete photovoltaic device requires additional layers with specific functions, such as collecting and conducting the charge carriers produced in the absorber or carrying the charges to an external circuit, in which they can be used. In the case of PSC, organic layers have been used to perform these tasks, but due to cost and stability issues these layers have been gradually changed to inorganic layers containing elements such as nickel or copper, among others [7, 8]. Additionally, transparent electrodes are also part of the cells [9]. Indium tin oxide and fluorine doped tin oxide have been traditionally used for this purpose [10].

The use of lead has been appointed as critical, due to the high toxicity of this element [11]. Other elements used for other layers are produced in limited amounts, leading to the motivation to quantify the amount of materials required for the future deployment of this technology and the amount of materials that can be dispersed into the environment because of this deployment. This work approaches the question of the material use and dissipation under different future scenarios, considering the future adoption of perovskite and the possibility of recycling of these materials. This work is not be misunderstood as a prediction but gives an overview of how the demand and the flows in the different life stages could develop if some of the assumptions made in this study are fulfilled in reality. Although the assumptions made for the study are as realistic as possible, high uncertainties remain in all the life stages in all scenarios.

2 Methodology

A material flow analysis (MFA) was done using the free “subSTance flow Analysis” (STAN) software developed by TU Vieanna that performs this kind of analysis according to the Austrian standard ÖNORM S 2096 [12]. The

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commercialisation of modules containing PSC technologies is forecasted to start in 2020. A horizon of 30 years was considered, since the life time of current commercial technologies is between 25 and 30 years. Hence the calculations were done for a horizon between 2020 and 2050. In the following sections, the different assumptions and methods used will be explained.

2.1 Materials Analysed

Two metals contained in two different layers were analysed in this work. The first one was the lead contained in the perovskite absorber, because this metal is one of the main components of the absorber layer. Although this material is not considered critical, it is considered hazardous and its use is restricted by the European Union in electronic components according to the Directive 2011/65/EU [13]. The stoichiometry employed in the calculations as an approximation to the formulation currently used in research was $FA_{0.85}MA_{0.15}PbI_3$, where FA is formamidinium, MA is methyl ammonium, Pb is lead and I is iodine [14]. Absorbers containing Caesium and Rubidium, instead of organic cations, have exhibited a higher stability regarding, but these materials are rather scarce, and quantities of annual production are not available [15]. The second material was Indium, which is mainly employed in the highly-transparent conducting material indium tin oxide (ITO) and is commonly deposited on glass as conductive layer or, in the case of monolithic tandem cells, as contact between the perovskite and the lower cell [16][17]. ITO is usually prepared from a mixture of Indium and Tin typically with a composition of 10:1. This material is considered as a critical raw material according to the European Commission [18]. Table 1 summarizes the annual production of the materials, when available, and the reserves of each material according to USGS.

Table 1. Annual production and reserves of different materials used in perovskite solar cells in 2017, taken from USGS [15]

Material	Production Tonnes/year	Reserves Tonnes
Lead	4.700×10^6	88.000×10^6
Iodine	31.000	6.400.000
Indium	720	-
Caesium	-	90.000
Rubidium	-	90.000

2.2 Market Scenario and Installation of Modules per Year

The installation of photovoltaic modules was assessed from the perspective of a 100% renewable energy scenario. According to the Lappeenranta University of Technology energy system model, an installed photovoltaic capacity of 11.958 GWp is expected for 2030, 27.400 GWp for 2050 and 42.000 GWp for 2100 [19]. The points between these values were obtained using the "smoothspline" algorithm contained in the software MATLAB ®. The installation rate per year was further estimated employing equation 1.

$$C_t = P_t - P_{t-1} \qquad (1)$$

Where,
C_t is the installation rate per year in the year t,
P_t is the total installed capacity in the year t,
P_{t-1} is the total installed capacity in the year t-1

The total installed capacity and the installation rate obtained from this method are shown in Figure 1.

