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Materials Availability for Large-scale Thin-film Photovoltaics

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The objective of this paper is to discuss to what extent materials availability could restrain the expansion of PV systems based on CdTe, CIGS, aSiGe and nano-crystalline dye-sensitised cells. The investigated elements are cadmium, tellurium, indium, gallium, selenium, germanium and ruthenium. Materials requirement, annual availability and available stock of resources are assessed. The material constrained growth of installed capacity in the year 2020 is estimated at about 20 GWp/year for CdTe and dye-sensitised cells, 70 GWp/year for CIGS and 200 GWp/year for aSiGe. These potentials are reached through decreased materials requirement and increased materials availability. Metal prices are assumed to rise. With pessimistic assumptions, the potentials decrease by one or two orders of magnitude. Implications for public policy and firm strategy are briefly discussed. Copyright © 2000 John Wiley & Sons, Ltd.

OBJECTIVE AND SCOPE

The objective of this paper is to discuss to what extent materials availability could restrain the size and growth of PV-systems based on CdTe, CIGS, aSiGe and nanocrystalline dye-sensitised cells.

The assessment comprises chemical elements that are part of the photon-absorbing layer. Contact and window layer materials are not included as there exist designs of the four assessed solar cells where contact and window layer materials are unlikely to pose any fundamental availability problem.¹ The investigated elements are cadmium, tellurium, indium, gallium, selenium, germanium and ruthenium. Materials requirement, annual availability and available stock of resources are assessed.

The assessment is mainly based on literature studies. There is a general lack of data for the investigated metals and most figures given are based on rough estimates.

Materials availability for solar cells, in particular indium availability, has been addressed in a few other studies.^{1–8}

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Table I. Material constrained PV expansion potentials

Solar cell	Metal	Baseline					Modified 2020
		Metal requirements* (g/m ²)	Reserves 1998† (Gg)	Refinery production 1997‡ (Mg/yr)	S_{MC} § (TWp)	G_{MC} ¶ (GWp/yr)	$G_{MC }$ (GWp/pr)
CdTe	Cd	6.3	600	20000	9	310	500
	Te	6.5	20	290	0.3	5	20
CIGS	Se	4.8	70	2200	1.4	46	300
	Ga	0.53	110	54	20	10	400
	In	2.9	2.6	290	0.09	7	70
aSiGe	Ge	0.44	2	63	0.5	14	200
Dye-sensitised	Ru	0.1	6	11	6	11	20

*Sources: CdTe (2 μ m);⁶⁸ CIGS (2 μ m)⁴ and the composition CuIn_{0.75}Ga_{0.25}Se₂; aSiGe (0.2 μ m) layer in double junction aSi/aSiGe cell,⁶⁹ atomic Ge:Si ratio is put to 2:3;⁷⁰ dye-sensitised.⁷¹

†Reserves data for all metals except for ruthenium and gallium are taken from the USGS.⁷² Older estimates of the reserves of gallium²⁶ and ruthenium⁵⁷ are used. Indium reserves only include indium contained in zinc ores. Harrower⁷³ estimates that the total indium reserves are in excess of 10 Gg. The given germanium reserves do not represent more than a part of actual reserves.

‡Refinery data for all metals, except for ruthenium and indium, are taken from the US Geological Survey (USGS).⁷² Secondary refinery production is included for all other metals except for gallium, but appears to be modest. Data for tellurium and selenium are completed with estimates from Crowson.⁴⁵

§Material constrained stock assuming that the 1998 reserves are used to produce 10%-efficient solar cell modules (100 Wp/m²).

¶Material constrained growth assuming that the 1997 refinery production levels were used to produce 10%-efficient solar cell modules (100 Wp/m²).

||For assumptions see Discussion.

FROM MEGAWATTS TO GIGAWATTS

This paper provides estimates of the material constrained growth (G_{MC}) of a PV system, i.e., the growth rate at which annual materials availability becomes a limiting factor. It also provides estimates of the material constrained stock (S_{MC}) of solar cells, i.e., the size of a PV system may reach before materials (metals) become too costly due to metal scarcity. The focus will mainly be on material-constrained growth. In an initial phase, the growth rate of a PV system will be equal to PV manufacturing, while in a later phase, PV manufacturing will include manufacture for replacement as well as for system growth.

Estimates of materials availability are commonly based on figures of current reserves and refinery production. Therefore, the reserves in 1998 and the refinery production rates in 1997 are used together with metal requirements to produce baseline G_{MC} and S_{MC} (Table I). Metal requirements represent current technology. Stabilised module efficiencies are put to 10% for all the four technologies. (All module efficiencies referred to in this paper are aperture area efficiencies.) Additional base case assumptions are 100% materials utilisation, 100% recycling and no competition for metals.

The base case G_{MC} for the four technologies falls in the range 5–14 GWp/year. Compared to the total PV sales in 1998 of about 0.16 GWp,⁹ these figures are large. However, if PV is to provide anything but a marginal part of global electricity production during the next century, the production rate needs to increase by orders of magnitudes. In 1995, the electricity production in the world was about 13,000 TWh.¹⁰ If we assume an average solar irradiation of 2000 kWh per square meter PV module and 20% system losses (BOS efficiency, power conditioning efficiency and temperature correction), this corresponds to some 8 TWp of installed PV capacity. To build up such a system in 50 years would require an average growth rate of 160 GWp/year of 1000 times the manufacturing volume in 1998 and 10–30 times the baseline G_{MC} .

The reserves, i.e., the known resources that could be economically recovered at current prices, correspond to stock of installed PV capacity from 0.09 TWp for CIGS to 6 TWp for the dye-sensitised

cell, with baseline assumptions about materials utilisation (baseline S_{MC} in Table I). These figures are much larger than the cumulative production of solar cells of about 0.001 TWp,^{9,11–13} but smaller than the 8 TWp that would be required to produce 13,000 TWh/year. To supply a major part of electricity demand during the next century, even larger systems are likely to be required. If the growth of electricity production in the period 1985–1995 of about 3% per year is continued, five times more electricity will be produced in 2050 than in 1995. Moreover, if significant amounts of fuel are to be produced with PV, yet larger systems are needed. In 1995, about two-thirds of global primary energy supply was used for purposes other than electricity production.¹⁰

The baseline G_{MC} and S_{MC} given in Table I are merely indicators, used here as a point of departure. G_{MC} and S_{MC} could increase if metals requirement decreases or if metal availability increases. Competition from other end-uses could limit the amounts of metal available for PV. In the rest of this paper these factors are analysed. The possibility for increased S_{MC} is outlined and an attempt to make more qualified estimates of G_{MC} for the year 2020 is pursued. The modified 2020 G_{MC} estimates are included in Table I.

