# Materials Availability:

## Potential constraints to the future low-carbon economy

## Working Paper I: Thin Film photovoltaics

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# Preface

This report has been produced by the UK Energy Research Centre's Technology and Policy Assessment (TPA) function. The TPA was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide authoritative reports that set high standards for rigour and transparency, while explaining results in a way that is useful to policymakers.

This working paper addresses some of the issues arising in the contemporary debate on materials availability, specifically examining metals critical to the development of low carbon technologies. The subject of this assessment was indicated as of importance during UKERC stakeholder engagement, involving independent experts from government, academia and the private sector.

The working paper was written by researchers and academics at the Centre for Energy Policy and Technology at Imperial College (ICEPT).

# Executive Summary

The impact that resource scarcity might have on the achievability of global carbon dioxide reduction targets and associated targets for renewable energy is the focus of a series of UK Energy Research Centre (UKERC) working papers and reports. The focus is on methodological issues as well as the range of findings that exist in the literature. This Working Paper is the first in this series and considers issues related to the availability of indium and tellurium for thin film photovoltaic applications.

The Paper considers first *demand* for indium and tellurium from the PV industry, now and in future. Whilst a range of scenarios exist for the role of PV in the global energy mix there is considerable agreement that the share of PV per se and thin film devices in particular is expected to expand considerably in the light of carbon abatement goals.

The relationship between the market for PV and markets for component materials such as indium and tellurium is not fixed however, since the material required per unit of capacity installed is a function of several key factors; density of material, thickness, efficiency of operation and material utilisation during manufacture. The Paper quantifies these relationships and develops a simple parametric model linking PV demand to requirements for indium and tellurium. This model is used to investigate existing literature on the demand for indium and tellurium. We find a wide range of assumptions are used and that key assumptions are not always dealt with transparently. Further, the material requirements required to meet a notional capacity of PV (we use 20 GW per year) ranges between 160t/y and 2320t/y and 1129t/y and 4216t/y for indium and tellurium respectively, using the assumption range found within the literature. Demand from the PV sector could become significant, exceeding existing production by a significant amount, particularly in the case of tellurium. It also concludes that a far more systematic approach to quantifying demand from the PV industry is merited.

The paper then considers the *supply* of indium and tellurium. It provides a detailed review of the processes used to extract and refine them, and discusses the issues associated with producing these *secondary metals* which are extracted as trace elements during the production of primary metals such as zinc and copper. The Paper finds that there are considerable complexities associated with reported reserves and an absence of meaningful data on resources. Again, existing estimates of availability for the PV market are reviewed. This also reveals considerable variation within the literature and the use of a wide a range of assumptions upon which to base resource availability.

The paper concludes that there is no immediate cause for concern about availability of either indium or tellurium. PV occupies a small fraction of current markets and there is evidence of considerable potential to increase the extraction of both metals because a sizeable proportion of the material potentially available from primary metal extraction is not currently utilised. Moreover, there is potential to increase recycling of products containing indium or tellurium, for example from flat screens. However, the scale of the roll out of PV

envisaged in some scenarios could imply a large expansion in the demand for indium and tellurium. There is no reason to believe that this is not feasible, however adequate data on reserves and resources do not exist. Resource estimates are not available and simplistic assumptions such as using current production or crustal abundance to estimate potential supply cannot provide any meaningful insight into future production. A scenario approach that links production to primary metals is appropriate. We conclude that considerable further research is needed to characterise indium and tellurium resources and the economic feasibility of expanding production.

# Glossary and definitions

| | |
|---|---|
| CIGS | Copper Indium Gallium (Di)Selenide |
| CdTe | Cadmium Telluride |
| USGS | United States Geological Survey |
| BGS | British Geological Survey |
| URR | Ultimately Recoverable Resource |
| TCO | Transparent Conductive Oxide |
| ITO | Indium Tin Oxide |
| IEA | International Energy Agency |

# Definitions

### Critical materials:

In this document we refer to *'critical materials'*, which is used to denote any material for which a future supply concern may have been expressed. This is a practical definition given that no consensus exists regarding the measurement of 'criticality'. Several other terms are used to denote this group. 'Critical' and 'strategic' are both variously used in conjunction with either 'metal', 'mineral' or 'material'. In addition to this inconsistency, the specific materials referred to may vary, as different reports identify different groups of materials considered 'critical'.

### End-of-life recycling

Defined as the proportion of materials recycled from PV modules as a proportion of the total weight of materials in modules which have reached the end of their useful lives.

### Material constraints

The phrase *'material constraints'* is defined as any potential constraint to manufacturing of a particular technology based on the supply of critical materials.

### Mined metal and recyclate

We refer to *'mined metal'*, which has been produced through the extraction and processing of ore, and *'recyclate'* which has been recovered by recycling end-of-life products.

### Photovoltaic (PV) efficiency

When referring to efficiency of PV we refer to the single junction efficiency of converting light to electricity under standard test conditions.

### Primary and secondary metals

*'Primary metal'* is one for which mining and processing operations were initiated historically, which is present in an ore in substantial quantities and which almost invariably constitutes the main economic value extracted from an ore. A '*secondary metal'* is one present in the same ore body, often in trace quantities which is separated from the primary metal as a result of processing and/or as a consequence of additional operations being carried out, often on residues of the primary extraction process. Secondary metals are often rare and found in trace quantities but should not be confused with rare earth metals (see below).

### Rare earth metals

Other rare metals, specifically element numbers 57 to 71 in the periodic table, which are also known as lanthanides. Unlike secondary metals (see above) these are not trace elements associated with a primary metal but are found together in several minerals known collectively as the rare earths. They are very similar in properties because the outermost electron shells are the same in all rare earth metals. Specifically they have particular electromagnetic and physical properties that give them particular commercial value.

### Reserves, Reserve base

Definitions of reserves, reserve base and resources vary depending on the reporting institution. Given that most data reproduced here is taken from the US Geological Survey (USGS), their definitions are presented below.

*'Reserves'* – That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system.

*'Reserve base'* – That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). The term 'geologic reserve' has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve-base category; it is not a part of this classification system.

### Resources

*‘Resource*’ – A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

### Utilisation

Utilisation is defined here as the weight of material (indium or tellurium) in produced PV modules as a proportion of the weight of material input in a given year. This includes the efficiency of material deposition in the manufacturing process, and any volume of wasted material which is recycled back to the manufacturing process.

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# 1 Introduction

## 1.1 A UKERC series on resource scarcity and low carbon energy

For over two centuries the availability of resources critical to the development of society and its economies has been a debated and contentious topic. This debate has included a range of resources, from agricultural production to exotic metals (Malthus 1798; EC 2010), and from fossil fuels to fertilisers (Jevons 1865; Cordell *et al.* 2009; Sorrell *et al.* 2009). More recently the availability debate has focused on resources which have been variously referred to as critical raw materials, 'high tech' metals or non-fuel resources. The definition of 'critical materials' is not widely agreed, but commonly includes the Rare Earth Elements (REEs), the Platinum Group Metals (PGMs), indium, gallium and cobalt (EC 2010). Box 1 provides a brief review of some key studies of critical materials.

Concern over the availability of critical materials has been driven by several factors, two of which seem dominant. First, the rapid economic growth of the developing economies, in particular China, has resulted in an expectation of sustained growth in future demand for many resources. This can be coupled with the geographical location of many of these materials and the industrial strategies (including export quotas) being pursued by some of those countries within which these materials exist (Bloomberg 2010). Second, although critical materials have uses in many sectors of the global economy, the use of critical materials in low carbon technologies may be of particular concern given the significant growth in this sector, driven by the decarbonisation agenda. Materials considered to be critical in the low carbon context include tellurium, which we discuss here, lithium for batteries, the subject of a separate UKERC report (under production at the time of writing) and the critical materials listed above.

The impact that **resource scarcity** might have on the achievability of **global carbon dioxide reduction** targets and associated targets for renewable energy is the focus of a series of UK Energy Research Centre (UKERC) working papers and reports. In the light of earlier UKERC work on global oil depletion (Sorrell *et al* 2009), the series considers the methodological difficulties associated with estimating the future abundance of various minerals and seeks to explain why estimates of availability differ. The series takes a *case study* approach in order to look in depth at particular low carbon technologies. This paper is the first of this series.

## 1.2 Thin Film PV, a case study on indium and tellurium

This paper investigates the possibility that scarcity of particular metals will impede the expansion of cost effective photovoltaic (PV) electricity generation. The IEA estimate that global installed PV capacity in 2050 may reach 3000GW, 200 times greater than global PV capacity in 2008 (IEA 2010a). Due to their relatively low cost and potential for continued cost reduction and efficiency improvement so called 'thin film' PV devices are expected to take an increasing share of the PV market as it expands(IEA 2008).

Copper-indium-gallium-(di)selenide (CIGS) and cadmium-telluride (CdTe) cells have both made major inroads into the PV market in recent years (Photon International 2010). Indium, gallium, selenium and tellurium are all relatively scarce metals, produced in small quantities globally. They feature in various recent analyses of 'critical' materials (see Box 1.1).

This working paper considers indium and tellurium in detail, seeking generic conclusions related to the assessment of availability and implications for low carbon development. While three component materials of CIGS PV cells have been highlighted as of supply concern, indium is expected to become the principal availability constraint (Keshner and Arya 2004; Feltrin and Freundlich 2008). Tellurium is believed to be the principal material availability concern with regards to CdTe (Feltrin and Freundlich 2008; Fthenakis 2009).

Indium and tellurium also provide interesting case studies for a number of reasons – both the differences between them and the similarities:

- Both are '***secondary***' metals present in trace quantities in an ore body that is mined in order to extract a ***primary*** metal which represents the majority of the economic value of the ore (also see definitions on page vii). As we explain below this means that conventional estimations of *abundance* may not be a good guide to future production.

- Demand for indium is growing rapidly (due largely to use in flat panel displays), whilst the market for tellurium has fluctuated historically, reflecting a diversity of uses.

- Finally, around 75% of global indium originates in China, which has recently imposed export quotas on a number of metals including indium. Tellurium is more widely distributed internationally.

The remainder of this paper investigates the following:

1. Projections of global growth in the market for PV and the prospective share that might be occupied by thin film devices.

2. The relationship between the growth of thin film PV devices and demand for indium, tellurium and other metals. This section emphasises the range of assumptions about materials requirements that exists in the literature and stresses the importance of clarity and transparency with regards to key determinants of *demand* in addition to market size; such as materials thickness, conversion efficiency and material utilisation rates in manufacture.

3. The sources of and production processes for indium and tellurium, hence what it is possible to say about their abundance and potential for future production to expand. These sections discuss the appropriateness of various techniques and assumptions used in the literature to assess the potential for growth in *supply* of indium and tellurium.

The paper concludes with a review of what we need to know in order to make judgements about the possibility of materials supply shortage affecting the growth of the PV industry.

We note that there is the potential for demand from CdTe and CIGS PV to require considerable expansion in the supply of indium and tellurium, although this will depend on both the expansion of the PV market overall and the share of different types of semi-conductor. Whilst resource scarcity would not appear to be of immediate concern there is a need for more systematic analysis of the factors that determine both demand for and supply of the metals considered in this case study. Supply data are poor and the demand side needs to be considered more systematically. Systematic assessment of this form will allow a clearer view of whether, and under what conditions, resource scarcity concerns will become significant.

## Box 1.1: CRITICAL MATERIALS: MATERIALS AVAILABILITY REVIEWS

During the late 2000s several high level studies began to highlight a range of minerals considered critical to the development of the future economy. These reports engage varying methodologies but have in common the attempt to identify the criticality of a range of materials through a defined methodology. Though their results differ a common theme is that many of the materials at the top of these lists are components of low carbon technologies. This may not be surprising given the seismic shift in the future energy economy envisaged by many scenario modelling exercises published in the last decade (CCC 2008; UKERC 2009; IEA 2010a). The link between the low carbon transition and critical materials is further supported by a report published by the US Department of Energy "Critical Materials Strategy" (USDoE 2010).

Several high level studies attempt to review a range of materials and identify those materials of most concern (Morley and Eatherley 2008; Angerer *et al.* 2009; EC 2010). A wide range of techniques and assumptions are used to define what is 'critical'. The range of findings is presented in table 1.

**Table 1.1: Summary findings of three 'critical materials' reports**

| **Angerer (2009)**[1] | **EC (2010)**[2] | **Resource Efficiency KTN** (Morley and Eatherley 2008)[3] |
|---|---|---|
| Gallium | Antimony | Gold |
| Neodymium | Beryllium | Rhodium |
| Indium | Cobalt | Mercury |
| Germanium | Fluorspar | Platinum |
| Scandium | Gallium | Strontium |
| Platinum | Germanium | Silver |
| Tantalum | Graphite | Antimony |
| Silver | Indium | Tin |
| Tin | Magnesium | Magnesium |
| Cobalt | Niobium | Tungsten |
| Palladium | PGMs (Platinum Group Metals) | Baryte |
| Titanium | Rare earths | Talc |
| Copper | Tantalum | Bismuth |
| Selenium | Tungsten | Palladium |
| Niobium | | Nickel |
| Ruthenium | | Boron |
| Yttrium | | Andalusite |
| Antimony | | |
| Chromium | | |

Notes:

[1] In order of scarcity, based on projected demand from 'emerging technologies' over production of material in 2006. Based on assessment of 15 materials and 32 emerging technologies.

[2] In alphabetical order, chosen based on minimum score for both economic and supply risk.

[3] Materials scoring >17 in assessment of criticality. Based on 8 risk criteria.

# 2 The global market for PV thin film devices and demand for indium and tellurium

## 2.1 Introduction

This section discusses the global market for PV, demonstrating the large expansion envisaged in many scenarios and focusing in particular on the potential market share of thin film devices now and in the future. Based on this it discusses the relationship between the market for PV, detailed configuration of thin film modules and demand for indium and tellurium. We highlight the set of factors that translate thin film market size into demand for component metals based upon the composition and construction of CIGS and CdTe devices.

We note that key factors are often poorly disaggregated in existing analyses of future demand for indium and tellurium from the PV sector and that judgements about efficiency, utilisation and other key considerations differ considerably between studies.

We conclude that there is a need to explore sensitivity to module design, efficiency and material requirement in the light of various scenarios for the growth of thin film devices and techno-economic assessment of the potential for efficiency and material utilisation to improve. In the absence of such work it is difficult to draw meaningful conclusions about the extent to which the PV market might be constrained by material availability.

However, we provide illustrative ranges for the demand that thin film PV might create for indium and tellurium, based upon a range of assumptions related to material requirements and PV market expansion consistent with that in the literature. The wide range of possible demands demonstrates the uncertainty inherent in this subject area. However we also note that it is possible, in principle, for demand from PV to become substantial relative to current production of both indium and tellurium.

## 2.2 The market for PV

Photovoltaics currently account for a small share of global electricity, around 0.6% of global installed capacity (EIA 2007; EPIA 2010). Nevertheless, cumulative installed capacity is in excess of 39 GW[1] (EPIA 2011) representing a 27 fold expansion relative to the year 2000 (EPIA 2010). Annual production of PV cells has grown from 287MW in 2000 to over 27GW in 2010 (Figure 2.1) and strong market growth is expected to continue. To provide an indication of the scale of growth expected, the European Photovoltaic Industry Association (EPIA) estimates annual installed capacities to reach nearly 30GW by 2014 (EPIA 2010) in their short term market forecast. This is a 316% increase from the market size in 2009.

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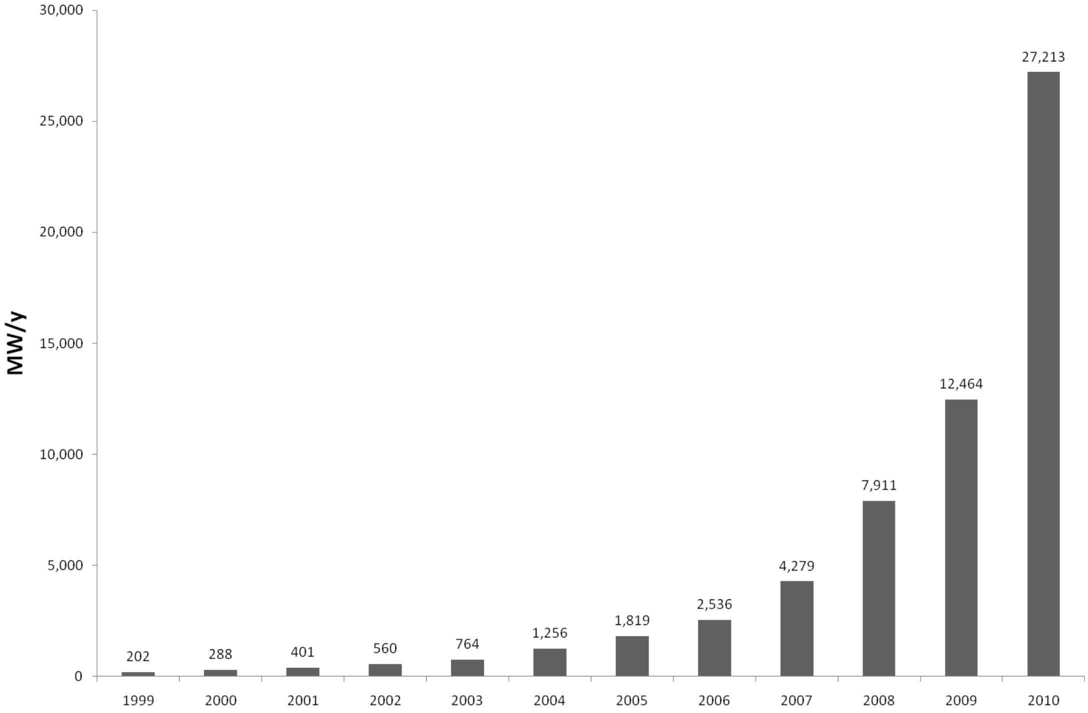
[1] Based on 2010 data

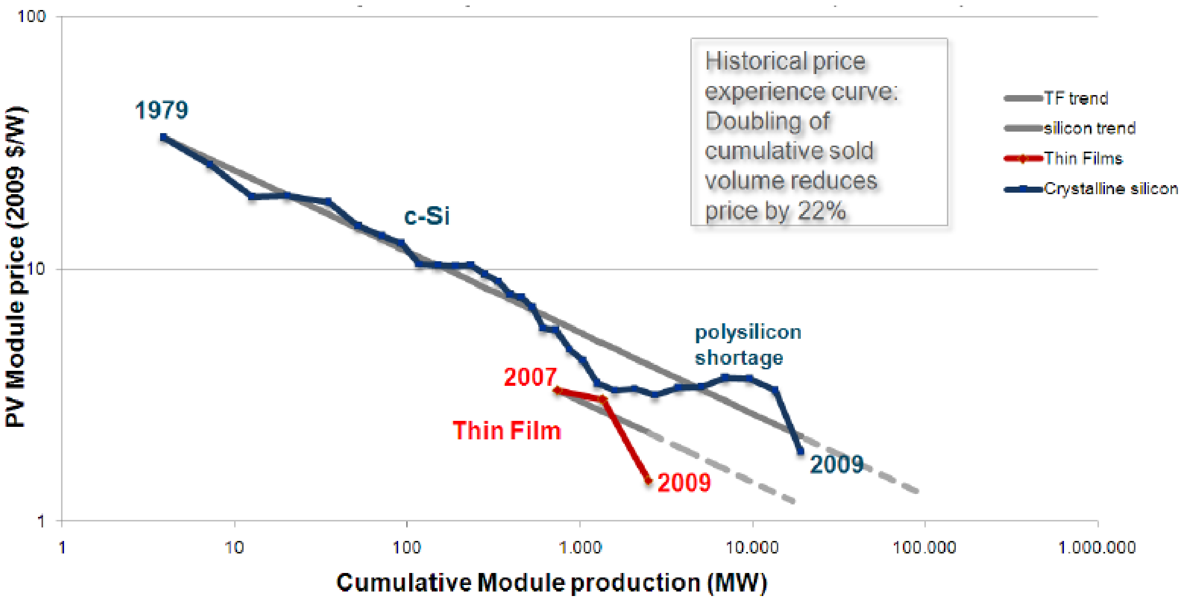
**Figure 2.1: Global Annual PV production**



*Source*: Hering (2011)

The cost of PV has fallen steadily most years since the technology was first introduced for use in satellites in the 1970s. The cost of commercial modules fell from around $70/Wp in 1976 to around $2/Wp in 2008 (Photon International 2009b). It is important to note that thin film CdTe devices are now amongst the cheapest available, at 0.75$/Wp (First Solar 2011).The potential for further reductions in cost in thin film technologies specifically is thought to be significant (Figure 2.2), and as we discuss further below, are expected to take an increasing share of the PV market as it expands over the coming decades (IEA 2008).

