High-technology elements for thin-film photovoltaic applications: A demand-supply outlook on the basis of current energy and PV market growths scenarios*

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Abstract

On the basis of current energy and photovoltaic market outlooks and scenarios, the total growth rate potential of thin-film photovoltaic (PV) techniques have been analysed and calculated. For the European Photovoltaic Industry Association (EPIA) Advanced Scenario [1] total thin-film PV annual production values of 2.4 GWp for 2010, 25 GWp for 2020 and 132 GWp for 2030, were calculated. These values were used to estimate individual annual production for each thin-film technology in order to predict the future thin-film PV material needs for indium, selenium, tellurium, germanium and gallium. Considering global reserve and refinery data, this work also provides estimations on the current static depletion time of these elements. Such estimations are of course an approximation but emphasise that some of the considered elements are highly constrained when assuming steady production rates. This is particularly the case for indium, for which we calculated a static depletion time of 22 years. Selenium and tellurium could be also in danger of running out soon if their consumption increases. This implies that additional efforts are needed in the exploration and evaluation of mineral deposits which can supply these scarce elements such as the deposits of the Iberian Pyrite Belt.

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1 Introduction

The U.S. Energy Information Administration (EIA) estimates the global consumption of electricity to roughly double until 2030 [2]. Together with the background of fast-climbing energy and fluctuating oil prices, a rapid conversion to more sustainable energy supply systems, including a significant share of PV technologies, is of outmost importance. This also includes thin-film PV technologies, which are now fully developed to enter the market in substantial amounts and already reached 196 MW or 8% of the total PV production (2.53 GWp) in 2006 [3].

2 Thin-film PV growth potential

Thin-film PV production and installation is expected to stay on a high growth level throughout the coming years. Exact growth numbers are dependent on several factors, which are to be briefly discussed in the following section.

2.1 Feasibility of thin-film PV

Policies and prognoses

European and global policies clearly worked in favour of PV dissemination during the last years. Recently, the EPIA agreed that photovoltaic energy could provide 12% of European electricity demand by 2020 [4]. It is also expected that overall grid-parity will be reached by 2020, with some southern European counties (Spain, Italy) reaching it earlier due to high solar irradiation.

Environmental problems

Thin-film PV feasibility could be affected by environmental restrictions. This is particularly the case for CdTe thin-film PV, with cadmium being a significant health risk if it escapes into the environment. Under normal operating conditions, CdTe solar cells are very resistant to environmental stresses and do not produce any emission of cadmium [5]. Possible escape of cadmium or other elements from waste modules to the environment could be avoided through module recycling. But this could raise extra costs, which have to be paid by the customers.

Competitiveness

Electricity generation costs have been decreasing significantly during the last decade, due to market growth, which has been stimulated by subsidy programs (e.g. feed-in tariffs), upgraded cell technologies and improved production processes. Gradual reduction of financial subsidies will compel the industry to make further efforts for effective cost competitiveness, which will be a very important factor during the upcoming period of market consolidation and economic slowdown.

Generally, PV electricity will become cost competitive to conventional electricity more easily in sunny regions like southern Europe, which benefit from solar irradiation up to 1800 kWh/m^2 per year. At the moment, average PV electricity costs in Europe are 0.30 € per kWh [6]. Assuming a lifetime of 30 years and energy payback times of 1-1.5 years [7], thin-film PV systems are able to produce 10 to 30 times the energy they consumed during manufacturing processes. This means that regarded over a module lifetime period, thin-film solar PV is a very feasible and competitive electricity generation method.

2.2 Extrapolation of global PV cell production growth

The extrapolation of annual global PV cell production up to 2030 is based on the EPIA Advanced Scenario growing rates (shown in Table 1) and starts with the 2007 total PV production value of 4.28 GW [8].

Average annual growth	EPIA Advanced
2007-2010	40%
2011-2020	23%
2021-2030	15%

Table 1: Average growth rates according to EPIA [1].