PROSPECTS FOR DECREASED METALS REQUIREMENT

The required amounts of metals could be lowered through dematerialisation or substitution (transmaterialisation). Dematerialisation, i.e., using less materials input to produce the same output, can be obtained through higher materials utilisation, thinner films or higher module efficiencies.

Specific elements can be partly replaced, but at some level there is likely to be a trade-off between substitution and cell performance. Gallium could substitute for indium in CIGS cells. Zweibel⁵ assumes that 75% substitution is likely and that near 100% substitution may happen. The CIGSS ($\text{Cu}(\text{In,Ga})(\text{Se,S})_2$) currently produced by Siemens Solar has a gallium–indium atomic ratio of 15:85 and a sulphur–selenium atomic ratio of 2:998.¹⁴ In a multiple junction amorphous silicon cell, the silicon–germanium layer can be omitted, or substituted for by nanocrystalline silicon, implying a 100% substitution of silicon for germanium. It is possible that other transition metal complexes could substitute for the currently preferred ruthenium complex in dye-sensitised cells.¹⁵

In Table I, a materials utilisation of 100% is assumed. Materials utilisation here denotes the fraction of metal feedstock that ends up in working solar cells. Near 100% utilisation implies that process losses and the number of defective cells are kept very low or that efficient recycling of this new scrap is undertaken. Alsema¹⁶ assumes process losses in the range of 30–85% for aSi, 20–40% for CIS and 1–10% for CdTe cells. Between 2% and 40% is assumed to be lost in defective cells and modules. Zweibel¹⁷ gives figures on process losses in the range 75–90% for germanium, 2–25% for tellurium and 50% for indium. Processes to recycle CdTe and CIS modules have been designed, with estimated costs in the range 3–10 USD/m².^{18–21}

In Table I, a module efficiency of 10% is assumed for all cells to facilitate comparisons. In 1999, Siemens Solar produced CIGSS cells with 11% efficiency¹⁴ and CdTe modules from solar Cells Inc. (now First Solar) were rated at 7.3%.²² Commercial aSi modules had stabilised efficiencies between 4% and 8%.²³ The highest independently confirmed *module* efficiencies through March 1999 were 12.1% for CIGS (CIGSS), 10.5% for CdTe and 10.4% for aSiGe (triple junction), while the champion *cell* has reached 18.8% for CIGS, 16.0% for CdTe, 13.5% for aSiGe (triple junction, unstabilised result) and 11.0% for dye-sensitised nanocrystalline materials.²⁴ Theoretical efficiencies fall between 25% and 30% for all cells.²⁵

In Table I, the thickness of CdTe and CIGS layers is assumed to be 2 μm . This reflects current technology reasonably well and facilitates comparisons. Both technologies were recently introduced on the market. In 1999, Solar Cells Inc. produced CdTe cells 3–4 μm thick²² and Siemens Solar produced 1.2 μm thick CIGS cells.¹⁴ Zweibel¹⁷ gives the figure 2 μm for CdTe from BP Solar as well as for CIGS from Global Solar. Regarding physical limits, Zweibel⁵ estimates that the thickness can be reduced to near 0.5 μm without light-trapping, and to 0.2 μm with sophisticated light-trapping.

Table II. The cost of metals and their potential value to PV production

Solar cell	Metal	Metal requirement* (A) (g/m ²)	Average metal price 1993–1997† (B) (USD/kg)	Metal cost (A × B) (USD/m ²)	Metal price equivalent of 10 USD/m ² (C = 10 USD/m ² A) (USD/kg)	Price ratio (C/B)
CdTe	Cd	6.3	2.3	0.01	1500	28
	Te	6.5	55	0.36		
CIGS	Se	4.8	9.9	0.05	3400	12
	Ga	0.53	430	0.23		
	In	2.9	280	0.81		
aSiGe	Ge	0.44	1400	0.62	23000	16
Dye-sensitised	Ru	0.1	1200	0.12	100000	83

*Source: Table I.

†Sources: USGS.^{28,72} For Ru the price is an average for 1997 only.⁵⁹ Prices for standard commodities are used and are thus not totally comparable. Purity: Cd 99.95% (3N), Te 99.7% (2N), Se 99.5% (2N), Ga 99.99999% (7N), In 99.97% (3N), Ge 99.99999% (7N), Ru not available. Prices (order of magnitude) for high purity materials: Te 6N 400–1200 USD/Kg,³⁴ Se 6N 30–50 USD/kg,⁴ In 7N 1500 USD/kg.⁵⁵

At current metal prices, the metal costs amount to a small fraction of projected costs for PV systems. Assuming 100% materials utilisation and standard grade metal, the metal costs would amount to less than 1 USD/m² (Table II). Even if the module cost and area-related BOS cost decreased to 50 USD/m² each, the cost for indium, the most costly metal, would amount to less than 1% of total area-related costs. Even if high purity metal is required (see notes in Table II), substitution or thinner cells would not be economically warranted at current metal prices if these strategies would increase other production costs by more than 5%, or decrease the module efficiency from, for example, 10% to less than 9.5%. Making cells thinner could reduce the time required for deposition and thereby reduce capital costs and thus become economically warranted for other reasons than materials saving.¹⁷ Given the few studies made of PV recycling, the cost of recycling defect cells could not be covered by the value of the recovered metals alone at current metal prices, but would have to be partly motivated by other factors, such as costs for waste disposal and recovery of substrate glass.²⁰

In conclusion, there exist options for decreased materials requirement. However, these options might not be economically warranted until metal prices have risen substantially and module production costs come close to long-term goals. The greatest potential for decreased requirements for CdTe and CIGS metals is the development of thinner films, which ultimately could reduce metal inputs by a factor of 10. Currently, the most important way to reduce germanium requirements is to increase materials utilisation.

