Resource Availability in Photovoltaics - Case Study: Tellurium

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Abstract

The most established thin-film technology with a 70% share of the thin-film market in Photovoltaics is based on Cadmium Telluride. However, the use of tellurium, a metal with a limited production per year, may constitute a bottleneck for the increasing deployment of this technology. Four scenarios, following the tendencies depicted by Energy [R]evolution study, were calculated using the software STAN to assess the material flow balance of Tellurium. The most ambitious scenario shows a peak of demand 464t/year by 2025. Compared with an annual Tellurium production of 400t in 2016 and a present requirement of only 26% share of the yearly production, this result appears to be high. The benefit of Tellurium recycling shows a high impact on the demand, especially when large amounts of modules start to reach the end of life. However, uncertainties throughout the scenarios are present and need to be considered.

Keywords: PV module, critical metals, material flow analysis, tellurium, STAN

1. Introduction

At the end of 2015 the global cumulative photovoltaic capacity was estimated as 228GWp, with an annual growth during that year of 50.7 GWp and an estimated module production of 62.7GWp (IEA-PVPS 2016). The technologies used for converting the sun irradiation into useful electricity are usually classified as wafer technologies or thin-film technologies (Jean *et al*. 2015). 3.6GWp of thin-film technologies modules produced in 2015(IEA-PVPS 2016). Among its advantages are the low fabrication cost, low thickness of the materials used, fast manufacturing process and lower greenhouse emissions during production compared with silicon technologies (Jean *et al*. 2015). However, lower efficiencies and the use of critical materials are still challenges to the development of these technologies. Among the commercial thin-film technologies are a-Silicon, Cadmium-Telluride (CdTe) and Copper indium gallium diselenide ($CuIn_xGa_{1-}xSe_2$ or CIGS), using materials such as tellurium, gallium and indium, which are considered critical (Moss *et al*. 2011;Zimmermann 2015; Zepf V. *et al*. 2014). Previous analyses regarding the use of materials for the construction of PV modules were made by other researchers (Marwede & Reller 2012; Zuser & Rechberger 2011; Zimmermann 2013). In addition, this study creates a link between an energy scenario and current market conditions to calculate the demand of a critical material like Tellurium, in order to supply the requirements of photovoltaic industry. Approximately 400 t/year of Tellurium and 23,000 t/year of cadmium were mined worldwide in 2016 (USGS 2017). World reserves of Tellurium are estimated to 25,000 ton (USGS 2017). Most of the tellurium is extracted as a by-product of copper refining and around 26% of the primary tellurium is used in the photovoltaics manufacturing industry today. Cadmium is usually produced from zinc refining (Zepf V. *et al*. 2014), and is considered a toxic and carcinogen substance (European Chemicals Agency 2017). It is estimated that Zinc ores contain 0.03% of Cadmium and the world reserves are estimated to 660,000 ton (Zepf V. *et al*. 2014). In this paper the material flow analysis for these elements used in PV is considered as relevant due to the uncertainty of the exact life-time of modules, the exact amount of resources needed and of future constraints in the supply of these materials.

2. Method

A dynamic material flow analysis (MFA) was done using the freeware “subSTance flow Analysis” (STAN) developed by TU Wien (Cencic & Rechberger 2008), that performs MFA according to the Austrian standard ÖNORM S 2096 and allows consideration of data uncertainties. A 45 years horizon between 2006 and 2050 was considered due to the available information, life-time of modules (approx. 30 years) and the horizon of the energy scenarios, usually forecasting up to 2050. The analysis included module manufacture, use, end-of-life, recycling and final disposing. Mining and extraction from ores were not considered in the study. The set of process steps used in the software STAN with the different processes can be seen in