The EPIA Advanced Scenario [1] turned out to fit in best with the annual growth rates of the last few years. Though the annual global PV production growth rates between 2007 and 2010 were higher, 45% (2005), 40% (2006) and 69% (2007) [8], the quoted growth rate values are useful as average values. Boosting growth rates in 2007, which are expected to be topped in 2008, were highly triggered by investment and market nervousness due to phasing out of several national subsidy programs.

Regarding the extrapolated data (Table 2) it is obvious that worldwide PV production in a range of 9 to 12 GWp in 2010 seems to be a reasonable estimation. This value matches more or less with other estimations, e.g. the 7 to 10 GWp estimation presented in the European Commission Status Report [3]. The values are of course hypothetical, but they can give an idea of the important role PV techniques will play in the coming years and that annual PV solar cell production surely will grow into the GWp range.

It is interesting to compare these extrapolations with predictions for the global PV production capacity, which is expected to be of more than 20 GWp by 2010, if all announcements of PV producers are considered [3]. Thin-film production capacity would lie in a range of 3 to 4.2 GWp and make up about one fifth of the total capacity.

	EPIA Advanced Scenario	
	Total PV	**Thin-Film PV**
	GWp	**GWp**
2007	4.28	0.43
2008	6.0	0.8
2009	8.4	1.3
2010	11.7	2.4
2011	14	3.0
2012	18	3.8
2013	22	4.8
2014	26	6.0
2015	33	7.6
2020	93	25
2025	187	57
2030	376	132

Table 2. Extrapolated global and thin-film PV and solar cell production data.

3 Material consumption

Material consumption calculation per MWp of electricity generation capacity of the main PV thin film techniques CdTe, CIGS/CIS and a-Si were carried out on the basis of material usage data available from Keshner [9] and CIS material usage data provided by the ZSW in Stuttgart, Germany [10]. The following Table 3 gives an overview over the material amounts needed to produce one square meter of PV cells.

	Keshner et al. [9]	ZSW [10]
Cd	7,29g/m²	
Te	7,59g/m²	
Se	7,42g/m²	6,11g/m²
In	4,64g/m²	3,11g/m²
Ga	0,46g/m²	
Ge	0,57g/m²	

Table 3. Compilation of material usage data for manufacturing of one square meter of thin film PV cell modules.

Additional data on the required PV area needed for the generation of 1 kWp [1], verified with data from some of the market dominating producers (Table 4), allows the calculation of the material consumption per MWp (or the net element intensity) of electricity generation (Table 5).

	size (cm²)	power (Wp)	m² need for 1 kWp
CdTe modules			
First Solar	7200	70	10,3
Antec	7200	50	14,4
EPIA [1]			**11**
CIGS modules			
Würth Solar	7200	80	9
Global Solar	7434	60	12,4
EPIA data [1]			**10**
amorphous Si modules			
EPIA [1]			**15**

Table 4. PV area needed for 1 kWp. Data sources: Module specifications and EPIA.

The net element intensity, defined as the mass of an element contained in the product per capacity unit, is the calculation base for the subsequent determination of the material amounts (4.1).

		Keshner [9]	ZSW (CIS) [10]
CdTe	Cd	80,19	
	Te	83,49	
CIS/CIGS	Se	74,2	61,1
	In	46,4	31,1
	Ga	4,6	
a-Si	Ge	8,55	

Table 5. Material consumption data in kg (or net element intensity) for the production of 1 MW of PV cells.

The exact material consumption depends on the thin-film fabrication technique used. For indium and selenium calculations, we selected two different values in order to get a value range and to see what small differences can cause on a large scale. It can be expected that to reduce costs and improve competitiveness, there will be a constant effort to spend less material per module unit.