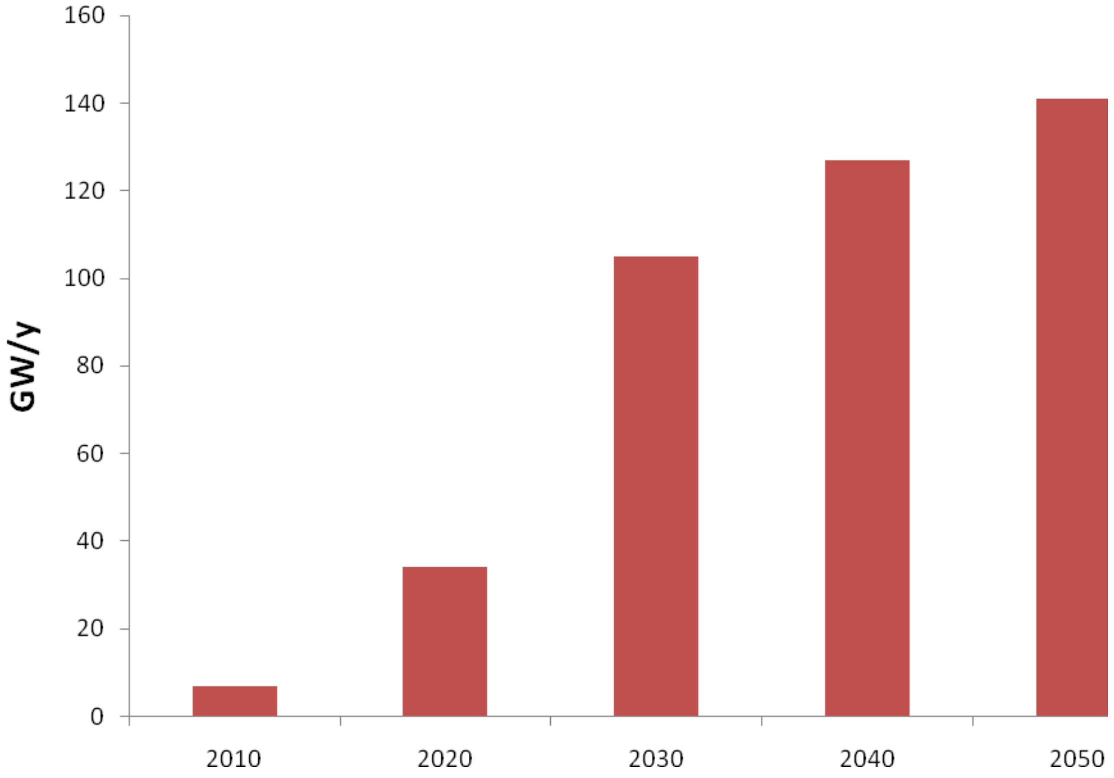
Figure 2.2: PV module price experience since 1979 (2009$/W)



*Source:* EPIA

Largely as result of these encouraging cost and installation trends the PV sector is expected to grow considerably in the future. The IEA Blue Map long term scenario estimates cumulative installed capacity to reach 3000GW by 2050, providing up to 11% of global electricity (IEA 2010b). We present this data in Figure 2.3. This is derived from the IEA Energy Technology Perspectives (ETP) 'Blue Map' scenario (IEA 2010a), which attempts to meet a global $CO_2$ reduction of 50% against 1990 levels by the year 2050.

Figure 2.3 IEA PV Roadmap



*Source*: IEA (2010a)

## 2.3 The market for thin film devices

The market for PV can be broken down by technology. It is currently dominated by crystaline silicon technologies, with thin film technologies representing a minority share. Photon International (Hering 2011) present the annual share of thin film, which represented 13.1% of the total market in 2010, with various forms of crystaline silicon accounting for the remaining 86.9% of the market. Of this thin film market CdTe represented 45%, amorphous silicone 42% and CIGS 13%, or in absolute terms 1.6GW CdTe, 1.5GW amorphous silicone and 0.5GW CIGS.

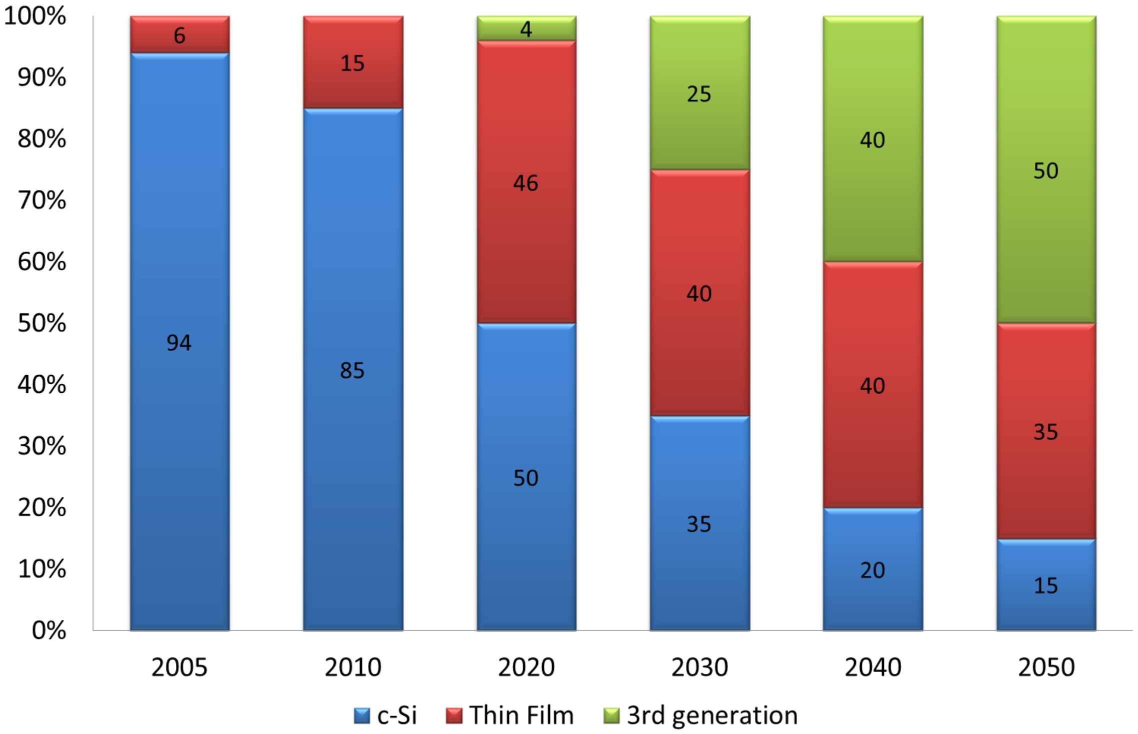
The future market for PV will also include other PV technologies (referred to as 3rd generation, see Figure 2.3) , though many estimates suggest that thin film technologies will represent an increasing share of the market in the medium term. Predicting future market share for thin film techologies is not straighforward as the results depend upon the future competitiveness of the technologies (versus ‘incumbent’ crystilline silicon technologies) as well as future maket developments both in terms of total PV demand and investments in capacity expansion. All these elements are difficult to predict. However, some estimates are presented in the table below.

**Table 2.1: Estimates of future thin film market share**

| Author | Thin film market share estimate |
|---|---|
| Photon International (2009a) | 40% of PV market by 2030 |
| Dimmler (2010) | 30% of PV market by 2020 |
| IEA (2008) | 40% of PV market by 2030 (see Figure 2.4) |

The IEA go further and present the changing share of all three generations of PV technology per decade from 2010 to 2050, which we present in Figure 2.4. If the thin film market share was 46% in 2020, this may be 16GW/y based on data in Figure 2.3 and Figure 2.4. On the same basis the annual PV market may reach 42GW/y in 2030, and 51GW/y in 2040.

**Figure 2.4: IEA estimate of future PV market share**



*Source*: IEA (2008)

The share of thin film PV technologies in the future PV market will of course have a significant bearing on the extent to which thin film materials such as indium and tellurium may constrain the overall PV market.

## 2.4 Linking PV markets to demand for raw materials

There are good reasons to expect that the market for thin film PV devices, hence for indium, tellurium and other component materials is expected to grow considerably. However, this provides relatively little information about the volumes of raw materials that will be needed, since the amount of indium, tellurium or other inputs per PV module has not yet been considered. Moreover, it is possible that the volume needed per device could change over time, such that the relationship between a growing market for PV and growth in the market for PV components and raw materials may not be linear. For example, is it possible for innovation to allow markets to grow whilst materials requirements are held down or even reduced? How much material might the future PV sector need, taking into account innovation and change in product design?

In order to explain, this section considers the theoretical relationships that affect material requirements, and defines a simple parametric model of material requirements. Next, we consider how thin film devices are constructed and provide typical figures for materials utilisation in current commercial devices.

### 2.4.1 From PV demand to demand for indium and tellurium

A range of estimates of the demand for indium and tellurium exist in the literature. However, as we discuss in detail below, assumptions about efficiency, material thickness or utilisation differ between studies. Moreover, few studies provide a clear and transparent review of the basic principles upon which the relationship between a volume of PV production and demand for component materials. The key factors are as follows:

- **Quantity of material per Wp**, expressed in g/Wp and a function of:
    - **Density of active material,** in this case either CIGS or CdTe
    - **Thickness of active layer,** measured in microns (μm)
    - **% of material in layer,** in this case measuring the share of tellurium in CdTe or Indium in CIGS and calculated by formula weight
    - **Efficiency,** a measure of the amount of energy captured per square meter under standard test conditions (STC), being an energy intensity of 1000W/m$^2$.
    - **Utilisation,** a measure of efficiency of material use in the manufacturing process.

These factors can be combined in the following mathematical relationship:

2.1

$$M_R = \frac{\rho F \mu}{U I_{SC} \eta}$$

Where $M_R$ is the material requirement in t/GWp, $\rho$ is the density of the active layer material, $F$ is the % of material in layer, $\mu$ is the thickness of the layer in microns (μm), U is the utilisation factor, $I_{SC}$ is solar insolation under standard conditions (1000W per $m^2$) and $\eta$ is the electrical conversion efficiency of the PV cell.

While several of these variables will have a significant impact on material demand, and wide plausible ranges of assumptions, others are less likely to change and therefore have a less significant impact on this analysis. Density of the active layer is one variable where plausible assumptions are likely to exist within a very narrow range. This figure could be reduced through reducing the purity of active layer materials, and while this may have a meaningful impact on the cost of materials, it is unlikely to significantly affect the material requirement. Likewise the percentage of tellurium in a layer of CdTe is unlikely to vary much given the stoichiometric relationship of the compound. This is not the case for CIGS, where the proportions of the alloy have a significant effect on materials requirements.

By multiplying $M_R$ by an assumed PV manufacturing rate the total annual demand for a specific material can be determined.

Conversely, by assuming a total annual material availability and dividing this by $M_R$ a total achievable PV manufacturing rate can be estimated.

This simple parametric model can be used to assess future demand under a wide range of assumptions, to test sensitivities to key variables and illustrate materials requirements for possible future PV markets under different assumptions. An illustration is provided in part 2.7. UKERC intends to explore sensitivities further in future work.

## 2.5 CIGS and CdTe: The technologies

### 2.5.1 CIGS modules

Copper Indium Gallium (di)Selenide (CIGS) is an alloy consisting of a mixture of copper indium (di)selenide (CIS) and copper gallium (di)selenide (CGS). CIGS has the chemical formula $CuIn_xGa_{(1-x)}Se_2$ where the value of x can be anything between 0 and 1. This is to reflect the variable ratio of CIS to CGS. If x=1 the alloy is pure CIS and if x=0 then the alloy is pure CGS. While the choice of x value may be used to optimise cell efficiency, it also has a bearing on the relative requirement of indium and gallium for a specific volume of CIGS material. It therefore has a bearing on any attempt to estimate future demand for either of these materials from the thin film PV sector.

The bandgap, or energy gap, of the material varies continuously with x from 1eV to 1.7eV, placing CIGS in the optimal range for PV theoretical efficiency. Based on the Shockley–Queisser limit[2] this gives CIGS a theoretical maximum efficiency of ~33%.

The basic structure of a CIGS thin film PV cell consists of several layers of material encapsulated in a sealant, such as a sandwich of glass. Glass forms a substrate, on which a layer of molybdenum is deposited, forming the back contact, the active layer of CIGS is then deposited, followed by a transparent conductive layer, often a combination of cadmium sulphur, zinc oxide and aluminium, forming the front contact.

Current commercial modules have the following specifications (Fthenakis 2009; Patrin *et al.* 2009; Seike *et al.* 2011):

- Material thickness of around 2µm
- Percentage of indium in the active layer is between 20 and 30%[3]
- Efficiency of around 10 – 12%
- Around 34% of material is utilised*

*NB – In the future it is expected that 'wasted' material will be recycled, as is the case in other layer deposition processes such as indium tin oxide (ITO) deposition in flat panel displays. We discuss utilisation and recycling in more detail in sections 2.5.3 and 3.2.5.

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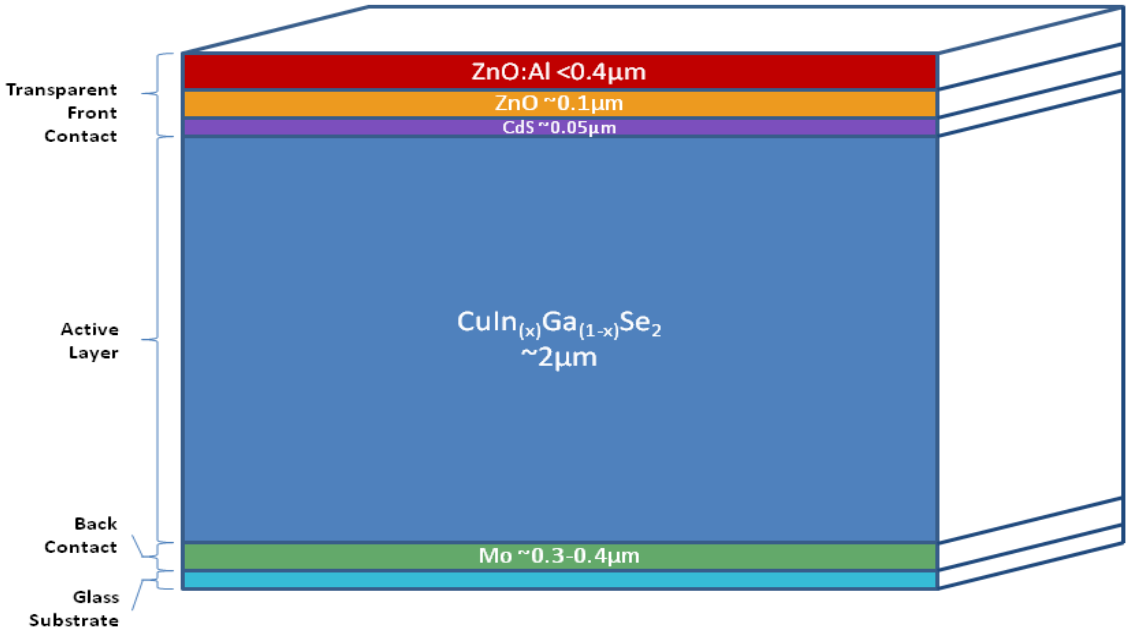
[2] First calculated by William Shockley and Hans Queisser in 1961, the Shockley Queisser limit refers to the maximum theoretical efficiency of a solar cell using a single p-n junction (Shockley and Queisser 1961).

[3] This is based on CIGS alloys of $CuIn_{0.5}Ga_{(0.5)}Se_2$ and $CuIn_{0.85}Ga_{(0.15)}Se_2$

Figure 2.5: Approximate structure of a CIGS thin film solar cell



*Note:* This is an example and does not represent an exact cell design.

## 2.5.2 Cadmium telluride modules

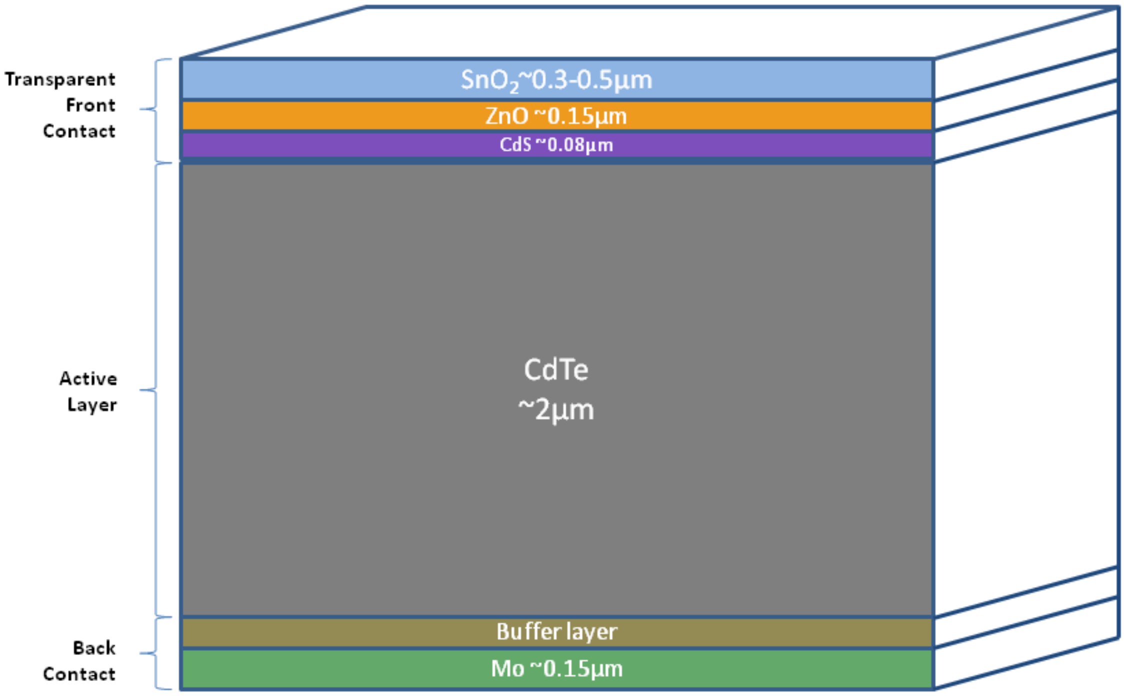
CdTe cells are similar in general structure to CIGS, with a transparent conductive oxide (TCO) layer as the front contact, an active layer (in this instance CdTe), and a back contact of some conductive material. It is slightly simpler to calculate the quantity of tellurium in a given quantity of CdTe given its stoichiometric relationship. The process of deposition is also reversed. In typical commercial production processes, a plate of glass is pre-coated with the TCO front contact material. CdTe is then deposited, with the back contact applied last. As with CIGS, this is then encapsulated in a sealant such as a sandwich of glass.

CdTe has a bandgap of 1.44eV and is therefore also near the top of the Shockley Quiesser limit. This gives a theoretical efficiency limit of ~33%.

Current commercial modules have the following specifications (Green 2010, Fthenakis 2009):

- a material thickness of around 2 µm
- Percentage of tellurium in the active layer is around 50%
- Efficiency of around 11%
- Around 40% of material is utilised

Figure 2.6: Approximate structure of a CdTe thin film solar cell



*Note:* This is an example and does not represent an exact cell design.

## 2.5.3 Production processess and Materials utilisation

The manufacturing process used to produce CIGS and CdTe cells plays a fundamental role in the use of materials. There is a wide variety of deposition processes used in thin film manufacturing which could be categorized in different ways, bifurcating them into physical versus chemical methods, or into vacuum versus non-vacuum processes, or else according to the substrate used (e.g. glass versus flexible substrates). Vacuum based processes are those currently mostly used in thin film PV manufacturing, among them sputtering (a mature deposition technique widely used in industry from film deposition) or chemical vapour deposition (which for example is used by the currently major thin film PV manufacturer, First Solar (NREL 2010).

In the case of sputtering a 'target' made from the material to be deposited is placed in a vacuum chamber adjacent to a substrate material. The chamber is then subjected to bombardment from energetic particles, which hit the target, ejecting individual atoms into the gaseous phase. A proportion of these atoms are deposited in a thin layer on the substrate. The remaining target atoms, however, are deposited on the walls of the chamber, and a significant quantity of active material is left in the spent target. In the case of vapour deposition a vapour of the active material is created and injected into a vacuum chamber containing the substrate. A quantity of the vapour is deposited onto the substrate, though material can be lost throughout the chamber, as with sputtering techniques. Both material deposited on vacuum chamber walls and material remaining in spent targets can be recovered, helping to maintain the utilisation rate. Utilisation rates are however, not 100%, as some material is ultimately lost.

Other deposition techniques with the potential of better materials utilization exists and are in the process of being developed, such as roll-to-roll material deposition, where active materials are deposited using a system analogous to ink-jet printing. Large rolls of metal foil substrate (such as aluminium) are fed through a system which progressively deposits liquid containing active layer materials. This foil can then be encapsulated, cut into cells and assembled (Kessler *et al.* 2005). This process results in very efficient use of active layer materials.

In this working paper we define utilisation as the weight of material (indium or tellurium) in produced PV modules as a proportion of the weight of material input in a given year. This definition therefore includes two distinct elements:

1. The efficiency of the manufacturing process, where a percentage (< 100%) of input materials are deposited on a cell substrate; and

2. The efficiency of the recycling process which aims to recover a significant proportion of the material not deposited on the substrate.

The material considered in the second element of utilisation may be material deposited on the vacuum chamber during sputtering or vapour deposition, the material left in the target, or other recoverable materials not deposited on the substrate.

A third element of manufacturing efficiency is 'yield' which is commonly defined as saleable modules as a proportion of the total number of modules produced. This accounts for the number of modules which for some reason are not suitable for sale, and are discarded, and may or may not be recycled. The yield achieved therefore has implications for the quantity of materials needed to achieve a given unit of module production. However, yield is not commonly discussed in the literature on materials availability for thin film PV applications.

We consider the recycling rates which may contribute to utilisation rates as distinct from end-of-life module recycling rates. We return to these concepts in section 3.2.5.

Current best practice in CIGS and CdTe manufacture suggests utilisation rates ranging between 30% and 50% for CIGS (for two stage selenization deposition process based on sputtering[4])(Fthenakis *et al.* 2009; Patrin *et al.* 2009) and around 40% for CdTe (Fthenakis 2009; Green 2010). As we discuss below, many studies of demand for indium or tellurium assume 100% utilisation. Whilst there is every reason to expect recycling rates from within

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[4] This deposition process is one of the most used in CIGS manufacturing. Sputtering utilization rates are higher when rotary target are used instead of planar targets

the production process to be high, 100% utilisation is some way from current best practice. We discuss this in more detail below.

## 2.6 Existing estimates of demand for tellurium and indium from thin film PV

Since the late 1990s an increasing body of academic literature has investigated material availability issues for large scale PV production. Throughout this Paper we consider four key studies when we discuss the existing literature (Andersson 2000; Keshner and Arya 2004; Fthenakis 2009; Wadia *et al.* 2009).

Table 2.2 and Table 2.3 summarise the literature focusing on assumptions and results for CIGS and CdTe technologies respectively. The studies vary considerably in terms of assumptions about the key factors described above. They assume different figures for cell efficiency, thickness of the semiconductor layers and material utilisation.

The data and methodologies used to assess future availability of indium and tellurium and share of the global material resource supply allocated to the PV industry also vary considerably among the studies. We return to this in Part 3.

### 2.6.1 Indium Demand

In Table 2.2 we present a summary of the findings of studies assessing demand for indium.