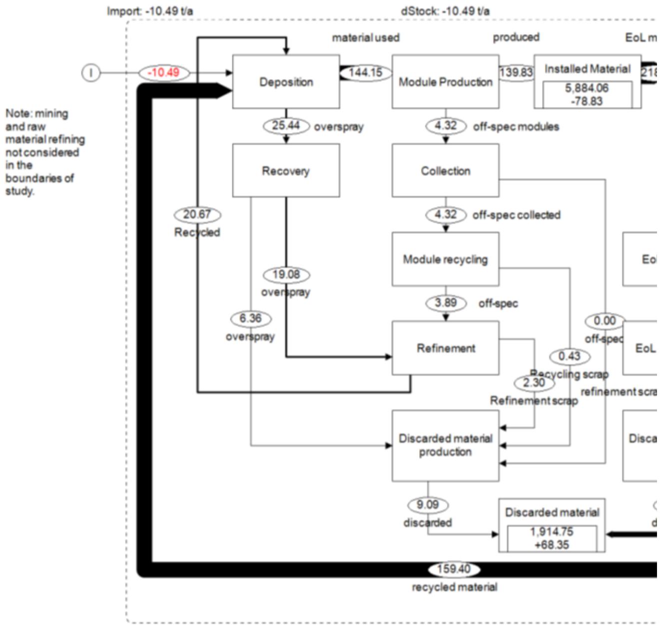


Figure 1. The different processes were extensively described by Marwede (Marwede & Reller 2012) and were used to build the process steps that comprise the analysed system.

1.1 Market scenario and installation per year

The production and installed capacities of commercial PV technologies were obtained from year 2006 to 2015 from International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) yearly publication "Trends 2016 in photovoltaic applications" (IEA-PVPS 2016). From 2011, the production of thin-film cells and particularly the production of First Solar and Solar Frontier went from a market share of thin-film technology of 62.3% in 2011 to 96.6%, having First Solar a share of 72.2% of the thin-film market in 2015 (IEA-PVPS 2016), making First Solar the main manufacturer of CdTe modules. Considering this, the market of CdTe modules was assumed fully described by First Solar. The CdTe module production between 2006 and 2016 was obtained from several reports (IEA-PVPS 2016; First Solar 2017; First Solar 2010). Discrepancies between the module production and the installation may arise due to the possibility of double counting in non-vertically integrated companies and module storage but is less likely in vertical integrated companies like First Solar. The actual installation was therefore used as calculation basis for the future forecast. Between 2006 and 2016 First Solar production was selected as input for this technology. A market share of 7.5% of thin-film technologies was supposed to stay constant from 2017 to 2050, being Cadmium Telluride technology 70% of thin-film market. These conditions are similar to the present market conditions. The installed photovoltaic capacity was calculated by interpolating the installed capacity given in the study Energy [r]evolution (Teske *et al.* 2015), generating a value for each year between 2017 and 2050 with the Matlab® algorithm "smoothspline".

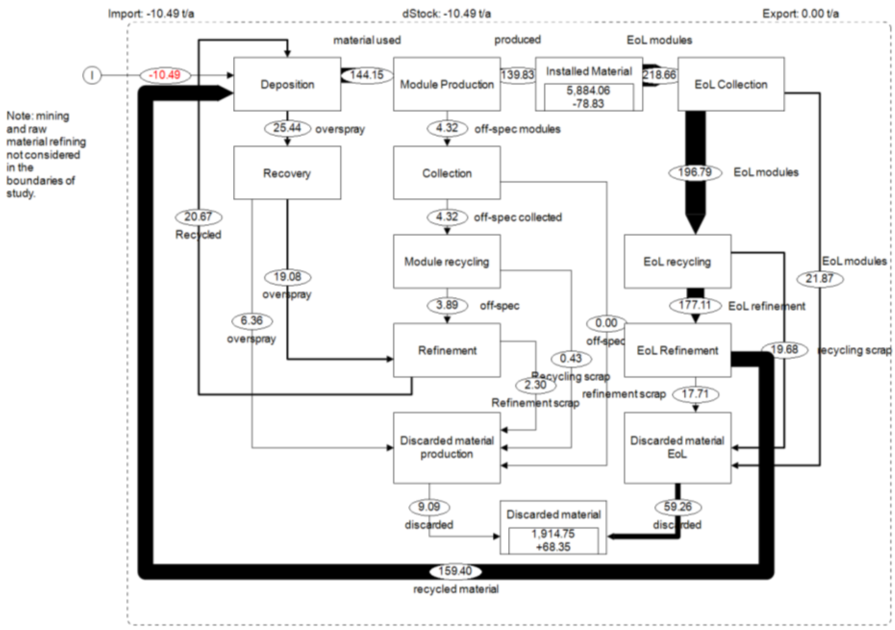


Figure 1. MFA in STAN for Tellurium in CdTe lifecycle, SC1 scenario static model for the year 2050, including accumulated material in installed modules. All quantities in t/year. Own elaboration.