4 Materials availability

4.1 Estimation of material amounts

To estimate the amounts of materials needed for future thin-film PV production, we used the above net metal intensities (Table 5) and applied them on the annual thin-film PV production values calculated on the base of the EPIA IV Advanced Scenario [1] (Table 2). These thin-film production values have been calculated assuming a total thin-film PV share of 20% for 2010 growing to 35% until 2030 [11]. Individual shares for each thin-film technology have been taken from a recent Prometheus Institute publication [12], assuming constant thin-film shares from 2012 on. The resulting values have been combined with the net element intensity to obtain estimations on material consumption. Table 6 shows the cumulative amounts of each element needed for thin film PV production from 2008 until the years 2010, 2015, 2020 and 2030, respectively.

Selenium and indium demand as calculated using ZSW data is significantly lower and shown in brackets. This estimation demonstrates that small decreases in material usage for thin-film PV production have a significant effect on large production quantities in terms of extending material availability.

Advanced Scenario EPIA IV					Keshner [9] (ZSW [10])
Te	**Se**	**In**	**Ga**	**Ge**	**period**
114	63 (52)	39 (26)	4	19	**2008-2010**
394	647 (533)	404 (271)	40	134	**2008-2015**
1266	2570 (2116)	1607 (1077)	159	510	**2008-2020**
8716	18989 (15637)	11875 (7959)	1177	3714	**2008-2030**
135	1550	510	103	100	*

Table 6. Estimated cumulative material amounts (metric tons) for the considered time ranges. Values in bottom row marked "*" are global refinery amounts for 2007 [13].

These estimations further lead to the conclusion that up to the year 2020, the material amounts are manageable, but afterwards there will arise serious supply problems for at least some of the considered elements. For example, if LCD technology production will continue to grow and use up more than half of the yearly indium production, then serious problems could emerge for CIGS/CIS PV technologies after 2020.

4.2 Material supply

All of the five elements considered in this work are scarce, that means they do not occur in large amounts in the continental or oceanic crust. Their average crustal abundance varies from 15 ppm for gallium to 0,005 ppm for tellurium [14]. Estimating the extractable reserves of many rare and precious metals is quite difficult because reserve data is mostly kept secret by the mining companies [15].

Indium

Indium is extracted mainly from zinc ores, but is also contained in other base metal ores, e.g. of copper and tin [16]. Usually, indium contents are found in deposits related to tectonically active or once active zones (e.g. subduction zones and plate margins). Therefore, it is possible that new indium deposits will still be found.

In the last few years, LCD production accounted for more than 50% of indium consumption [17]. It is questionable, if there will be enough indium to produce both, billions of LCD units per year and thin-film PV modules in GW ranges. Some authors predict that under current average consumption scenarios, the primary indium supply could be exhausted as soon as 2017 [18]. On the other hand, the LCD industry is apparently turning into an oversupply situation [19], which will result in a slow down of the growing rates. The static depletion time (reserve to current annual refinery ratio) for indium is determined to be of 22 years (Table 7). Indium is by far the most constrained element.

Selenium

Selenium reserve and reserve base are mainly correlated to copper deposits. Coal contains significant contents of selenium and could increase selenium reserve values in the future, though no recovery from coal is carried out up to date. With a static depletion time of 53 years, selenium is also quite constrained.

	In	Se	Ga	Ge	Te	
Crustal abundance [21]	0.05	0.12	15	1.4	0.005	ppm
Typial grade in ore [21]	4	4	50	20	1.5	ppm
Reserve base (2007)	16000	170000	>1000000	500 (US only)	47000	tons
Reserve (2007)	11000	82000	>1000000	?	21000	tons
Annual refinery (2007)	510	1550	103	100	135	tons
Static depletion time (2007)	22	53	9700	?	155	years
Andersson (2001) [22]	25	37	200	25	37	years

Table 7. Crustal abundances, typical element grade in ore, reserves and static depletion time estimations of thin-film PV elements. Reserve and refinery data are extracted from USGS [13]. For comparison, the static reserve life (in this case the reserve to extraction ratio) calculated by Andersson (2001) [22] has been added. For gallium, the reserve data are global resources (economic and uneconomic). Andersson used U.S. resources only for gallium.