Table 2.2: Assumptions on indium requirement in CIGS manufacturing

| Author | Density ($g/cm^3$) | Thickness (μm) | % In in layer | Utilisation (%) | Efficiency (%) | Material Requirement (g/Wp) |
|---|---|---|---|---|---|---|
| Andersson (2000) Base Case | 5.5[1] | 2 | 26.5[5] | 100 | 10 | 0.0291 |
| Andersson (2000) 2020 Expansion potential | 5.5[1] | 0.5 | 18.3[6] | 100 | 14 | 0.0036 |
| Fthenakis[2] (2009) Conservative | 5.8[3] | 1.2 | 20[7] | 90 | 14 | 0.011 |
| Fthenakis[2] (2009) Most likely | 5.8[3] | 1 | 20[7] | 90 | 15.9 | 0.0081 |
| Fthenakis[2] (2009) Optimistic | 5.8[3] | 0.8 | 20[7] | 90 | 16.3 | 0.0063 |
| Keshner & Arya (2004) Current production | 5.8 | 2 | 30[8] | 75 | 12 | 0.0382 |
| Wadia *et al*(2009) | 5.6 | 0.05 | 24[1,9] | 100 | 33 | 0.0002 |

*Notes:*

[1] Back calculated using stated assumptions and the relationship in Equation 2.1

[2] Fthenakis estimates for 2020

[3] Not stated by Fthenakis (2009). Assumed from Keshner & Arya (2004)

[4] Based on data extracted using Engauge digitizer

[5] $CuIn_{(x)}Ga_{(1-x)}Se_2$ assumption x=0.75

[6] $CuIn_{(x)}Ga_{(1-x)}Se_2$ assumption x=0.5

[7] $CuIn_{(x)}Ga_{(1-x)}Se_2$ assumption x=0.55

[8] $CuIn_{(x)}Ga_{(1-x)}Se_2$ assumption x=0.85

[9] $CuIn_{(x)}Ga_{(1-x)}Se_2$ assumption x=0.67

[10] Andersson (2000) states that 7GWp is the constrained annual production possible with 290 tonnes of indium annual production. However, with a stated metal requirement of $2.9g/m^2$, an efficiency of 10% and a manufacturing rate of 7GW/y the demand for materials would be ~204t/y. It is unclear how this disparity arises.

### Discussion of estimates

**Andersson presents a 'base' case** for CIGS. Assumptions are intended to be representative of CIGS in the year 2000. Cell layer thickness of 2µm, and efficiency of 10% are assumed – both close to current best commercial cells (Patrin *et al.* 2009; Seike *et al.* 2011). This can be compared to best lab cells with efficiencies of 20% (Repins *et al.* 2008). Andersson states that the CIGS formula assumed is $CuIn_{0.75}Ga_{0.25}Se_2$, and presents the indium metal requirement assumed as 2.9g/m2. From this we calculate the assumed density of the layer at 5.5g/cm$^3$ and the % of indium in the layer at 26.5 based on formula weight.

Andersson makes the additional assumptions of 100% utilisation rate. It is not clear if the authors assume that 100% utilisation is achievable through improved manufacturing, recycling, or both. In addition the achievability of either is not discussed. Combining the above assumptions with the estimated figure for indium availability of 290 tonnes/y gives a PV market growth of 5GWp/y.

**Andersson's 'Expansion Potential'** scenario some adjustments are made to the baseline case to reflect potential for improvement by 2020. Efficiency of CIGS cells is increased to 14%, and thickness of the layer is decreased to 0.5µm. It is unclear how achievable these revised assumptions for efficiency and layer thickness are, though they are both within best achieved lab results and theoretical maximums or minimums (Repins *et al.* 2008; Wadia *et al.* 2009).

CIGS composition is altered to $CuIn_{0.5}Ga_{0.5}Se_2$ in the active layer, giving a percentage of indium in the layer of 18.3%. This reduces demand for indium but necessarily increases gallium requirement, though the implications of gallium requirement and supply on future PV manufacturing is not assessed here. The authors note that they assume efficiency not to be negatively affected by reduced indium content. But the physical relationship between indium content and efficiency is not examined in this study, or any of the others reviewed here. Other assumptions are unchanged.

**Keshner and Arya (2004) present a "current production"** scenario. Density of the active layer is assumed to be 5.8 g/cm$^3$ based on the average density of CuSe, In Se and Ga Se. Layer thickness is assumed at 2µm, in the higher end of current estimates (Seike *et al.* 2011). Utilisation rate of 75% is also assumed for CIGS manufacturing. Cell efficiency is not stated, but can be back calculated using Equation 2.1. Using the assumptions described here conversion efficiency must be ~12%, comparable to current best estimates for commercial efficiencies (Andersson 2000; Seike *et al.* 2011).

**Wadia *et al* (2009) present theoretical limits** for all relevant assumptions. Utilisation is assumed at 100%. Material density of 5.6g/cm$^3$ is assumed and can be derived from the stated layer thickness of 0.05µm and the material intensity of 0.28g/m$^2$. A cell efficiency of 33% is assumed, based on the 'Shockley-Queisser' limit.

**Finally, Fthenakis presents a conservative case; a most likely case; and an optimistic case** for material demand for CIGS PV. Cell layer thickness is assumed to be 1.2µm, 1µm and 0.8µm in conservative, most likely and optimistic cases respectively. Cell efficiency is assumed at 14%, 15.9% and 16.3% in each case respectively. These efficiencies are greater than assumed by the majority of other authors (Excluding Wadia *et al*). Utilisation is estimated at 90% for all three cases. However, density and relative weight of indium in the active layer are not stated. If we assume a value of 5.8, we can solve Equation 2.1 for $F$ to give a relative weight of ~20%. This is equivalent to a CIGS formula of $CuIn_{0.55}Ga_{0.45}Se_2$, near the lowest assumptions for indium weight, though within the range of estimates presented.

### 2.6.2 Summary

The literature reviewed above contains a variety of assumptions, some of which are not explicit and need to be deduced. The main findings can be summarised as follows:

- Density is almost uniform across the studies reviewed.
- Layer thickness varies from theoretical min of 0.05µm to conservative estimates of 2µm, the latter well within current best commercial layer thickness.
- Percentage of indium in the layer varies significantly with indium:gallium ratio, from 18% to 30%. No link between the composition of CIGS and the efficiency of the resulting cell is acknowledged.
- Utilisation is not always considered, some authors implicitly or explicitly assume 100% utilisation rate. Otherwise, utilisation is assumed to be between 75% and 90%.
- Efficiency assumptions range from 10% to 33% with the former available in current commercial cells and the latter being the theoretical limit.

Existing reviews are characterised by a range of assumptions related to materials requirements, utilisation and efficiency, in many cases key assumptions are not transparent. Optimistic assumptions about material availability are combined with conservative assumptions about material utilisation, or vice versa. Overall, the relative importance of key factors and key sensitivities is difficult to discern. A more transparent and systematic approach would yield greater clarity and perhaps help reduce controversy. We return to this point in concluding this chapter, however before doing so we provide a parallel review of the literature on tellurium.

### 2.6.3 Tellurium Demand

In Table 2.3 we present a summary of the findings of studies assessing demand for tellurium.

Table 2.3: Tellurium requirement in CdTe manufacturing

| Author | Density (g/cm³) | Thickness (µm) | % Te in layer | Utilisation (%) | Efficiency (%) | Material Requirement (g/Wp) |
|---|---|---|---|---|---|---|
| Andersson (2000) Base Case | 5.69[1] | 2 | 51 | 100 | 10 | 0.058 |
| Andersson (2000) 2020 Expansion potential | 5.85[1] | 1 | 51 | 100 | 12 | 0.0249 |
| Fthenakis[2] (2009) Conservative | 6.2[3] | 2.5 | 51 | 75[3] | 13 | 0.0811 |
| Fthenakis[2] (2009) Most likely | 6.2[3] | 1.5 | 51 | 75[3] | 13.2 | 0.0479 |
| Fthenakis[2] (2009) Optimistic | 6.2[3] | 1 | 51 | 75[3] | 14 | 0.0301 |
| Keshner & Arya (2004) Current production | 6.2 | 1.8 | 51 | 75 | 11 | 0.069 |
| Wadia *et al* (2009) | 6.2 | 0.436 | 52[1] | 100 | 33 | 0.0042 |

*Notes:*

[1] Back calculated using stated assumptions and the relationship in Equation 2.1

[2] Fthenakis estimates for 2020

[3] Not stated by Fthenakis (2009). Assumed from Keshner & Arya (2004)

[4] Based on data extracted using Engauge digitizer

### Discussion of findings

**Andersson's base case** adopts assumptions representative CdTe PV in the year 2000. Cell layer thickness is 2µm, and efficiency of 10% – both better than available commercial cells of the time but close to current best commercial cells. A case study of First Solar, a leading company in CdTe PV cell manufacturing, estimated that cells produced in 2009 had achieved layer thicknesses of 2.1µm, with learning rates expected to deliver layers of 1.9µm by 2013 (Green 2010). The same study estimates that efficiency of these cells will reach 11.7%, also by 2013. Andersson (2000) states the g/m² requirement for tellurium and cadmium as 6.5 and 6.3 respectively, giving approximately 51% tellurium in CdTe layer. Given the stoichiometry, proportionality in CdTe layers is not likely to vary much from the formula weight proportionality of 53% tellurium and 47% cadmium.

Andersson assumes 100% utilisation. Current measured utilisation rates in best commercial manufacturing plants are estimated at 40% (Green 2010), though this does not include any recycled material. From Andersson's assumptions on tellurium availability (see Part 4) we can calculate a density of 5.69g/cm$^3$.

In **Andersson's (2000) 'Expansion Potential'** scenario some adjustments are made to the baseline case to reflect potential for improvement by 2020. Efficiency of CdTe cells is increased to 12%, and thickness of the layer is decreased to 1µm. The revised estimate of efficiency seems within current expectations of learning rates (Green 2010). Tellurium% in the active layer and utilisation are all maintained.

**Keshner and Arya (2004) present a 'current production'** scenario. Density of the active layer is assumed to be 6.2 g/cm$^3$. Layer thickness is assumed at 1.8µm, in line with current estimates (Green 2010) utilisation is 75%. This is higher than quoted current utilisation rates and it is unclear how achievable this utilisation rate is. Cell efficiency is not provided by the authors, however using the data present on Te availability (see Part 4) we can back calculate a figure of ~11% – comparable to near future estimates for commercial efficiencies.

**Wadia *et al(2009)* presents calculable theoretical limits** of CdTe PV material demand assumptions. Utilisation is assumed at 100%. Material density of 6.2 is assumed and can be derived from the stated layer thickness of 0.436µm and the material intensity of 2.7g/m$^2$. A cell efficiency of 33% is assumed, based on the 'Shockley-Queisser' limit.

**Fthenakis presents a conservative case; a most likely case; and an optimistic case for CdTe PV.** Cell layer thickness is assumed to be 2.5µm, 1.5µm and 1µm in conservative, most likely and optimistic cases respectively. This represents a range from greater than current commercial best to 44% less than short term learning rate forecasts (Green 2010). Cell efficiency is assumed at 13%, 13.2% and 14%. These efficiencies are all more optimistic than commercial short term learning rate forecasts (Green 2010). Density, percentage of tellurium in the layer, and utilisation are not stated. However, if we assume a density of 6.2g/cm$^3$ and that 51% of the layer by weight is tellurium, and hold these assumptions for each of the three cases, we can estimate an assumed utilisation rate of 75% by solving Equation 2.1 for $U$.

### 2.6.4 Summary

The information gathered in Table 2.3 can be summarised as follows:

- Density is almost uniform across the studies reviewed.
- Layer thickness varies from theoretical min of 0.436µm to conservative estimates of 2.5 µm, the latter well within current best commercial layer thickness.

- Percentage of tellurium in the layer is also consistent reflecting the stoichiometric inflexibility of CdTe chemical structure.
- Utilisation is not always considered, implying an assumption of 100% utilisation rate. Otherwise, utilisation assumed is 75%.
- Efficiency assumptions range from 10% to 33% with the former comparable to current commercial efficiencies and the latter being the theoretical limit.

## 2.7 Illustrative Ranges of demand for indium and tellurium

The discussion above indicates that there is considerable variation in existing estimates of the amount of indium or tellurium required to deliver a particular capacity of CIGS or CdTe PV. We have also discussed the size of the current thin film market, and the available estimates of future PV market growth and presented potential future thin film market sizes, which may be 16GW/y in 2020 42GW/y in 2030, and 51GW/y in 2040 (see Part 2).

In this section we provide an illustration of the potential range of *demand* for indium and tellurium given the diversity of views on key assumptions such as thickness of the active layer and efficiency. We present this illustration in terms of the current thin film market of 1.6GW/y CdTe and 0.5GW/y for CIGS. We also present the implications of the range of demand-side assumption in terms of the potential future thin film market in 2030 of 42GW/y. Evidence of the likely distribution of market share between the thin film technologies is scarce, and we make the simple assumption that 50% of this market is CdTe calls and 50% is CIGS, approximately 20GW/y each[5]. We consider the prospects for *supplying* this demand, taking into account competing uses for indium and tellurium, in parts 3 and 4.

Given that the theoretical limits assumed by Wadia *et al* (2009) are unlikely to be achieved we exclude these from the ranges of assumptions presented below.

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[5] This ignores the potential contribution of amorphous silicon and rounds to 20 GW.

Table 2.4: Range of potential demand for indium at 0.5GW/y current market and 21GW/y future market

| Variable | Lowest material use | Highest material use |
|---|---|---|
| Layer Thickness (µm) | 0.5 | 2 |
| Utilisation (%) | 100 | 75 |
| Efficiency (%) | 16.3 | 10 |
| Indium Content (%) | 18 | 30 |
| Range of demand (t/y) | | |
| Current market: 0.5GW/y | 1.6 | 23.2 |
| Market 2030: 20GW/y | 70 | 970 |

Table 2.5: Range of potential demand for tellurium at 1.6GW/y current market and 21GW/y future market

| Variable | Lowest material use | Highest material use |
|---|---|---|
| Layer Thickness (µm) | 1 | 2[1] |
| Utilisation (%) | 100 | 75 |
| Efficiency (%) | 14 | 10 |
| Range of demand (t/y) | | |
| Current market: 1.6GW/y | 36.8 | 137.6 |
| Market 2030: 20GW/y | 480 | 1810 |

[1] Lower than maximum assumption in Table 2.3 based on most recent data(Green 2010).

These findings can be compared to the current production of indium of around 570 tonnes per year and tellurium of around 113 tonnes per year (BGS 2010; USGS 2011). We note that at the current time the CIGS market accounts for between 2% and 5% of the global indium market(Fthenakis 2009; Shon-Roy 2009) and CdTe around 11% of the market for tellurium (Shon-Roy 2009).

Hence despite uncertainties about future demand, if the CIGS or CdTe PV market of the future were 20GW/y for each technology this could account for 12% to around 170% of the current production of indium and around 430% to 1600% of the current production of tellurium. We can conclude therefore that the demand for indium and tellurium could expand considerably (by orders of magnitude for tellurium) if the total market for either type of cell became a large fraction of a large global market. It is also extremely notable that the combined implications of efficiency, thickness and utilisation rates are very substantial. Achieving the lowest material use in the range discussed above results reduces material demand to just 6% and 26% of the material demanded in the highest demand case for indium and tellurium respectively.

Part 3 discusses the potential for the production of indium and tellurium to expand, including the potential for recycled materials to help meet demand.

## 2.8 Conclusions

Demand in the thin film PV sector is widely expected to increase significantly in the coming decades. Whilst the total market for PV and the share for thin film are both difficult to predict several scenarios suggest that the market for PV could grow to many tens of GW per year,  by the period 2030 to 2050 and that the thin film market might occupy of the order of 40% of this.

Translation from thin film demand to materials demand depends upon the **quantity of material per Wp**, expressed in g/Wp and a function of:

- **Density of active material,** in this case either CIGS or CdTe
- **Thickness of active layer,** measured in microns (μm)
- **% of material in layer,** in this case measuring the share of tellurium in CdTe or Indium in CIGS and calculated by formula weight
- **Efficiency,** a measure of the amount of energy captured per square meter under standard test conditions (STC)
- **Utilisation,** a measure of efficiency of material use in the manufacturing process.

Whilst our review found a number of existing studies, the wide range of assumptions and different degrees of transparency create considerable uncertainty as to the potential materials requirements of both CIGS and CdTe.

- First, the sensitivity of demand per unit of energy capacity is unclear due to the range of differing assumptions and the inconsistent treatment of variables.

- Second, the relative practical achievability of differing assumptions is opaque. Studies present differing levels of optimism in their assumptions and do not always discuss the relative likelihood of achieving them. Some studies combine optimistic assessments of some variables with pessimistic assessments of others.

- Some studies effectively ignore key variables likely to impact on future material requirement in PV manufacturing. Utilisation and yield are both neglected in this way and while they are likely to improve on current levels, perhaps markedly, they are unlikely to reach 100%. This is not addressed at all in several studies.

- Finally, the indium content of CIGS cells may be varied significantly, though most studies assume it is held constant. When indium-gallium content is changed it is important to assess the implications for efficiency, ideally with some discussion of the rationale for existing CIGS proportions. This is not explicit in existing studies.

To illustrate the potential implications this paper has used the PV market and thin film shares in the IEA blue note scenario, and divided the thin film market in 2030 between CIGS and CdTe. This would result in a global market for CIGS and CdTe of around 20 GW/y each in 2030. The resulting demand for indium and tellurium lies in a range of around 70 to 970 t/y and around 480 to 1800 t/y respectively, depending on the assumptions made about each of the above factors. ‘Worse case’ estimates of indium demand are 14 times higher and tellurium demand almost 4 times higher than in the most material efficient instances we found in the literature.

The wide range of possible outcomes and considerable disagreement between existing estimates suggests that a more systematic approach to assessing the future of efficiency, utilisation and cell thickness would offer considerable benefits. Varying key assumptions systematically, testing key sensitivities and presenting the outcomes in a clear and transparent fashion would greatly aid understanding and discussion of materials requirements.

# 3 Extraction, production and main uses of indium and tellurium

## 3.1 Introduction

Section 2 reviewed the *demand* for tellurium and indium that might emerge from an expanded market for thin film PV. Section 3 is concerned with the *supply* of tellurium and indium, their occurrence, extraction and historical production data.

The section also discusses the main end uses for each metal, hence the relative importance of the PV market as an end use.

The section deals first with indium, then tellurium, before drawing generic and specific conclusions. For each metal we discuss background, recovery and refining, production volumes, markets and end-uses, and reserves.

## 3.2 Indium

Indium is a group 13 metallic element, with an atomic weight of 114.82. It has an estimated crustal abundance of 0.1ppm (Suess and Urey 1956), comparable to that of silver (0.05-0.1ppm). It was discovered in 1863 by F. Reich and T. H. Richter while conducting spectrometric analysis of Sphalerite ores, an important source of the metal today (Felix 2000). Indium was named after the indigo blue spectral lines which led to its identification.

Indium does not occur in its native state and is found in trace amounts in various ore types. Sphalerite, one of the most important for modern production, is mined primarily for the base metal zinc. It contains widely varying concentrations of indium, from typical concentrations of 10-20 ppm to around 10,000 ppm (1% by weight) in some extreme cases. These concentrations are considered high relative to other indium containing ore (Table 3.1). Indium is therefore most commonly associated with zinc production, though copper, tin lead and other base metal bearing ores also contain indium (Table 3.1). We refer to indium as a secondary metal, with the associated base metal referred to as the primary metal (see Glossary and Definitions).

Table 3.1: Minerals associated with indium

| *Mineral* | *Composition* | *Indium content,* Ppm |
|---|---|---|
| **Sphalerite** | $ZnS$ | 0.5–10,000 |
| **Galena** | $PbS$ | 0.5–100 |
| **Chalcopyrite** | $CuFeS_2$ | 0–1500 |
| **Enargite** | $Cu_3AsS_4$ | 0–100 |
| **Bornite** | $Cu_5FeS_4$ | 1–1,000 |
| **Tetrahedrite** | $(Cu,Fe)_{12}Sb_4S_{13}$ | 0.1–160 |
| **Covellite** | $CuS$ | 0–500 |
| **Chalcocite** | $Cu_2S$ | 0–100 |
| **Pyrite** | $FeS_2$ | 0–50 |
| **Stannite** | $Cu_2FeSnS_4$ | 0–1,500 |
| **Cassiterite** | $SnO_2$ | 0.5–13,500 |
| **Wolframite** | $(Fe,Mn)WO_4$ | 0–16 |
| **Arsenopyrite** | $FeAsS$ | 0.3–20 |

*Source:* Reproduced in (Felix 2000)

### 3.2.1 Recovery and refining

The extraction of indium begins with the extraction of its associated primary metal. The vast majority (~95%) of zinc mined is from sulphide ore deposits in which the sphalerite ($ZnS$) is mixed with sulphides of Cu, Pb and Fe. Zinc content is usually between 3 and 10%.

There are many different processes used to recover indium from zinc or other base metal ores. Some of these are described in Felix (2000), demonstrating the variety and complexity of refining processes. Annex 1 provides more detail on indium recovery and refining.

Indium recovery processes typically have low extraction efficiency, which may incentivise end of life recycling in the future (see Section 3.2.5). Given this complexity, low efficiency, and the low concentrations relative to the primary metal, the economics of secondary metal extraction are more complicated than those of primary metals or other mineral resources. The incentive to produce indium is not only driven by the indium price, but also by the price of zinc (or price of other associated base metal), value of other trace elements and the type of ore extracted, as well as the cost of the production processes used.

Though specific concentrations of indium can be measured in the ore it is recovered from (see Table 3.1), not all of this material will be produced. Some of these ores are processed at refineries that have no indium recovery capability. The indium in these ores is therefore discarded in tailing and other wastes. For those refineries that have indium recovery capability the extraction of indium is subject to a recovery factor of less than 100%, with the remaining indium discarded in tailings and other wastes. The Indium Corporation estimate that currently only 30% of indium extracted in zinc ore is produced, with the remaining 70% discarded in wastes (Mikolajczak 2009). Wastes containing indium are difficult to treat but may potentially be used as a resource of indium in the future (Mikolajczak 2009), though the economics of this recovery are likely to be less favourable than exploitation of more conventional resources. Authors have estimated indium recovery factors from zinc processing concentrates at between 50% and 80%, though it is unclear why this variation exists, or how much this recovery factor can be increased in the future (Fthenakis 2009; Mikolajczak 2009). The examination of potential increase in recovery rate, particularly the potential to recover indium from tailings, is an important area for future research.