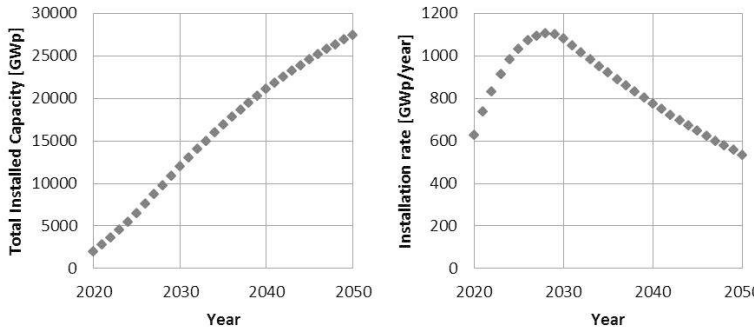

Figure 1. Total photovoltaic installed capacity and annual installation rate according to the interpolation and data from Breyer et al. [19]

For the purpose of this work, two levels of market penetration where considered for perovskite technologies, increasing linearly from 1% in 2020 to 20% and 80% in 2050, as a way to cover a scenario of low and high market penetration.

2.3 Material Flow System and Transfer Coefficients

Previous studies described the material flow system for CdTe and CIGS technologies [20, 21]. Although the production of PSC might differ in the type of deposition processes used to produce absorber layers, the material flow system would have similarities with the ones previously studied for other technologies, because PSC is also a thin film technology. Hence a similar system was used for the calculations done in this work and is summarized in Figure 2.

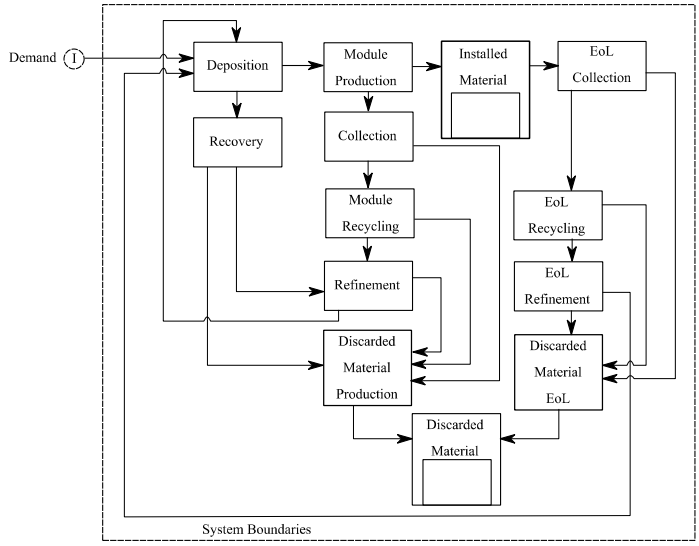

Figure 2. Material Flow System for Perovskite Solar Cells, adapted from Marwede et al. [21]

As depicted in Figure 2, the materials are initially used to perform the deposition process. A part of the material is deposited to produce cells, while the other part is not deposited and goes to a recovery phase. From this stream, a part is refined, while the other is discarded. The deposited material is later used to produce modules that are the final product. A part of these modules is defective and is further collected, recycled and the materials contained are refined to be reused in the deposition process, while another part goes directly to the discarded material. The use phase is represented by the installed material. In this process, the material is accumulated until the modules reach the end of life. After reaching the end of life, the material is collected, a part is recycled, and a part is directly discarded. In the subsequent processes, the material is recycled and refined to be again used in the deposition process or discarded. Finally, all the discarded material is accumulated in a virtual step called discarded material, although in a real situation this would be dissipated to the environment.

The transfer coefficients describe the proportion of the total input of material that is directed towards one output stream. As depicted in Figure 2, 11 processes redirect the materials to other processes, while two processes accumulate materials. The processes named “Discarded Material Production” and “Discarded Material EoL” gather inputs form other processes but have only one output. Hence, the transfer coefficient for these two processes towards the discarded material is 1. The transfer coefficients for other processes are summarized in Table 2. Values for all the years were obtained with linear changes between the beginning and the end of the calculation. Most of the transfer coefficients were chosen considering the study previously done by Marwede et al [21].

Table 2. Annual production and reserves of different materials used in perovskite solar cells

Transfer Coefficient		Lead		Indium	
From	To	2020	2050	2020	2050
Deposition	Module Production	0,80	0,95	0,17	0,50
Recovery	Refinement	0,50	0,75	0,80	0,93
Module Production	Installed Material	0,95	0,97	0,95	0,97
EoL Collection	EoL Recycling	0,80	0,90	0,80	0,90
EoL Recycling	EoL Refining	0,85	0,90	0,85	0,90
EoL Refining	Deposition	0,90	0,90	0,90	0,90
Collection	Module Recycling	0,95	0,99	0,95	0,99
Module Recycling	Refinement	0,90	0,90	0,90	0,90
Refinement	Deposition	0,85	0,90	0,85	0,90