PROSPECTS FOR INCREASED AVAILABILITY

The low ratio of metal costs to total PV costs has another implication. If the use of a certain scarce element allows for production of somewhat less costly electricity, the PV industry could be willing to pay for metal recovery costs many times above the current price level. In Table II, this effect is illustrated by showing the metal price equivalent of a cost share of 10 USD per square meter module. A PV system with area-related BOS costs of 50 USD/m² and 10% efficient modules that cost 50 USD/m² would produce electricity at about 0.06 USD/kWh. Assume that such a system is competitive on the mass markets for electricity. Then, if, for example, CIGS modules were to reach 11% efficiency, up to 10 USD/m² could be spent on indium and the module would still be competitive. This corresponds to an indium price of 3400 USD/kg for a 2 µm thick layer, or more than 10 times the current price for standard grade indium, and to 34,000 USD/kg, or more than twice the price of gold, for a layer than is 0.2 µm thick. Up to

23,000 USD/kg could be paid for germanium if a 0.2 μm silicon–germanium layer would increase the efficiency of an amorphous silicon cell from 10% to 11%. As a third example, if the cost for producing 10% efficient dye-sensitised cells amounted to less than 45 USD/m², 50,000 USD/kg could be paid for ruthenium.

The question then is how an increased demand for PV metals and higher metal prices could alter the availability of PV metals.

The general picture: rare, scattered and minor metals

The seven metals considered are rare or geochemically scarce (Table III). The average abundance in the continental crust varies from 0.0001 ppm for ruthenium to 15 ppm for gallium. This makes ruthenium less abundant than gold and gallium almost as abundant as copper. However, while copper is enriched by a factor of 200–800 in ores that are mined at present, gallium seldom forms any minerals of its own and a high concentration in any mineral is exceptional.²⁶ This is also the case for germanium, selenium and indium. These metals are therefore sometimes classified as ‘scattered metals’.²⁷ The rarer element tellurium is enriched by a factor of about 300 in copper ore and the rarest element, ruthenium, is found in concentrations about 10,000 times above the crustal average in some platinum-group ores. The combined effect of crustal concentrations and enrichment factors makes the typical ore grades for these

Table III. Geological and economical characteristics of some minor and major metals

	Crustal abundance* (ppm)	Typical grade in mineral ore† (ppm)	Enrichment: Grade ratio‡ ore/crust	Price 1993–1997§ (USD/kg)	Ore value¶ (USD/Mg)	Primary refinery prod. (Gg/yr)	Value of production** (MUSD/yr)
<i>Cu-ore</i>							
Cu	25	5000	200	2.5	12	10000	25000
Se	0.12	4	30	9.9	0.04	2	20
Te	0.005	1.5	300	55	0.08	0.3	17
<i>Zn-ore</i>							
Zn	65	40000	600	1.1	44	7000	7700
Cd	0.1	200	2000	2.3	0.4	20	46
Ge	1.4	20	10	1400	25	0.05	70
In	0.05	4	80	280	1	0.2	56
<i>Bauxite</i>							
Al	80000	200000	3	1.6	320	20000	32000
Ga	15	50	3	430	21	0.05	22
<i>PGM-ore</i>							
PGM*	0.001	6	6000	10000	60	0.3	3000
Ru	0.0001	0.8	10000	1200	1	0.01	12
<i>Au-ore</i>							
Au	0.0025	5	2000	13000	65	2	26000

*Average concentration in the continental crust.⁷⁴

†Typical copper grade for US mines, world average zinc grade, typical aluminium grade.⁴¹ The bases for selenium, tellurium, cadmium, germanium, indium and gallium grades is given in Table IV. Ruthenium rich PGM ore is selected (UG2) with a total PGM (PGM* + Ru) grade of about 7 ppm⁷⁵ whereof 12% is ruthenium.⁵⁷ The gold grade represents the average for mined South African ore.⁷⁶

‡Column 3 divided by column 2.

§Average price. Source: Table II and USGS.^{28,72} Varying purity (see Table II).

¶Value of metal contents in ore *in situ*: ore grade (column 3) times price (column 5).

||Approximate figure for refined metal from primary sources. Source: Table I and USGS.²⁹

**Approximate value of annually refined primary metal: price (column 5) times annual primary refinery production (column 7).

six metals fall in the range 0.5–50 ppm. Cadmium shows high enrichment factors and is not as rare in the crust as tellurium and ruthenium. It is recovered from zinc ores with cadmium grades of about 200 ppm.

Due to the low grades in combination with relatively low prices, the seven metals are recovered as by-products. Tellurium and selenium are by-products of copper refining. Indium and germanium are mainly by-products from zinc recovery. Also gallium is somewhat concentrated in zinc ore, but is mainly recovered from bauxite. Ruthenium is a by-product of the recovery of other platinum-group metals (PGM). They typically generate less than 1% of the revenues from recovering the principal products. In economic terms, all the seven metals considered are minor metals. The value of the total annual refinery production is small compared to base metals such as copper, zinc and aluminium due to the small amounts refined, and compared to gold and platinum due to relatively low prices (Table III).

The availability of these minor metals depends on *mining* primarily driven by demand for major metals, on *recovery* from mined ore and on *recycling* of secondary materials.

Prospects for recycling

Currently, secondary sources represent only a minor fraction of total refinery production of the seven metals.^{28–30} At present, it is difficult to determine the recycled fraction of produced old scrap (scrapped products). Accordingly, it is difficult to say how much metal is sent to landfills or how much is emitted to the environment. The potential for increased contribution from secondary sources can thus not be determined here. As mentioned above, it seems feasible to recover metals efficiently from solar cells.

Prospects for increased recovery from mined materials

The minor metals are not recovered from all mined ore where they are present, and when they are, recovery rates are in general low. Table IV presents an estimate of the amounts of PV-metals in mined minerals. Even if other sources exist, the most important flows are believed to be covered. For the seven metals, with the exception of cadmium and ruthenium, a rather small fraction of the amounts contained in mined minerals are recovered and refined to metal. This discrepancy is especially large for the more geochemically abundant elements, gallium and germanium.