Finally, the produced indium, often at concentrations of between 95% and 99.9% purity, must be refined to purities of 99.9999% for many semiconductor uses. This typically involves electro refining, where indium electrodes are placed in an electrolyte through which electric current is passed. Impurities collect in anode slimes, where they are isolated and extracted. This process is repeated until the desired purity is reached.

### 3.2.2 Production volumes

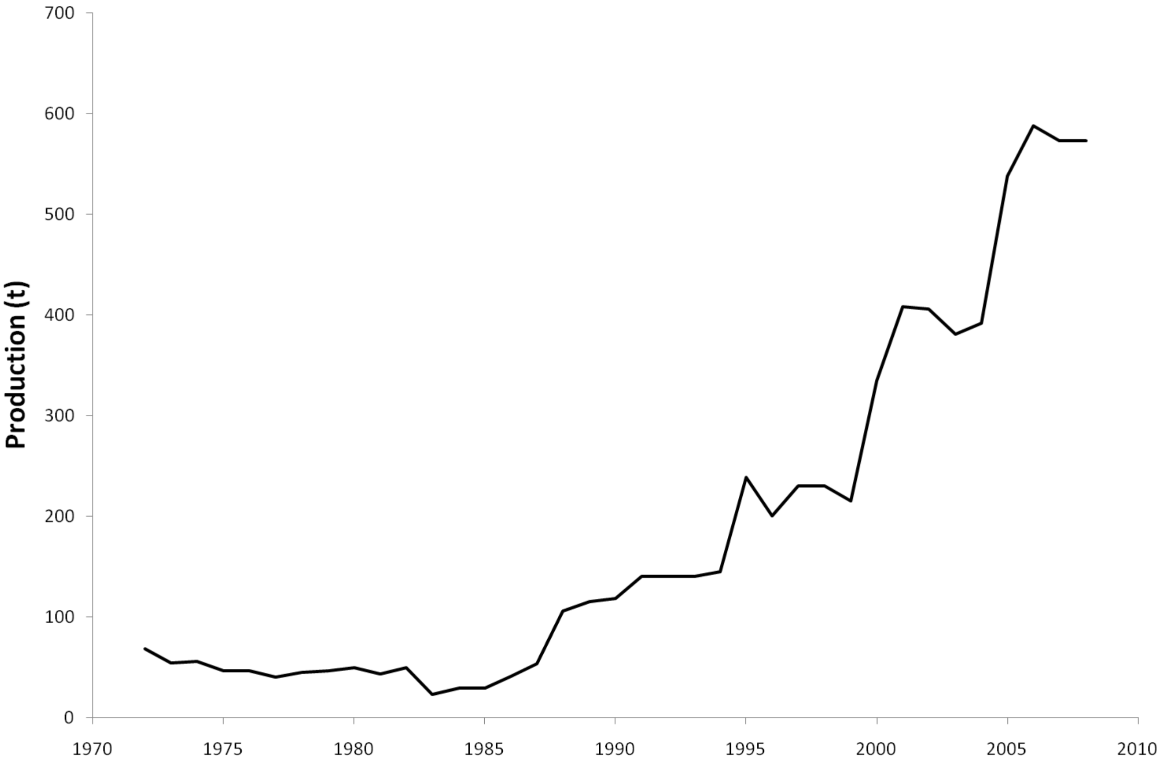
Several sources of data exist on indium production including consultancy reports such as those produced by Roskill Information Services, freely available US Geological Survey (USGS) publications. The British Geological Survey (BGS) does not record indium production data, though they do cover other economically important metals. The USGS is the most commonly quoted source of minerals data for these and many other minerals due to its availability. There are, however, some issues regarding the data presented by the USGS which we discuss below.

Figure 3.1 presents USGS data for historical production of indium from 1972 to 2009. Production appears to have grown exponentially over this period, from a low point of ~25 tonnes per year in 1983, to a high of 600 tonnes per year in 2009. It is worth noting however, the following limitations.

Annual editions of the USGS Mineral commodity summaries since 1995 have stated that the US did not recover any indium from its zinc mining operations. However, the USGS have quoted indium reserve figures in the past which may indicate potential indium recovery in the future.

World indium production figures only include indium recovered during zinc mining operations. Though zinc is the primary base metal with which indium is associated, there are several other ore bodies containing indium. It is unclear from the USGS data how much indium may potentially be produced from other ores and therefore how great any potential error may be. Other issues exist, including changing from measurement of smelter production of indium to refined indium in 1974. This is unlikely to have a significant impact on the analysis here.

Figure 3.1: Historical world production of indium as reported by the USGS



*Note:* World production data were for production of indium for the years 1972–74 and for refined indium for the years 1975 to the most recent. Data for the years 1972 to the most recent do not contain U.S. production.

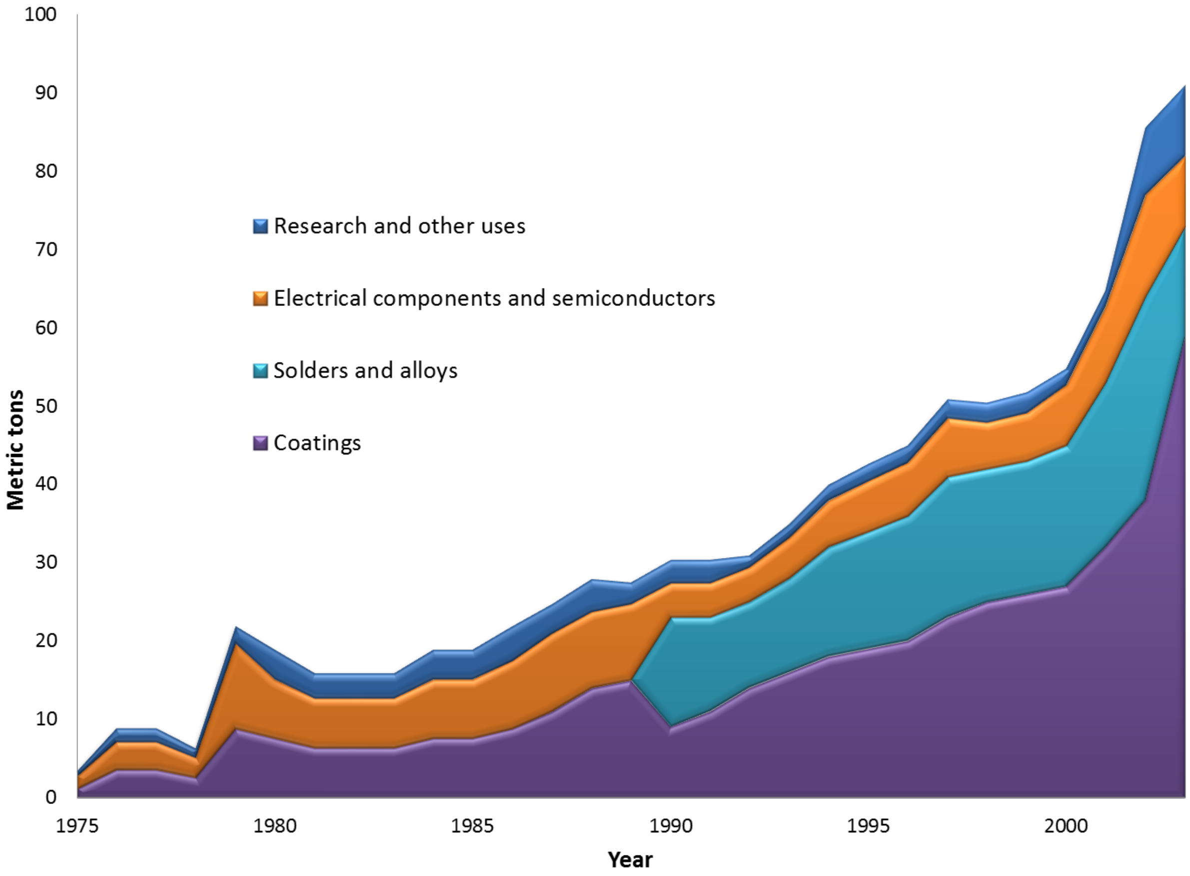
### 3.2.3 Indium markets: main end uses

Indium is used for a wide variety of purposes. Some reflect its properties as a conductor or (as alloy) semiconductor, others its physical properties. The significant rise in indium production presented in Figure 3.1 appears largely driven by growth in demand for ITO (USGS 2009; USGS 2011). ITO demand has increased largely because of the growth in flat panel display technologies like LCD TV screens and flat screen computer monitors (USGS 2009; USGS 2011).

Other uses of indium include: in its metallic form in vacuum seals in low temperature sealed storage containers; in the electrolyte of zinc alkali batteries; indium trichloride is used in sodium vapour lamps to deposit ITO on the inside of the lamp tube for improved efficiency; and in LED applications where properties of the bulb are suitable for data communication through fibre optics, and to a lesser extent in LED displays (USGS 2011). Indium is also a constituent of several low melting point alloys used in a variety of industrial applications and consumer products.

Data on end-use consumption is not widely available but Figure 3.2 presents some indicators of the trend in indium consumption. The US consumption over the period 1975–2006 shows significant growth in indium demand in coatings applications, including ITO coatings in flat panel display technologies. Over this period, coatings as a share of total indium consumption in the US grew from 31% to 66%.

**Figure 3.2: US indium consumption by end use**



*Source:* USGS

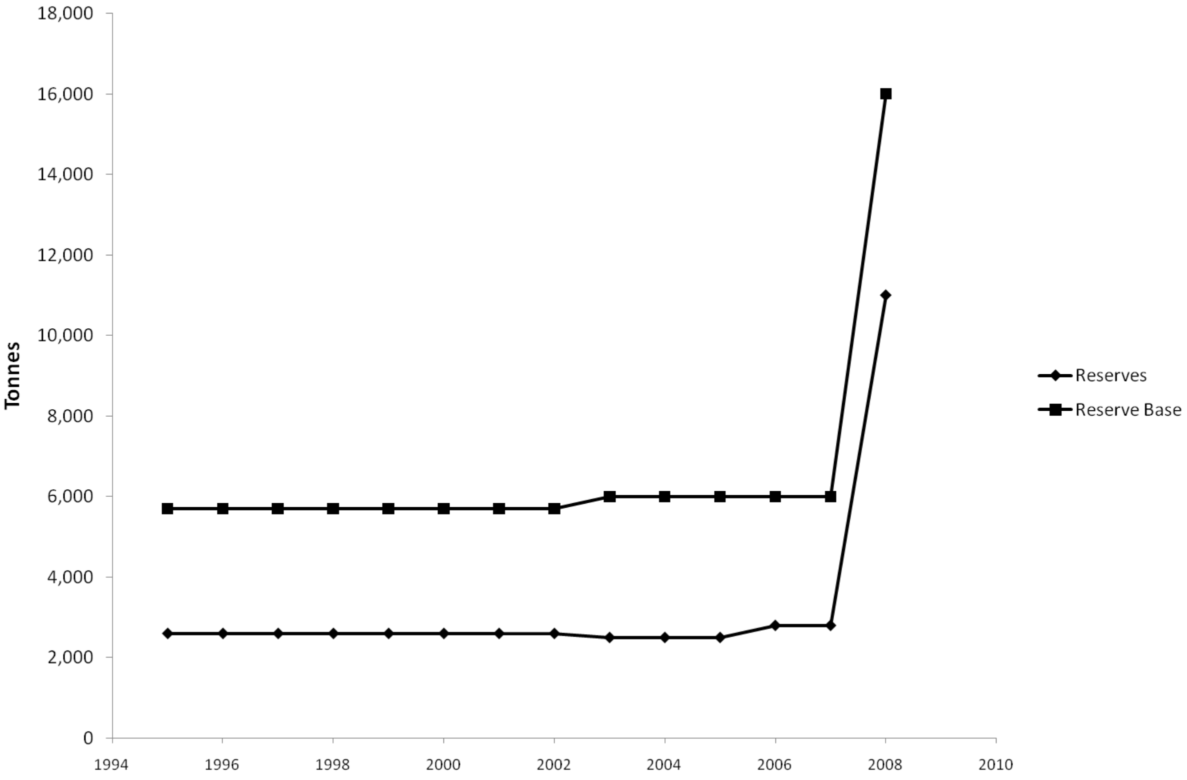
*Note*: Coatings includes ITO

Data on PV market share in demand for indium are not common, though authors have made some explicit assumptions in this regard. Current estimates state that photovoltaic use of indium accounts for an estimated 2-5% of the primary indium production, with use of ITO in flat panel displays accounting for 65% of annual indium production, and around 30% used in other electrical and industrial applications(Fthenakis 2009; Shon-Roy 2009).

### 3.2.4 Reserves and resources

Historically, bodies such as the US Geological Survey (USGS) have reported estimates of reserves for indium, as well as other materials. Figure 3.3 presents the USGS data on world indium 'reserves' and 'reserve base' between 1995 and 2008. 'Reserves' seeks to report that part of the reserve base that is currently economic, whilst reserve base includes a wider set of potential resources which could be extracted in future if production cost decreases or price increases made extraction economically viable. See page vii for a full definition.

**Figure 3.3: Historical indium reserve and reserve base data**



*Source:* USGS

*Notes:* Both reserves and reserve base figures discontinued in 2009.

From these definitions we can place a high probability that all material reported as 'reserves' of a metal will be produced given stable or increasing prices of the commodity, but producing more than currently reported as 'reserve base' is less certain. With metals such as indium these probabilities are not quantitatively defined as is the case with other resources such as oil (Sorrell *et al.* 2009). At any given time the quantity of extractable metal is subject to the costs of extraction, and the price of the metal. These will both change over time and resource estimates do not capture the sensitivity to these changes. If the price of a material increases significantly, reserve figures are likely to increase as more of the known resource becomes economic to extract.

The data presented in Figure 3.3 shows a period of stable reserve and reserve base estimates until 2008, with reserves between 2,500 and 2,800 tonnes and reserve base between 5,700 and 6,000 tonnes. In 2008 both measures increase by a factor of 3, based on large increases in China's stated reserves (USGS 2010). In 2009 the USGS ceased to report reserves or reserve base for indium. The USGS state that reserve base figures are no longer reported due to lack of up to date assessment previously provided by the now defunct US Bureau of Mines. This is the case across the range of materials covered in the USGS Minerals Commodity Summaries and Minerals Yearbook reports. The USGS state that world reserve figures are not sufficiently well delineated to be consistent. The USGS still report reserve figures for most other metals.

Indium reserves data reported by USGS, as with indium production data, are only those associated with zinc bearing ore. As presented in Table 3.1 many non-zinc ores have associated indium, recent press reports have highlighted the potential of UK tin. Therefore, future indium production could include indium currently not considered reserves, though the quantity and economic cost of extracting them are unclear.

The reporting of reserves is a complex practice given the uncertain nature of reserve estimation techniques, the varying reporting definitions and nomenclature, the dynamic nature of reserve economics, and the time and cost associated with estimating reserves. This means that any quoted reserve data is subject to biases. For elements that have well established markets, the incentive to understand the resource base is increased, and the occurrence and availability of a metal may be relatively well understood. For other metals with less well established markets, the location and quantity of resources may be less well informed.

The fact that indium is a secondary metal, produced from materials which arise when zinc is extracted, adds additional complexity to the process of estimating reserves. For any known indium resource, an assumption must be made regarding the proportion of indium in sphalerite or other zinc yielding ore concentrates that can be recovered. This figure is typically less that 100% though future recovery as high as 70%-80% has previously been assumed (Fthenakis 2009). The USGS definition of reserves would suggest that recovery assumptions should be based on current rates, but it is not clear what assumption is made by the USGS in this regard.

We conclude that reserve and reserve base estimates provide relatively little insight regarding future production. This is the case with many resources, where estimates of reserves particularly, are conservative, and based on static economic assumptions which do not accurately reflect likely futures. These metrics are particularly problematic for indium and tellurium, where economic incentive for extraction is based in part on the market for its associated primary metal. Can estimates of these resources be improved?

### Resource estimates

It is common amongst minerals, as it is in oil exploration and production, to extract more metal over time, than initially reported as reserves. This is a function of the naturally conservative nature of reserve estimates and means that an estimate of reserves plus the cumulative production of metal at any given time and region is likely to be less than the quantity of material ultimately produced over all time. In essence, estimates of reserves are likely to give an underestimate if used to derive future production potential. In oil resource assessment, this issue has given rise to the concept of Ultimately Recoverable Resource (URR), a definition which attempts to account for the naturally conservative definition of reserves.

In the case of secondary metals such as indium, present in low concentrations in particular ores knowledge of the resource is limited. Estimates of crustal abundance provide no meaningful guide to prospective future production and in the view of the authors it is not appropriate to use crustal abundance as a guide to future supply of indium or any other element.

An inclusive assessment of the existing indium resource would be a more appropriate measure on which to base estimates of future production potential. This could include the total concentration of indium in all ores, the potential future indium concentration in undiscovered ores, the recovery factor associated with this resource, and an estimate of the economic, and technological factors which may improve this recovery factor. An estimate such as this would be analogous to the assessments of URR of oil. Unfortunately, however, such an assessment of indium resources has never been conducted.

It therefore appears that at the current time assessment of the potential to increase production of indium over the long term is limited. We know that a significant fraction of the indium present in waste materials from zinc extraction is currently discarded and that reserve and reserve base estimates increased prior to 2009. Whilst we have no evidence to conclude that indium production faces any immediate threats we also conclude that considerable further work is needed to provide meaningful estimates of indium reserve base and resources. We return to this point in discussion of the literature on CIGS and indium supply, and in conclusion.

### Geographical distribution

Figure 3.4 presents the main producers of indium. This shows the relative importance of China's production and reserves of indium within the global market in 2008[6]. While China has some 54% of production it has 75% of reserves, suggesting significant long-term control

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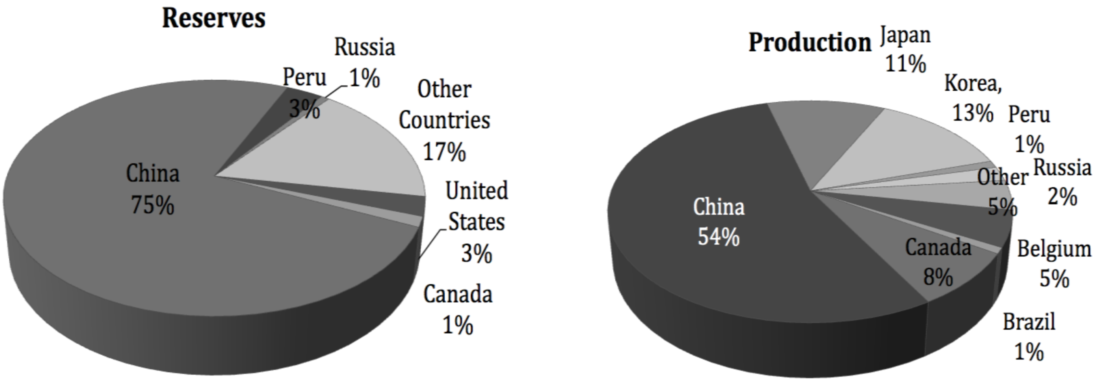
[6] This is the last year for which reserve data is available.

over the global indium market. As discussed above, China significantly increased its reserve estimates in 2008. Based on 2007 data, China had only 280 tonnes of stated reserves. This increased to 8000 tonnes between the 2007 and 2008 editions of the USGS MCS publication. Interestingly, China's production of indium in 2006 was greater than its stated reserves in 2007, suggesting imminent depletion of the reserve. China has clearly produced significant quantities since 2007. These apparent discrepancies and dramatic variation in stated reserves suggest that these data should be treated with caution.

Figure 3.4: Endowment of indium reserves by country



*Source:* USGS MCS (2008)

The geopolitical issues associated with materials availability have received increasing attention in recent industry reports. For example, China has placed export quotas on various metals including indium, reducing export quotas by some 30% in the second half of 2010 (USGS 2011), sparking a debate about the long-term security of their supply (Metal Pages 2010). While some argue that these types of intervention are an attempt to influence the global market, others suggest that the quotas are intended to encourage the high value end of the supply chain to relocate to China. The USGS (USGS 2011) suggest that these quotas are primarily designed to encourage LCD manufacture to move from Japan to China.

Overall it is difficult to draw firm conclusions about the impact of geopolitical issues on the long-term future of indium supply to the PV market. We can merely note that in addition to considerable uncertainty about reserves and resources political factors are likely to affect prices and perhaps the location of PV manufacture.

### 3.2.5 Recycling

#### recycling during manufacturing

Large quantities of material are wasted in many of the common industrial processes which utilise indium, creating a significant opportunity for recycling to improve process utilisation. The process used to deposit ITO on flat panel displays is a particular example, with most of the indium remaining in unused target material, in overspray, and other wastes. Only 30% of the ITO target is actually deposited on the substrate (USGS 2011). An estimated 60 – 70% of the target is recycled (Hsieh *et al.* 2009; Mikolajczak 2009; USGS 2009). Often the user returns this recovered material to the supplier who reprocesses it into new indium targets, closing the material supply loop. Around 1000 tons per annum of indium is recovered in this way (Mikolajczak 2009) and is additional to mined metal supply. The result is that more indium circulates in this industrial resource loop than is demanded in mine produced indium. For simplicity, however, we can consider that the mine produced indium into this industrial process is equal to the weight of indium leaving the system on flat panel displays, plus the quantity of material lost during the process. Based on the data above, the material lost may be between 5% and 10% in the case of flat panel display manufacturing. This experience may indicate the potential for process recycling in CIGS manufacturing, which has similarly low utilisation in the 30%–50% range[7] (Fthenakis 2009).

#### End of life recycling

Given the complex nature of indium primary extraction and refining processes, and the inherent low efficiency of the process, recycling of indium from end-of-life products containing the metal is likely to be incentivised by economic and environmental reasons. However, details on the recycling market and its future potential are scarce. The USGS state that there is a process to recover indium directly from used displays, though no details are provided on the quantities of recyclates produced. Lab based efficiencies of 92% have been reported for such recycling processes (Hsieh *et al.* 2009). In principle waste flat screens using ITO could also become a significant source of indium, given the relatively short life of many consumer electronic products this may emerge within the next ten years. Recycling rates for other end-uses of indium are not known, but expected to be small given the size of those markets.