Slot dye coating was considered as the most suitable process to perform the deposition of the perovskite absorber due to the high use of precursors. According to one equipment manufacturer, the material use for this process is over 95% [22]. As a conservative approximation, 80% was considered for 2020 increasing to 95% in 2050. ITO is usually deposited using sputtering. Two technologies are usually employed to do this process: using static planar targets and rotary targets containing a mix of indium and tin. This target is eroded, and the atoms are transferred to the material to be coated. The performance of the process is measured by the target utilization and the substrate collection efficiency. The first aspect is the amount of material eroded from the target compared to the initial amount of material, whilst the second aspect is the amount of material from the target that coats the desired surface. Lippens and Muehlfeld describe a target utilization of 34% and a substrate collection efficiency of 50% for planar target technology, while an optimal target utilization of 87.5% and a collection of 57.5% is expected for rotary targets [16]. The initial condition in 2020 was assumed as using planar target technology. Hence a total of 17% of the material is finally deposited on the cell surfaces, 66% remains in the targets and the rest is deposited in other parts of the equipment. The targets were assumed as totally recoverable, while 80% of the material sputtered elsewhere was assumed to be recovered. Hence, the initial transfer coefficient from deposition to module production of indium was assumed at 17% and the one from recovery to refinement at 80%. The optimum condition with rotary targets was assumed for 2050, considering that 50% of the target is deposited on the cells, all the remaining material in the targets are recovered and 90% of the material that is not deposited in the cells is recovered.

2.4 Material Embedded in Cells

The material embedded in the modules was calculated according to the stoichiometry of the different layers considering the descriptions made by different authors. The inflow of material was calculated employing equation 2, according to the approach of Marwede et al. [21].

$$F_{in}(t) = \frac{d_t \rho w_r}{I \eta_t} C_t \qquad (1)$$

Where,
F_{in} is the input of material
d_t is the thickness of material for the year t
ρ is the density of the material (4159 kg/m^3 and 7140 kg/m^3 for perovskite absorber and ITO respectively [23][24])
w_r is the mass concentration of the material in the layer, according to its stoichiometry
C_t is the installed capacity during the year t
I is the irradiance in standard testing conditions (1000W/m^2)
η_t is the efficiency of the module in the year t (16 – 24% for single junction, 25 – 30% for tandem)

Two architectures for perovskite solar cells were considered. The first architecture was in single junction, meaning that only one perovskite layer is used as absorber in the cell. In addition, tandem layers contain multiple layers that act as absorbers, allowing in theory a higher conversion of the incident light into electricity. However, more layers are included in the process to manufacture the cells. This can be seen in Table 3, where the tandem has more ITO layers compared to the single junction cells. To model improvements in the manufacturing of the cells, the thickness of the material and the efficiency of the module were varied linearly along the simulated years to simulate the optimization and improvement of the technology for the perovskite layer. In the case of the ITO layer, the thickness was considered constant through the calculations. The assumptions regarding these two parameters are summarized in Table 3 and were mainly taken from the architecture proposed by Bush et al for single junction perovskite solar cells and monolithic tandems containing a perovskite solar cell and a crystalline silicon cell [14].

Table 3. Thickness assumptions for different layers of single junction and tandem PSC/Si cells for the years 2020 and 2050

Layer	Single Junction		Tandem PSC/Si	
	2020 (nm)	2050 (nm)	2020 (nm)	2050 (nm)
Perovskite Absorber	500	300	500	300
Glass ITO contact	180	180	-	-
Bottom ITO contact	-	-	20	20
ITO contact between PSC and Si cell	-	-	20	20
ITO top contact	-	-	150	150

2.5 Life Time of the Modules

The life time of the modules was appointed using a Weibull in a cumulative distribution function, according to the modelling done by IRENA [25]. The proportion of modules that reach the end of life was calculated as the difference between the cumulative year for a year and the cumulative value for the previous year, as depicted in equation 3.

$$f_k(t) = \left(1 - e^{-((t-k)/T)^{\alpha}}\right) - \left(1 - e^{-(((t-1)-k)/T)^{\alpha}}\right) = e^{-(((t-1)-k)/T)^{\alpha}} - e^{-((t-k)/T)^{\alpha}} \quad (3)$$

Where,
$f_k(t)$ is the proportion of modules installed in the year k that reach the end of life in the year t
α is the shape factor of the Weibull distribution (α=5.3759 [25])
T is the average lifetime (Lifetimes of 5 years and 30 years was considered in this study)
t is the year in which the calculation is done
The total output of material was calculated using equation 4.