Tellurium

Tellurium is obtained from electrolytic copper refining. Demand for tellurium increased during the last years because of the growing demand for PV cell production and thermal cooling applications.

The figures shown in Table 7 for the reserve and reserve base of tellurium include only tellurium contained in economic copper deposits and assume that less than half of it is actually recovered, therefore representing a significant underestimation of the possible tellurium refining capacity [20]. The static depletion time for tellurium is estimated to be 155 years.

Germanium

Germanium is also increasingly used in solar cells. The available resources of germanium are associated with zinc or lead-zinc-copper sulphide ores. Significant amounts of germanium are also contained in ash flue dusts of coal combustion. The given reserves and reserve base figures (Table 7) do not consider the latter. In this study, a static depletion time was not calculated because of the lack of data, but we assume it to be much higher than that for indium, selenium or tellurium.

Gallium

Gallium is mostly extracted as a byproduct of bauxite treatment, but it also occurs in small concentrations in coal and some sulphide ores. The world bauxite reserve base is so large that much of it will not be mined for many decades [13]. World resources of gallium in bauxite are roughly estimated to exceed 1 billion kilograms. For Gallium, no data on world production is available because output data of the few producers are considered to be proprietary. Refined gallium production in 2007 was estimated to be of 103 metric tons, including some scrap refining. We estimate the static depletion time for gallium to be of around 9700 years.

4.3 Material recycling and substitution

Recycling of technical devices including PV modules is one option to extend high-technology element availability. Difficulties arise out of the fine dispersion of used technical devices and of the complexity in terms of their element composition. The amount of indium-containing technical units produced per year is estimated to number more ore less one billion units [18].

Global secondary indium production caught up primary production during the past few years [16]. Tellurium and selenium recycling is currently not carried out in significant amounts. But of course, this could change in the future if CdTe and CIGS/CIS thin-film PV become major applications. Substitution is another possibility to extend material availability. Further research into element substitutes will be stimulated if respective element market prices rise significantly.

A fundamental way to enhance material supply is through intensified exploration for mineral deposits. This search could focus in promising areas, where high-technology elements are already known to exist as subproducts of base metal extraction. This includes the Iberian Pyrite Belt (IPB), a metallogenic province known for its massive sulphide ore resources. The IPB contains 82 inactive and working mines, including world-class deposits such as the Neves Corvo mine, a giant producer of copper, tin and significant indium [23].

Our current INCA project comprises a detailed study of several sulphide ore deposits of the IPB, in order to identify and characterise ores anomalous in high-technology element contents. Presently, indium is being recovered in significant amounts from ore concentrates from the Neves Corvo mine. Several other ore deposits within the IPB may also contain economic amounts of indium and additional high-technology elements and are currently being investigated. Promising indium contents (up to 90 ppm) have already been determined in sulphide ores from the still unexploited Lagoa Salgada massive sulphide deposit, which is situated in the northwestern part of the Portuguese IPB.

5 Conclusions

This work confirms serious material constraints for the element indium and to a less extent for selenium, tellurium and possibly germanium. Our estimations show that until 2020, the material amounts determined for thin-film PV are quite manageable. But assuming the EPIA Advanced Scenario [1] for PV production growth and a thin-film PV future as predicted by the Prometheus Institute [12], serious supply problems for at least some of the considered elements will arise beyond 2020. This is especially the case for indium, with a current static depletion time of 22 years. To secure long-lasting supply of the vulnerable elements and facilitate thin-film module production in GWp ranges, exploration for new mineral deposits is essential. Therefore, the INCA project comprises a detailed study of several sulphide ore deposits of the Iberian Pyrite Belt (IPB), in order to identify and characterise ores anomalous in high-technology element contents. Significant indium contents have already been determined in the Lagoa Salgada massive sulphide deposit, situated in the northwestern part of the Portuguese IPB.

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