The potential to recover indium from end of life PV modules is unclear. The similarity between the structure of flat panel displays and PV modules may indicate that high recycling efficiencies are possible, and the literature reviewed in Part 4 includes end of life recycling estimates of 80%, comparable to current ITO end of life recycling (Fthenakis 2009; Hsieh *et al.* 2009).

### 3.2.6 Indium: conclusions

Indium is a secondary metal, found in trace amounts in a range of ores but most commonly Sphalerite, which is mined to produce zinc (the primary metal). Production of indium has grown steadily over time, with particularly rapid growth in recent years as demand for indium has grown to produce ITO for flat screens, an application that it is reasonable to expect to continue to expand in the immediate future. At present, PV accounts for perhaps 2-5% of the market for indium(Fthenakis 2009; Shon-Roy 2009).

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[7] In the case of two stage selenization deposition process based on sputtering, one of the deposition techniques currently mostly used in CIGS manufacturing.

The economics of secondary metal extraction are more complicated than those of primary metals or other mineral resources. The incentive to produce indium is not only driven by the indium price, but also by the price of zinc (or price of other associated base metal), value of other trace elements and the type of ore extracted, as well as the cost of the production processes used. This also makes estimating reserves and resources complicated, since it is not possible to consider the economics of extracting indium separately from production of primary metals and other trace elements. In addition, the data on reserves appear to be subject to economic and political factors and the USGS no longer report indium reserves. Indium is inherently recyclable and a large amount of indium is recovered from various production processes (materials wasted in manufacture). End of life recycling is also feasible and has the potential to become a significant source of indium in future years.

Whilst reserve estimates provide some indication of short run production potential they provide little guide to long run opportunities. Knowledge of the economically accessible resource is also limited, in part because of the issues associated with the economics of secondary metals. Estimates of crustal abundance provide no meaningful guide to prospective future production and in the view of the authors it is not appropriate to use crustal abundance as a guide to future supply of indium or any other trace element. It therefore appears that understanding of the potential to increase production of indium over the long term is limited. We know that a sizeable fraction of the indium present in waste materials from zinc extraction is currently wasted and that reserve and reserve base estimates increased prior to 2009. Whilst we have no evidence to conclude that indium production faces any immediate threats we also conclude that considerable further work is needed to provide meaningful estimates of indium reserve base and resources.

## 3.3 Tellurium

Tellurium is a group 16 metalloid[8] element, with an atomic weight of 127.6. It is a crystalline, white-silver substance, and is brittle and easily crushed. It has an estimated crustal abundance of 0.01ppm (Knockaert 2000), comparable to that of platinum (0.005 ppm) and scarcer than the rare earth metals. Tellurium was discovered in 1782 by Muller von Reichenstein and named by Klaproth in 1798, from the Greek *tellus* meaning earth.

Tellurium is occasionally found in its native state, though it is more usually found as precious metal telluride or in association with base metals including copper or tin. However, the concentration of tellurium in these minerals is not sufficient to be economically mined for primary tellurium extraction, as is the case for indium. Therefore, the recovery of tellurium is instead reliant on its concentration in slimes arising from the extraction and refining of base metals. Copper ore is the most significant source of tellurium, which is concentrated during the electrolytic refining process, along with precious metals and selenium. Tellurium is also concentrated during the refining of zinc, gold and lead (Knockaert 2000).

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[8] An element whose properties are between those of metals and solid non-metals.

### 3.3.1 Recovery and refining

Tellurium recovery is largely reliant on its concentration during the recovery and refining of copper, where it is extracted from anode slimes near the final stages of the copper recovery process. Copper is recovered from several ores throughout the world and through several processes. In Annex 2 we deal with some of the issues surrounding the extraction recovery and refining of copper from its associated ores. Below we deal with the issues of tellurium recovery from copper anode slimes in more detail.

Anode slimes which arise from the recovery and refining of copper contain concentrations of tellurium between 0.5% and 10%. Knockaert (2000) presents the composition of anode slimes from three different mining companies, presenting a selected range of metals (Figure 3.5). The slime then undergoes a series of processes designed to concentrate the various valuable metals present. Processes vary, but as with indium, these processes are complex, and the concentrations of tellurium present relatively low, making the economics of secondary metalloid extraction difficult. The incentive to produce tellurium is therefore linked, not only to the tellurium price, but also by the price of copper (or price of other associated base metal), the type of ore extracted, and the production process used.

As with indium, not all of the tellurium present in extracted ore will be recovered. Some processes discard all tellurium present in ores (Lifton 2009). Others will recover a percentage of tellurium which is less than that originally present(Green 2006). Many refineries have not engaged in tellurium recovery due to the small size of the tellurium market (Ojebuoboh 2008). This tellurium content is discarded in anode slimes in which the tellurium is concentrated. Authors have tried to estimate recovery rate, presenting a current range of between 33% and 40% (Green 2006; Ojebuoboh 2008). This suggests that the majority of tellurium in anode slimes is discarded, though these rates also include tellurium discarded in refineries that have no tellurium recovery. Any wastes, and tailings containing tellurium are difficult to treat, and it is uncertain whether these wastes could be considered a resource for future exploitation. It has been suggested that recovery rates may have increased to ~50% in recent years, driven by the price of tellurium (Fthenakis 2009) though it is unclear how high tellurium recovery rates may feasibly reach and at what price. Examination of the potential to increase future tellurium recovery rates from anode slimes is an important area for future research.

It is also possible that tellurium production could decrease as a result of changing sources of copper.  Richer ore bodies are becoming exhausted and although copper containing ores remain plentiful they contain lower copper content (0.2 – 0.3%).  Extraction from these lower concentration ores demands different extraction techniques, and some mines have moved from electro winning techniques to solvent extraction. Unfortunately tellurium is not recovered through solvent techniques, and the tellurium fraction of these ores is discarded. Should the price of tellurium increase significantly, however, mine operators may be encouraged to recover tellurium (Lifton 2009).

**Figure 3.5: Various elements present in anode slimes of three refining companies**

| **Element** | **Typical concentration, wt %** | | |
|---|---|---|---|
| | Canadian Copper Refiners | Nippon Mining | Inco |
| **Cu** | 20.3 | 4.73 | 17 |
| **Bi** | 0.36 | 1.6 | 0.1 |
| **Sb** | 0.95 | 0.95 | 0.05 |
| **Se** | 10.9 | 15.23 | 7 |
| **Te** | 3.19 | 3.64 | 2 |
| **Pb** | 8.5 | 6.54 | 1 |
| **Au** | | 0.99 | 0.1 |
| **Ag** | 21.3 | 20.58 | 6 |
| **As** | 1.83 | 1.59 | 0.8 |
| **Ni** | 0.52 | 0.03 | 26 |

*Source:* Knockaert (2000)

### 3.3.2 Production volumes

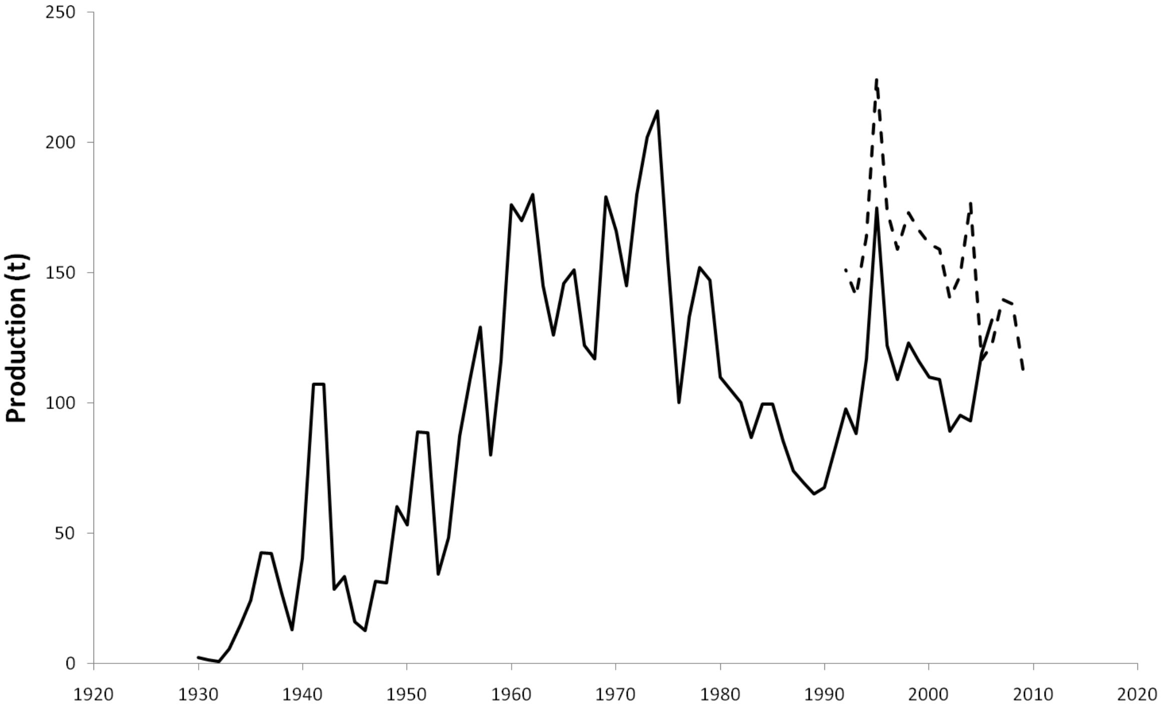
Several tellurium production data sources exist including consultancy reports such as those produced by Roskill Information Services, the BGS, and the USGS. The USGS is the most commonly quoted source of minerals data for these and many other minerals due to its availability. BGS data is less often quoted.

Figure 3.6 presents USGS and BGS data for historical production of tellurium, with USGS data from 1930 to 2009 and BGS data from 1992 to 2009. Figure 3.7 presents only the data between 1972 and 2009 for comparability with indium data in Figure 3.1. Production of tellurium appears to have been highly variable. This is in contrast to indium data, which shows growth over the period between 1972 and 2008. Tellurium demand is discussed in section 3.3.3.

The BGS appear to report higher levels of production than the USGS for those years where data from both exist. This can be explained by the fact the BGS estimate US production of tellurium, while USGS data excludes US production for proprietary reasons. Data for other countries is reported by the countries themselves, though Japan did not report in 2008 and 2009, where estimates were used instead.

World tellurium production figures only include tellurium recovered from copper mining operations. Production of tellurium from other ores, however, is unlikely to be significant. In addition, the USGS ceased reporting tellurium production data after 2006. It appears that this is the result of uncertainty in ‘other countries’ data, which the MCS states is inadequate to form a reliable estimate of global production (USGS 2011).

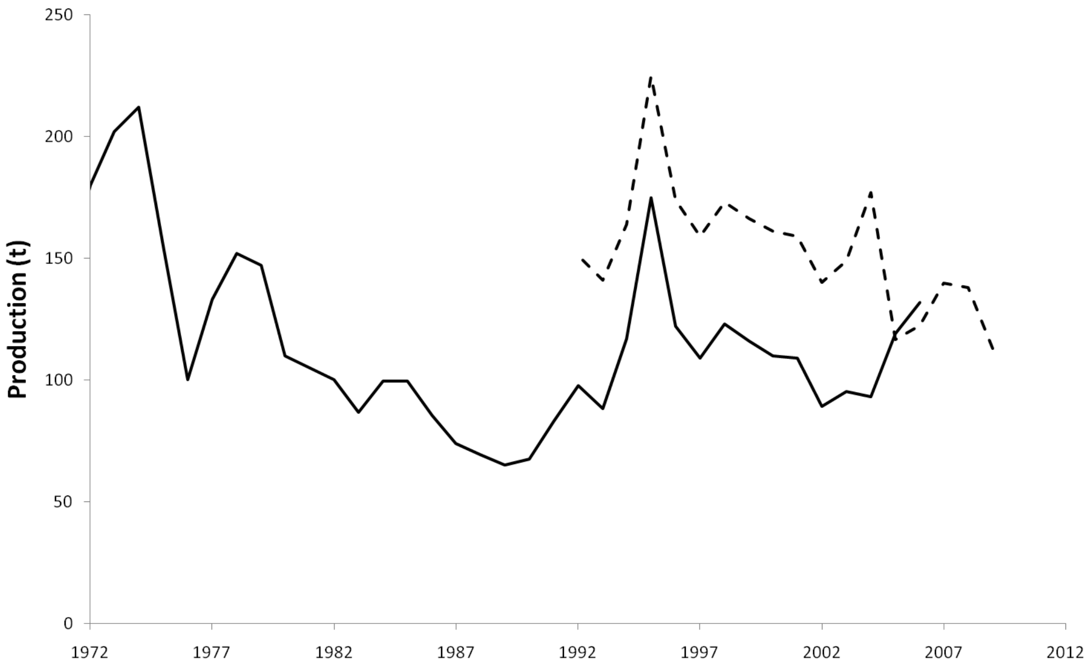
Figure 3.6: Historical world production of tellurium as reported by the USGS (solid) and the BGS (dotted)



*Source:* (BGS 2010; USGS 2011)

*Note:* USGS world production estimates do not include U.S. production data for the year 1931 and for the years 1976 to 2006 because the U.S. data are proprietary. After 2006, USGS world production was not available. BGS world tellurium data includes estimate of 50 tonnes per year for US production.

Figure 3.7: Historical world production of tellurium from 1972 to 2009 as reported by the USGS (solid) and the BGS (dotted)



*Source:* (BGS 2010; USGS 2011)

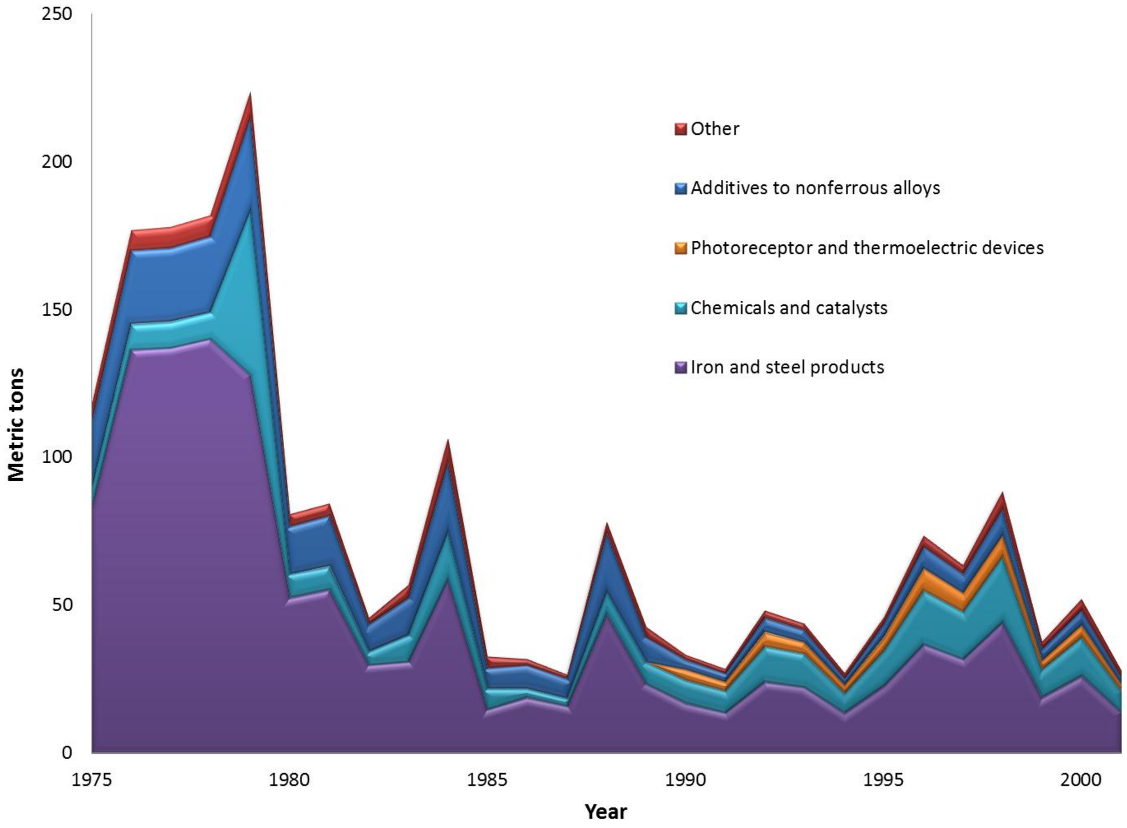
*Note:* USGS world production estimates do not include U.S. production data for the years 1976 to 2006 because the U.S. data are proprietary. After 2006, USGS world production was not available. BGS world tellurium data includes estimate of 50 tonnes per year for US production.

## 3.3.3 Tellurium markets: main end uses

Data on end-use consumption is not widely available. The USGS listed three main groups of end-use in its Minerals Yearbook 2009. Alloys are the major use of tellurium, where it improves the machinability of steels and other metals, or resistance to vibration and fatigue in lead. Several chemical uses exist also, including use in synthetic rubber as a vulcanising agent, use in catalysts for synthetic fibre production, and use as a pigment for colouring ceramics and glass. Finally electrical applications include use in thermal imaging and in photovoltaics.

Figure 3.8 presents some indicators of the trend in tellurium consumption. Tellurium consumption in the US reduced significantly after the late 1970s, with iron and steel products decreasing significantly. In the beginning of the late 1980s and beginning of the 1990s the first demand for tellurium from thermoelectric and photoreceptors can be seen. This includes materials used for thin film PV.

Figure 3.8: US tellurium consumption by end use



Source: USGS

Figure 3.8 is confined to US usage, and the decline of some sectors will reflect global trade patterns (for example the relative decline of US steel production, with corresponding increases in other countries). Nevertheless the overall pattern of global production illustrated in Figure 3.7 is consistent with the highly variable demands shown in Figure 3.8 and the relative declines both from 1970 to 1990 and post 2000. There is some evidence that demand is increasing because of CdTe PV production, which accounted for approximately 11% of the market for tellurium in 2009 (Shon-Roy 2009).

The decrease in demand for tellurium seen in recent years has been attributed to the recent high price of tellurium, which has encouraged many manufacturers of tellurium based products to reduce their usage, or substitute for other materials (USGS 2009). In the period 1995-2000 prices of tellurium fell steadily from $23 to $17/lb. The fall continued until 2002/03 when the price was in the range $8-$10/lb. However, during the year 2004 and 2005 the tellurium price rose rapidly to $136/lb by mid-year before falling back to around $100/lb by the year end. This sudden price rise was attributed to increased requirements from China and anticipation of increased use for CdTe in solar cells. The USGS cite wrote: "*...in 2004 and 2005, demand greatly outstripped supply, causing the price to climb rapidly.*

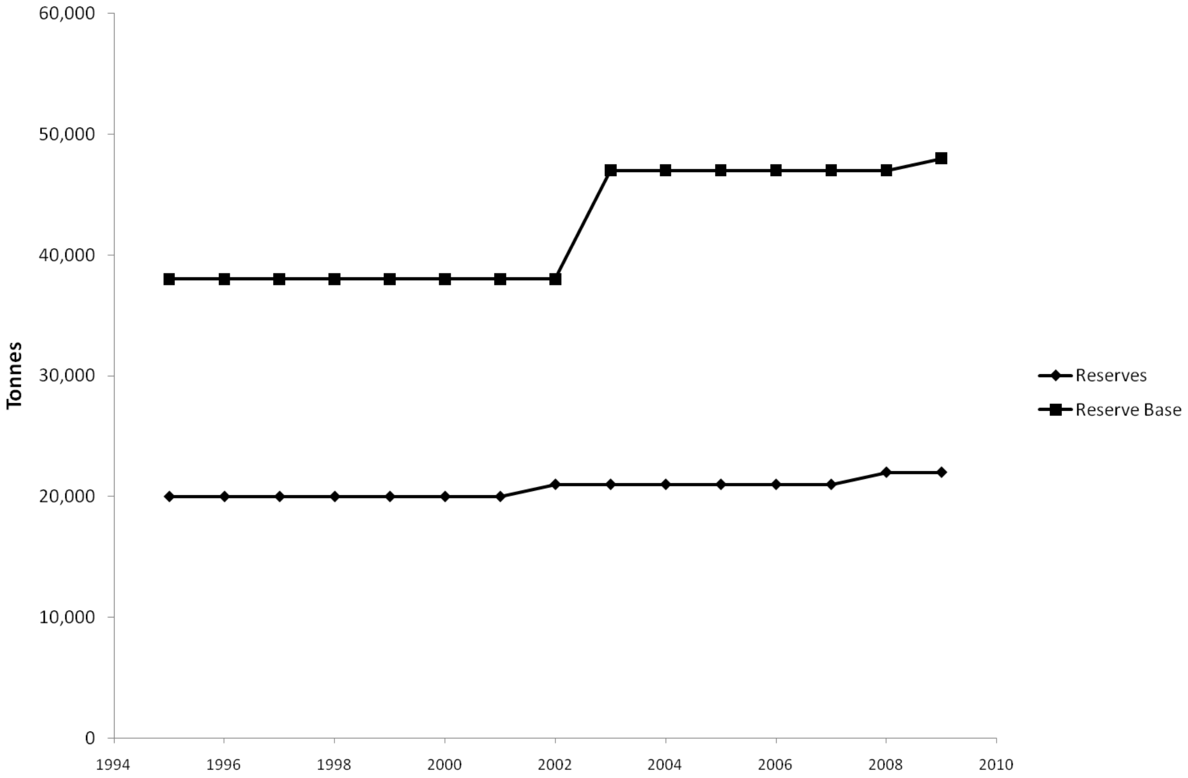
*In 2006, tellurium consumption was expected to increase further, chiefly from the solar cell industry. Production was expected to remain relatively unchanged, extending the supply shortfall*' (USGS 2005). The tellurium price has continued to fluctuate in recent years but has remained considerably higher than before 2004. In contrast to indium markets, the lack of a dominant and growing use may have been contributory to this volatility.

