MSc Program
Renewable Energy in Central and Eastern Europe

The impact of the availability of critical metals for the development of thin film PV and Lithium based batteries for electrical vehicles - A case study for Indium, Tellurium and Lithium

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by

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29th September 2011, Vienna

Affidavit

I, **Mag. Trink Thomas** hereby declare

1. that I am the sole author of the present Master Thesis, “The impact of the availability of critical metals for the development of thin film PV and Lithium based batteries for electrical vehicles- A case study for Indium, Tellurium and Lithium", 68 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

Renewable technologies are seen as a possible path for a sustainable energy system. On the other hand a variety of metals is needed for both the production and the operation of renewable technologies, which are not available in infinite amounts.

This work discusses the importance of rare metals for renewable energy and sustainable technologies. This theme is discussed based on research for thin-film photovoltaic (PV) systems working with Indium and Tellurium and batteries for electrical vehicles working with Lithium.

Based on existing literature the specific metal demand for the technologies and the available amounts of resources are discussed. For both values very different numbers could be found. The specific metal demand is between 22-109 g Indium per kW PV module, 31-279 g Tellurium per kW PV module and 100-423 g Lithium per kWh battery storage. In five business scenarios (three for PV and two for electrical vehicles) the future demand for the metals is calculated and compared to the available resources. The material demand in the year 2050 among the scenarios varies between 4,518–31,130 t Indium, 9,486-65,352 t Tellurium and 20-27 Million t Lithium.

The results show, that optimistic scenarios regarding the usage of PV and electrical vehicles might lead to significant shortage of the needed metals. However due to improvements in production efficiency or because of the discovery of new depots the picture might change in the course of time.

Recycling technologies are discussed as one strategy as well as the impact of certain recycling rates.

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1 Introduction

1.1 Motivation

The last decades have shown that the limited availability of fossil fuels is becoming more and more of a problem for the economy and society we are living in, for both systems are highly depending on those energy providers. The energy production from fossil fuels also causes environmental problems – e.g. increase in CO2 concentration or oil spill disasters. Therefore an energy system based on environmental friendly and sustainable technologies is needed.

Renewable technologies are seen as a possible path for such an energy system. On the other hand different metals are needed for the production and operation of renewable technologies, which are also not available in infinite amounts. In this respect the usage of very rare metals or the ones involving high costs in mining or refining is of particular interest. Different industries and producers of technologies are competing for these metals since they are employed in a variety of production processes. The growing usage of renewable energies leads to an increasing demand for those materials.

1.2 Aim of the study

This work discusses the importance of rarely available metals for technologies pertaining to the production of renewable and sustainable energy. This topic will be discussed with reference to thin-film photovoltaic (PV) systems and to batteries for electrical vehicles based on Lithium. Both technologies are crucial to several concepts focusing on a sustainable future transport system.

In order to discuss the importance of scarce metals for thin-film PV systems and of Lithium for batteries for electrical vehicles, the basic principles and key characteristics of these technologies will be described first. Particular attention will be paid to the critical metal demand. Also the quality and accuracy of the available data will be discussed. For the three metals - Indium, Tellurium and Lithium - the global availability will be shown as well as the geographical distribution of the known deposits. The example of the quality and the differences in the data for oil resources shows, that resource data often differ among the available sources. Therefore a bandwidth for the availability of the three metals will be given which allows estimating the accuracy of the data available.

Based on a variety of different studies regarding the potentials and prospects of renewable energies and electrical vehicles the following thesis will calculate a number of scenarios. These will indicate possible pathways for the (thin-film) PV usage as well as for the usage of electric vehicles. For the different scenarios, the annual material demand will be shown as well as the resources bound in the PV (for Indium and Tellurium) and electrical vehicle-battery-stock (for Lithium). Comparing these data with the resources known to be available allow a brief discussion, whether the limited availability of these different metals can prove to be an obstacle for these technologies. To decrease scarcity as a negative factor the effect of recycling will be shown for the different scenarios. Finally some possibilities and some problems regarding recycling will be discussed.

2 Technologies considered

2.1 Introduction

This chapter will give a brief overview on the theme of thin-film photovoltaic (hence: PV) technologies and for batteries for electrical vehicles. Two specific thin-film PV systems will be described in more detail as well as the case of Lithium-based batteries. For these technologies the material demand for Indium, Tellurium and Lithium will be given.

2.2 Thin-film PV Systems

Thin-film PV systems form a subgroup of a specific PV-technology. According to IEA 2008 (see Figure 1) four big groups of technologies can be found. PV systems based on crystalline silicon have the highest market share. The prices for these modules dropped in the last years due to huge increases in utilization. The market share of concentrating PV technologies and of organic solar cells have so far proved to be negligible in terms of business. They are still mainly subjects for research. The fourth technology is the thin-film technology.

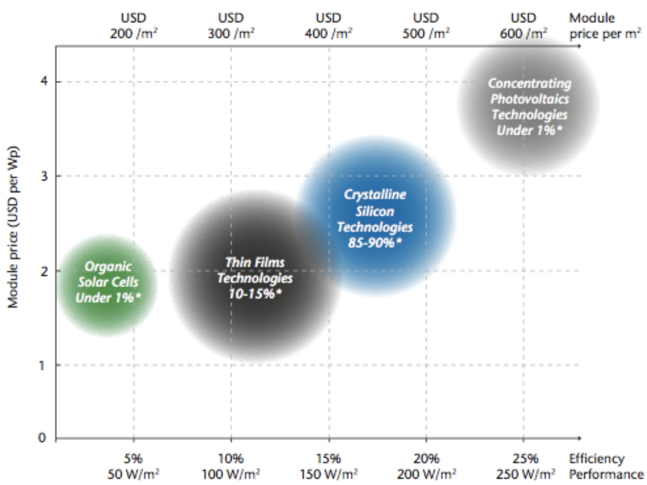

Figure 1: Current performance and price of different PV module technologies (source: IEA 2008, 2008).

The general idea of photovoltaic systems is that in a PV cell the energy from the sun is transferred to some electrons. The energy level of these electrons increases and thus frees them. Using different materials a built-in barrier is constructed, which acts on the electrons to produce a voltage (Bhubaneswari et al. 2011). In thin-film PV cells the semiconductor is only a very thin layer.

It is predicted that thin-film PV systems will contribute significantly to the transformation to a low carbondioxide society. In the course of recent years the industry had high growth rates. Therefore the total share of thin-film PV Systems has risen from 6% in 2005 to 10% in 2007 and 16 – 20% in 2009 (Jäger-Waldau 2010). It is probable that in the near future the share of thin-film in the total PV market will increase even further. Figure 2 predicts that the market share of thin-film PV systems will have risen to about 30% by 2015. The reason for this success is that thin-film PV systems have various advantages in comparison to conventional PV systems:

- a flexible substrate allows for an easier integration into a given infrastructure,
- a better performance under high temperature,
- a lower resource demand for the production of PV cells.

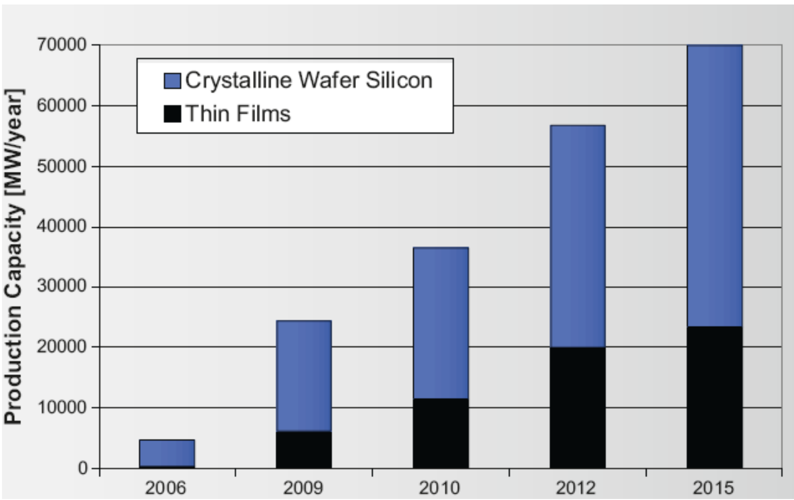

Figure 2: Development and projection of PV-market (source: Jäger-Waldau 2010, p. 23)

In the future the lower costs will appear as the major advantage of thin-film PV systems. Due to the lower resource demand and because of innovative production processes which are currently under development, cost advantages compared to conventional PV systems are expected. Especially the "Roll-–to–Roll" production process seems to be a promising path. It allows high throughputs and will thus mean a significant minimization of production costs. Past years have already seen production costs falling due to an increase in production. In the year 2004 the production costs were 2.94 $/W with a manufacturing capacity of about 6 MW. By 2006 production capacity had risen to about 90 MW entailing a price drop to about 1.25 $/W production costs (Ullal and von Roedern 2007). Thin-film PV systems have currently similar or lower costs if compared to PV systems based on crystalline silicon (see Figure 1).

2.2.1 Technology overview

The technologies for thin-film PV systems can be subdivided into three different categories (Pagliaro/Palmisano/Ciriminna 2008):

- Inorganic thin-films
- Organic thin-films
- Organic – Inorganic thin-films

Inorganic thin-film technologies rely on semiconductors that are produced from crystalline silicon or on a variety of metals. Organic Thin-film modules are using semiconductors based on hydrocarbon substances. These polymers are much cheaper to produce, however, their efficiency is currently much lower than that of inorganic thin-film modules. As a third form there are hybrid PV systems involving both inorganic and organic materials.

The aim of this work is a closer examination of the material demand for scarce materials needed for PV technologies. Therefore the focus is on inorganic thin-film technologies. As shown in Figure 3 three technologies are dominating the world market. Thin-film silicon and CdTe account for about 90%, whereas technology based on CIS (a description of CdTe and CIS- technologies is given in section 2.2.1.1 and 2.2.1.2) has a market share of about 5%.

As the availability of silicon is not critical, the following study concentrates on the technologies called CIS and CdTe (the following paragraph will explain these abbreviations) which both require scarce metals for their production.