$$F_{EoL}(t) = \sum_{k=2020}^{k=t} f_k(t)\, F_{in}(k) \quad (4)$$

Where,
$F_{EoL}(t)$ is the total output of material in the year t
$f_k(t)$ is the proportion of modules installed in the year k that reach the end of life in the year t
$F_{in}(k)$ is the input of material in the year k

2.6 Scenarios

Four aspects were explored to create the different scenarios: perovskite technologies, market penetration of perovskite technology in single or in tandem configuration, lifetime of the modules and finally disposal at the end of life with recycling or without it. As to PSC, two configurations were considered: single junction and tandem of perovskite topping silicon solar cells. In the case of single junction an initial efficiency in 2020 of 16% was assumed, while for 2050 the efficiency assumed was 24%. In the case of the tandem PSC/Si, 25% and 30% were assumed as initial and final efficiencies respectively. The market penetration was considered in two levels: 20% and 80%. The mean lifetime was considered 5 or 30 years, respectively, and finally the cases considering no recycling at the end of life were done making the transfer coefficient 0 to discard all the modules. Considering all these aspects, 16 scenarios were generated. The scenarios were codified using the codes summarized in Table 4 and in the order Technology – Market Penetration – Lifetime of modules – Disposal at the end of life.

Table 4. Scenario codes description

Aspect of the scenario	Code description
Technology	SJ: Single Junction T: Tandem PSC/Si
Market penetration in 2050	20: market penetration from 1% to 20% 80: market penetration from 1% to 80%
Lifetime of the modules	R: regular end-of-life with T=30 years A: accelerated end-of-life with T=5 years
Disposal at the end of life	RC: Recycling NR: No recycling

2.7 Limitations of the Method

No replacement of modules after the end-of-life was considered. This can lead to errors, since the modules used for replacements also require materials to be produced. However, it is uncertain if the modules will be replaced by the same technology or a different one. Another assumption was that no material is lost during the use phase of the module due to failure of the encapsulation, which can lead to the dissipation of materials into the environment.

3 Results

3.1 Technology Impact

Figure 3 shows the requirements of lead necessary for the two perovskite technologies considered in this work in scenarios of adoption of 20% and 80% by 2050. The demand for lead is always lower for the tandem technology, due to the higher achievable efficiency. In all cases the demand reaches a maximum between 2033 and 2035, due to the decrease in the installation rate and the impact of recycling as a new supply. The demand for lead in the highest case reaches 1.094 tonnes, representing approximately 0,02% of the total annual production in 2017. Hence, the impact of the demand for lead for photovoltaic purposes might not have an important impact on the supply of this material. If the highest adoption scenario was considered for the single junction case, there would be a demand of 24.735 tonnes of lead for an installation of 9.645GW_p of modules, which would represent approximately 2 days of current lead production. These results are in line with the predictions close to one day previously made by Jean et al [26]. On the other hand, the lead contained in discarded material might reach an amount of 2.229 tonnes in 2050, representing approximately 9% of the total lead demanded by the system in the 30 years of calculation. This amount can be reduced through collection after the use, improvement in the refining and recycling processes and improvements in the production processes.

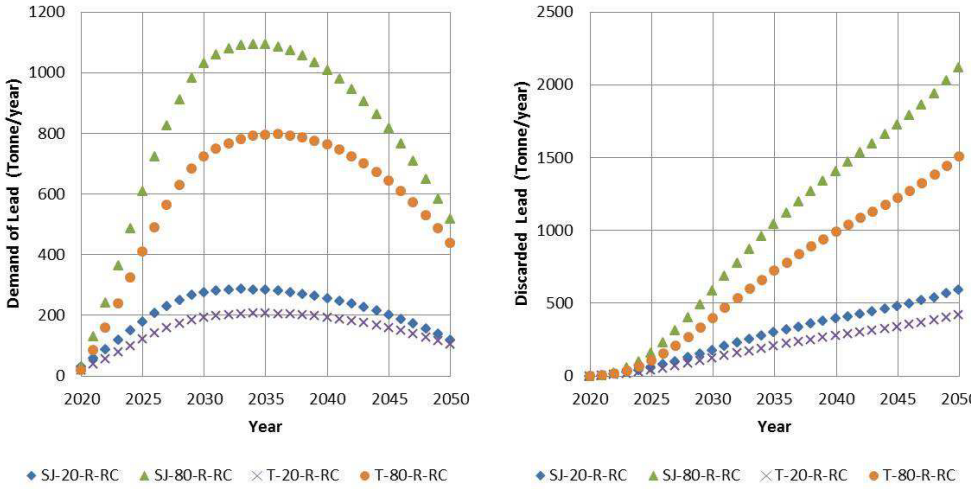

Figure 3. Demand for lead (left) and discarded lead (right) as a function of module technology and adoption in a scenario of normal lifetime and recycling at the end of life