As was shown above, a successful development of thin-film PV technologies could result in drastically increased demand and a higher value for some scarce metals. In the long run, an increased demand for germanium or gallium would probably result in a raised output, possibly without much elevation in prices, due to the large amounts of metal present in mined materials at reasonable high grades. Guiling⁷ used an overall efficiency of 40% for gallium recovery from bauxite. Applying this recovery rate to the figures in Table IV gives a potential gallium output of 2300 Mg/year, i.e., 50 times current primary refinery production. Large amounts of gallium are also believed to be present in phosphate ore.³¹ Coal ashes could become an important source for gallium and germanium (Table IV). Germanium was commercially recovered from germanium rich coal ashes in the UK between 1950 and 1970.³² If germanium were priced as high as gold, the germanium metal value in average coals (not taking recovery costs into account) would be about 80 USD/tonne coal or about twice the current price of coal (based on an average germanium grade of 6 ppm³³). Moreover, due to the low utilisation of gallium and germanium refinery capacity, it seems likely that supply can meet demand also in the short run.

Tellurium is concentrated during recovery of copper, lead, zinc and gold.³⁴ In 1982, more than 90% of the recovered tellurium was derived from electrolytic refining of copper, with most of the remainder coming from electrolytic refining of lead.³⁵ No data have been found for tellurium contents in zinc, lead or gold ores, nor for tellurium contents in residues from zinc, lead and gold recovery fed into copper smelters. Selenium is also mainly derived from electrolytic refining of copper.

About 20% of copper metal production is not refined by electrolysis.³⁶ The recovery efficiency from anode slimes at refineries where tellurium and selenium are processed is estimated at 33% for tellurium^{37,38} and 30–80%, averaging 52%, for selenium.³⁹ Selenium recovery in copper smelting is

Table IV. Flows of primary metal (Mg/yr)

	Metal contents in mined ore (annual average 1993–1997)*					Refined metal (% of mined) 1993–1997	Refinery capacity 1992**
	Zn-ore†	Cu(Ni)-ore‡	Bauxite§	PGM-ore‡	Coal¶		
Cd	<u>36000</u>				2000	19000 (50%)	26000
Te		<u>3700</u>			100	280 (7%)	450
Se		<u>9300</u>			7000	2200 (13%)	2300
Ga	540		<u>5700</u>		23000	45 (0.2%)	450
In	<u>860</u>	730			27000	52 (0.2%)	270
Ru		2		<u>27</u>	5	11 (32%)	n.a.

*Underlined figures denote the present major source of refined metal.

†Figures are based on production of zinc concentrates,²⁹ 90% zinc recovery in the concentration step,⁴¹ and estimates of concentrations in sphalerite (ZnS) for cadmium (3000 ppm),⁷⁷ gallium (45 ppm) and germanium (300 ppm).⁵⁴ The indium grade in zinc concentrate (60% zinc) is assumed to be 50 ppm and the concentration recovery efficiency 70%.⁵¹

‡Ruthenium figures are based on ruthenium–platinum grade ratios from Buchanan,⁵⁷ a platinum recovery efficiency of 75%⁵⁸ and platinum refinery production from USGS.²⁹ All other figures are based on copper mine production²⁹ and a copper concentration recovery efficiency of 85%. Tellurium and selenium contents in one tonne blister copper refinery feed is assumed to be 200 g and 500 g respectively.^{38,39} Smelter and concentration recovery efficiencies are put to 60%³⁹ and 85%,⁴¹ respectively (see the text). The ratio between produced blister copper and primary smelter feed is estimated at 92% based on data from Edelstein⁷⁸ and Chapman.⁴¹ Indium and germanium contents in chalcopyrite of about 20 ppm⁵⁴ are used to estimate the indium and germanium contents of copper ore at 60 g per tonne contained copper.

§The figure is based on bauxite mine production.⁷⁹ The average Ga concentration in bauxite is assumed to be 50 ppm.²⁶ Weeks⁵⁴ gives the figure 60 ppm.

¶Figures are based on coal 'production' figures from BP,⁸⁰ and typical contents in coals for cadmium (0.5 ppm),^{33,81} selenium (1.5 ppm), gallium (5 ppm) and germanium (6 ppm).³³ An indium grade of 0.02 ppm is applied here.⁸² Smith *et al.*⁵¹ estimate that US coals generally contains 0.04 ppm indium. Schweine³³ estimate that most coals have indium grades in the range 0.01–0.2 ppm. The tellurium content is estimated to be in the same order of magnitude as indium. Davidson and Lakin⁴³ assume a selenium–tellurium ratio of 100. One study on US coals indicates that PGMs in coal occur in concentrations of the order of 1 ppb (0.001 ppm) or less. Ruthenium was present in amounts greater than the limit of detection (2–3 ppb) in only nine samples out of 122.⁸³ A grade of 1 ppb is applied here.

||Ruthenium data represent average demand for primary ruthenium for 1996 and 1997.⁵⁹ Indium data represent average primary refinery production for 1994–1997.⁷³ Secondary refinery production is included for all other metals except for gallium, but this fraction appears to be modest. Refinery data for all metals except for ruthenium and indium are taken from US Bureau of Mines and US Geological Survey.^{29,84,85} Data for tellurium and selenium are completed with estimates from Crowson.⁴⁵

**Data are taken from Crowson.⁴⁵

estimated to be 25–70%,⁴⁰ averaging 60%.³⁹ Since data for losses in the concentration step (mining, milling and concentration) for selenium and tellurium is lacking, the average efficiency of copper recovery (85%) is used.⁴¹

To calculate reserves and potential recovery, the US Bureau of Mines and the US Geological Survey have, for a number of years, used an estimate of 500 g of selenium and 200 g of tellurium per tonne of blister copper fed into refineries.^{37,38,42–44} Based on this assumption and recovery efficiencies of 85% for concentration and 60% for smelting, the average tellurium and selenium contents of mined copper ore are estimated at 9300 and 3700 Mg/year, respectively, on average over the years 1993–1997. A comparison between these figures and refinery production demonstrates that 8% of the tellurium and 24% of the selenium contained in mined copper ore are recovered. The tellurium-to-copper recovery ratio has decreased by about 30% from around 1970 to the 1990s.^{28,29,45–47} (Figures given by Roskill³⁵ indicate lower efficiencies for tellurium recovery. However, Roskill also states that tellurium grades in copper ores vary between 0.1 and 5 ppm, and nowhere exceed the upper limit. At present, the average copper grade in mixed ore is about 1%.^{41,48} Given the copper–tellurium ratio calculated above, tellurium grades in copper ore would at present average 3 ppm.)