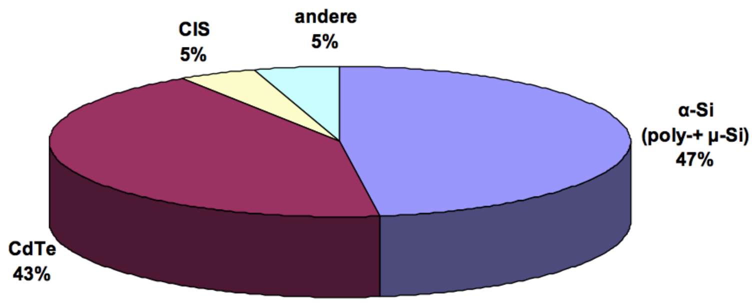

Figure 3: Market shares of different thin-film cell types in the year 2007 (source: Angerer et al. 2009)

2.2.1.1 CIS and CIGS

CIS stands for Copper-Indium-diSelenide, since the semiconductor of a CIS solar cell is a compound involving these materials. Several different CIS-technologies exist, but the CIGS (Copper Indium Gallium diSelenide) is one of the most widely used one.

One way of constructing a solar cell based on CIGS is presented in Figure 4. A glass is covered by molybdenum (serving as an electrode) on which a p-type layer of CuInGaSe is put. A thin n-type layer made of CdS is covered by the transparent top electrode (e.g. ZnO). The thickness of this construction is just a few µm.

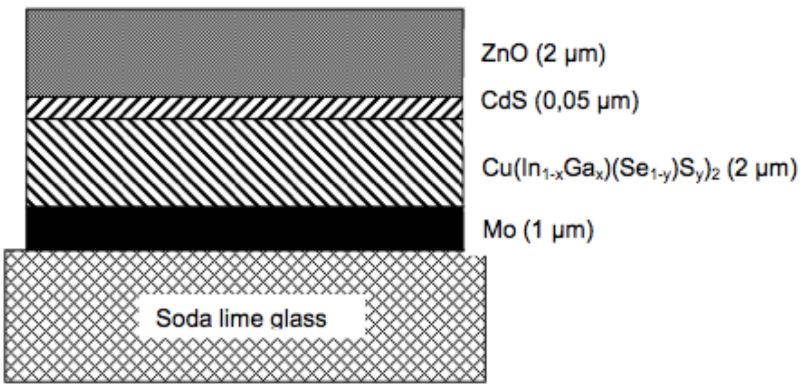

Figure 4: Body of a CIGS cell (source: Angerer et al. 2009, p. 142)

CIGS solar cells have reached efficiencies between 12-15%. Under laboratory testing conditions the record performance of a CIGS solar cell has been established at 20.1%. This was achieved at the Centre for Solar Energy and Hydrogen Research ZSW in the year 2010 (ZSW 2010).

2.2.1.2 CdTe (Cadmium Telluride)

Besides the CIGS PV cells another well known representative of this class is the CdTe (Cadmium Telluride)-cell. Figure 5 shows the typical construction of a CdTe module. A thin layer of a transparent oxide is applied to the front cover made of glass. Both Indium thin-oxid (ITO) or a fluorescent thin-oxide can be used. The next layer is an n-type CdS followed by the CdTe layer. The contact layer may consist of a Tellurium- and a metallic layer (e.g. Molybdenum). The efficiency of CdTe PV cells has been established at about 17% under laboratory testing conditions. Commercial versions of these cells have a level of efficiency between 7 and 9%.

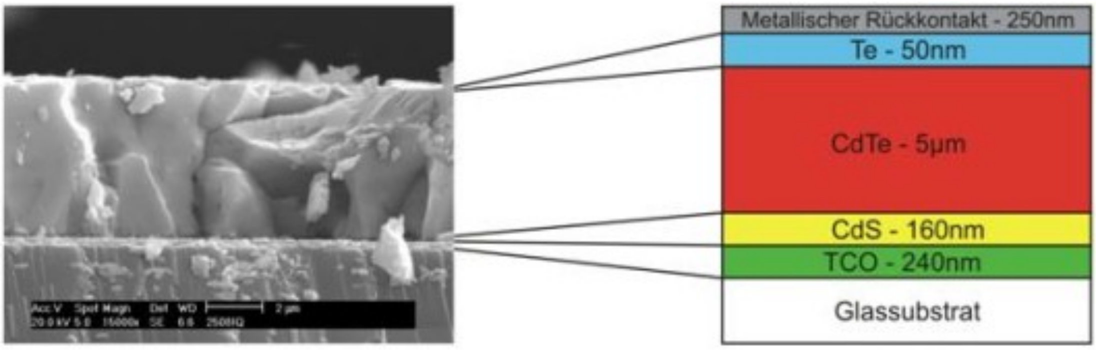

Figure 5: Construction of a CdTe cell (source: TU Darmstadt)

2.2.2 Material demand

The material demand for thin-film PV systems varies among the different technologies and production processes. Chemical elements (e.g. Indium and Tellurium) account only for a very small fraction of the total material demand. In Table 1, the composition according to Ökopol 2004 for a thin-film PV system is given. It shows the highest amount of material to be glass, followed by the materials for the construction of the frame. Chemical elements only account for about 0.1% of the weight of a thin-film PV system.

The data for the material demand available vary significantly according to the different sources. In Table 2 and Table 3 show different values for the material demand for CIGS and CdTe modules from different sources.

Table 1: Composition of an Thin Film PV system (source Ökopol 2004)

material	% of weight
glas	74.53
frame	20.4
EVA	3.5
electrical equipment	1.1
chem. Elements	0.1

For the CIGS modules it can be seen that the results are clustering around two values: One dominant opinion in the literature calculates values for the Indium demand per square meter of about 3.5 g. This corresponds to about 25 g per kW. The second major tendency estimates values for the Indium demand of around 10 g/m^2. Phylipsen et al. give a bandwidth between these two groups and Angerer et al. (2010) suggests a value of 6.9 g/m^2 which is in between the two groups. Not all sources publish values for the Gallium demand and those that are given vary between 0.5 and 6.5 g/m^2.

Table 2: Comparison of different sources regarding the material demand for CIGS modules

Material demand for CIGS cells *

Source	Indium g/m²	Gallium g/m²	Conversion factor **** m²/kW	Indium g/kW	Gallium g/kW
McDonald and Pearce (2010)	**10.8**	**6.5**	7.27	*70.4*	*47.6*
Angerer et al. (2009)	*6.9*	*6.05*	7.27	**50.0**	**44.0**
Ökopol (2004) *	**10-15**		7.27	*73-109*	
U.S. Department of Energy (2010) **	*3.5*	*1.6*	7.27	**25.3**	**12.7**
VEECO	**3.2**	**0.8**	7.27	*23.0*	*5.5*
Iken (2010)	*3.6*		7.27	**26.0**	
Burnell	**3.0**	**0.5**	7.27	*21.8*	*3.6*
Phylipsen et al.	**2.9-9.8**		7.27	*21.1-71.3*	

* Total of CIGS-compound is given

** According to the U.S. Department of Energy (2010): *"about 4 tonnes of indium and 2 tonnes of gallium were purchased to produce 158 MW CIGS cells in 2008"*

*** Bold values are taken from the literature; Italic values are converted using the given conversion factor

**** The conversion factor is calculated under the assumptions of a module efficiency of 12.5% and an global radiation of 1100 W/m²

The Tellurium demand given in different sources shows also two different characteristics. One group in the sources predicts a Tellurium content between 6.5 and 9.5 g/m^2. The assumption of a global radiation of 1100 W/m^2 and a cell efficiency of 9% yields a demand for Tellurium between 65.7 and 96.3 g/kW. The other group of sources anticipates a significantly higher resource demand between

25 to 28 g/m², corresponding to 253 to 279 g/kW. The lowest values can be found for the Tellurium demand in Angerer et al. (2010) with 50 g/kWp which is equal to 3.1 g/m². Only three studies consider the question of the demand for Cadmium. These vary between 9.1 and 22 g/m².

Table 3: Comparison of different sources regarding the material demand for CdTe modules

Material demand for CdTe cells ***

Source	Tellurium g/m²	Cadmium g/m²	Conversion factor **** m²/kW	Tellurium g/kW	Cadmium g/kW
McDonald and Pearce (2010)	**9.5**	**9.1**	10.10	*96.3*	*91.6*
Angerer et al. (2009)	**3.1**	**9.9**	10.10	**31.0**	**100.0**
U.S. Department of Energy (2010) *	*27.6*		10.10	**279.0**	
Wikipedia **	**25.0**	**22.0**	10.10	*252.5*	*222.2*
Iken (2010)		*9.9*	10.10		**100.0**
Burnell	**6.0**		10.10	*60.6*	
Phylipsen et al.	**6.5-8.8**		10.10	*65.7-88.9*	

* According to the U.S. Department of Energy (2010): *"about 100 tonnes of tellurium were purchased to produce 258 MW CdTe cells in 2008"*

** The losses during production process are not accounted. Due to the losses the material demand would rise for further 40%

*** Bold values are taken from the literature; Italic values are converted using the given conversion factor

**** The conversation factor is calculated under the assumptions of a module efficiency of 9% and and global radiation of 1100 W/m²

In order to produce the necessary compounds of elements and materials, different types of production processes are employed. In the case of CIGS for example we find ten different processes of production developed and applied by the different manufacturers in the year 2007 (Ullal and von Roedern, 2007). In these different production processes a different ratio of material is wasted. If using a sputter process, only 23% of the used material is actually attached to the surface of the solar cell. The remaining material is commonly recycled. On the other hand, using a wet-chemical electrodepositing process, almost 100% of the material is applied to the solar cell. Further about 1.4 g Indium solder is used for each square meter of CIGS cells (Angerer et al. 2010).

The losses in production are considered in the values given in Table 2 and Table 3.

An overall number for the demand of critical metals for the different thin-film technologies cannot be given, since the material demand varies significantly between the different manufacturers. The reason for this is the different thickness of the layers and the different production processes used. For the purpose of further calculations an Indium demand for CIGS is assumed at about 6.3 g/m² (a bit lower than the value given by Angerer et al. 2009) and for CdTe a Tellurium demand of 9.5 g/m^2 is assumed according to McDonald and Pearce (2009).