Figure 4 depicts the demand for Indium for both technologies under the two adoption scenarios. In both cases, the single junction modules require a higher demand for Indium compared to the tandem modules. As in the last case, this is mainly due to the higher efficiency assumed for the tandem modules, making the used material per unit of peak capacity lower. In the 20% adoption scenario, the demand of this material reaches a maximum demand of 704 tonnes per year, close to the current estimated supply of 720 tonnes per year, as indicated in Figure 5 with a black line. With a higher adoption, the requirement of this material exceeds with up to 272% the current production of Indium. Although not presented here, the cumulative discarded indium in 2050, for the higher adoption case, single junction technology, regular lifetime of 30 years and recycling at the end of life amounts to 21.708 tonnes.

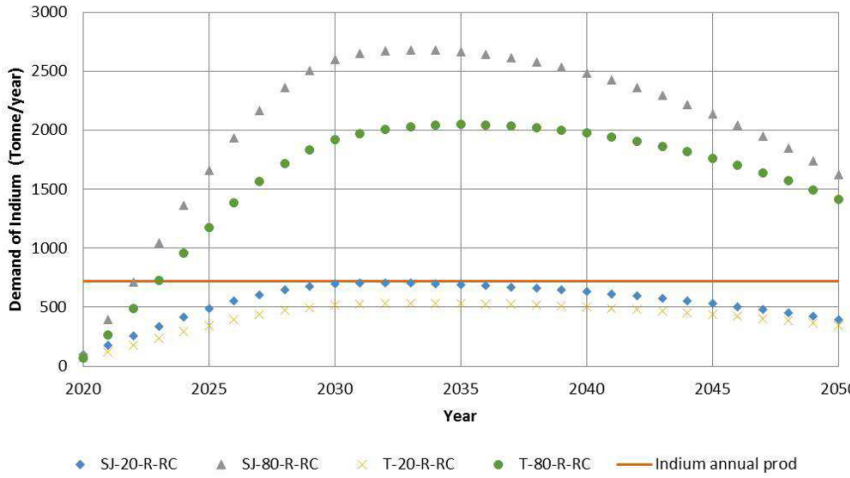

Figure 4. Demand for indium as a function of module technology and adoption in a scenario of normal lifetime and recycling at the end of life in comparison to the annual production in 2017

3.2 Lifetime impact

Lifetime of modules can also have an important impact on the demand for materials, particularly if they are recycled and incorporated again in the production. Figure 5 shows this effect for scenarios of 5 and 30 years of lifetime. In the case of a higher lifetime, the demand is higher because less material becomes available form old modules to be reprocessed and transformed into new modules. Yet, more material is also discarded due to the prompt reprocessing of these modules. For instance, the discarded material for a scenario of reaching a market share of 80% in the year 2050 with a lifetime of 30 years equals the discarded material for the scenario with a market share of 20% for the year 2050 and 5 years of lifetime. However, this work does not consider the replacement of modules, which would require more material and would generate more waste.

A different trend depicted in Figure 5 (left) is the anticipated peak of demand in the case of the scenarios considering a short lifetime. While the maximum demand for lead in these cases is reached in 2028, in the case of long lifetimes it is reached between 2033 and 2034, due to the anticipated supply of lead from recycled modules.