1.2 Material embedded in modules

The material embedded in modules was considered dynamic and was calculated using the stoichiometry of the materials present in each layer, taking into account module efficiency, layer thickness and density. The inflow of material was calculated as is depicted in equation 2 (Marwede & Reller 2012).

$$F_{in}(t) = \frac{d_t \rho w_r}{I \eta_t} C_t \quad (Eq. 2)$$

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, w_r is the mass concentration of the material in the layer, C_t is the installed capacity during the year t, I is the irradiance in standard testing conditions (1000W/m^2) and η_t is the efficiency of the module in the year t. The ratio in equation 2 is the material embedded or how much of the metal is required per unit peak installed. During the calculations the thickness and the efficiency were considered dynamic due to the continuous technological development. Between 2006 and 2016 efficiencies of First Solar models increased from 9.5% to 16.6% (First Solar 2017; First Solar 2015). A maximum efficiency of 22.1% has been described for this technology (Green *et al*. 2017) and was considered as the maximum efficiency achievable for the year 2050. This was modelled by doing a fitting between efficiency in 2016 and considering a sigmoid function with maximum value 22.1% and medium point in 2009, as is shown in Eq. 3.

$$\eta = \frac{0.221}{1 + 2.643e^{-(0.3003(t-2009))}} \ (Eq.3)$$

The thickness of the CdTe layer was considered 3μm in 2007 decreasing linearly till 2 μm for 2011 and subsequently linearly decreased until 2050, reaching 1 μm, considered by many authors as a reachable value (Rigby *et al*. 2011;Moss *et al*. 2011;Zimmermann 2013;Marwede & Reller 2012; Marwede & Reller 2014). On the other hand, the composition of the layer was described by stoichiometry of CdTe with a content of 56.3% m/m of Tellurium and 43.7% of Cadmium. Density of CdTe was considered 6.2 g/cm^3 for the calculations (Marwede 2013). The capacity installed per year was obtained as the difference between the capacity of one specific year and the previous year, as shown in Eq. 4.

$$C_t = P(t) - P(t-1) \ \ (Eq.4)$$

In this case replacement of old panels was not taken into account since a replacement of one module of one technology by other of the same technology is accompanied by high uncertainties.

1.3 End-of-life Material

The material obtained from End-of-life modules was computed considering the probability of the modules to reach the lifespan according to the Weibull distribution presented in its differential way in equation Eq. 5 (Marwede & Reller 2012).

$$f(t) = \left(\frac{\alpha}{T}\right)\left(\frac{t}{T}\right)^{\alpha-1} e^{-(t/T)^{\alpha}} \ (Eq.5)$$

In Eq.5 t represents the time in years, T the average lifetime and α the shape factor. 30 years is considered the lifetime of a PV panel (IRENA 2016). This study considered a scenario with regular loss (α=5.3759) (Zimmermann 2013) and a scenario with early loss (α=2.4928) (IRENA 2016), the latter with a higher proportion of modules ending their life prematurely. Considering the probability of reaching the end of life after a number of years of installation, the total output for certain year was estimated as the addition of all modules and the embedded material installed in previous years that reach the end of life , as is shown in Eq. 6 (Marwede & Reller 2012).

$$F_{EoL}(a) = \sum_{t=0}^{a} f(t)\, F_{in}(a-t) \ (Eq.6)$$

1.4 Transfer coefficients

The transfer coefficients are dependent on the distribution of materials after each process. Having 9 different process steps requires 9 different transfer coefficients to perform the calculations. Assumptions made by Marwede & Reller (Marwede & Reller 2012) in its steady scenario were used as a basis for the calculations. For the manufacturing phase, a deposition efficiency of 65% increasing linearly to 85% by 2050, a module production efficiency of 95% increasing up to 97% by 2050 and an overspray recovery of 50%, increasing to 75% by 2050 were assumed. As assumption all the off-spec modules generated during the manufacturing process were collected, with a 90% material recovery from these modules. An efficiency of 85% in the refinement process of the material obtained from the recycling of off-spec modules was assumed, increasing to 90% by 2050. After the end of life of the product, 80% collection rate was achieved in 2011, increasing up to 90% by 2050. From the material collected, 85% recovery was used as initial value for 2011, increasing to 90% by 2050. A 90% of efficiency in the refining process regarding the material coming from end-of-life modules was supposed. First Solar maintains a recycling program to collect and recycle the materials used for the modules, reporting an efficiency of 95% regarding the semiconductor materials(Krueger 2010). Photovoltaic modules have been included in the Waste Electrical and Electronic Equipment Directive of 2012 (WEEE) of the European Union and hence must be collected and recycled (IRENA 2016). Probably in the future other regions or states will adopt similar directives, increasing collection and recycling rates.