2.3 Lithium batteries for electrical vehicles

About 30% of the world energy demand is consumed in the transport sector. Growth rates indicate, that this share will even increase in the course of the next decades. Especially the emerging countries have dynamically increasing rates for energy used for transportation. According to one source we find these to be in non-OECD countries at 4.5% (2007), 7.3% (2008) and 3.2% (2009) (EIA 2010). The energy consumption in the transport sector relies heavily on oil-based liquid fuels. 93% of the energy consumed within the transport sector have been provided by oil products (see IEA Energy statistics www.iea.org). Therefore the increase of the energy demand arising in this field is the major driver for the increase in liquid oil based fuels demand. Finding a sustainable path for the future transportation systems and low carbon technologies for the transportation needs therefore is crucial for reducing the global emission levels of CO2.

Electrified vehicles promise to be one way to diminish the carbon output in the transport sector. Hybrid vehicles are seen as an important intermediate step in the transition from the conventional petrol driven cars to electrical vehicles. These hybrid vehicles combine combustion engines with electrical engines in a number of different ways. The hybrid technologies differ with regard to the degree in which they employ the electrical engine as well as the question in what operation phases of a vehicle (e.g. starting, driving) it is being used. Two main issues can be faced here: One is the question of how to increase the renewable electricity production in order to supply these vehicles with low carbon electricity. The other deals with the energy storage for the electrified or hybrid vehicles. This latter problem proves a major bottleneck needing to be solved to allow for a substantial market penetration.

The requirements for energy storage systems differ both for hybrid vehicles and for electrical vehicles. Table 4 produces an overview of the different requirements for the different types of electrified vehicles. A much higher energy amount is required for electric vehicles, if compared to the different types of hybrid vehicles, since the former class lacks a combustion engine. The range of a hybrid car is defined rather by the size of the petrol tank than by the energy storage capacity of the battery system. Also the amount of discharge power needed is higher for electric vehicles since the maximum power of the car is defined by the discharge power. The values for the different categories given by Köhler 2010 also point to significant differences among the cars available from the different companies. For example the Tesla Roadster has a much higher discharge power (power of engine: 225 kW) and a much higher energy content (about 45 kWh) as the values given in Table 4 for a conventional electric vehicle.

Table 4: Requirements for different types of electrified vehicles (source: Köhler 2010)

		Electric Vehicles	Full Hybrid*	Mild Hybrid**	Micro Hybrid***	Plug-in Hybrid****
voltage range	V	200-300	200-300	100-200	12-14	200-300
discharge power	kW	>50	>35	>15	>5	>40
charge power	kW	>15	>30	>15	-	>10
energy content	kWh	>20	1.5-2	0.7-1	0.5-1	>6

* The battery system is used in those phases where the combustion engine would be inefficient. Up to 40% of petrol can be saved

** Mainly during starting and driveaway the battery system is used. 15-20% petrol can be saved

*** The combustion engine stops when the vehicle is not driving and starts automatically.

**** The vehicle can be charged via the electricity grid like the full electric vehicle. By low charge of the battery system the vehicle can be driven by the combustion engine.

2.3.1 Technology overview

Energy storage systems can be grouped according to the form of energy stored:

- thermal energy storage: e.g. a seasonal hot water storage system,
- chemical energy storage: e. g. hydrogen or biofuels,
- mechanic energy storage: either kinetic (e.g. flywheel) or potential energy (e.g. pumped storage, compressed air),
- electrochemical energy storage: e.g. batteries, fuel cells, flow batteries (e.g. redox flow batteries),
- electrical energy storage: e.g. capacitor or supercapacitor, superconducting magnetic energy storage.

According to their different characteristics (regarding costs, lifetime, storage duration, energy storage energy) these systems are use for a wide range of applications.

In the case of electrical vehicles mainly chemical and electrochemical energy storage systems can be found, which are either already being applied or being currently developed.

Different electrochemical energy storage technologies are available on the market. A lot of them are used in different applications. The variety range of battery systems is large since they are needed in many different applications (e.g. tools, mobile phones, household, renewable energies in isolated systems,...) which havewith different requirements on the battery system. In the beginning of the development of electrical cars, battery systems based on lead Lead have been used. However, due to their low energy density, the Lead battery has been redeemed superseded by Lithium Ion batteries.

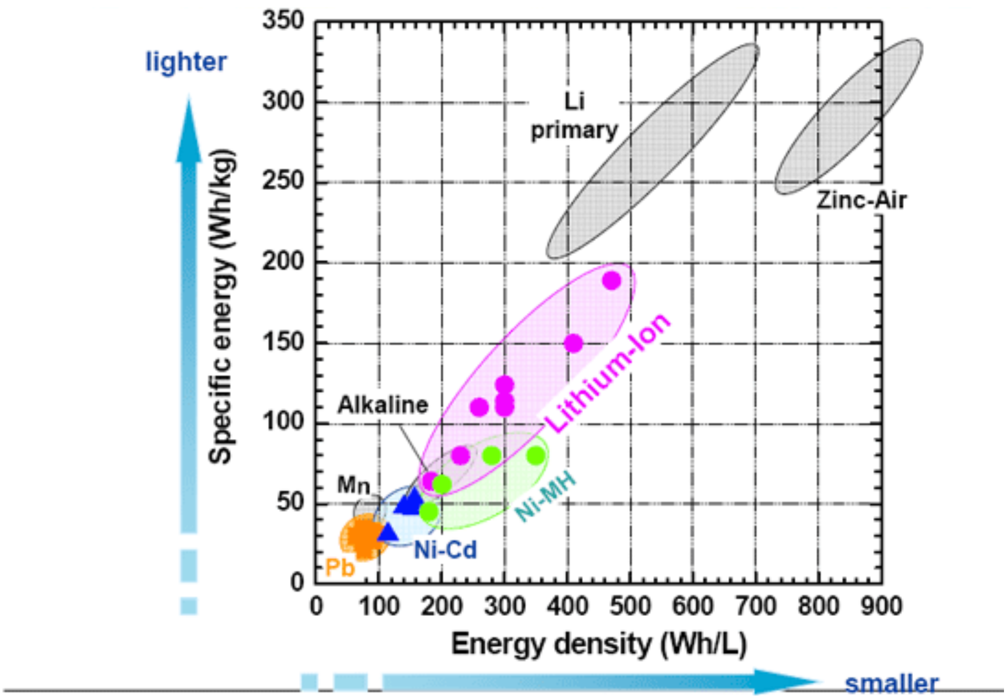

Figure 6: Energy density of various batteries (source: Leonardo Energy)

Figure 6 shows the energy density and specific energy of different battery systems. A higher amount of specific energy means firstly that the weight of the battery and therefore also that of the car itself can be reduced and secondly that the volume of the battery is lower. As shown in Figure 6 these two values are correlated. For lead batteries the lowest values are given. Since volume and maximum weight for the battery system in cars is limited by the construction pattern and because of the energy required for any additional weight, the shift from Lead to Lithium Ion batteries is reasonable. For the time being Lithium-based batteries are the most promising energy storage system for electrical vehicles. The following discussion of the vulnerability of this technology arising from the limited availability of the materials will focus on Lithium Ion batteries. But before that the next chapter will introduce briefly the working of such batteries.

2.3.2 Lithium Ion batteries

Figure 7 shows the principal functionality of a Lithium Ion battery. It is constructed with a positive electrode (cathode), made of a metal oxide, and a negative electrode (anode), usually made of graphite. For both cathode and anode it is crucial that they allow the unencumbered moving of the Lithium into and from them. The electrolyte consists of an organic solvent mixed with Lithium salt. During discharge, the Lithium ions, which are embedded in the anode, are set free and migrate through the electrolyte into the metal oxide. For each Lithium-atom six carbon-atoms are needed. For the cathode, different materials can be used, which are defining both the current and the capacity of the battery. Cobalt, Manganese, Iron phosphate and Nickel can be used to provide the base for the metal oxide for the cathode. So far it has not been established which system is the most appropriate for the usage in electrical vehicles. Current research focuses on increasing the capacity of Lithium ion batteries.

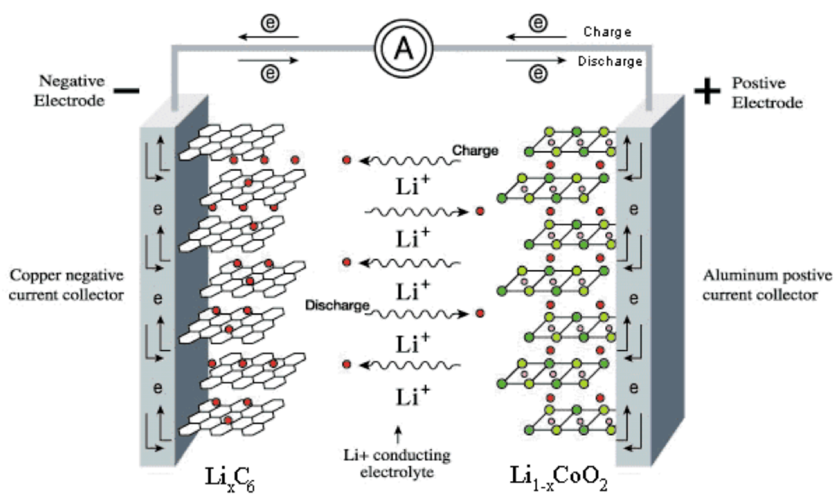

Figure 7: Principal functionality of a Lithium Ion Battery (source: Angerer et al. 2009)

2.3.3 Material demand

Table 6 shows the amount of Lithium required for the production of Lithium ion batteries. The demand differs depending on the different materials used for the cathode. According to the Zentrum für Sonnenenergie- und Wasserstoff-Forschung and to Angerer the lower bound for the Lithium demand lies between 100 and 120 g/kWh and the upper one between 150 and 180 g/kWh.

Gaines and Nelson (2010) predict a much wider scope for the Lithium demand with 113-433 g/kWh. Here we find the highest amount of Lithium required for a battery with an anode consisting of a compound containing Lithium (Li4Ti5O4). In the case of the others the anode is based on graphite.