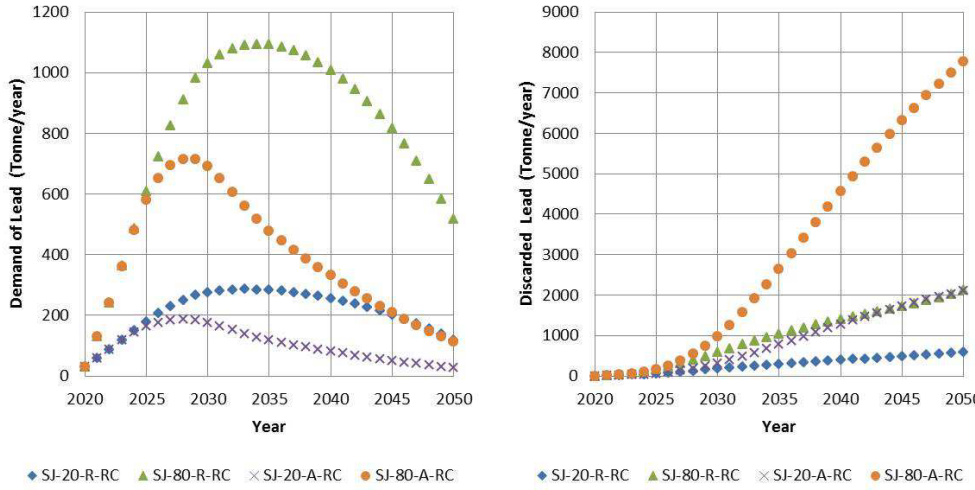

Figure 5. Demand for lead (left) and discarded lead (right) for single junction modules for low and high adoption scenarios under consideration of a lifetime of 30 years and 5 years

Figure 6 shows the results regarding indium, showing a similar qualitative result when compared to the results obtained for lead. However, both demand and discarded material are higher amounts in this case, exceeding again the current

supply of indium in the cases with a higher market share. The discarded indium depicted in Figure 6 (right) has quantities an order of magnitude higher than those obtained for lead. This is derived from the higher losses in the deposition process, as summarized in Table 5. In this table, lead and indium are compared, showing that in the cases with a lifetime of 30 years, most of the material is discarded from the production process. When the lifetime is reduced, a lower amount of material is discarded from the production process compared to the material generated at the end-of-life.

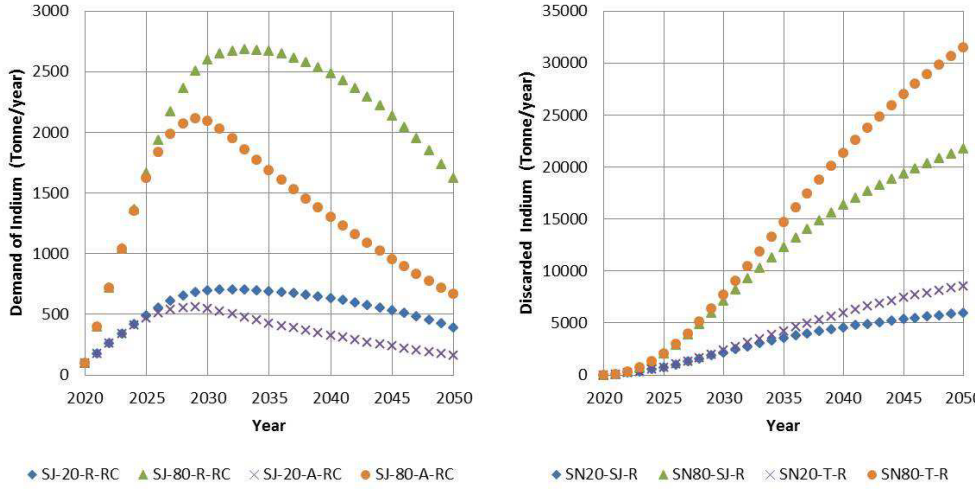

Figure 6. Demand for indium (left) and discarded indium (right) for single junction modules for low and high adoption scenarios under consideration of a lifetime of 30 years and 5 years

Table 5. Cumulative material discarded from production in comparison to the total discarded material in 2050

Material	Lead				Indium			
Scenario	SN20-SJ-R	SN80-SJ-R	SA20-T-R	SA80-T-R	SN20-SJ-R	SN80-SJ-R	SA20-T-R	SA80-T-R
Cum. material discarded from prod. (%)	81,21	83,03	22,88	22,65	98,29	98,7	68,44	68,02

3.3 Impact of Recycling at the End-of-Life

Figure 7 shows the impact of recycling on the demand for lead and the amount of lead discarded, which is particularly pronounced once the modules start to reach the end of life. For the case with low penetration of perovskite technology, the discarded lead increases to 48%, whilst in the case of high market penetration the increase is 43%. Figure 8 shows the lower impact of recycling in the case of indium, generating an increase of approximately 7% in the discarded quantity in both market penetration cases. This low sensitivity in the case of indium derives again from the high losses in the manufacturing process, compared to the loss of material at the end of life.