### 3.3.4 Reserves and resources

The complexities of reserve reporting discussed with reference to indium also apply to tellurium reserve estimation. Tellurium is a secondary metal, affected in large part by the economics of the copper industry. It is also subject to the same problems with reserve reporting described in 4.2.5. However, tellurium is more widespread geographically (see below) and it would appear that the reserve estimates available for tellurium have not been subject to the same dramatic reserve reporting increases seen for indium.

Figure 3.9 presents the USGS data on world tellurium 'reserves' and 'reserve base' between 1995 and 2008.

**Figure 3.9: Historical tellurium reserve and reserve base data**



*Source:* USGS

*Notes:* Both reserves and reserve base figures discontinued in 2009.

As with indium, it is reasonable to expect both reserve and reserve base estimates to increase over time. Discoveries of new reserves, increasing price of the metal, increased understanding of the resource and improvement in extraction technologies are all likely to increase production over that implied by current reserve estimates.

The data presented in Figure 3.9 shows reasonable stability over the time series, and does not include the significant changes in reserves data seen in the indium data. Reserve base data remain around twice that of reserves for the period covered. As with all reserve base reporting by the USGS, tellurium reserve base data was discontinued in 2009 due to lack of up to date assessment previously provided by the now defunct US Bureau of Mines.

Tellurium reserves data reported by USGS, are only those associated with copper bearing ore. The USGS estimated that copper anode slimes produced in 2006 contained 1200 tons of tellurium.  As discussed previously several other metals also concentrate tellurium during extraction. Therefore, future tellurium production could include resources currently not considered, though the quantity and economic cost of extracting them is unclear. The US Bureau of Mines previously calculated tellurium reserves based on an assumed ratio of 0.065kg of tellurium per tonne of copper produced (USGS 1994). It is unclear if this ratio is still used by the USGS to calculate tellurium reserves but it is clear that this assumption will have significant bearing on tellurium reserve estimates. If, as some authors have assumed, recovery rates for tellurium could more than double in the coming years (Ojebuoboh 2008), this would have a significant positive impact of reserve estimates.

As we note above however, a less optimistic take is possible, since depleting copper ore bodies could lead to extraction processes which do not yield tellurium(Lifton 2009).

### resources

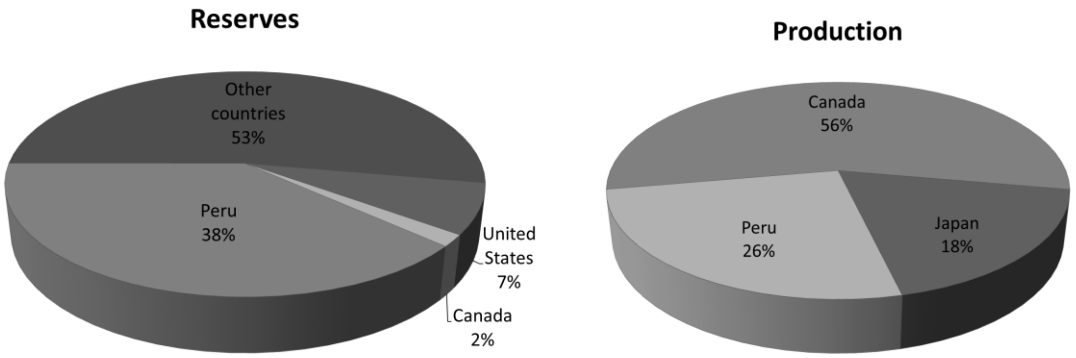
For the reasons discussed with respect to tellurium, the use of reserve or reserve base data to predict future production of tellurium is difficult, and the reliance on so temporally variable a measure to define material availability in the long term future is extremely unsatisfactory. Again however, estimates based on crustal abundance provide very little indication of how much material could be produced at some point in the future.

For the reasons discussed with respect to indium, the development and use of some sort of measure of resources (similar to URR) would be advantageous to future tellurium availability estimation. Unfortunately, it is unlikely that such an assessment is currently achievable. It is therefore sensible to use the available resource data with caution, if using them to estimate future tellurium production, or availability.

### Geographical distribution

The geopolitical issues associated with materials availability appear less important with reference to tellurium than indium. Figure 3.10 presents the relative share of reserves and production of tellurium by country, as reported by the USGS in 2008. Tellurium reserves are distributed around a number of countries, with the ‘other countries’ grouping representing the largest share. This includes reserves reported in Australia, Belgium, China, Germany, Kazakhstan, the Philippines, and Russia. Production data does not include US production. Production from other countries is also excluded, as the USGS argue that "available information is inadequate for formulation of reliable production estimates" (USGS 2003). The wide spread of reserves across many countries, and the perceived political stability in the countries for which the USGS present production figures suggests that geopolitical issues are unlikely to have any significant impact on the availability of tellurium in the foreseeable future.

Figure 3.10: Relative share of tellurium reserves and production by country



*Source:* USGS

*Note:* Other countries include Australia, Belgium, China, Germany, Kazakhstan, the Philippines, and Russia

### 3.3.5 Recycling

As with indium, tellurium is a secondary metal with difficult extraction processes and economics, so the recycling of material from end of life products containing concentrated tellurium may be economically attractive. However, current industrial uses of tellurium are mostly dissipative, and tellurium is not widely recycled (USGS 2011).

The concentration of tellurium in CdTe PV cells is some 500ppm making end of life cells a concentrated source of tellurium (Fthenakis 2009). If installed capacities of CdTe PV cells increases, a significant installed base of tellurium containing products would emerge. Stated recycling efficiencies of 90% to 95% can be found in the literature (Krueger 2010; Suys 2010) though commercial recycling rates are likely to be less than this unless driven by legislation. Collection of panels for recycling is likely to be subject to such legislation given the toxicity concerns of cadmium (Enkhardt and Harris 2010), potentially enhancing tellurium recycling rates. The potential impact of future indium availability from recyclate is discussed further in section 3.3.5.

### 3.3.6 Conclusions about tellurium supply

Like indium, tellurium is a secondary metal found in trace quantities in ores primarily mined for other metals. Tellurium is extremely scarce; its crustal abundance is similar to that of platinum and considerably scarcer than indium. Demand for tellurium has fluctuated considerably over time and at present is not subject to the strong demand growth currently seen for indium. At present, PV accounts for approximately 11% of the market for tellurium (Shon-Roy 2009).

As with indium the economics of tellurium production are bound up with those of the base metal, most commonly copper or tin. The incentive to produce tellurium is not only driven by the tellurium price, but also by the price of copper (or price of other associated base metal), the value of other trace elements and the type of ore extracted, as well as the cost of the production processes used. This also makes estimating reserves and resources complicated, since it is not possible to consider the economics of extracting tellurium separately from production of primary metals and other trace elements. Many industrial uses of tellurium are dissipative. Nevertheless, recycling potential from CdTe cells is expected to be significant, with current lab efficiencies of 90-95% (Krueger 2010; Suys 2010).

The issues related to reserve estimates also mirror those associated with indium. Reserve estimates provide some indication of short run production potential but provide little guide to long run resources, in part because of the issues associated with the economics of secondary metals. Estimates of crustal abundance provide no meaningful guide to prospective future production and in the view of the authors it is not appropriate to use crustal abundance as a guide to future supply. Future supply is difficult to predict. Increasing the rate of extraction appears possible, since some processes discard all tellurium present in ores and others will recover only a percentage of tellurium available. Many refineries have not engaged in tellurium recovery due to the small size of the tellurium market. An additional factor in the case of tellurium is that some of the processes used to extract copper do not permit tellurium extraction. Again, whilst short run supply would not appear to be under threat, considerable further work is needed to properly characterize potential resources.

## 3.4 Conclusions

Both indium and tellurium are trace elements, the production of which is secondary to the production of primary metals, mainly zinc (in the case of indium) and copper (tellurium). This makes the economics associated with the production of both metals quite complex, as they are interdependent with that of the base metal. Assessments of future production need to be linked to that of the primary metal with which they are associated, factoring in the relative economics of both primary and secondary materials.

There appears to be potential to increase the recovery rate of both metals, with a substantial fraction of the metal potentially available discarded at refineries at present. There are also no reasons to believe either is subject to overriding constraints. Recycling rates could be increased from the manufacturing sector (pre-consumption material recovery) and there is potential to recycle PV and other consumer products at the end of their useful lives.

Reserve data appear to be subject to a variety of economic and political factors, especially in the case of indium. At best they offer a guide only to short term production potential. Estimates of long run resources are complicated by the economics of secondary metal production and by uncertainties related to the potential to improve the amount of material contained in the waste products of primary metal extraction. In both cases neither reserve estimates nor estimates of crustal abundance provide a meaningful guide to future supply potential and considerable additional work is required in order to characterise the resource base effectively.

# 4 Estimates of indium and tellurium availability: a discussion of the literature

## 4.1 Introduction

Part 3 provides a discussion of a range of issues associated with estimating the future abundance of indium and tellurium. It suggests that crustal abundance is not a useful guide to future supply, whilst reserve and reserve base estimates are inherently short term and meaningful estimates of resources are not available. The 'secondary' nature of both indium and tellurium create difficulties for assessing future supply, since the demand for and supply of the primary metals they are associated with will affect the economics of these secondary metals.

Insights gained from our review of indium/tellurium extraction, production and reserves can assist in assessing the usefulness of assumptions made in existing studies of availability of both metals for PV production. Part 4 therefore reviews the body of academic literature that has investigated the availability of indium and tellurium for large scale PV production (Andersson *et al.* 1998; Andersson 2000; Keshner and Arya 2004; Feltrin and Freundlich 2008; Wadia *et al.* 2008; Fthenakis 2009; Wadia *et al.* 2009).

## 4.2 The range of assumptions in the existing literature

Table 4.1 presents the material availability assumptions made in this literature for both indium and tellurium. The 'assumed availability' for indium and tellurium are reported as either total 'cumulative' availability, or as 'annual' availability.

The literature in Table 4.1 presents a significant range of availability assumptions, and does not present any clear consensus on future availability. In order to develop a clear understanding of the range of future material availability potential for tellurium and indium we examine these estimates in more detail. We begin by examining estimates for indium.

Table 4.1: Summary of mineral assumptions in literature

| Paper | | Assumed indium availability (tonnes) | Assumed tellurium availability (tonnes) |
|---|---|---|---|
| Andersson *et al* (1998) | *Reserves:* | 2,154 | 21,818 |
| | *Max Resources:* | 3,500,000–46,666,667[a] | 120,000–2,400,000[a] |
| Andersson (2000) | *Reserves:* | 2,600 | 20,000 |
| | *Base Case:* | 290 | 290 |
| | *Expansion Potential:* | 348 | 551 |
| Feltrin and Freundlich (2008) | *Reserves:* | 625[c] | 5,250[c] |
| Fthenakis (2009)[d] | *Conservative:* | 65 | 480 |
| | *Most Likely:* | 663 | 3,132 |
| Keshner and Arya (2004) | *Current Production:* | 335 | 130 |
| | *Potential Production:* | 26,143[b] | 2,000[b] |
| Wadia *et al* (2009) | *Reserves:* | 6,000 | 47,000 |
| | *Production:* | 588 | 128 |

*Notes:*

a Figures based on 0.01% of average crustal abundance down to 4.6km in the earth's crust. Ranges given where differing estimates of crustal abundance vary by more than a factor of 2.

b Authors estimate of potential future production based on crustal abundance.

c Figure based on 25% of reported reserves.

d Production in 2050 based on a scenario forecast of future material supply to 2075. Does not include recycled metal.

### 4.2.1 Estimating Indium availability

Four authors present estimates of cumulative indium availability (i.e. the total availability of indium in the future) based on USGS estimates of either indium reserves, or indium reserve base. Depending on the year from which these estimates are taken this gives a figure of 2100 to 2600 tonnes for reserves derived estimates and 6000 tonnes for reserve base derived estimates. Feltrin and Freundlich (2008) assume only 25% of this figure is available for PV applications, with the remainder used in other applications.

As discussed in Part 3, indium production is intrinsically linked to the production of its primary metal, most often zinc. Therefore, total reserves figures have less influence on achievable production rates. We therefore focus on annual production assumptions.

Figure 4.1 presents estimates for indium supply found in the literature against the USGS data for historical production seen previously in Figure 3.1. Andersson (2000) provides an estimate of annual availability achievable by 2020, while Fthenakis presents two scenarios for availability as it develops between 2008 and 2100[9]. Keshner & Arya (2004) and Wadia *et al* (2009) present future availability potential without specifying the time horizon.

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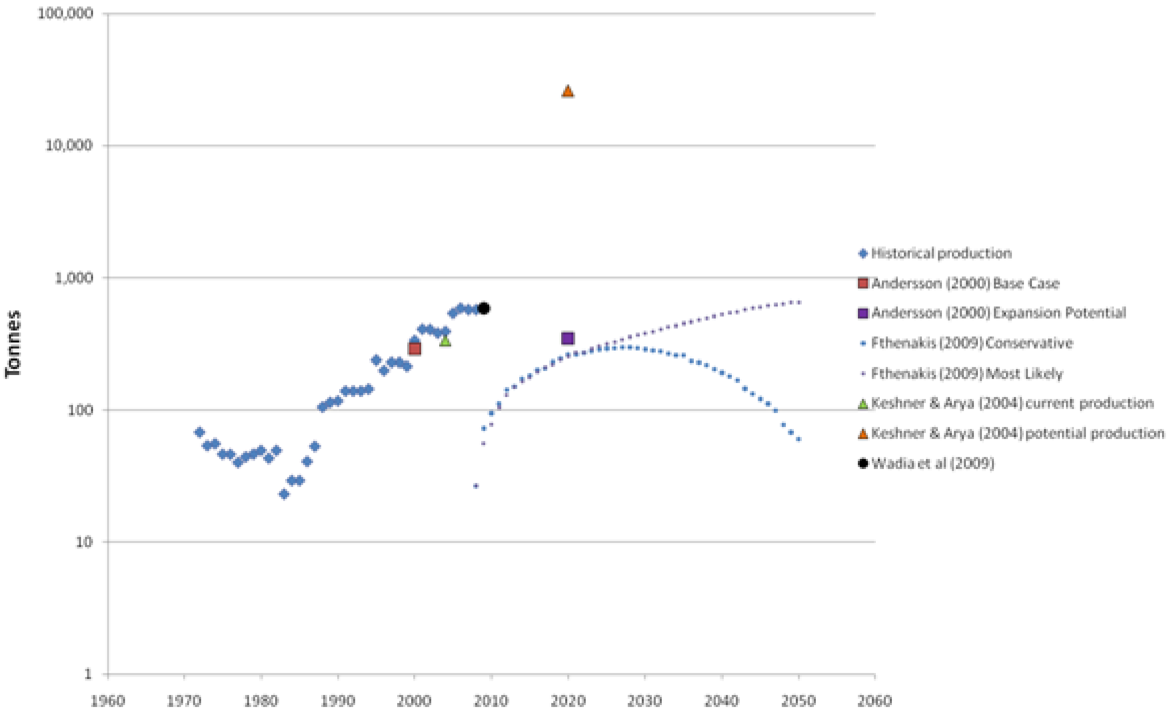
[9] Only the scenario data to 2050 is presented.

Figure 4.1: Comparison of indium availability assumptions with USGS historical production data



*Notes:* Data for Fthenakis extracted from figures using Engauge Digitizer v4.1. Data does not include additional material from recycling.

Andersson (Andersson 2000) presents two figures for CIGS PV manufacturing potential, based in part on two separate assumptions of future indium availability. The first, used in Andersson's 'Base Case', assumes annual material availability of 290 t/y, based on indium production in 1997. The origin of this data is not clear since USGS data for 1997 is only 230t/y and Andersson notes that "Refinery data for all metals, except for [...] indium, are taken from the US Geological Survey." Andersson does not state which other source is used to derive the indium figure, though Crowson (1994) is a source cited for production data of other materials. The second figure, used in Andersson's 'Expansion Potential' case, is an estimate of availability in 2020 based on increased mining of primary metal (in this case zinc), and increased recovery of indium from those ores. By increasing overall availability by a factor of 1.2, indium availability is increased to 348t/y in 2020. These two estimates are represented by the red square and purple square data points in Figure 4.1.

The two estimates presented by Andersson are below modern production rates. In the decade since Andersson published, indium production has increased to approximately twice the base case estimate, and is around 250t/y greater than the expansion potential case. This highlights the difficulty in using current production to give an estimate of future production. Since production of a finite resource is unlikely to remain the same over any significant length of time the estimation of the future trajectory of production is of more importance. Andersson attempts to estimate this trajectory with his 2020 estimate of production expansion potential. However, Andersson's assumptions now look conservative in light of historical production to 2008.

Keshner and Arya (2004) also provide two assumptions of future indium availability, designated 'current production' and 'potential production'. The first assumption is based on production of indium in 2000, estimated by the USGS as 335t/y. The potential production assumption is based on indium availability of 26,143 t/y, two orders of magnitude greater than production in 2000. This estimate is arrived at based on a fixed percentage of estimates of crustal abundance though the percentage, or crustal abundance assumed is not disclosed. These assumptions are represented by the green and orange triangular data points in Figure 4.1. The difficulty in using crustal abundance as a measure of resource was discussed in Part 3. The appropriateness and usefulness of this estimate is therefore rather questionable.

Fthenakis (2009) presents the most sophisticated basis for assumptions on future availability of indium, and gives a time series of production from 2008 to 2100 (only data to 2050 is presented) in Figure 4.1. Two cases are presented: a 'conservative case' and a 'most-likely' case[10]. Fthenakis derives this scenario by first assuming future zinc supply. Fthenakis notes that zinc extraction has grown at 3.2% between 1910 and 2002, and that growth in the last one to two decades is consistent with the historical average(Gordon *et al.* 2006; USGS 2008). Fthenakis takes the average refinery production between 2007 and 2008 to be 545t/y and then applies to this a growth rate of 3.2%, and a peak in production in 2025 for the conservative case and 2055-2060 in the most likely case. This peaking profile is assumed based on the similarities Fthenakis draws between zinc and copper[11], and reflects the copper/tellurium scenario adopted in reference to Fthenakis CdTe analysis, discussed further in section 4.2.3. A recovery efficiency of 70%-80% is stated, though Fthenakis does not state his assumption for indium content in zinc ores. Finally Ftheankis assumes that current competing uses, such as flat panel displays, will increase in the future, and therefore allocates only 50% of future indium production growth to the PV market. These two scenarios are represented in Figure 4.1 by the purple and blue dotted lines.

Fthenakis applies a level of sophistication to availability assumptions which is not replicated by other authors. However, not all of the assumptions needed to derive these figures are entirely explicit, and it is not possible to judge in all cases whether those assumptions are optimistic, conservative or otherwise.

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[10] An 'optimistic' case is also referred to, though the material availability profile is not presented.

[11] Fthenakis cites a similar reserves to production (R/P) ratio between zinc and copper as justification for assuming the same production profile. However, authors have written previously about the inadequacy of R/P ratios for analysis of future production (Bentley *et al.* 2007; Sorrell *et al.* 2009), suggesting that this may not be the best basis to defend this analogy.

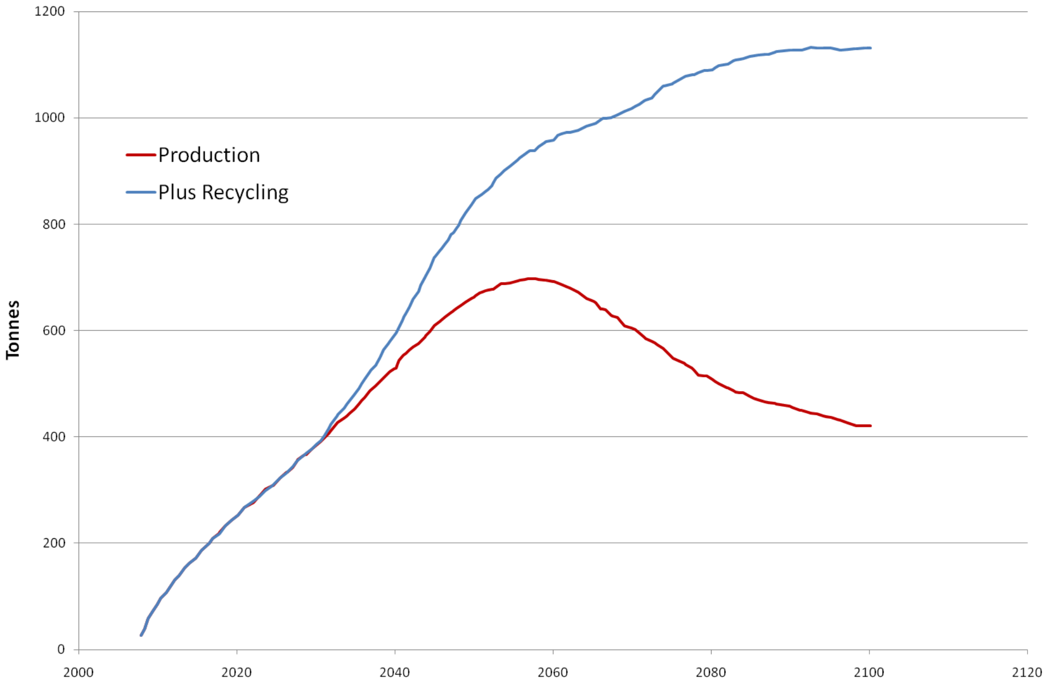
Finally, Wadia *et al* (2009) estimates CIGS production possible given annual production of indium in 2006. USGS production data were used, which estimated global indium production to be 588t/y. Again this is not an estimate of future production potential and in light of previous discussion it is unlikely that this will prove representative of indium production in the future. This is represented by the black circle in Figure 4.1. It is interesting to note that this assumption does not appear to be particularly optimistic, which is in contrast to the demand side assumptions made by Wadia *et al* (2009).

### 4.2.2 Recycling estimates

In general the assumptions on future recycling seem simplistic, given the potential contribution recycling could make to availability in the future, and the variables associated. Andersson states that he assumes 100% recycling, though it is unclear if this applies to utilisation or end-of-life cells. The distinction is important given the difference, particularly in terms of collection from end-of-life products and the assumed lifespan of these products. Wadia *et al* (2009), and Keshner & Arya (2004) both make no assumption regarding recycling and therefore all indium considered in their estimates is from mining of metals.