If the estimates above are reasonably correct, recovery of tellurium from all slimes produced from electrolytic refinery of copper could increase the refined amounts by 70%, to 500 Mg per year. Guilinger⁷

states that the refinery recovery efficiency would increase to 50%. An increase from 33% to 50% would raise the refinery production to 750 Mg. According to this calculation, if demand increases, moderately raised prices could increase tellurium output by a factor of 2–3. Higher recovery rates would probably imply a substantially raised tellurium price. Processes to recover metals from copper anode slimes are optimised to recover gold and other precious metals.³⁸ In the United States, one tonne of blister copper fed into refineries contains about 10 g of recoverable gold (estimate based on Lucas⁴⁹). This gives a tellurium–gold ratio of about 20:1. Thus, to approach the by-product values generated from gold recovery, the tellurium price would need to increase about 10-fold. To reach the level of revenues earned from copper, and give incentives to alter smelter and concentration processes and to increase the share of electrolytic refinery, the price of tellurium would need to increase about 100-fold (see Table III).

Indium is mainly derived from zinc recovery, although it is also present in copper, lead and tin materials.⁵⁰ The indium concentration in sphalerite (ZnS) varies between 0.05 and 10,000 ppm.⁵⁰ In an extensive survey of indium contents in various ores, Smith *et al.*⁵¹ use an estimate of 50 g indium per tonne zinc concentrate based on Kaiser⁵² and assume 70% concentration recovery efficiency. A zinc content of 60% in concentrates and a 90% zinc recovery in concentration⁴¹ gives an average indium grade of 70 ppm in sphalerite, or 100 g indium per tonne zinc (on average 4 g indium per tonne ore), and 860 Mg indium per year contained in mined zinc ore in the time period 1993–1997. These assumptions show that about 20% of the indium contained in mined zinc ore were refined to metal. (Based on the statement that sphalerite available to mills and smelters commonly contains 10–20 ppm indium,^{53,54} Roskill⁵⁰ uses the grade 15 ppm indium in sphalerite to calculate indium contents in mined zinc ore. For 1993–97, this would yield 180 Mg indium per year or 10 Mg less than the amount that is refined!) Due to the great variations of indium grades even within single zinc deposits,⁵⁰ the usefulness of this type of calculation exercise can be questioned. In comparison to zinc ore, copper ore seems to have even more varying indium grades.⁵¹ Due to the large amounts of copper ore mined, the associated indium flow might be noticeable despite low grades (Table IV).

Indium recovery is a complex process⁵⁵ and cost estimates of recovery improvements are beyond the scope of this study. From the early 1970s to the late 1990s, the indium-to-zinc recovery ratio has increased by about 200%.^{28,29,45–47,50} The recovery efficiency is expected to increase further.⁵⁶ Guilinger⁷ states that current recovery rates are estimated at 50–70%. Assuming that this refers to smelting and refinery recovery, the total recovery efficiency is 35–49%. Accordingly, refinery production could almost double (from 20%) if a sustained increase of demand emerged. For ore containing 100 g indium per tonne zinc on average, the value of the contained indium represents 2% of the value of the contained zinc (Table III). For indium to reach co-product status in such ores, the indium price would need to increase about 50 times, to the price level of gold and platinum. For some mines, indium could become the principal product at a much lower price. Ore from one Japanese mine is, for example, reported to contain 1200 g indium per tonne zinc (150 g indium per tonne ore).⁵⁰ The Mt. Pleasant tin mine has an average indium grade of 100 g per tonne ore.

The ruthenium contained in mined platinum-group metal ore and nickel–copper ore is estimated at 29 Mg/year, implying that 38% of the ruthenium contained in these ores are refined to metal. The calculation is based on ruthenium–platinum ratios given by Buchanan,⁵⁷ primary refinery production of platinum metal, and an assumed efficiency of platinum recovery of 75%.⁵⁸ The ruthenium–platinum ratio in South African ores differs for Merensky Reef and the UG2 chromite layer. Based on rhodium–platinum grade and refining ratios, an ore distribution of 65% from Merensky Reef and 35% from UG2 is assumed for the period 1993–1997.

If South Africa is assumed to be the single source for ruthenium, about 41% of the ruthenium mined in South Africa was refined and used in products, the rest not being recovered or being stockpiled. It appears likely that ruthenium recovery could nearly double to 75% if demand increases. This argument is supported by rhodium statistics. Ruthenium is currently the least expensive PGM metal with an average price of 1200 USD/kg in 1997,⁵⁹ while in the time period 1993–1997 rhodium was the most expensive PGM metal, with a price average of 19,000 USD/kg.⁷² In 1997, the recovery of rhodium from South African ore was about equal to ruthenium demand,⁵⁹ while the rhodium grade in mined ore was about