Table 5: Lithium demand for batteries

Material demand for Lithium Ion batteries

Source	Lithium g/kWh
ZSW (2010)	**100 - 150**
Angerer et al (2009)	**120 - 180***
Gaines and Nelson (2010)	**113 - 423****

* 120 g/kWh is given for systems using iron-phosphate for the cathode and 180 g/kWh is given for systems using cobalt oxide.

** The values are calculated for four different battery chemistries based on different electrodes systems: Lithium-Nickel-Cobalt-Aluminium Cathode; Lithium-Iron-Phosphate Chathode; Lithium-Manganese Cathode (once with a Graphite anode and once with a Lithium-Titanate salt). Also different battery sizes for different vehicle ranges have been analysed (4, 20, 40 and 100 miles). The lithium demand differes only slightly among the different battery sizes, hower differ significantly among the different chemical systems.

No values dealing with the issue of losses of Lithium during the production processes have been found in the literature. Therefore the diagrams contain a certain degree of uncertainty. The following calculation assumes a Lithium demand of 150 g/kWh.

An average electrical vehicle with an energy capacity of 20 kW/h (distance range of about 100 km) would need about 3 kg of Lithium for the battery system. For plug-in hybrid cars with an energy content of 6 kW/h a Lithium demand of 0.9 kg is assumed and for hybrid cars with a energy content of 1.5 kW/h the Lithium demand is assumed to be 0.225 kg.

3 Materials

3.1 Introduction

In the following chapter for the elemtes Indium, Tellurium and Lithium a brief overview of the charcteristics will be given. Further the available production and reserves are shown as well as some recent market developments which may change the near future demand for the elements.

3.2 Indium

3.2.1 Characteristics

Indium (In) has the atomic number 49. It is a crystalline, silver-white metal, which is soft and can be cut with a knife. Indium is the fourth element of the boron group, very rare and does not occur reclusively. The melting point is very low at 429.75 K, whereas the boiling point is relatively high at 2353.15 K. The Indium concentration of the earth crust is estimated to be about 0.05 ppm (parts per million) for the continental and 0.072 ppm for the oceanic earth crust. Therefore Indium has a scarcity comparable to that of silver. Since Indium only occurs in combination with other materials, the most important minerals for the production of Indium are sphalerite, tin ores and zinc ores. The highest concentration at which Indium can be found is about 1% (see Angerer 2010, UNEP 2009 and Rutherford Online-Lexicon).

3.2.2 Production and Reserves

The production of Indium concentrates mainly on the recovery of Indium unearthed as a by-product of during Zinc-mining. Therefore most data on the availability of Indium are based on data on the content of Indium in Zinc ores (Angerer 2010). The source most often cited for the availability of Indium is the US Geological Survey. According to data from the US Geological Survey 2007, 2008 and 2010, the production of Indium rose between 2005 and 2009 from 480 to 600 t (+25%). The production of the US is not included. According to the US Geological Survey 2010:

"[...] Indium was not recovered from ores in the United States in 2009. Indium-containing zinc concentrates produced in Alaska were exported to Canada for processing. Two companies, one in New York and the other in Rhode Island, produced indium metal and indium products by upgrading lower grade imported indium metal." US Geological Survey 2010 (p. 78.)

Figure 8 shows that China accounts for half of the global production of Indium. If the other two main producers Japan and Korea are added, it means that 75% of the global production are currently obtained in Asia.

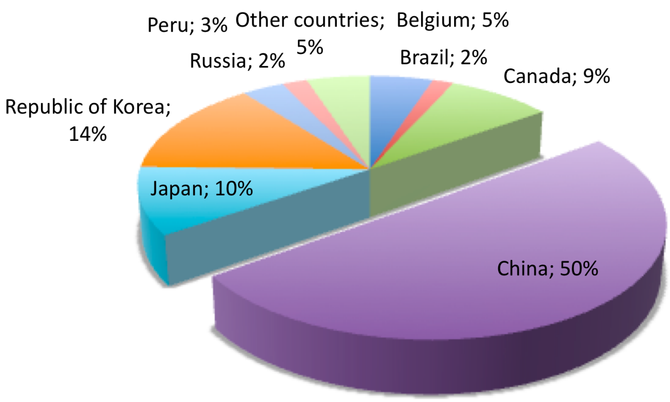

Figure 8: Indium Production by country for the year 2009 (source: own illustration based on US Geological Survey 2010)

For the reserves the data available have do not possess the same quality as those for production. Since 2009 the US Geological Survey does no longer has ceased to publishes data for the Indium reserves. One reason might be the insecurity of the used sources. According to the US Geological Survey 2008 the reserves amount for to 11,000 t and the reserve base for to 16,000 t.

The difference between reserves and reserve base is, that the reserves only include reserves which

"[…] could be economically extracted or produced at the time of determination",

whereas the reserve base is defined as

"[...] the in-place demonstrated (measured plus indicated) resource from which serves are estimated. 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)" (US Geological Survey 2010, p. 189).

The comparison of the data of the US Geological Survey 2007 and 2008 shows that the reserves have increased substantially in the course these years. A big change in the data occurred between 2006 and 2007. The reserves increased from 2,800 t to 11,000 t and the reserve base from 6,000 t to 16,000 t. The main changes in the reserves data apply to China (increase from 1,000 to 8,000 t), to the aggregate "other countries" (increase from 800 to 1,800 t) and to Canada (decrease from 1,000 to 150 t). These changes in the database indicate that the data have to be used with caution.

Figure 9 shows the reserves for the different countries. China accounts for 75% of total reserves of Indium. The next biggest reserves (360 t) are located in Peru.

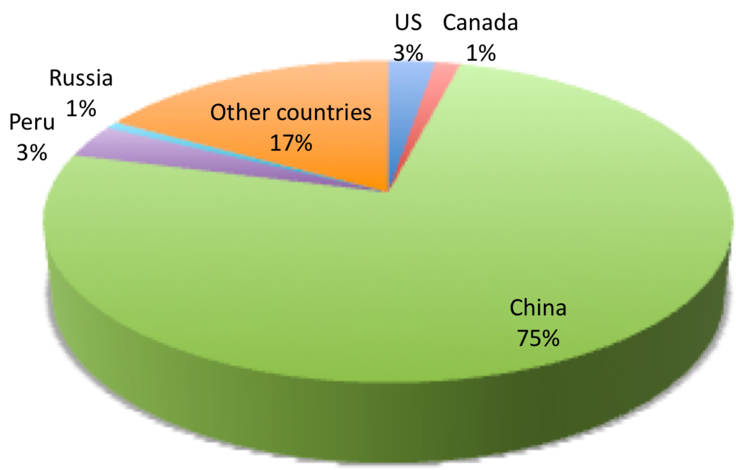

Figure 9: Indium Reserves by country for the year 2007 (source: own illustration based on US Geological Survey 2008)

Candelise, Spiers and Gross (2011) give an overview of the Indium and Tellurium availability extracted from different studies. Most of these use the US Geological Survey as database, but they calculate different potentials for Indium and Tellurium by including other data. As shown in Table 6 the availability of Indium differs between 625 and 6,000 t

The Indium Cooperation has also surveyed the reserves of the metals. They conclude that about 50,000 t of Indium is available as well as enough Indium required for the introduction of the new technologies (Mikolajczak 2009).

Table 6: Summary of Indium data and assumptions in literature (Candelise, Spiers and Gross 2011)

Paper	Data	Assumed indium availability (tonnes)	Assumed tellurium availability (tonnes)
Andersson *et al* (1998)	Crowson (1992)	*Cumulative:* 2,153	*Cumulative:* 21,818
Andersson (2000)	USGS MCS (1998); Harrower (1998); Crowson (1994)	*Annual:* 290 *Cumulative:* 2,600	*Annual:* 290 *Cumulative:* 20,000
Keshner and Arya (2004)	USGS MCS (2004)	*Annual:* 26,143[a]	*Annual:* 2,000[a]
Feltrin and Freundlich (2008)	USGS MCS (2005)	*Cumulative:* 625[b]	*Cumulative:* 5,250[b]
Fthenakis (2009)	Green (2006); Ojebuoboh (2008); Menzie (2006); Kapur (2005); Ayres *et al* (2002); Tilton *et al* (2007); Gordon *et al* (2006); USGS MY (2006)	*Annual:* 1,412[c]	*Annual:* 797[c]
Wadia *et al* (2009)	USGS MCS (2007)	*Annual:* 588 *Cumulative:* 6000	*Annual:* 128[d] *Cumulative:* 47,000

Notes:
a Authors estimate of potential future production based on crustal abundance.
b Figure based on 25% of reported reserves.
c Production in 2020 based on a scenario forecast of future material supply to 2075. Does not include recycled metal.
d Does not include US production.

3.2.3 Market developments

Indium is used for various applications. The main usage is as ITO (Indium Thin Oxid) for which 84% of the Indium in the year 2007 has been appropriated. Other applications are usages in alloys or for soldering (8%), as semiconductors and in electrical components (2%), for research and development (1%) and in other compounds (5%) (Angerer 2010).

ITO has quite a few excellent properties, which explain why the demand for the element has risen so sharply in recent years. ITO is condictable, but still transparent and is used for the production of liquid crystal displays (LCD), organic light emitting diode (OLED)-displays or plasma displays (PDP). The specific demand for Indium in these different fields varies between 0.4 g/m^2 (LCD), 0.02 g/m^2 (OLED) and 0.009 g/m^2 (PDP).

Indium and its derivatives are not only integral to the production of TV screens, but furthermore the element is required for screens for notebooks, smart phones, table- and tablet computers. In the last decade these consumer products have become very popular and therefore the market volume has risen enormously. For the future this trend is assumed to continue. Angerer (2010) published the following sales figures for 2006:

50.5 Million LCD's- and 11.1 PDP's for screens larger than 10 inches, and 3.6 billion LCD and 36 Million OLED-displays and for screens smaller than 10 inches.

Angerer has also made a rough estimate for the market in the year 2030. According to him the amount of sold units will increase from about 3.9 billion to somewhere between 6.2 and 9.8 billion. As the demand for Indium depends heavily on the different display technologies chosen, the future ITO demand will also be determined by the development of the market share of each display technology. Taking into account that not only the units sold will increase but also the size of the units, a huge demand increase for ITO can be expected.