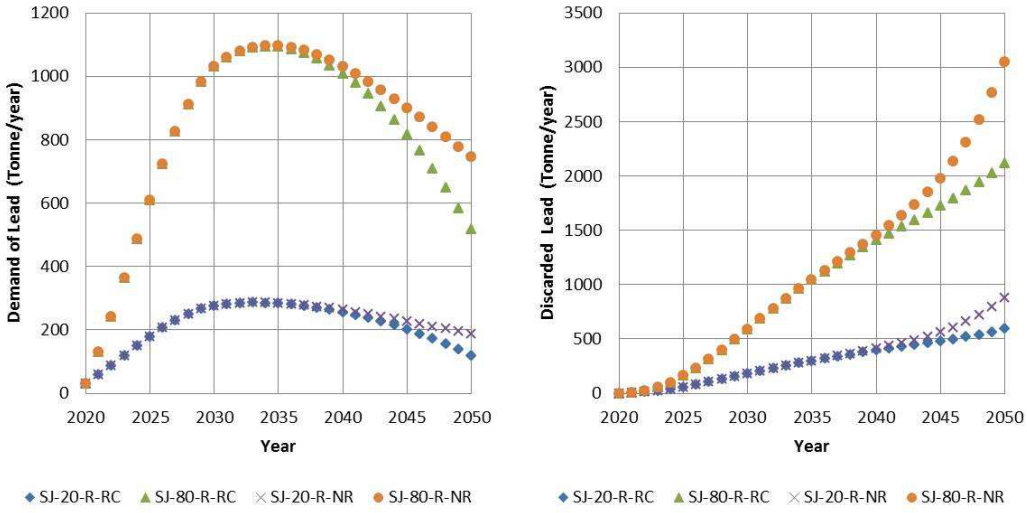

Figure 7. Demand for lead (left) and discarded lead (right) for single junction modules for low and high adoption scenarios with and without recycling

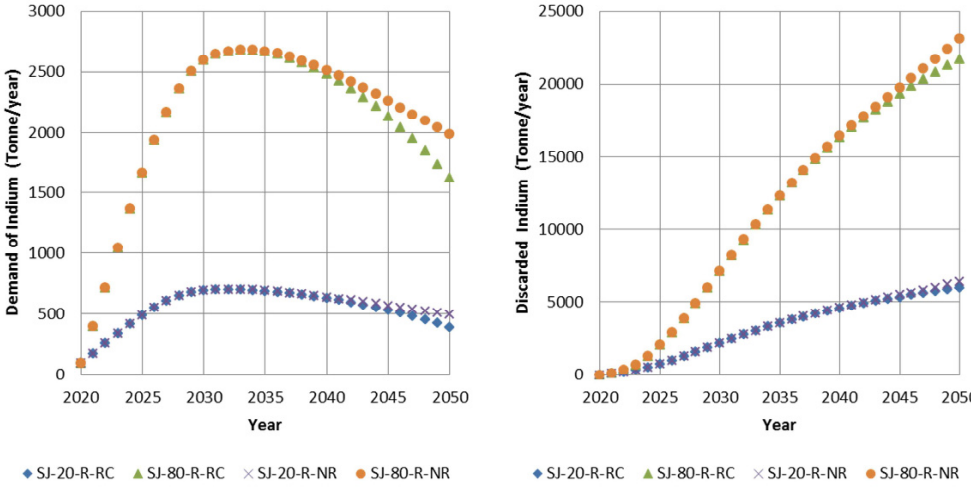

Figure 8. Demand for indium (left) and discarded indium (right) for single junction modules for low and high adoption scenarios with and without recycling

3.4 Summary of all Scenarios

Table 6 compiles the maximum demand and the discarded quantities for both materials and all the scenarios. The maximum demand for lead for single junction cases was 1.096 tonnes, whilst for the tandem it was 799 tonnes, representing in that case a reduction of 27%. In the case of indium, the maximum demand calculated was 2.684 tonnes for the single junction cell, while for the tandem it was 2.052 tonnes, representing a reduction of approximately 24%. Nevertheless, the most important variations between the scenarios are in the discarded amount of materials. For instance, in the scenario for single junction, high market penetration, long lifetime and no recycling at the end of life, the discarded lead is 9.9 times the amount discarded in the scenario for single junction, high market penetration, long lifetime and recycling. Hence, in case of adoption of this technology, the recycling must play an important role to avoid high environmental effects from the dispersion of lead into the environment.