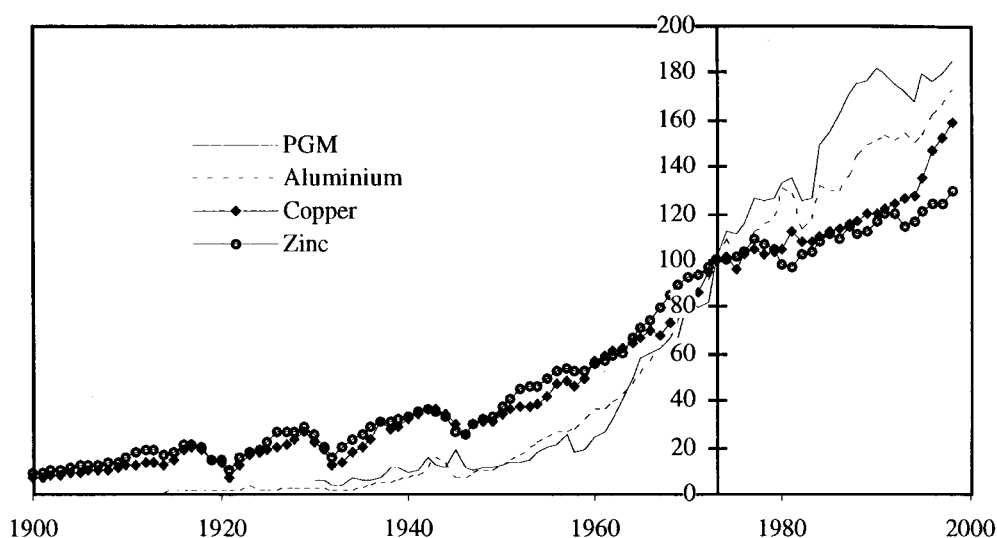


Figure 1. Relative development of mine production before and after 1973 (mine production of copper and zinc and primary refinery production of aluminium and PGM^{28,29,46,60,90}

half the ruthenium grade. The ruthenium-to-PGM recovery ratio decreased from about 6% in the early 1970s, to 3% in the early 1990s and rose to 4% in the late 1990s.^{29,45,59–61}

Prospects for increased mining

The potential output of the seven investigated by-product metals depends on the development of the mine production of major metals, primarily copper, zinc, aluminium and the PGMs.

Figure 1 shows the historical mine production of copper, zinc, aluminium and the platinum-group metals. In the period 1948–1973, the growth rate of mine production was about 5% per year for copper and zinc and about the double for PGMs and aluminium (bauxite). The growth rates have slowed down and were, in the period 1973–1998, in the range 1% per year for zinc to 2.5% per year for PGMs (Figure 1, Table V). The demand for the base metals aluminium, copper and zinc is likely to be driven by general economic growth, while the demand for the PGMs could be more sensitive to how specific technologies, such as catalytic converters or fuel cells, develop. From a supply perspective, metals such as PGMs and aluminium that have large reserve-to-production (R/P) and reserve-base-to-production (RB/P) ratios, have a greater potential for high growth rates (Table V). The relatively high growth in copper output in recent years related to increased demand, has not yet been balanced with a corresponding increase of reserves. Accordingly, the R/P-ratio has decreased by 42% since 1974. Aluminium is abundant and will be available at reasonable cost in quantities far exceeding the current bauxite reserves. This is not the case for

Table V. Growth in mine production and reserves-to-production ratios

	Annual growth of mine production* (%)		R/P 1997†	RB/P 1997†	R/P change
	1948–1973	1973–1998	(years)	(years)	1974–1997‡ (%)
PGM	9.4	2.5	240	270	+130
Bauxite	9.1	2.0	200	280	–3
Cu	4.8	1.9	30	57	–42
Zn	4.8	1.0	25	59	+28

*Metallgesellschaft AG and World Bureau of Metal Statistics, USGS and Roskill.^{28,29,46,60}

†USGS.²⁸

‡Metallgesellschaft AG and World Bureau of Metal Statistics, USGS, Roskill and Tilton.^{28,46,60,86}

the other metals that are highly enriched in mined ore (Table III).⁶² It is thus possible that land-use regulation and increased cost for mining and metal recovery could come to hamper growth rates of copper and zinc in the not-too-distant future. About 90% of the PGM reserves and 97% of the ruthenium reserves are located in one country, South Africa.^{28,30} This would make PGM supply more vulnerable to monopolistic behaviour and geopolitical incidents.

The minor metals grades vary significantly between different ores of the same major metal. Therefore, the potential output of the minor metal is not just determined by the total mine production of major metals, but also by which specific deposits are mined. For example, if demand for ruthenium increases, investment could focus upon the mining of ruthenium-rich ore from the UG2 layer in South Africa at the expense of other ores. A movement in this direction is already occurring due to an increased demand for, not ruthenium, but rhodium.³⁰ As mentioned above, indium grades differ by orders of magnitude from mine to mine. There exist at least two tellurium deposits that could be economically developed primarily for tellurium recovery, one in Mexico (1.7 Gg tellurium, with an average grade of 0.2%, 8.5% of the reserves) and one in China.⁷ If the prices of the minor metals increase substantially, new types of ores could become of economic interest. Manganese nodules on the ocean floor are believed to be a future source of manganese, nickel, copper and cobalt.⁶³ The few samples where the tellurium content has been measured indicate high tellurium grades. Out of 70,000 samples recorded in the Marine Minerals Database,⁶⁴ the tellurium content is measured for only 30 samples from 16 different locations. The median tellurium grade for the 16 locations is 45 ppm (range 5–220 ppm). A tellurium price at a level with gold and platinum prices could make nodules with tellurium grades of about 30 ppm economically recoverable for their tellurium, nickel, cobalt and manganese contents (estimate based on Hoagland⁶³).

In general, the annual output of the minor metals is likely to continue to be heavily dependent on the long-term development and the short-term boom-and-bust cycles of major metal output. However, considering the potential willingness to pay for the minor metals (see discussion above) and their ore grades, it is not impossible that demand for these metals could become an additional driver for increased mining (Tables II and III). Substantially raised prices could also lead to new discoveries and draw attention to resources that have previously been overlooked.

Stocks of available resources

The reserves of tellurium, indium, germanium and ruthenium limit the size of a solar cell system to a fraction of the current electricity system: CdTe to 4%, CIGS to 1%, aSiGe to 6% and dye-sensitised cells to 75% (Table I). In Table VI, other stocks are presented and compared to the reserves. The grand totals, of which only a fraction is likely to be recovered, amount to 80, 150, 4000 and 1.7 times the reserves for tellurium, indium, germanium and ruthenium, respectively. While a major part of ruthenium stocks are included in ruthenium reserves, only a small part of germanium stocks are included in germanium reserves. Almost 60% of total tellurium stocks are contained in deep-sea manganese nodules and 75% of the germanium stocks are contained in coal reserves. The stock of metal refined until 1998, now dissipated in products, waste dumps and the environment, is unlikely to become a large source for any of the four metals, while recovery from old residues from mineral processing possibly could become important, since recovery factors have been low. The accessibility of such residues is believed to vary. While indium rich residues are believed to be stockpiled, tellurium not recovered initially is stated to be 'permanently lost'.⁷