1.6 Scenarios

Calculations were made for two growth scenarios and two end-of-life probability distributions, generating 4 scenarios. Scenario 1 (S1) and scenario 2 (S2), considered normal market conditions, taken from the Energy[R]evolution study regular loss and early loss respectively; on the other hand, scenario 3 (S3) and scenario 4 (S4) make use of the optimistic penetration of renewable energy in the energy matrix with regular loss and early loss respectively.

3. Results and discussion

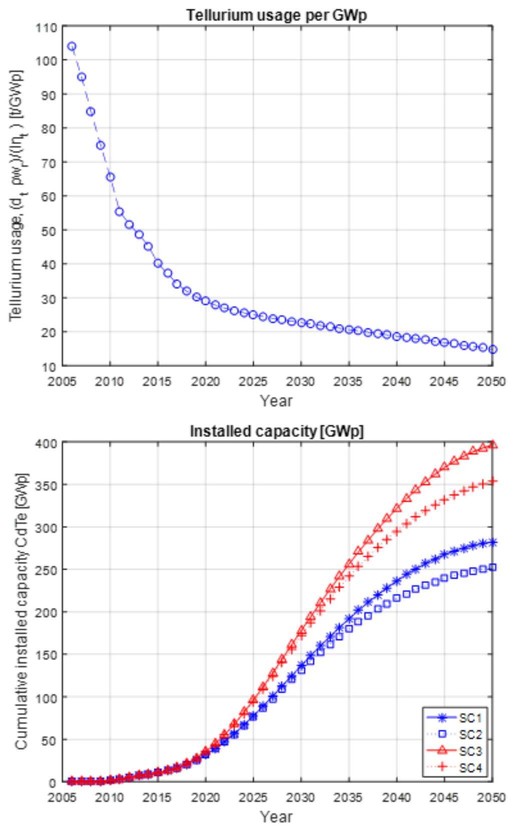


Figure 2-A shows the calculated material needed for the different years, according to the equation 2 and the assumptions previously described. Reduction of material depends on substantial increase in efficiency and reduction of CdTe layer thickness.

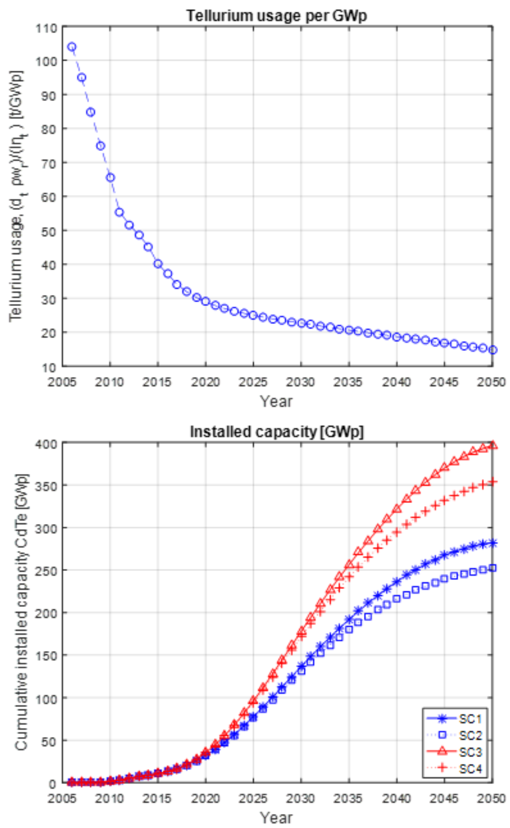
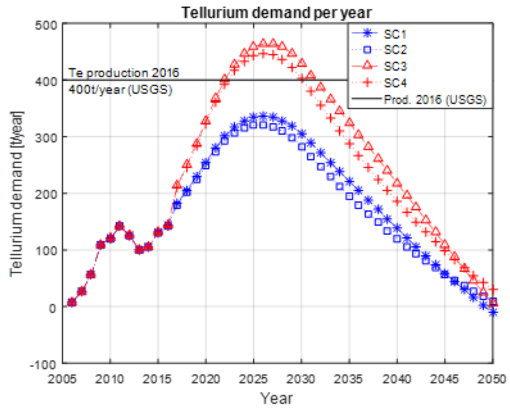


Figure 2 B shows an increasing installed capacity, depicting higher capacity in the case of the optimistic scenario than in the normal scenario. Scenarios with early loss exhibit less installed capacity due the premature end of



life.