Table 6. Summary of maximum demand and discarded material for all the scenarios studied in this work

Scenario	Max. demand Pb (t/y)	Discarded Pb 2050 (t)	Max. demand In (t/y)	Discarded In 2050 (t)
SJ-20-R-RC	285	591	704	5953
SJ-80-R-RC	1.094	2.119	2.679	21.708
SJ-20-A-RC	186	2.098	558	8550
SJ-80-A-RC	715	7.770	2.110	31.499
SJ-20-R-NR	277	876	705	6.385
SJ-80-R-NR	1.096	3.052	2.683	23.134
SJ-20-A-NR	286	5.626	705	14.645
SJ-80-A-NR	1.096	20.974	2.684	54.455
T-20-R-RC	206	418	531	4.483
T-80-R-RC	796	1.506	2.048	16.430
T-20-A-RC	130	1.503	413	6.467
T-80-A-RC	503	5.588	1.558	23.928
T-20-R-NR	207	610	533	4.793
T-80-R-NR	799	2.140	2.052	17.457
T-20-A-NR	207	4.048	533	11.129
T-80-A-NR	799	15.139	2052	41.532

4 Conclusions

The main aim of this work was appraising the amount of lead and indium required in the future for the commercialization of perovskite solar cells. This work proved that under current conditions, perovskite solar cells are not constrained by the supply of lead used in the absorber. On the other hand, the use of indium tin oxide for the transparent conducting layers may increase the demand for indium considerably beyond current production. Since indium is not mined directly and is recovered from the production of zinc, these could cause a supply constraint. However, substitute materials might be used to reduce this risk. A maximum demand for lead of 1.096 tonnes and a maximum demand for indium of 2.684 tonnes were obtained as a result of the calculations done for modules containing single junction perovskite solar cells, a market share of 80%, mean lifetime of 5 years and no recycling. Most of the variation was presented in the discarded material, showing that recycling and lifetime extension can minimize the quantity of materials that is dissipated into the environment and can have potential environmental impacts.

This work also proved that the use of new architectures, such as tandems of perovskite absorbers with silicon, can decrease the quantity of lead and indium that is used per GW_p of modules, due to the higher efficiency of the cells. Although this reduction is desirable, the additional processing stages and the energy use in the manufacturing processes can impact the costs and environmental impact of these novel cells and in the long run their adoption as main photovoltaic technology.

Increasing the lifetime from 5 to 30 years may in the long run increase the demand for lead and indium due to the absence of recycled material to supply the production of new modules, but can also prevent the dissipation of these metals into the environment and their negative effects.

The discarding of indium was found to be more dependent on the production process, since the transfer coefficients for the deposition are rather low due to multiple factors related to the sputtering process. Hence, the recycling at the end of life has less impact on the demand of material and discarding of material, compared to the case of lead. However, this is a motivation to either replace this material, increase the efficiency of deposition or decrease its use in the cells via thickness reduction of the layers.

These kinds of calculations contain many assumptions and uncertainties. Although they should not be misunderstood as a prediction of the future, they can provide an idea of the effect of different aspects in the material requirements. The development of perovskite solar cells is a dynamic field of research. Hence, with new architectures and materials, these calculations must be updated to deliver realistic results in the future.

5 Zusammenfassung

In diesem Beitrag werden mittels einer Materialflussanalyse Bedarf und Ausschuss von Blei und Indium in Szenarien der zukünftigen Einführung von Perowskit-Solarzellen berechnet. Für die Erstellung der Szenarien wurden vier Faktoren berücksichtigt: Zum einen wurden als Typen der Perowskit-Solarzelle entweder Einzelverbindungszellen oder Tandems mit Silikonsolarzelle angenommen. Der angenommene zukünftige Marktanteil lag zwischen 20% und 80% in 2050. Als Lebensdauer der Module wurde entweder 5 Jahre oder 30 Jahre angenommen. Zuletzt wurden Szenarien mit und ohne Recycling evaluiert. Die Ergebnisse zeigen, dass der Bedarf an Blei voraussichtlich nicht signifikant im Vergleich zum bestehenden Marktangebot sein wird. Die Verwendung von Indium im Szenario mit hohem Marktanteil könnte dagegen das heutige Angebot übersteigen. Die Verwendung von Tandemtechnologien könnte den Materialbedarf aufgrund der

höheren Effizienz in der Energieumwandlung verringern. Zudem könnte eine höhere Lebensdauer sowie ein Recycling am Ende des Lebenszyklusses die Menge an Material verringern, die an die Umwelt abgegeben wird.

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