COMPETITION FOR METALS

As indicated above, PV manufacturers could become willing to pay metal prices many times above current prices. Therefore, it seems likely that solar cells could claim a large share of annual supplies of the minor metals in the future. However, the metal demand from solar cell production will not be significant for many years. By the time solar cells do claim their share of metal resources, a large part of the least

Table VI. Metal stocks

	Tellurium		Indium		Germanium		Ruthenium	
	Gg	(x R)*	Gg	(x R)*	Gg	(x R)*	Gg	(x R)*
<i>Total in deposits</i>	1400	(70)	310	(120)	6900	(3300)	9.6	(1.6)
Reserves (R)†	20		2.6		2.1		6	
Additional contents in copper, zinc and PGM deposits‡								
Reserves	84	(4)	37	(14)	75	(36)	—	
Sub-economic	95	(5)	44	(17)	94	(45)	0.6	(0.1)
Other resources	1200	(60)	200	(78)	500	(240)	2	(0.3)
Contents in coal reserves§	20	(1)	20	(8)	6200	(3000)	1	(0.2)
<i>Total mined</i>	150	(8)	70	(27)	1500	(730)	0.6	(0.1)
Cumulative refinery production¶	13	(0.7)	4	(2)	3	(1)	na	
Additional contents in mined materials								
Metal ore	130	(7)	60	(23)	130	(64)	na	
Coal	5	(0.3)	5	(2)	1400	(670)	0.2	(0.03)
<i>Grand total</i>	1600	(80)	380	(150)	8400	(4000)	10	(1.7)

*Multiple of reserves.

†Source: Table I.

‡Major metal resource data from USGS,²⁸ minor metal contents from Table IV. Manganese nodules represent 900 Gg of other tellurium resources based on an average grade of 10 ppm and 90 Pg of nodules.⁴³ Additional not quantified resources exist, for tellurium in lead and gold ores, and for indium in tin ores.

§Coal reserves from BP⁸⁰ and metal contents from Table IV.

¶Estimates based on data from USGS/USBM,^{28,29,47,54,61,84,85,87,88} Crowson⁴⁵ Roskill.^{32,50}

||Based on cumulative mine production of copper, zinc, PGM^{28,29,46,60,89,90} coal^{80,91} and on minor metal contents from Table IV. The total amounts of mined ruthenium from metal deposits are estimated at 0.4 Gg.

expensive resources that are known at present will either have been wasted or recovered for use in other applications. These amounts could possibly become available if residues are stockpiled and products efficiently recycled.

The demand trend for indium points upwards. Since 1980, indium refinery production has quadrupled (Figure 2). The refinery production of tellurium and ruthenium has remained relatively constant, while germanium output has decreased by 50%. The use of thin-films on glass for LCD displays is the main driver for increased indium demand. Demand is expected to keep rising, but substitution and increased

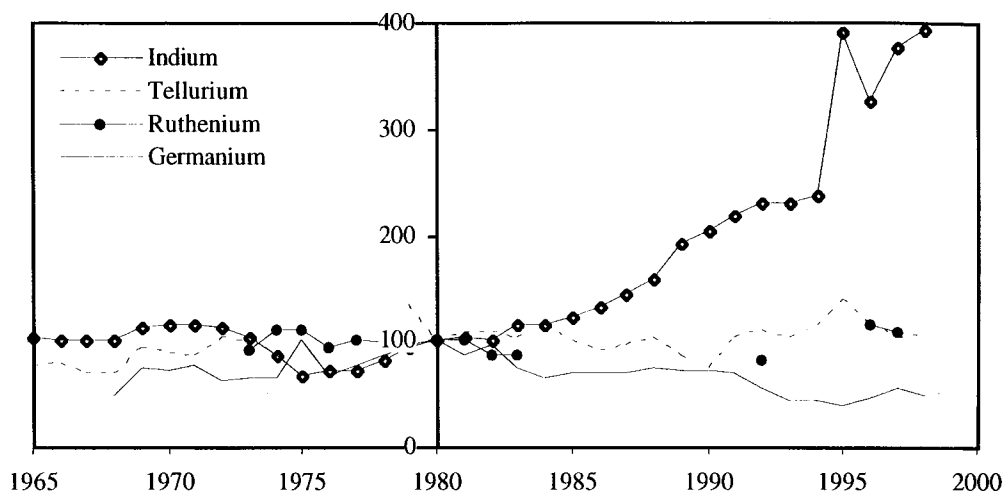


Figure 2. Relative development of refinery production before and after 1980^{28,29,32,45,47,50,59,61,84,85}

recycling could moderate the demand for primary indium if the indium price rises.⁵⁶ The major use of tellurium is in steel alloys. Tellurium demand is not increasing and the price is currently falling.⁶⁵ The dominating use of germanium is in fibre optics and the demand from this area is expected to increase.⁶⁶ Ruthenium demand has increased slightly during the 1990s, but is not expected to increase substantially in the near future.⁵⁹ In the longer-term, the development of fuel cells for vehicles could come to require large quantities of ruthenium.⁶⁷

DISCUSSION

If PV production grows by 30%, the baseline G_{MC} of 5 GWp/year and 14 GWp/year will be reached in 2011 and 2015, respectively. At a growth rate of 20%, these levels are reached in 2017 and 2023. In Table VII, the PV expansion potentials are recalculated for the year 2020, based on the findings in previous sections. Different factors are given as corrections to the baseline assumptions. The numbers should be treated as optimistic guestimates. Increased prices are assumed.