Overall Angerer et al. expect an increase in the demand for Indium from 234 t (2006) to 1,911 t (2030) – which means that the annual growth rate for the Indium demand is about 9.1%. Comparing this future demand with the current production of about 600 t per year leads to the conclusion that the production capacity has to increase by about 300%.

The price for 1 kg Indium is about 700 $/kg (www.metalprices.com). Looking at data from previous years reveals that prices were low (between 100 and 300 $/kg) in the years 1995 to 2002. Then prices rose to 1,000 $/kg in the year 2005. After this peak they fell steadily until 2010. From then on the price has risen again from about 300 to 700 $/kg (see Figure 10 for prices from 2006 to 2011).

The price volatility is caused by a various factors. Economic growth, especially in China and India, has led to an overall price increase for raw materials. The price jump from 2002 to 2005 is related to a massive expansion of the ITO production and the growing concerns about the availability of Indium. Due to increases in production capacities the prices decreased and dropped after the start of the financial crisis in the year 2007. Further reasons for price volatility are the insecurity of supply data and speculation. A recent event which caused a price increase from about 550 to 700 $/kg was the announcement of China to reduce the export of Indium significantly. Since China keeps 75% of the Indium resources, changes in the Chinese export policy play a decisive role in the formation of prices.

On the May, 25th 2011 the price for Indium (ingots) was between 800 (low) and 870 (high) $/kg.

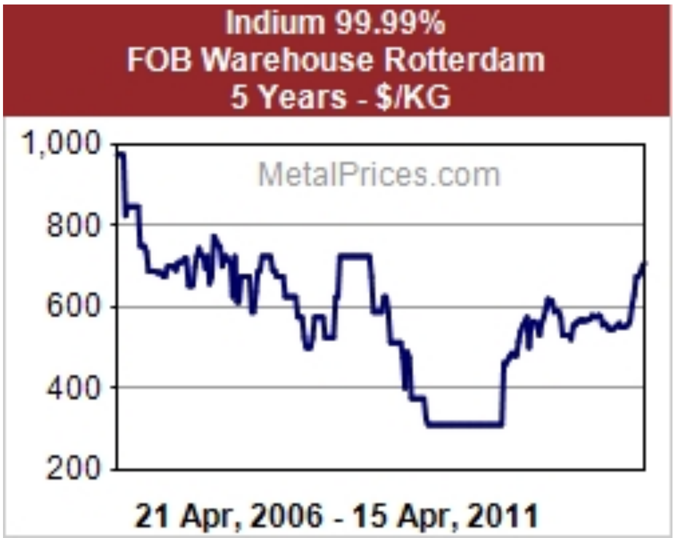

Figure 10: Indium prices 2006 to 2011 (source: metalprices.com)

3.3 Tellurium

3.3.1 Characteristics

Tellurium (Te) has the atomic number 52. Two different appearances of Tellurium with different characteristics are known. One is a silver-metallic brittle crystal and the second is a brown amorphous powder. The Tellurium concentration in the earth crust is about 0.01 ppm (see Rutherford Online Lexikon). Although tellurium occurs reclusively the main production of Tellurium is from anode slimes collected from electrolytic copper refining together with selenium (UNEP 2009).

3.3.2 Production and Reserves

Tellurium is mainly (about 90%) produced as a byproduct of the Copper refining and smelting process. The remaining share is

"[…] derived from skimming's at lead refineries and from flue dusts and gases generated during the smelting of bismuth, copper, and lead ores" (US Geological Survey 2010).

Therefore the data about reserves and production are inevitably linked to theses processes. The data from the US Geological Survey 2010 show that data are available only for a few countries. Production data are only published for Canada (20 t), Japan (40 t) and Peru (30 t). According to an older survey from NREL (2009), the production of Tellurium in the year 1997 amounted to a quantity between 200 and 300 t. Furthermore the survey shows the potential Tellurium production is always linked to the quantities of electrolytic Copper and refined Lead that have been produced. The assumption that 50% of the contained Tellurium can be used, will yield an annual production of Tellurium of 859 t According to NREL (1999) the US and Chile had contributed 351 t to the annual production. The US Geological Survey contains no production figures for Tellurium for these countries. But it can be observe that the Copper production has increased significantly since 1999. This indicates, that the data calculated in 1999 possibly have to be adjusted upwards.

The US Geological Survey predicts global reserves adding up to 22,000 t. This value only includes the amounts of Tellurium that can be gathered as the byproduct from the production processes described above. However, there are also some mines known, where Tellurium could be obtained.

Figure 11 shows that the US accounts for about 14% of the reported reserves. The biggest share (73%) is split among the aggregate "other countries".

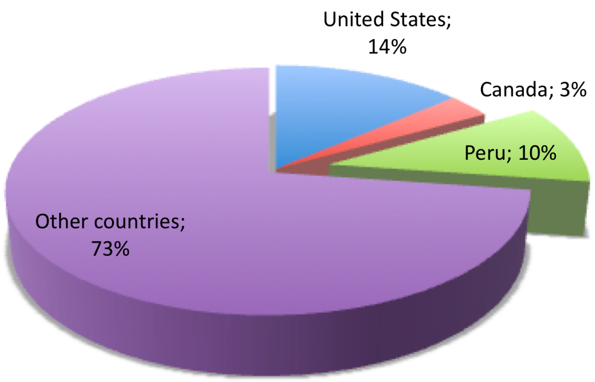

Figure 11: Tellurium Reserves by country for the year 2009 (source: own illustration based on US Geological Survey 2010)

Candelise, Spiers and Gross (2011) – see Table 6 – show that the predicted resources range between 5,250 and 47,000 t and the potential annual production ranges between 128 and 797 t.

3.3.3 Market developments

Tellurium is mainly used as an additive in the metallurgical alloying process. It is added to steel and Copper to improve the machining characteristics. And we find it furthermore employed in the production of Lead, cast Iron and malleable Iron. For the production of rubber, Tellurium is used as a catalyst. In the last years two new - rapidly growing - markets have triggered off an increased demand for Tellurium. It is now a substantial ingredient for memory media like CD-RW and for flash memory devices. And it is furthermore an important material for semiconductors in Thin-film PV systems. This increase in demand in conjunction with "rocketing" prices has led to Tellurium being substituted in some applications (especially in metallurgical alloying processes) by other materials in recent years. (US Geological Survey 2010, UNEP 2009.)

Reliable data for the current quantities of Tellurium on the market that would allow the calculation of future demands are not available due to reasons of secrecy. We can, however, observe that prices for Tellurium have risen significantly in the course of the last decades. On May 25th, 2011 it fetched between 360 and 450 $/kg.

3.4 Lithium

3.4.1 Characteristics

Lithium has the periodic number 3. It is a soft, silver-white metal that belongs to the alkali group and is also the most lightweight existing metal. The melting point is at 453.69 K and the boiling point at 1590 K. The Lithium concentration in the earth crust is about 60 ppm (see Rutherford Online Lexikon). Thus it cannot be classified as a rare earth metal.

Lithium occurs only as a compound in nature. In this form it is detectable in very small fractions in almost every eruptive rock. Approximately 150 minerals are known containing lithium. Important examples are petalite and spodumene (LiAlSi2O6). Spodumene concentrate is used for the production of Lithium carbonate.

Furthermore natural brines (e.g. in the Atacama desert in Chile) with contents of Lithium chloride are important sources for the Lithium industry (UNEP 2009, p. 47).

3.4.2 Production and Reserves

Since Lithium is a compound found in different minerals, there are different extraction processes. Lithium that is bound in Spodumene is the most economical source for Lithium production, because the Lithium concentration is very high. For the extraction of Lithium bound in brines, the brine - with a Lithium concentration of about 800 to 1000 ppm - runs through a cascade of bond systems. This process takes about 15 months. Due to the evaporation, the Lithium concentration increases to about 6%. From this saturated brine either Lithium carbonate, Lithium oxide or Lithium chloride can be processed (Aul and Krause 2010).

According to the US Geological Survey about 18,000 t of Lithium have been produced in the year 2009. The production data for the US are not included in this figure. The US produces only an insignificant amount of Lithium, but they are the largest importer of Lithium containing minerals and compounds and also the leading producer of value-added Lithium materials (US Geological Survey 2010). Chile (7,400 t) accounts for about 40% of the global production. Australia (4,400 t), China (2,300 t) and Argentina (2,200) are also major producers.

From 2008 to 2009 the production volumes decreased significantly from 25,400 to 18,000 t, which might indicate uncertainties in the data. Data on the predicted resources also saw considerable changes in the estimates. In the US Geological Survey 2009, reserves of 4,100,000 t for the year 2008 have been recorded. In the US Geological Survey 2010 reserves of 9,900,000 t are given for the year 2009. Australia has not reported data for the year 2008, but the biggest change are the revised data for Chile. The reserves increased from 3 millions to 7.5 million t. Figure 12 shows the distribution of the global Lithium reserves. The biggest share is accorded to Chile (about 75%). A new Lithium production seems to start in the near future in Austria. According to information from newspapers, in the region of Carinthia 18 million t of lithium ores with a Lithium content of 1.6% have been detected. This would yield 288,000 t of Lithium.

In the literature the values regarding the Lithium reserves vary significantly. Gruber and Medina (2010) compared the data regarding resources and reserves of Lithium.

The values for the resources vary between 19.2 and 64 million t and the data for the reserves between 4.6 and 39.4 million t. Differences result from different methods and assumptions, different opinions of the Lithium content of the ores and from different data used. Verified data regarding the resources and reserves are not available.