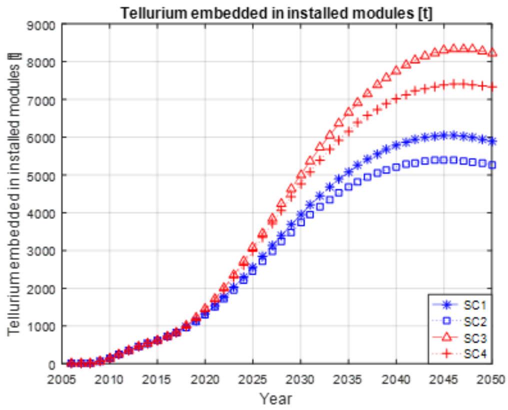


Figure 3- A presents the results of the dynamic MFA regarding the Te demand. A decrease of the use of tellurium is depicted from 2011 and 2014 due to the important decrease in the material usage as previously indicated in **Error! Reference source not found.**-A, followed by an increase after 2015 caused by higher module installations. In all the scenarios the consumption of tellurium reaches a maximum between 2025 and 2026 followed by a decrease due to lower material intensity generated by higher efficiency and lower material thickness. Recycling also plays an important role, supplying more tellurium as feedstock and generating a surplus in S1 and S2 scenarios for 2049 and 2050 respectively. In all these cases the amount of tellurium embedded in the modules reaches a peak between 2045 and 2050 and starts to decrease as the modules are substituted by new models with lower material usage. Reducing material intensity and increasing the reuse of material coming from end-of-life modules allow reducing considerably material requirements. The results for future years are slightly higher than the calculations performed by other authors (Marwede & Reller 2012). As shown in

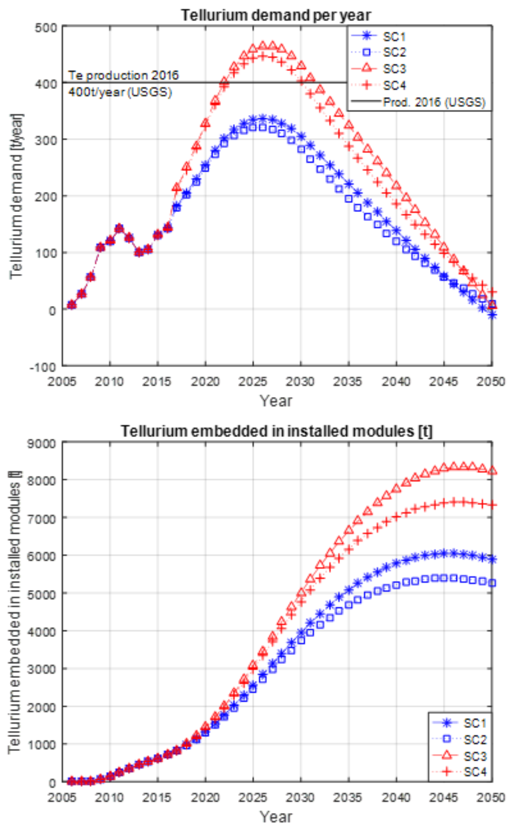


Figure 3, only advanced growth scenarios require more tellurium than the supplied amount estimated for 2016. However, considering that the supplied tellurium is used for other uses such as metallurgy (42%), chemicals and catalysts (21%), and electronics (11%), a higher production would be required for a sufficient supply to the photovoltaic industry without bottlenecks. Since this metal is usually produced as a by-product of copper refining process and is not commonly mined directly, improvements in its recovery might lead to a certain limit. Nevertheless, the Te production will be constrained by the copper production. Although this was not considered in this study, replacement of modules may play an important role and can considerably increase the amount of materials required, particularly when a high amount of modules reach their end-of-life.