Fthenakis again represents the most sophisticated assumptions of the authors presented. First he assumes an aggregate rate of 80% recycling, which consists of a 90% rate for recovery of modules, and a further 10% loss of material during separation. In addition, a lifespan for cells of 30 years is given, defining the time horizon at which these materials will become available. Figure 4.2 presents these results, depicting the impact of these recycling assumptions on annual production.

**Figure 4.2: Future production of indium, plus recycling, estimated by Fthenakis (2009)**



Given the 30 year period assumed for PV cell lifespan the impact of recycling is largely limited until after 2040. However, it is interesting to note that, even though Fthenakis uses scenarios where indium production is predicted to peak before 2060, PV manufacturing increases after this point, and throughout a period of significant decline in indium production.

While recycling of end-of-life PV cells is treated inconsistently across the literature reviewed here, the future potential for recycling from other uses is consistently absent. In the case of indium particularly, demand is subject to a competing and growing use in flat panel displays. The flat panel display market is therefore also a potentially significant resource of indium in the future. A better understanding of the implications of competing uses and recycling of other products at the end of their life is therefore important in improving future indium supply estimates.

### 4.2.3 Estimating Tellurium availability

We now examine the tellurium availability assumptions adopted by the authors presented in Table 4.1. Given the similar nature of the assumptions relative to the indium discussion above many similar elements emerge.

Four of the authors presented in Table 4.1 provide estimates of PV manufacturing potential based on cumulative availability of tellurium. For each author this cumulative availability is based on either USGS estimates of reserves (Andersson *et al.* 1998; Andersson 2000; Feltrin and Freundlich 2008) or reserve base (Wadia *et al.* 2009). This gives cumulative availability figures in the order of 20,000 tonnes for reserve derived estimates and 47,000 tonnes for reserve base derived estimates (as per the reserves data in Figure 3.9). In the case of Feltrin & Freundlich (2008) this availability for PV applications is assumed to be 25% of total availability.

As discussed in Part 4 and in relation to indium availability, tellurium production is intrinsically linked to the production of its primary metal, most often copper.

Four of the authors present estimates of future annual availability of tellurium. Figure 4.3 presents these estimates against the USGS and BGS data for historical production. Andersson (2000) provides an estimate of annual availability achievable by 2020, while Fthenakis presents a scenario for availability as it develops between 2008 and 2100[12]. Keshner & Arya (2004) and Wadia *et al* (2009) present future availability potential without specifying the time horizon.

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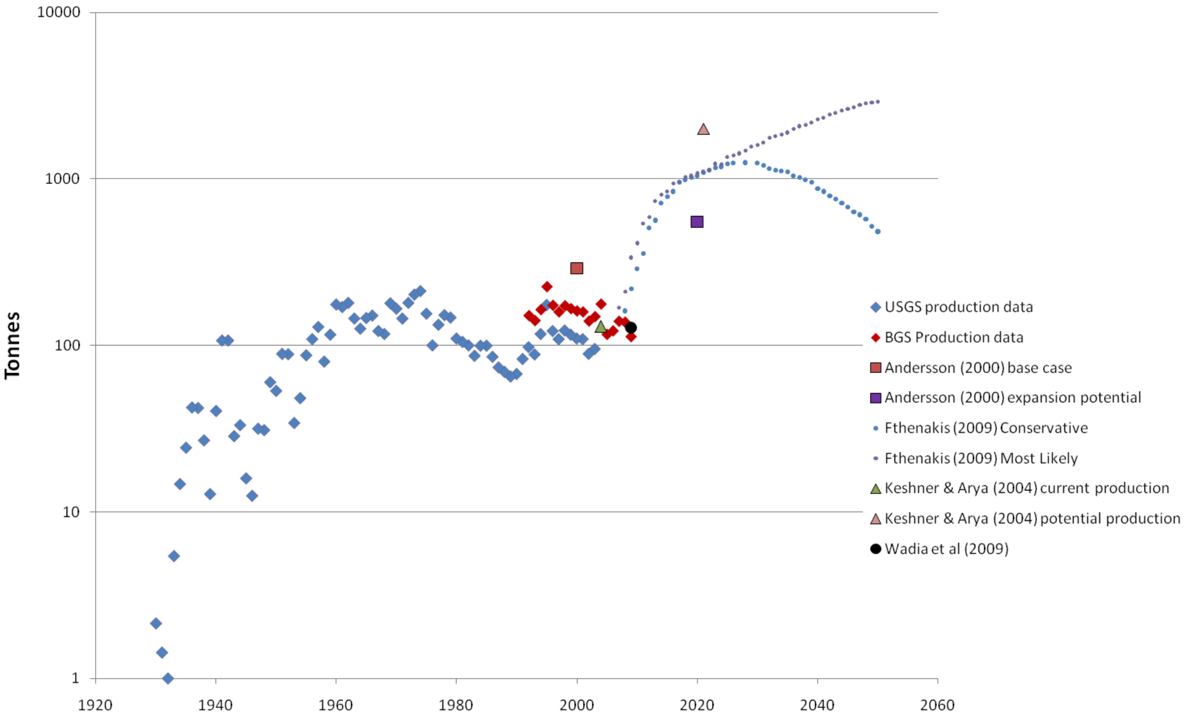
[12] Only the scenario data to 2050 is presented.

### Figure 4.3: Comparison of tellurium availability assumptions with USGS historical production data.



*Notes:* Data for Fthenakis extracted from figures using Engauge Digitizer v4.1. Data does not include additional material from recycling.

Andersson (2000) presents the same ‘base case’ and ‘expansion potential’ discussed above, this time with respect to CdTe manufacturing and tellurium availability. The base case tellurium availability assumption is based on annual material availability of 290t/y, based on tellurium production in 1997. This is based on from Crowson (1994). The expansion potential assumption is an estimate of availability in 2020 based on increased mining of primary metal (in this case copper), and increased recovery of tellurium from those ores. By increasing overall availability by a factor of 1.9, tellurium availability is increased to 551 t/y in 2020. These two estimates are represented by the red and purple square data points in Figure 4.3.

In contrast to the indium assumptions above, the assumptions on availability of tellurium made by Andersson (2000) are higher than current production levels, and do not appear attainable based on recent trends. In this respect the estimates appear optimistic. This is a reflection not only of Andersson’s assumptions[13], but of the differing trends in tellurium and indium production in recent years. As discussed Part 3, indium production has seen significant growth over recent years, while production of and demand for tellurium has

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[13] Crowson’s data assumed by Andersson (2000) seems significantly greater than both USGS and BGS data for production in 1997

contracted. Again this highlights the issues associated with assuming current production to be representative of future production. In this case the contraction in production highlights the potential to overestimate future production, though this contraction may not reflect physical availability. This does not preclude the possibility of meeting Andersson's assumption of production in 2020 (480% greater than production in 2003), but makes it appear reasonably unlikely.

Fthenakis (2009), presents two tellurium production profiles from 2009 to 2100: a conservative case and a 'most-likely' case[14]. Fthenakis derives these figures by first estimating future copper supply. Copper demand and copper production are assumed to be equivalent, and a growth rate for copper supply of 3.1% is assumed based on USGS estimates of demand growth (Fthenakis 2009). An average tellurium content in copper anode slimes is calculated from other estimates (Green 2006; Ojebuoboh 2008) and used as a starting point. The growth rate of 3.1% is then applied. Recovery of tellurium from anode slimes is assumed to increased from below 40% to 80% during the first 5-10 years (based on Ojebuoboh (2008)). Based on copper demand scenarios estimated by Kapur (2005) and Ayres *et al* (2002) a peak in demand is assumed in 2025 in the conservative case and between 2055 and 2060 in the most likely case. It should also be noted that Fthenakis subtracts competing uses for tellurium in the figures presented. Use of tellurium in steel (42% in 2006) and chemicals (23% in 2006) is expected to remain flat for the period of the estimate, giving a value of 322t/y subtracted from the estimate. These two cases are represented by the purple and blue dotted lines in Figure 4.3.

Again, the assumptions by Fthenakis for tellurium both appear significantly more optimistic than similar assumptions for indium availability. This is driven by the small role assumed by Fthenakis for competing uses of tellurium, which is static, and less challenging than the assumptions made for indium. This reflects the more competitive nature of indium demand, though it is unclear whether these assumptions on competing uses are an accurate reflection of future indium and tellurium markets. This optimism is also driven by the contraction in tellurium production and demand discussed above.

Keshner and Arya (2004) provide two assumption cases, as they do for indium, based on current production and production potential. Their current production assumption is based on production of tellurium in 2000, stated as 130t/y based on USGS data. The production potential assumption is derived in a slightly different way to that seen in their indium assumption, giving a tellurium availability of 2000t/y, an order of magnitude greater than production in 2000. This estimate is arrived at by assuming an average tellurium concentration of 5% in copper anode slimes, assuming that this can all be recovered, and assuming a figure of 41,000t/y for copper anode slimes. Since no time horizon is given this estimate is attributed to 2020. These two assumptions are represented by the green and orange triangles in Figure 4.3.

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[14] An 'optimistic' case is also referred to, though the material availability profile is not presented.

The same trend seen in Andersson (2000) and Fthenakis (2009) tellurium availability assumptions are also observed in Keshner and Arya's (2004) assumptions. The current production based assumption appears in line with the trend over recent years seen in BGS data. The production potential assumption is significantly higher, though not the two orders of magnitude leap seen in the indium assumption. It appears highly unlikely that this production level will be achieved in the medium term given the order of magnitude between current production, which has also contracted over recent years, and the production potential assumption.

Finally, Wadia *et al* (2009) presents a graph which includes estimates of CdTe production possible given annual production of tellurium in 2006. USGS production data was used, which estimated global tellurium production to be 128 metric tonnes. This is represented by the black circle in Figure 4.1. This provides a reasonably conservative assumption for future availability, being equal to or below historical production. Again, this assumption is not in keeping with the highly optimistic nature of assumptions made by Wadia *et al* (2009) on PV demand for tellurium, which we discuss in section 2.6.3.

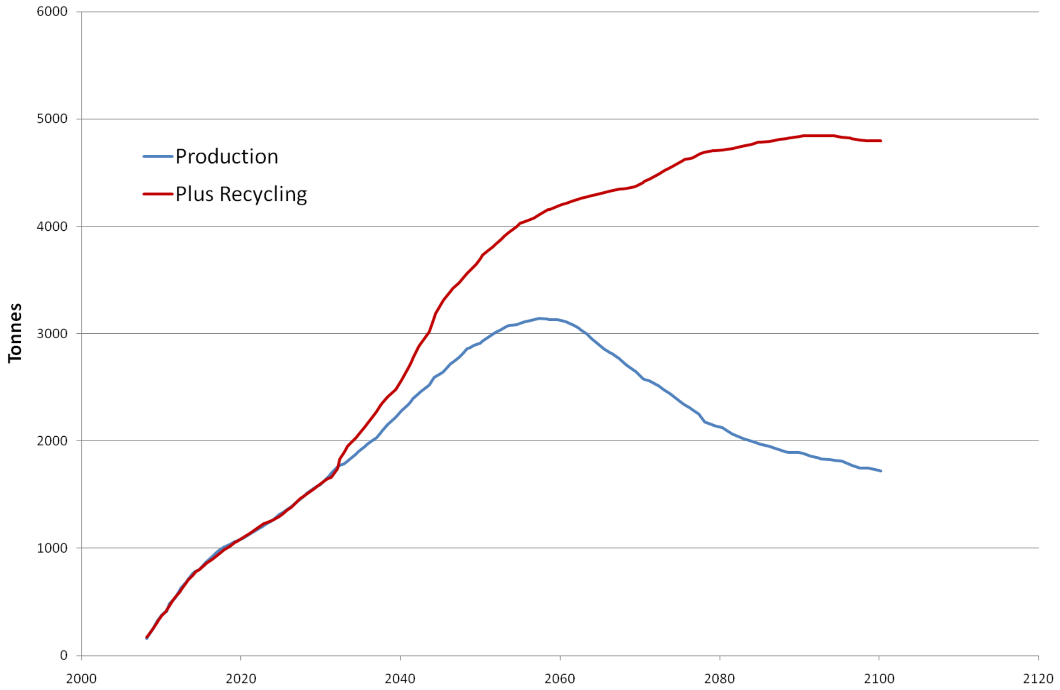
### 4.2.4 Recycling

As in the case of indium, the literature takes a diverse set of views on recycling. Andersson 2000 assumes 100% recycling, though little detail on the derivation of this assumption is given, and it is unclear if this applies to utilization efficiency or end of life cell recycling. Andersson does, however, state that development of recycling infrastructure for used PV cells by 2020 to 2030 is an important policy goal. Complete utilisation might be possible given modifications to manufacturing processes. However, 100% end-of-life cell recycling is ambitious. Lab based recycling processes have achieved between 90% and 95% efficiency, and commercial processes are likely to be less efficient. If we also include less that 100% recovery of end-of-life cells, this further decreases the total recycling rate.

Wadia *et al* (2009) and Keshner & Arya (2004) do not assume any end-of-life recycling. Keshner & Arya (2004) mention recycling frequently, though this is only applied to utilisation efficiency, which we treat here separately. For these authors, all the material included in annual material production assessment is derived from mined metals.

Fthenakis includes some more sophisticated assumptions regarding recycling, including the same assumptions used for estimating future CIGS recycling. It is not clear whether this is appropriate, or whether the differing nature of the two technologies might result in different recycling rates in practice. From these assumptions a second material availability curve is derived, consisting of the mined metal scenario presented in Figure 4.3 plus the material recovered through end-of-life recycling. Figure 4.4 presents these two scenarios for Fthenakis 'most likely' case.

Figure 4.4: Future production of tellurium, plus recycling, estimated by Fthenakis (2009)

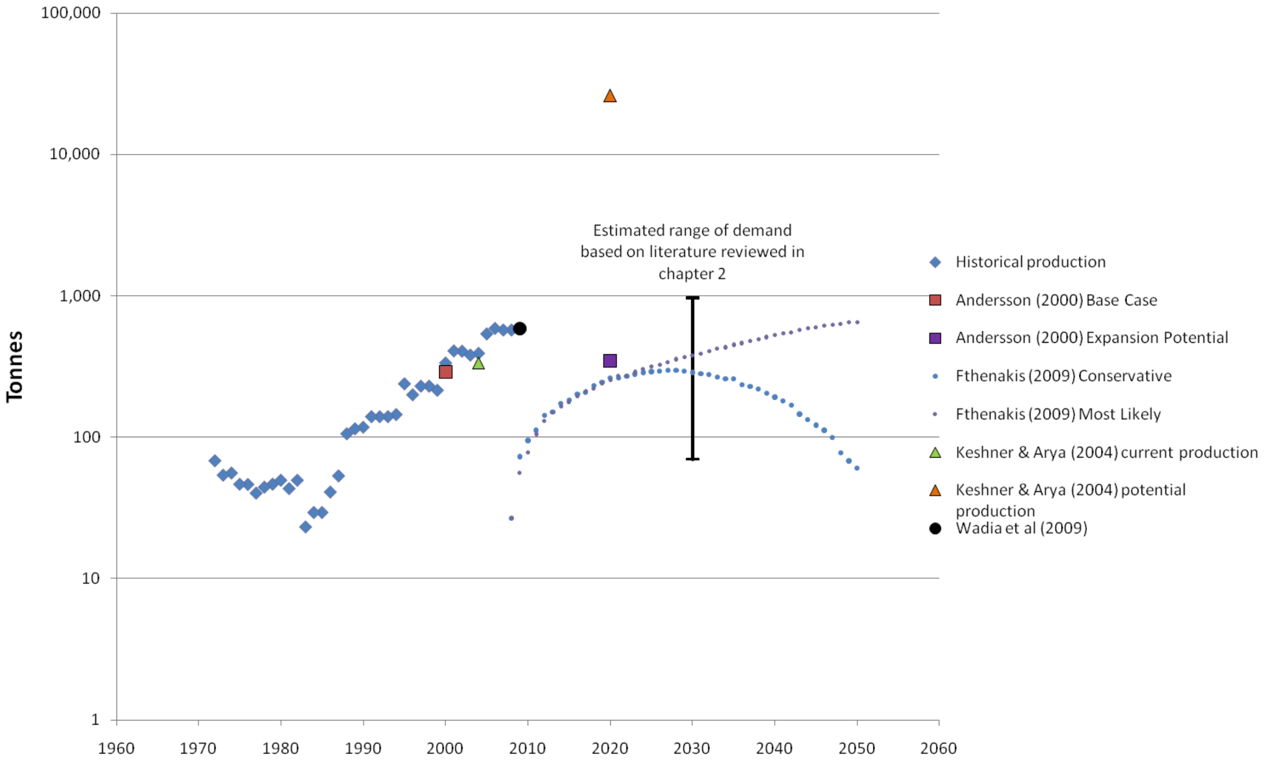


Given the 30 year period assumed for PV cell lifespan the impact of recycling is limited until after 2040. However, it is interesting to note that, even though tellurium is predicted to peak before 2060, PV manufacturing increases after this point, and throughout a period of significant decline in tellurium production. This mirrors the case of indium.

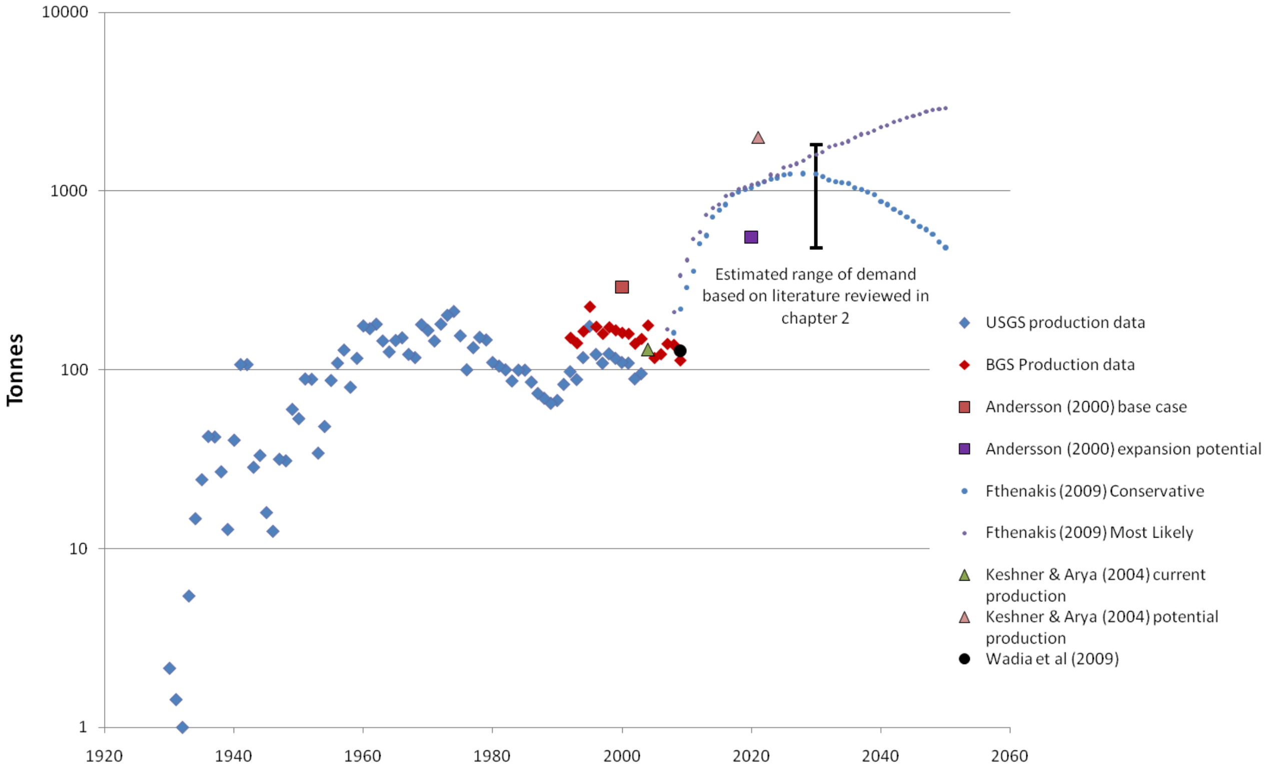
## 4.3 Conclusions and comparison with demand estimates from Chapter 2

Existing literature on the demand for and availability of indium and tellurium in the PV sector presents a very diverse picture. Assumptions about future availability differ widely. Figures 4.1 and 4.3 both demonstrate large variations in assessments of available resources, manifold in the case of indium and orders of magnitude apart in the tellurium case. In Figures 4.5 and 4.6 we present the range of supply estimates reviewed above alongside the range of demand out turns we derived in Part 2.

## Figure 4.5: Indium supply ranges and 2030 demand ranges derived in Part 2



## Figure 4.6: Tellurium supply ranges and 2030 demand ranges derived in Part 2



Several studies make relatively simplistic assumptions, from future production based upon historical levels to an assumed fraction of crustal abundance. In the light of the discussion in Part 3, it is clear that neither provides a useful guide to potential future production.

The most sophisticated of the studies reviewed here takes a scenario approach to both indium and tellurium and links production of the secondary metal in question to the base metal with which it is associated (Fthenakis 2009). As such, this study is consistent with the issues we describe in Part 3. Fthenakis accounts for growth (and ultimate decline) in production of zinc and copper and for the possibility to increase recovery rates for both indium and tellurium. He also factors in the possibility of end of life recycling and takes into account the range of competing uses for each metal.

The specific assumptions and judgements used by Fthenakis can of course be challenged and discussed. However, the analysis presented in Part 3 supports the use of a scenario approach that links production growth to that of the primary metal and allows for a wide range of uncertainty. An improved understanding of resources, recycling and all of the factors discussed in Part 3 would greatly enhance the possibility of providing useful estimates of future supply.

# 5 Conclusions

## 5.1 Demand for PV materials

### The PV market

The thin film PV market is widely expected to expand significantly in the coming decades. Whilst the total market for PV and the share for thin film are both difficult to predict several scenarios suggest that the global market for PV could grow to over 100 GWp per year, by the period 2030 to 2050 and that the thin film market might occupy of the order of 40% of this. Hence, whilst the current market for CdTe amounts to less than 2 GW and that for CIGS only around 0.5 GW per year, it is possible to envisage markets of tens of GW per year for either technology in the next 20 to 30 years.