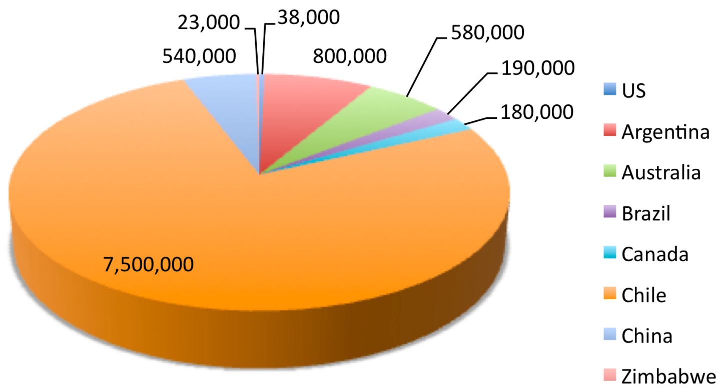

Figure 12: Lithium Reserves by country for the year 2009 (source: own illustration based on US Geological Survey 2010)

3.4.3 Market developments

About 23% of the global Lithium production goes into batteries. The biggest share of the Lithium demand is used for the production of ceramics and glass (adding Lithium in the production process reduces the melting point). Figure 13 shows the different sectors where a significant demand for Lithium can be discerned. Pharmaceutical appropriation of Lithium is subsumed under the category “others”.

Batteries based on Lithium have dominated the battery-market for several years. About 60% of all cell phones and 90% of all laptops use batteries employing this metal (UNEP 2009). Here also the biggest driver for the increasing demand for Lithium can be found, because the demand for electronic devices like cell phones and laptops increases yearly by about 7 to 12% (Zentrum für Sonnenenergie- und Wasserstoff-Forschung 2010).

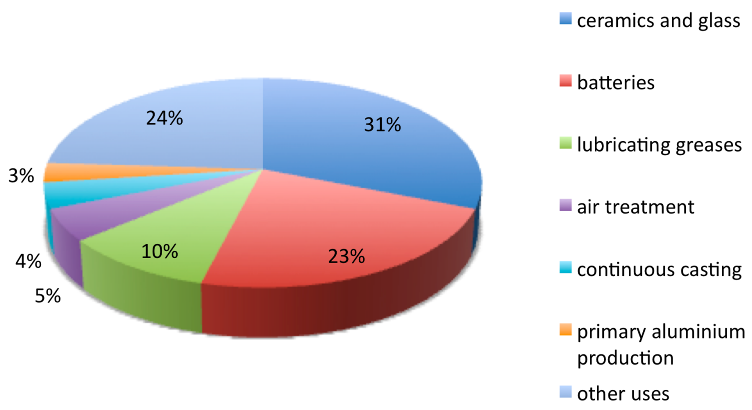

Figure 13: Demand for Lithium divided by sectros (source: own illustration based on US Geological Survey 2010)

According to a conference paper presentation offered by Edward R. Anderson, president of the TRU Group (see http://trugroup.com), Edward R. Anderson in January 2011, the annual growth in demand growth between 2002 and 2007 was between 7 and 8% (see http://trugroup.com/Lithium-Market-Conference.html). Apart from a decrease during the recession in the year 2009-2011 these growth rates are expected to continuous or even to increase thanks to a higher due to the increase usage of electrified vehicles. Also the Lithium demand, which is not linked to e-mobility, is expected to increase with a rate of 3-4% p.a. according to another expert (COO of the largest producer of Lithium carbonate: Sociedad Quimica y Mineral de Chile).

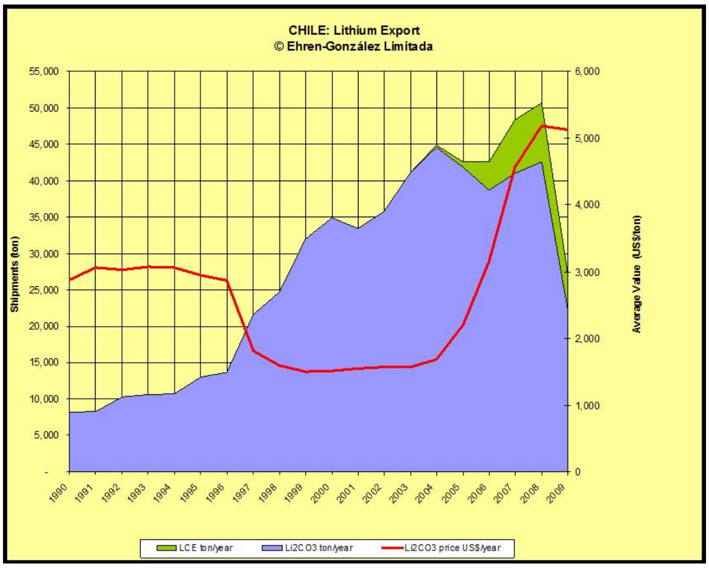

Figure 14: Export and price data for Lithium carbonate (source lithium-stocks.net)

Prices for Lithium vary among the different qualities, types and purity. Figure 14 shows the volumes of the Chilean export of Lithium (lithium hydroxide, lithium chloride and lithium chloride solution are given in lithium carbonate equivalents – LCE) as well as the average spot prices. Between 1990 and 1996 the prices where stable at about 3,000 $/ton. Due to an increase in production capacity in the following decade the prices fell to about 1,500 $/ton. But between 2005 and 2008 prices again were on the rise, because of the huge demand for Lithium for batteries. Then with the financial and economic crisis the prices dropped slightly in the year 2009. Today the spot price for Lithium is approximately 6,150 $/ton (lithium-stocks.net).

4 Scenarios

Scenarios and forecasts are used for example for policy advising, for the development of business strategies or in scientific works. The formulation of scenarios can be based on different methods. As the starting point often the historical development up to the present is taken. As the next step the forecasts for future trends are calculated by employing key drivers identified as crucial. Based on the assumptions regarding the development of these factors (e. g. by consulting experts) different scenarios for the future can be formulated.

The International Energy Outlook: IEA 2009 – published each year – is recognized as one of the key sources when it comes to data and predictions concerning the global energy demand. But there is a number of furtherreliable scenarios and forecasts at hand, e. g. the Shell energy scenarios (Shell 2008) or Energy [R]evolution (Greenpeace 2010). When interpreting these scenarios, it must be taken into account, that they are always based on different assumptions. These assumptions might reflect the view or the wishes of the different authors or the organizations commissioning the scenario when it comes to evaluating future prospects.

In this chapter the historical data for electricity consumption as well as for the mobility sector will be described. For future prospects of the anticipated demands in these two fields different scenarios will be introduced. Based on assumptions concerning the share of Thin-film PV and the usage of electrical vehicles different scenarios for the future demand for Lithium, Indium and Tellurium will be calculated.

4.1 Past and future electricity demand and the vehicle market

4.1.1 Electricity market

Electricity consumption has grown fast over the last decades. From 1980 to 2000 the global electricity consumption has almost doubled from 6,799 TWh to 12,642 TWh (IEA 2009). So it has increased with a rate of about 3.15% p.a. From then up to the year 2007 this factor has risen even further to about 3.8% p.a. So in that year it amounted to 16,429 TWh.

But this commodity is distributed very unequally across the world. The countries of the OECD consume about 56% of the total amount, although in terms of population these countries are inhabited by only 18.6% of the world population. But regional growth rates in the last years show significant differences as well. Whereas in the OECD the electricity consumption has only a moderate annual growth rate of about 1.6% the electricity consumption in Asia has doubled (with a growth rate of about 10.6% p.a.) between 2000 and 2007. It can observe that the lower income countries catching up with global big shots when it comes to the consumption of electricity.

The IEA World Energy Outlook (see Table 7) predicts a peak value for global electricity consumption for the year 2030 at 28,930 TWh. This means that the consumption will continue to increase by about 2.5% p.a. The IEA also formulated an alternative scenario – the 450 ppm-scenario, which anticipates the implementation of policy measures that result in a stabilization of the global GHG emissions concentration at the level of 450 ppm. This expertise calculates the consumption of electricity consumption in the year 2030 with an amount of 25,400 TWh. This means a growth rate of 1.9% p.a. If the prospects as foreseen by the IEA reference scenario are compared with the trend of the Greenpeace reference scenario it turns out, that the same growth rates with 2.5% p.a. has been assumed. The Energy R[evolution]-scenario assumes a significantly lower electricity consumption for the future. The annual growth rate in this scenario is about 1.65% and the total final electricity consumption is 25,829 TWh.

Table 7: Scenarios for the future electricity demand (source: IEA 2009, Greenpeace 2010)

	IEA World Energy outlook		IEA - 450 ppm scenario		Greenpeace Reference		Greenpeace r[evolution]	
	consumption [TWh]	growth % p.a.	consumption [TWh]	growth % p.a.	consumption [TWh]	growth % p.a.	consumption [TWh]	growth % p.a.
2007	16,429	2007-2030:	16,429	2007-2030:	17,734	2007-2030:	17,734	2007-2030:
2020		2.5%		2.5%	24,670	2.5%	22,642	1.65%
2030	28,930		25,400		31,277		25,829	
2050					42,672		31,404	

Since economic growth and that of the population show significant variations for the different regions in the world, also the regional annual growth rates for electricity display an uneven distribution across the world:

- OECD countries: 1.0%
- EU: 0.9%
- US: 0.9%
- Non OECD countries: 3.9%
- Asia: 4.7%
- Eastern Europe/Eurasia: 1.8%
- Africa: 3.1%
- Latin America: 2.2%

These values show, that very optimistic assumptions regarding the impact of energy efficiency and sufficiency on the growth rates for the future global electricity consumption are not very likely to be achieved. The biggest share of the growing demand for electricity results from countries that have presently a comparatively low demand for both energy and electricity (as well as a low GDP/per head) and they are striving for standards (and a GDP/per head) equaling that of the industrialized countries.

For the further calculation a electricity demand growth rate according to the IEA 2009 World energy outlook with 2.5% p.a. is assumed. Therefore the assumed electricity consumption in the year 2030 is 28,930 TWh.

4.1.2 Vehicle market

The global demand for transportation has been increasing for decades. Improvements in the transportation technologies – in terms of comfort, security and speed – have accelerated this development. People are able to lengthen the distances they have to overcome for getting to work, while working and for leisure activities. Schäfer (2006) singles out two key forces for the travel demand: the growth in per income per head and the population growth. Between 1950 and 2000 the global annual total distance traveled by all individual has increased from 3.6 to 33 billion kilometers.