Conclusion and Outlook

The MFA indicates a maximum demand of 463 t/year for the year 2026 as a result of improvements in efficiency and layer thickness, but also expanding demand. Today's yearly production of Tellurium is estimated to be 400 t/year, with a share of 26% dedicated to the photovoltaic industry. In the future this requires an improved recovery of this metal from copper refining, direct mining or less

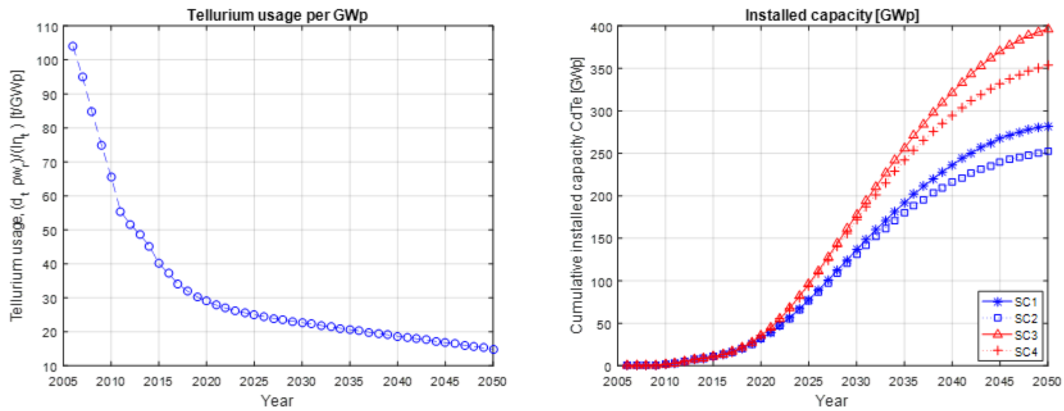


Figure 2. Calculated Tellurium usage in ton/GWp (A) and installed capacity for Energy [R]evolution (blue) and Advanced Energy [R]evolution (red) scenarios (B) according to the developed model between 2006 and 2050. Own elaboration.

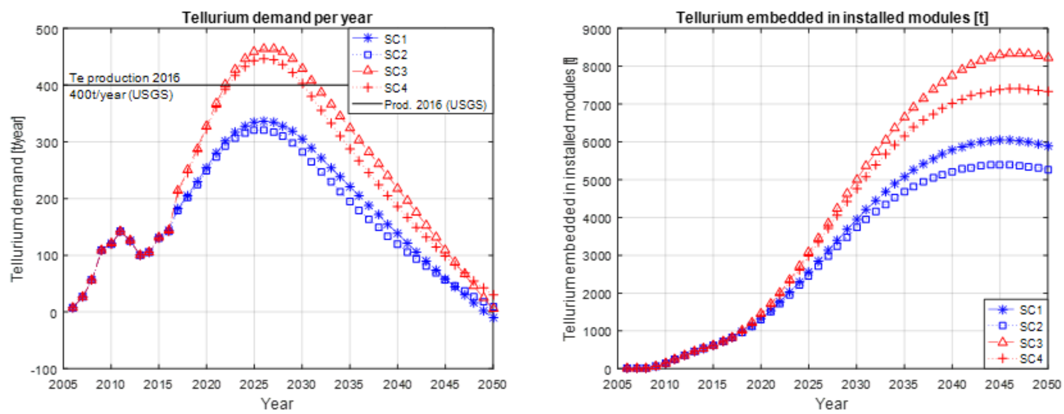


Figure 3. Tellurium demand (A) and tellurium stored in installed modules (B) for Energy [R]evolution (blue) and Advanced Energy [R]evolution (red) scenarios, considering thin-film share of 7% and 70% CdTe within the thin-film market between years 2011 and 2050. Own elaboration.

material usage in CdTe modules. For the year 2050, the recycled modules may be an important supply of secondary tellurium on the market to ecycled modules may be an important supply of secondary tellurium on the market to recycled modules may be an important supply of secondary tellurium on the market to manufacture new modules, supplying almost all the necessary materials to maintain the production or even surplus in the less optimistic scenario. Still, big uncertainties remain in the material needs within these technologies and the lifetime of the devices, especially if political drivers come into place to either slow down or even enhance CdTe module installations.

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