### Materials demand

Translation from thin film demand to materials demand depends upon the quantity of material per Wp, expressed in g/Wp and a function of:

- **Density of active material,** in this case either CIGS or CdTe
- **Thickness of active layer,** measured in microns (µm)
- **% of material in layer,** in this case measuring the share of tellurium in CdTe or Indium in CIGS and calculated by formula weight
- **Efficiency,** a measure of the amount of energy captured per square meter under standard test conditions (STC)
- **Utilisation,** a measure of efficiency of material use in the manufacturing process.

These factors are seldom brought together in a transparent and systematic way in the literature. This paper therefore combines them using the following function:

$$M_R = \frac{\rho F \mu}{U I_{SC} \eta}$$

Where $M_R$ is the material requirement in t/GWp, $\rho$ is the density of the active layer material, $F$ is the % of material in layer, $\mu$ is the thickness of the layer in microns (µm), U is the utilisation factor, $I_{SC}$ is solar insolation under standard conditions (1000W per $m^2$) and $\eta$ is the electrical conversion efficiency of the PV cell.

### The range of demands

Whilst our review found a number of existing studies, the wide range of assumptions and different degrees of transparency create considerable uncertainty as to the potential materials requirements of both CIGS and CdTe. Active layer thickness, efficiency and utilisation all differ markedly between studies and some studies use optimistic assessments for developments in one area combined with pessimistic judgements in another.

To illustrate the potential implications of the wide range of possible developments this paper has used the 2030 PV market and thin film shares in the IEA Blue Map scenarios (IEA 2008, IEA 2010a), and divided the thin film market in 2030 equally between CIGS and CdTe. This would result in a global market for CIGS and CdTe of around 20 GW/yr each in 2030.

Using the range of assumptions about future efficiency, layer thickness, utilisation and so on described above the resulting demand for indium and tellurium lies in a range of around 70 to 970t/y and 480 to 1800 t/y respectively. Our 'worse case' estimates of indium demand are 14 times higher and tellurium demand almost 4 times higher than in the most efficient instances we found in the literature. However in all cases the demand from the PV sector would exceed current production for *all uses.* The range of this expansion is extremely wide, from 12% in the case of indium to as much as 1800% for tellurium.

We consider the prospects for meeting this demand growth below. However, the wide range of possible outcomes and considerable disagreement between existing estimates suggests that a more systematic approach to assessing the future of efficiency, utilisation and cell thickness (as well as the size of the PV market and share of CIGS, CdTe and other device types) would offer considerable benefits. Varying key assumptions systematically, testing key sensitivities and presenting the outcomes in a clear and transparent fashion would greatly aid understanding and discussion of materials requirements.

## 5.2 The Supply of indium and tellurium

### Uses

Current estimates state that photovoltaic use of indium accounts for an estimated 2-5% of the primary indium production, with use of ITO in flat panel displays accounting for 65% of annual indium production, and around 30% used in other electrical and industrial applications. Production of indium has grown five fold since the mid 1980s. The photovoltaic use of tellurium accounts for around 11% of the market. Other uses are mainly in industrial processes. Whilst global production demonstrates considerable annual variation there is no clear growth trend apparent in the market for tellurium.

### The economics of secondary metals

Both indium and tellurium are trace elements, the production of which is secondary to the production of primary metals, mainly zinc (in the case of indium) and copper (tellurium). This makes the economics associated with production of both metals quite complex, as they are interdependent with that of the base metal. In both cases a large fraction of the metal available in principle in zinc/copper refinery wastes is not recovered. Estimates vary but it is believed that at present the zinc and copper industries recover around 30% of indium available from zinc refining and 30 – 50% of tellurium available from the anode slimes associated with copper refining. There would appear to be potential to increase recovery rates for both metals but this will depend on the choice of extraction and refining techniques, particularly in the case of copper/tellurium.

#### Reserves and resources

Reserve data appear to be subject to a variety of economic and political factors, especially in the case of indium. For example, China's reserve estimates increased from 280 tonnes in 2007 to 8000 tonnes in 2008.The USGS no longer report reserves of either metal and there is a paucity of independent data on current reserves. Even with good data reserve estimates offer a guide only to short term production potential. Estimates of long run resources are not available for indium or tellurium. Any attempts to provide an estimate of economically available resources will be complicated by the economics of secondary metal production and by uncertainties related to the potential to improve the amount of material contained in the waste products of primary metal extraction.

In both cases neither existing reserve estimates nor estimates of crustal abundance provide a meaningful guide to future supply potential and a key conclusion of this review is that considerable additional work is required in order to characterise the resource base effectively.

#### Recycling

Both metals are recyclable. We have discussed both recycling from production processes and recycling PV panels and other products at the end of their lives. The pre-consumption recovery of metal is encompassed within our discussion of 'utilization' above. There is potential to improve the utilization of both metals during manufacture, both through manufacturing processes that avoid material waste and through more effective recycling of pre-consumer waste. In the case of indium large amounts of metal are already recovered from various manufacturing processes including the production of PV. Several industrial uses of tellurium are more dissipative, making recycling more difficult. Within the PV sector a sizable fraction of material waste from manufacture is already recycled, and can increase in future. In both cases it is possible that end of life PV panels could become a significant source of material from the mid 2020s onwards. Recycling of other consumer products, notably flat screens using ITO could also become a significant source of indium, increasing potential supply considerably and possibly in a shorter timeframe given the relatively short life of many consumer electronic products.

## 5.3 Overarching Conclusions and future research needs

This review has revealed several striking features of the evidence base related to the demand for and supply of indium and tellurium from the photovoltaic sector:

- Although there is considerable uncertainty about the growth in the market for thin film PV a very significant source of uncertainty about the demand for indium and tellurium arises from the range of possible developments within thin film cell design and manufacture. Efficiency, layer thickness and material utilisation are key. A very wide range of assumptions are used in existing studies and there is a need for greater transparency and a systematic evaluation of key sensitivities.

- Despite these uncertainties, if the market for either CIGS or CdTe grows as substantially as some IEA scenarios for global decarbonisation suggest they will occupy a large fraction of the market for indium and tellurium. Indeed it is possible to envisage a manifold increase in global demand for both metals, particularly tellurium for CdTe.

- The potential to expand production of indium and tellurium is unclear, since data are poor and reporting has been reduced. Resource data are largely absent and the economics of production are tied in with those of the primary metals that indium and tellurium are associated with.

- However, it appears that a larger fraction of the indium and tellurium present in various primary ores could be extracted. There is also no prima facie reason to believe that the supply of either is severely constrained or that production cannot be increased. In the period since the mid 1980s the production of indium has increased fivefold. End of use products may also become an important source of material as consumer products reach the end of their lives and if recycling rates increase.

- Future analysis of production potential needs to explicitly link the production of indium and tellurium to the primary metals with which they are associated. Resource potential needs to be better characterised and competing end uses accounted for.

As the PV market is characterised by a wide range of device types, including alternative thin film designs, there is no reason to believe that the *development of PV*, *per se*¸ will be undermined by the findings above. In the short to medium term there is no evidence that the thin film sector faces resource constraints. In the longer term a substantial expansion in indium or tellurium production could be needed. This may be perfectly possible, however a thorough assessment of the long term role of CdTe or CIGS requires a much improved understanding of the potential to increase production and recycling of both metals and the economic implications of doing so.

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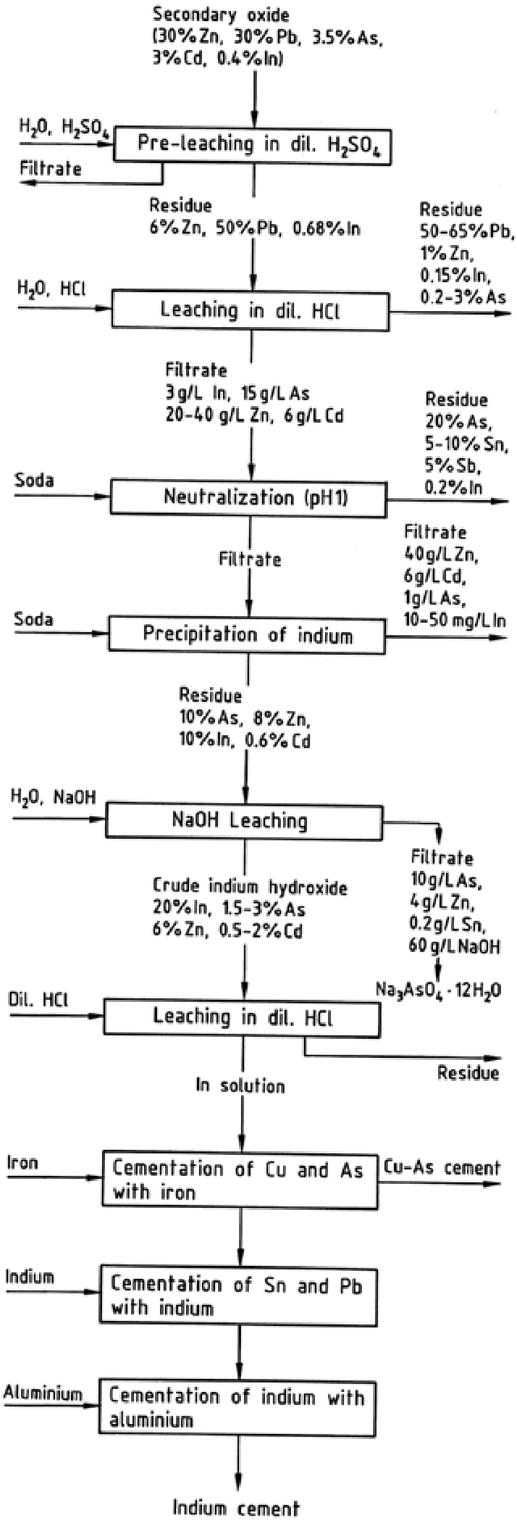
# Annex 1 Indium Extraction and Refining

Indium is found in ores of zinc, copper and tin.  Zinc is by far the most important host.  Most zinc bearing ores are sulphidic.  Indium content of such ores is generally in the range 10–100 ppm. (Alfantazi and Moskalyk 2003) Even in zinc concentrates from ore processing, indium content is generally less than 0.1%.  Because of the reliance of indium on production of zinc as its primary source, USGS estimates of indium reserves are based on those of zinc.  For that reason it is worthwhile examining methods of processing and smelting of zinc for an understanding of how the indium is concentrated and separated from its host.



95% of zinc mined is from sulphide ore deposits in which the ZnS (sphalerite) is mixed with sulphides of Cu, Pb and Fe.  Zinc content is usually between 3 and 10%.  The waste or gangue material present in the mined ore is removed by froth flotation.  The ore is crushed to a powder and mixed with water to form a slurry.  Chemical reagents are added and the slurry is aerated causing the sulphide particles to rise with the froth, while the gangue is wetted and sinks.  The resulting concentrate contains up to 50% zinc with sulphur, iron, silica and some copper and lead.

Two different processes are used to separate zinc.  Most plants operate an electrolytic process while some use a high temperature smelting operation.  Both electrolytic and pyrometalurgical production of zinc require oxides as a starting material, rather than sulphides. The concentrate is therefore roasted on fluidised bed or sinter roasters to transform sphalerite to zinc oxide and sulphur dioxide.

$$2ZnS+3O_2 \rightarrow 2ZnO+2SO_2$$

The $SO_2$ is passed on for conversion to sulphuric acid.

For electrolysis the calcined oxide is dissolved in sulphuric acid from the roasting process. For efficient electrolysis the solution is purified, first by removal of iron either as jarosite or oxide, then by addition of zinc powder to remove impurities of Cu, Ni, Cd, Co, Ge and In.

The purified solution is then electrolysed to produce zinc metal.

The mixed trace metals from the precipitation process above can be treated by dissolving selectively in hydrochloric acid and selectively re-precipitating with copper dust.

A process is described for separating indium metal from a zinc refining plant operated in Canada. In the preparation stages for electrowinning zinc metal, following iron removal (as jarosite), then cadmium removal, copper dust is used to remove Ag and Pb after which indium is separated by solvent extraction (Jorgenson and George 2005).

The largest zinc producer in the world operates in Belgium, Australia and USA. All zinc is produced electrolytically. The zinc concentrate is processed by leaching in dilute sulphuric acid (90% dissolved) then strong acid (remainder of zinc dissolved).

The solid leach residue contains precious metals and is sold on. The dissolved iron is removed as goethite, jarosite or haematite.

Trace impurities such as Cd, Co, Cu, Ni are removed by cementation using zinc powder (Nystar 2011). Indium will also be removed by this process. The by-products are generally sold to others.

A similar process is shown in the process flow diagram. After leaching out most of the zinc with dilute sulphuric acid, dilute hydrochloric acid is used to leach the residue, leaving most of the lead undissolved. The filtrate is part neutralised with soda to pH1 which causes precipitation of As, Sn and Sb. Addition of more soda to the solution causes precipitation of indium hydroxide together with remaining zinc and arsenic. Leaching with caustic soda solution partly dissolves these leaving indium hydroxide together with remaining zinc and arsenic. Releaching with dilute hydrochloric acid redissolves the indium hydroxide. Cementation using iron then indium causes removal of further impurities. After this aluminium is used to cement the indium itself. After all cementation process the indium cement is washed to remove acid and can then be melted using molten caustic soda as a flux. The flux is removed from the surface of the molten indium which can then be cast into anodes for refining.

High Temperature Smelting, Zinc-Lead blast furnace

As previously stated When the lead content of the concentrate is high, the sinter, in the form of lumps and metallurgical coke are loaded into the furnace then heated air is injected via tuyeres at the base (cf iron blast furnace). The air converts the coke to carbon monoxide which at the furnace temperature of approximately 950°C reduces the zinc and lead oxides to metal. The zinc metal exits the top of the furnace as a vapour which passes to a condenser. The lead liquid with copper and molten gangue is periodically tapped from the bottom of the furnace.

Indium accompanies the zinc through the processes of concentration (froth flotation) and roasting to oxide.

In the blast furnace smelting process 50% indium lost to lead bullion, while the remainder accompanies the Zinc where it is recovered to metal at plants with the required facility (not defined).

## Indium Refining

The most effective and often used process for refining metallic indium is electrolysis. The electrolyte is acidic; the favoured acid is hydrochloric acid although certain others have been used. The acid strength should ideally be between pH 1 and 2.

Indium to be refined electrolytically should preferably contain no more than 2% of impurities. Common impurities are other non-ferrous metals, such as Pb, Sn, Cd, Ni, Zn, Tl, Bi and Cu.

The impure indium is cast into anodes to suit the general shape and size of the refining tank. They are typically square or rectangular in section and about 2.5 cm thick. The anodes are often contained in cloth or paper bags which allow the electrolyte to pass but retain solid impurities that form as the anode is consumed (anode slimes). These anodes are connected to and suspended from conducting bars that straddle the top of the refining tank. Also suspended in the tank are starter cathodes of similar profile to the anodes but normally in the form of thin sheets or plates. Sheets of refined indium can be used, as can sheets of graphite or titanium.

The anodes and cathodes are positioned alternately in the tank, and connected by conducting bars or cables to the power supply. The connections and electrode support bars are usually made of copper, coated as necessary to prevent contamination of the electrolyte.

The electrolyte should employ acid of suitable purity for the grade of indium to be produced. Except in very small tanks, the electrolyte is stirred throughout the process, a convenient method of stirring being to pump electrolyte gently from one end of the tank to the other.

A potential is applied between anodes and cathodes causing indium to be dissolved at the anodes leaving impurities in the bags. Refined indium plates out on the cathodes. When the process is complete the cathodes are removed and thoroughly rinsed in deionised water before being melted under a caustic flux and cast into ingots.  Anode stumps are removed and remelted with the next batch.  The refining process can be repeated until the indium is of the required purity.

# Annex 2 Tellurium production and refining

Tellurium is one of the rarest metals in the earth's crust ($0.001 x 10^{-6}$). This makes tellurium about as rare as platinum and considerably more scarce than the rare earth elements (Webelements 2011).

Tellurium is in group 6 of the periodic table with oxygen, sulphur and selenium. Being below selenium in the group it is more metallic, being shiny, with a silver metallic lustre. It is classed as semi metallic with a hexagonal lattice structure.

Tellurium is a secondary metal in the extraction and refining of copper. Secondary in this context refers to the fact that tellurium arises as a by-product of copper processing.

(Compare – annual world copper production – about 15 million tons. Tellurium annual production not more that 500 tons)

Specifically, tellurium is found in the anode slimes from the electro refining of copper. This refining process is generally the last process before copper is converted into its required form (eg wire, sheet etc). Tellurium therefore follows the primary metal through virtually all processing from mine to finished product.

## Copper Extraction

Copper ores can be oxides or sulphides. The most common ore is chalcopyrite, $CuFeS_2$ which accounts for 50% of all copper production.

Most ores contain only a small percentage of copper, 0.6% is typical. The proportion of ore mineral is less than 2% of the rock volume. The remainder, gangue is mainly silicates and oxides often of no value.

After mining of the ore the first process, known as communication, is crushing and milling that reduces the lumps of ore to course powder. The next stage is concentration of the copper by separating it from the gangue. The method of separation depends on the type of ore. Oxidised ores including oxide, carbonate, silicates and sulphate are acid soluble, so can be leached to remove the copper using diluted sulphuric acid. $CuO+H_2SO_4 = CuSO_4+H_2O$. Leaching is usually carried out by heap leaching or dump leaching. Copper is then removed from copper sulphate solution by solvent extraction followed by electro winning of copper metal. Sulphuric acid is regenerated for reuse.

Alternatively, copper can be separated from the sulphate liquor by cementation using scrap iron.

$CuSO_4+Fe \rightarrow Cu+FeSO_4$.

The leached solids are normally rinsed and disposed of. Leaching with sulphuric acid does not extract tellurium, so it will be lost with solids as above.

The copper in sulphide ores is concentrated using froth flotation. The ore is ground to a suitably fine powder. The powder is slurried with water containing additions which react with the copper sulphide particles to make them hydrophobic. The slurry is passed to water filled tanks containing surfactants, the mixture is aerated and the sulphide particles rise to the surface as a froth which is skimmed off, cleaned and is then ready for roasting. The remaining unfloated solids, mainly rock-forming minerals can be processed to extract any other content of value but is normally disposed of as waste. The concentrate can contain 25-35% copper; the remaining impurities are principally iron and sulphur.

Historically the concentrate was converted to copper metal by two separate processed, roasting and smelting. In the roaster the concentrate is partially oxidised according to the equation:-

$2CuFeS_2+3O_2 = 2FeO+2CuS+2SO_2$.

The calcined product is next smelted with coke and silica in air at 1200°C. Scrap copper for recycling can be introduced to the smelter. At the elevated temperature iron oxide and sulphide react with oxygen to form a silicate slag while copper sulphide melts to form the matte. The slag floats above the matte and is tapped off for disposal or retreatment. The matte containing about 70% copper as $Cu_2S$ (with some FeS) is converted to blister copper by further air blowing at high temperature.

$$Cu_2S+3O_2 \rightarrow 2Cu_2O+SO_2$$
$$Cu_2S+2Cu_2O \rightarrow 6Cu+SO_2$$

Remaining FeS is converted to slag. $SO_2$ is passed to sulphuric acid plant. The blister copper is approximately 98% pure. Excess oxygen is removed in reduction stage and the copper is cast into anodes for electro refining.

Over a period of many years the above described roasting and smelting processes have slowly been abandoned in favour of a process called flash smelting. This process was first developed by the Finish company Outokumpu, although several variants are also used.

In outline the copper concentrate together with silica and lime are ground to fine powder and are fed through a nozzle into a fluidised bed reactor where high temperature processes progressively smelt then oxidise and reduce the molten products to remove sulphur and iron. Flash smelting processes are highly exothermic; very little external heat is required. The process uses an autogenic principle using the energy contained in sulphur and iron.

In combination with a flash converting process, it is possible to produce blister copper directly from concentrate.

## Copper Refining

The deoxidised blister copper anodes are suspended in tanks containing acidified copper sulphate solution. Cathodes are made from sheets of refined copper. Anodes and cathodes are suspended alternately in the acid solution. When a potential is applied between the anodes and cathodes, copper from the anode enters the electrolyte as $Cu^{2+}$ ions. Metals more reactive than copper also enter solution. Metals more noble than copper do not enter solution but form anode slimes on the tank floor. These metals include precious metals as well as selenium and tellurium. At the cathode, copper ions plate out as copper metal but more reactive metals such as nickel and zinc stay in solution. The net effect is transfer of copper from anode to cathode, with cathode copper being more pure because impurities remain in anode slimes or dissolved in the electrolyte. When the electrodes are stripped from the refining tank for melting the slimes are removed from the tank, they are de-watered and dried. These slimes contain typically 2% of tellurium (see Moats and others Copper refining Data 2007 p 204-207). The USGS estimated that copper anode slimes produced in 2006 contained 1200 tons of tellurium.

## Treatment of slimes

Slimes consist of copper and precious metals as well as selenium and tellurium.

The process of separation of the constituent metals and semi metals is as follows:-
The slimes are roasted in air at 500°C with sodium carbonate. The metal ions are reduced to metals (copper, precious metals) while selenium and tellurium are converted to sodium selenite $Na_2SeO_3$ and sodium tellurite $Na_2TeO_3$ respectively. The tellurite can be leached in water to sodium hydrotellurite while selenium is also leached as selenites. On addition of sulphuric acid, the tellurium salt forms tellurium dioxide which is insoluble while the selenites remain in solution.

$TeO_2$ is converted to metal either by electrolysis in alkaline solution or by reaction with sulphur dioxide in sulphuric acid.

## Quanitities produced

By country, 2009 estimated tellurium production was Canada 16 tons, Russia 34 tons, Japan 38 tons, Peru 30 tons. Information from USA was withheld while Australia, Belgium, Chile, China, Columbia, Germany, Mexico, The Philippines, Poland and some countries of the CIS are known to produce tellurium but quantities were not reported. In 2009 Minerals Yearbook, Selenium and Tellurium, USGS estimated total world production of tellurium to be between 450 and 500 tons per year. (No explanation of the basis for this estimation is offered).