Table VII. 2020 PV expansion potentials (modifications to baseline assumptions)

		CdTe		CIGS			aSiGe	Dye-s.
		Te	Cd	In	Se	Ga	Ge	Ru
<i>Requirements</i>	<i>x</i>	<i>2.4</i>	<i>2.4</i>	<i>8.4</i>	<i>5.6</i>	<i>2.8</i>	<i>1.1</i>	<i>1</i>
Utilisation	x	1	1	1	1	1	1	1
Efficiency	x	1.2	1.2	1.4	1.4	1.4	1.1	1
Thickness	x	2	2	4	4	4	1	1
Substitution	x	1	1	1.5	1	0.5	1	1
<i>Availability</i>	<i>x</i>	<i>1.9</i>	<i>0.7</i>	<i>1.2</i>	<i>1.3</i>	<i>13.8</i>	<i>10.8</i>	<i>2.2</i>
Recovery	x	2	1	2	1.5	10	10	2
Mining	x	1.2	1.2	1.2	1.2	1.5	1.2	1.7
Competition	—	0.5	0.5	1.2	0.5	1.2	1.2	1.2
<i>Total</i>	<i>x</i>	<i>4.6</i>	<i>1.7</i>	<i>10</i>	<i>7.3</i>	<i>39</i>	<i>12</i>	<i>2.2</i>
G_{MC}								
Base case	(GWp/yr)	5	310	7	46	10	14	11
2020	(GWp/yr)	<u>20</u>	500	<u>70</u>	300	400	<u>200</u>	<u>20</u>

See text for explanations.

Materials utilisation is assumed to be high (close to 100%) for economic and environmental reasons. The efficiency is raised to 14% for CIGS, 12% for CdTe and 11% for aSiGe to reflect the differences in module and cell efficiencies that have been achieved. Based on potentials and differences in current production, the thickness is put to 1 μm for CdTe and to 0.5 μm for CIGS. The indium–gallium ratio is lowered from 3 to 1 without assuming any loss of efficiency ($\text{CuIn}_{0.5}\text{Ga}_{0.5}\text{Se}_2$). These changes decrease indium requirements by eight times.

Recovery of metal from mined materials is assumed to increase by a factor of two for tellurium, indium and ruthenium. For ruthenium this is an upper limit, while tellurium and indium recovery could increase further if prices rise substantially. At the same time, while ruthenium recovery most certainly can increase by a factor of two, there is a greater uncertainty regarding a doubling of tellurium and indium recovery rates without significantly raised prices. The currently low recovery efficiencies of gallium and germanium are reflected in high increases. The factor of 10 is probably not an upper limit. Mine production of copper and zinc is assumed to increase by 1% per year, bauxite by 2% and PGM by 2.5%. Competition is assumed to be weak for tellurium, selenium and cadmium. This is illustrated by reducing the use in current

applications by 50% at elevated prices. The increase of demand for indium, gallium, germanium and ruthenium from other applications is put to 1% per year. A prerequisite for this low number is a development characterised by high materials utilisation, miniaturisation, recycling and substitution.

The modified G_{MC} for the year 2020 for the four technologies becomes about 20 GWp/year for CdTe and dye-sensitised cells and about 70 and 200 GWp/year for CIGS and aSiGe.

We should note that the rather bright future outlined in Table VII is based on significant change from the current situation. If materials requirement for indium in CIGS and tellurium in CdTe, for example, remain at the current level, if the primary refinery production cannot be increased, and if strong competition only makes 20% of primary indium and tellurium available for PV production, then the G_{MC} for CIGS and CdTe are only about 1 GWp/year and 0.5 GWp/year, respectively.

The potential stocks given in Table VI, in combination with lowered materials requirements, indicate that any of the investigated technologies could in time contribute significantly to world electricity production. However, if the growth of PV production is slow and a significant metal demand does not arise until way into the next century, all of the currently known low cost resources of indium and tellurium, in particular, could be lost in wastes or be locked-in in other technological systems.

The minor metal prices required to raise recovery factors or affect mining rates could come to offset part of a potential cost and efficiency advantage for a solar cell technology. In a scarcity situation, the extra profits generated from producing superior solar cells would be transferred to the companies and states that own high-grade ore.

There is a long way from the current situation to a situation where solar cells are the dominating use for one or many metals. In the medium term, fast changes in supply and demand could induce large fluctuations in metal prices and encourage speculation. This would increase risks and possibly frighten investors.

Significantly raised metal prices and increased metal demand could change the environmental pressure caused by solar cell production in different directions. If the price of a metal rises, it is likely that less of this metal will be emitted to the environment. As an example, 1 GWp of CdTe cells could sequester 60 Mg of cadmium that otherwise could have been wasted or used in short-lived products. But raised metal demand could also lead to accelerated mining, which could increase sulphur dioxide emissions and metal leakage from waste dumps and cause large-scale land transformations. As an example, if indium demand became a driver for the mining of zinc ore, 1 GWp of CIGS modules could set free some 3000–6000 Mg of cadmium. In this sense, cadmium could become a larger problem for CIGS than for CdTe. If the minor metals considered here become major metals due to demand from the PV industry, this industry could be held responsible for a large share of the environmental effects of mining. To recover 1 g of Te from copper ore one needs to mine more than 1 tonne of ore. In terms of turn-over of materials, solar energy could become the 'coal industry' of the 21st century, extracting about as much material from the crust for every kWh of electricity produced.

IMPLICATIONS FOR POLICY AND STRATEGY

If thin-film solar cells based on scarce metals become an integral part of a fast growing PV industry, high materials utilisation (including recycling of new scrap) and thinner films will be a key issue for PV manufacturers 10 years from now. Long term contracts with the metal industry will decrease risks for sharply increased metal costs. Vertical integration could become one solution. The production of more than one type of solar cell will decrease risks. Systems for recycling of used solar cells need to be fully developed in 20–30 years.

Mining and metal companies should carefully consider stockpiling residues from which minor metals cannot be recovered economically at present. The effects of drastically altered demand for PV metals ought to be considered when new long-term investments are made.

Public policy might be needed to stimulate a timely build-up of organisation and infrastructure for recycling of minor metals. Publicly available information on minor metal resources needs to increase. A possible development of strong alliances between PV manufacturers and mining companies needs to be

balanced with strict environmental regulation and research in a variety of PV technologies. The window of opportunity needs to be kept open for new solar cell designs.

As has been shown, the potential for CdTe, CIGS, aSiGe and dye-sensitised nanostructured cells could be fairly large. If the potential turns out to be small due to metal scarcity or environmental concerns, it will be important for the future development of PV that these technologies come to function as bridges that facilitate the growth of technologies with greater potential and not as dead-ends that delay the transition to a more sustainable energy system.

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