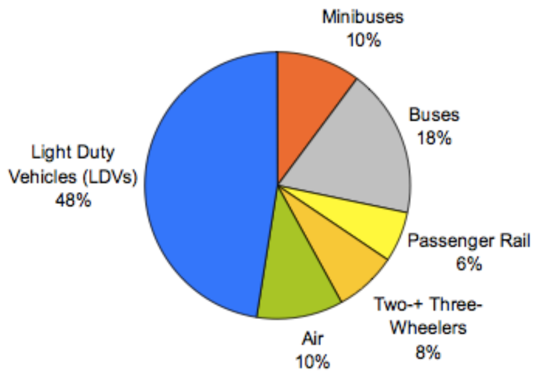

Figure 15: Current distribution of global transport (source: Gül and Turton 2009)

Schäfer (2006) has also shown, that in the course of time and economic progress, a shift in the means of transport can be observed: low-speed public transportation (the aggregate of buses and low-speed railways) is replaced by light-duty vehicles (automobiles and personal trucks, which for reasons of simplicity will be referred to as automobiles). This group in turn is superseded by high-speed modes of transportation (aircraft and high-speed rail). Figure 15 shows the current distribution of modes of transport (excluding non-motorized transport), 48% of which is covered by light duty vehicles. Only four decades ago, in 1971 transportation accounted for about 19% of the total production of greenhouse gas (GHG), but in 2006 this contribution had risen to 25% (Moriarty and Honnery 2008). And those are only proportional figures. This shift and the enormous increase in travel demand, which is assumed to continue, have a significant impact on the greenhouse gas emissions. The transport sector is becoming the biggest source for global greenhouse gases.

A good indicator for the development in the mobility sector is the figure of car ownership. The global average car ownership in 2003 was 114 cars per 1000 inhabitants, when about 715 million cars where used and the overall population was estimated to be 6.27 billion people. However, the distribution of the car ownership is of course very unequal. 65% of the global population live in countries, where the car ownership averages at 20 cars/1000 persons, 18.5% live in countries with 20 to 200 cars/1000 persons and 16.5% live in a country where more than 200 cars/1000 persons are registered (e.g. in the USA 777 cars per 1000 persons) (Moriarty and Honnery 2008). So this approach according to regions shows not only a crucial unevenness, but also the enormous size of the future car market and the consequences for the environment (e.g. greenhouse gases and toxic emissions), when assuming that all people are striving for a living standard like that of the industrial countries. Due to substantial rises in income in China and India above the level of mere sustenance, the market for cars in these countries is already increasing at a very rapid pace.

For the future demand Moriarty and Honnery (2008) formulate the following scenario for the year 2030:
"For 2030, the UN median projection for world population is 8.20 billion, and for 2050, 9.08 billion. Assume car owner- ship per 1000 world population reached an average of 300 in 2030 (which would allow most presently non-motorised coun-tries to attain a basic automobility level of 200 cars/1000 persons), and that the present average p-km/car remains unchanged. World cars would then total 2.46 billion. This projected 2030 value for both total cars and global car p-km is 3.44 times the present world total."

This projection means an annual growth both in passenger kilometers traveled and in registered cars of more than 5% p.a. for the next two decades.

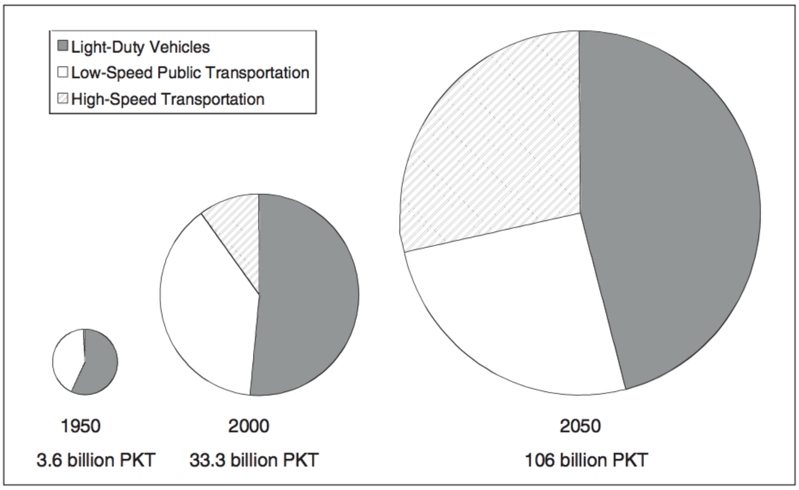

Figure 16: Global passenger-km traveled, by major mode of transport, in 1950, 2000, and 2050 (projected). (source: Schäfer 2006)

Schäfer (2006) estimates a much lower growth rate for the future travel demand until 2050. According to his prediction passenger kilometers traveled between 2000 and 2050 will increase from 33.3 billion to 106 billion km (see Figure 16). This would mean an annual growth rate of about 2.3% p.a.

Our further calculations will assume that the global car ownership increases from 715 million cars (2003) to about 1600 million cars (2030). This equals an annual growth rate of about 3% and it therefore falls in between the Schäfer's estimate and the values introduced by Moriarty and Honnery. Furthermore the growth of car ownership is expectedto continue between the years 2031 and 2050, but with a lower factor: So a decrease by 0.1% for each year has been calculated. This means by 2050 the growth rate is 1% p.a.

4.1.3 PV usage and thin-film PV usage

To what extent can renewable energy contribute to the future supply of electricity? This question is the subject of several studies. The key drivers regarding the contribution of PV in the energy system are:

- the cost of electricity produced by PV modules,
- the cost of electricity produced by other competitors (e.g. fossil based, nuclear, hydro power) and
- assumptions regarding the future energy and environmental policies (e.g. supporting schemes, cost of CO_2).

Constraints regarding the available roofs or suitable areas are taken into account by some studies that estimate the potential of PV. But the number of those studies calculating future trends for PV that consider the constraints with regard to the availability of resources to be even lower.

According to the IEA 2009 Reference scenario, the generation of electricity from PV sources will rise to 280 TWh until 2030. This equals an annual growth rate of about 19%. But still the share of PV in the total electricity consumption in 2030 will account only for about 1%. By then the installed capacity is predicted to amount to 200 GW.
The IEA 450 ppm-scenario is more optimistic, regarding the contribution of PV with the assumption of 525 TWh being generated by PV in the year 2030. This means an annual growth rate of about 24% and would result in a contribution of PV to the total electricity consumption of 2.1%. The Greenpeace scenario is based on the same values for the usage of PV as the one by the IEA. However, in the Greenpeace Energy [R]evolution scenario PV will generate 1,481 TWh electricity in the year 2030. This is the roughly the 2.8 fold amount of the PV usage assumed by

the IEA 450 ppm-scenario. Energy [R]evolution anticipates a share of electricity generated by PV at 5.1% of the total[1].

Peter and Lehmann (2010) develop two scenarios for the global future PV usage. In the high variant scenario the installed capacity of PV will increase from 11 GW by 2010 to 701 GW by 2030. The produced electricity amounts in 2030 to about 850 TWh. In the low variant scenario the installed capacity increases to 258 GW in 2030 and the produced electricity to about 380 TWh.

Values for the future electricity production from thin-film PV could not be found in the existing literature. Some sources indicate the estimated market share of thin-film PV in the whole PV market, as given in Figure 2.

In the course of a conference presentation Würth Solar published their interpretation of how the markets for PV will develop. According to this prediction the market share of thin-film PV increases until 2020 up to 30% and until 2030 to 40%.

Frankl et al. (2006) present three different scenarios regarding the PV usage, which try to estimate the different market shares for the different PV technologies: crystalline silicon, thin-film and novel devices. In two scenarios (very optimistic and optimistic) thin-film modules are seen to reach a market share of 45% by 2025, which then will decrease to 35% up to the year 2050. The pessimistic scenario anticipates that the market share for thin-film PV will reach only a 15% margin until 2025, but it will then increase to 45% until 2050.
These are the corresponding capacities of the installed thin-film PV systems:

- “very optimistic scenario”: 260 GW (2025) and 3,100 GW (2050)
- “optimistic scenario”: 190 GW (2025) and 840 GW (2050)
- “pessimistic scenario”: 30 GW (2025) and 240 GW (2050)

4.1.4 Electrical vehicle usage

The market share of electrical vehicles on the global market will depend on the prices for the vehicles and on the prices for electricity and fossil fuels. If compared

[1] The share of 5.1% regards the electricity consumption of the IEA reference scenario. Taking the electricity consumption of the Greenpeace [R]evolution scenario would result in an share of 5.7%.

to the PV market, the one for cars, however, is far more complex. Future market shares will hinge upon developing commercial concepts for charging infrastructures and new forms of ownership for electrical vehicles. Furthermore the purchasing of a car is still connected with intense emotions. And this will probably remain so. Therefore the success of electrical vehicles will also depend on good marketing strategies of the car manufacturers and whether the manufacturers can offer electrical vehicles that are meeting the requirements of the consumers. Policy measures that are accelerating the diffusion of the needed infrastructure (e.g. charging places) as well as supporting schemes for electrical vehicles will be needed.

Hacker et al. (2009) present an overview of a variety of different scenarios for the future market penetration of PHEV (Plug in Hybrid electrical vehicle) and EV (electrical vehicle). As it can be seen from Figure 17 their predicted market share for the year 2020 varies between 0% and 25% and between 8% and 50% for the year 2030. The anticipated distribution for 2050 predicted by the studies lies between 10% and 90%, yielding a variation of 80%.

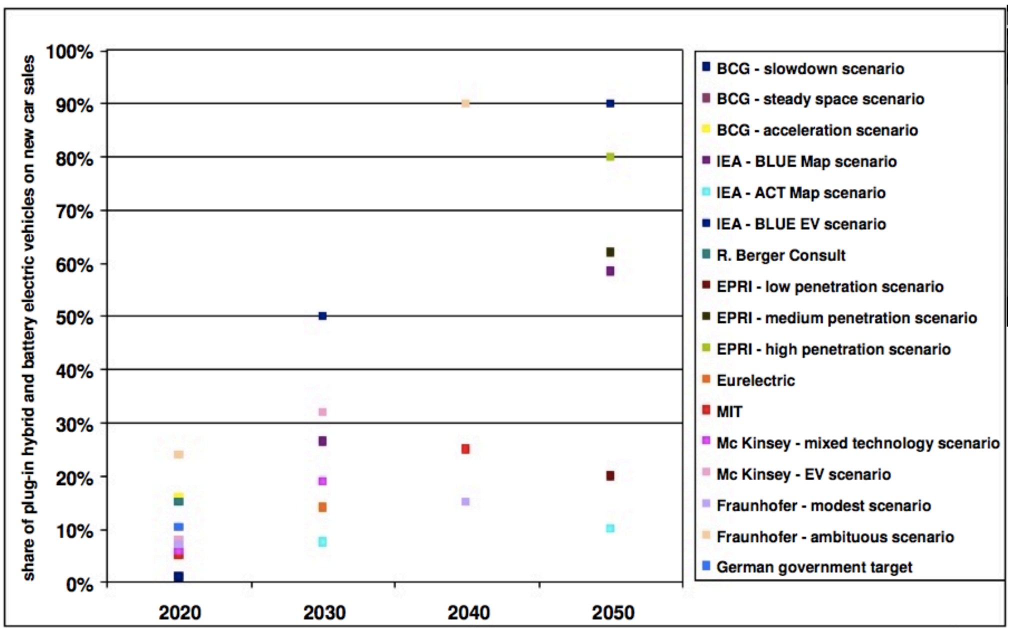

Figure 17: Market penetration scenarios – share of plug-in hybrid and battery electric vehicles on new car sales (source Hacker et al. 2009).

According to Pötscher et al. (2010) different consulting companies published estimates concerning the market for cars in 2020. Therefore the market share of EV and PHEV will amount to some 20%, 25% EV and 75% PHEV.

The Reference Scenario (see Figure 18) of the IEA foresees almost no sale of any electrical vehicles prior to the year 2030. The market share for hybrid vehicles would simultaneously amount to 7%. On the other hand the 450 ppm-scenario assesses the market share of hybrid vehicles around 30% between 2020 and 2030 and that of PHEV would increase to 12% in 2020 and to 21% in 2030. EV would reach a market share of 4% (2020) and 7% (2030).

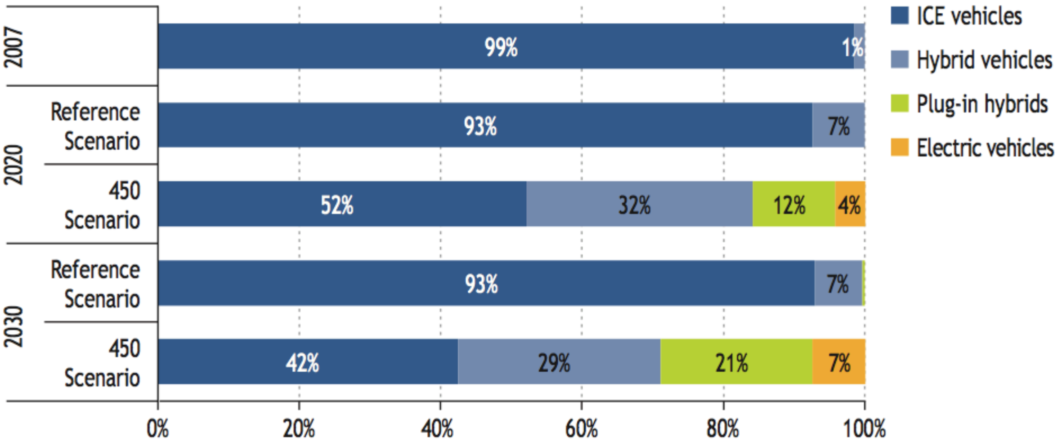

Figure 18: Share of global passenger vehicle sales by engine technology and scenario (source IEA 2009)

4.2 Scenarios for PV usage

4.2.1 Development of PV usage

Using the parameters of the scenarios described above, this study formulates three different scenarios concerning the development of the future PV usage. All of them are based on the assumption, that the global demand for electricity will grow at 2.5% per year.

- *Scenario A:* This scenario is mainly based on the reference scenario of the IEA. The growth rate for the electricity production from PV lies at 38% between 2010 and 2015. Between 2016 and 2020 this figure will decrease to 16.9% and then further diminish to 11.2% for the years 2021 to 2025. Then, from 2026 to 2030, electricity production from PV increases per year by 10.1%. From 2031 to 2050 the annual growth rate settles at 6%. The installed capacity does not increase with the same pace. Due to improvements in their efficiency, fewer modules have to be installed. With these assumptions the share of PV in the total electricity demand rises

to about 1% in 2030 and to 2% in 2050. If the total demand for electricity remained stable, the share of PV electricity production would be 1.6% in 2030 and 5.1% in 2050.
So this means that although the growth rates for PV are high during the entire period, the share of PV on the total electricity production remains moderate.

- *Scenario B:* This scenario follows the trends regarding PV usage predicted by the 450 ppm-scenario of the IEA. The assumed growth rates are 31.7% for the period between 2010 and 2020. Then, for the duration of the next decade an annual increase in PV production of 13.8% is assumed. After 2031 the growth rate stays constant at the level of 8%.
On the base of these more optimistic values for PV utilization, the share of electricity generated by PV systems amounts to 1.8% in 2030 and to 5% in 2050 of the total electricity production. If the global electricity consumption would settle on the level of 2010, the share of PV would be at 2.9% (2030) and at 13.9% (2050).

- *Scenario C:* This scenario utilizes the Greenpeace energy [R]evolution scenario. It predicts an enormous growth for PV usage between 2010 and 2020 with annual growth rates of about 47% (!). For the period from 2021 to 2030 this figure lowers to about 13%. And for the following two decades a growth rate of 5.8% is assumed. Even if this figure for the years between 2031 and 2050 is lower compared to scenarios A and B, the absolute numbers of the yearly increase in electricity production form PV predicted by scenario C still is much higher if compared to the other two.
In this very optimistic scenario the share of PV in the overall production of electricity would rise to 5.1% in 2030 and would reach 9.9% in 2050. If improvements in efficiency would stabilize the global electricity demand on the level of our current consumption, PV would, according to this scenario, then contribute 8.3% (2030) and 26.4% (2050) towards the global electricity production.

All these scenarios demonstrate that if a significant contribution of PV on the total electricity production is desired for the near future, huge efforts have to be undertaken in order to allow an increase of PV utilization of the magnitude developed by the Scenarios B or C.

Furthermore it can be seen, that energy efficiency is also a key for any system relying on the production of sustainable energies. A comparison of scenario A with the low PV usage growth rates and scenario C with much more optimistic predictions shows, that similar results regarding the share of PV can be achieved, if for scenario A a stable electricity demand is accepted and for scenario C the global electricity demand is assumed to grow by 2.5% p.a.

The capacity currently installed for the production of electricity from PV is almost negligible if compared with the future demands.

All three scenarios of the current study are based on the premise that the market share of thin-film PV systems on the total PV market starts at 18% and that this number will steadily rise to 45% until 2030. From then on for the duration of the next two decades it is anticipated to settle on this 45%-plateau. Within the market for thin-film PV systems it is assumed that one third will be covered by CIGS modules, one third by CdTe modules and the remaining third by other thin-film technologies.

As described in chapter 2.2.2 the demand for Indium per installed capacity for 1 GW is assumed to be about 45.7 t. For CdTe modules the Tellurium demand is calculated with 96 t/GW. No improvements in the productivity are being considered; therefore the material demand remains constant for the period evaluated by our scenarios.

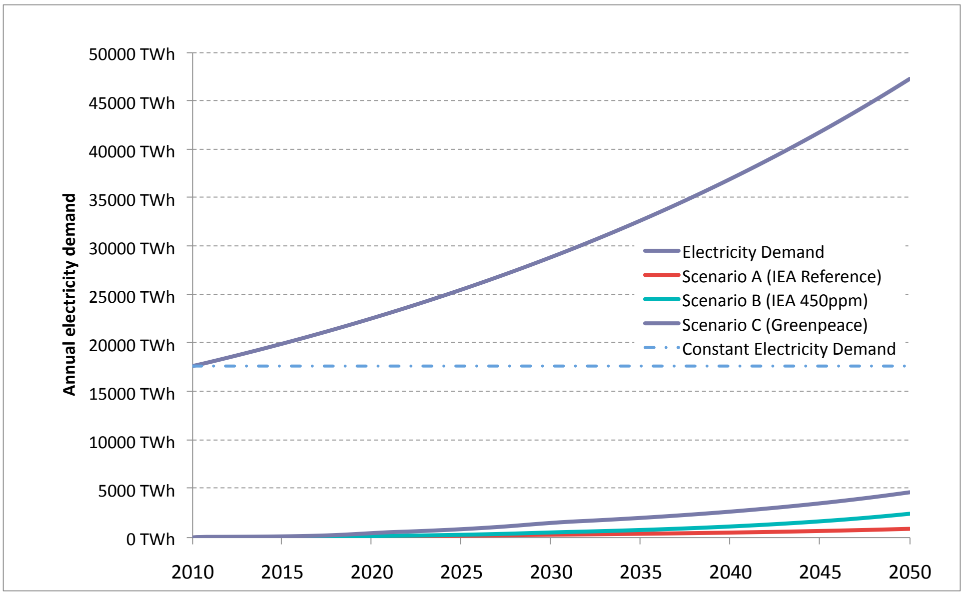

Figure 19: Electricity demand and electricity production from PV for scenario A, B and C (source: own illustration).

Figure 19 predicts increases in the electricity demand from 17,692 TWh (2010) to 22,623 TWh in the year 2020 and further increases to 28,929 TWh (2030) and to 47,301 TWh (2050). By that year electricity solely produced by means of PV will have risen to the following quantities:

- Scenario A predicts 905 TWh, with an installed capacity of about 640 GW,
- Scenario B predicts 2,460 TWh with an installed capacity of about 2,280 GW and
- Scenario C predicts 4,670 TWh with an installed capacity of about 4,330 GW.

The full load hours differ between the different scenarios and also change among the time. For Scenario A the average full load hours has been assumed with about 1400 h/a up from the year 2030. For the Scenario B and C the average full load hours are for this time period is assumed to be lower (1080 h/a). This takes into account that in a more optimistic scenario also regions with not so ideal solar radiations have to be used for electricity production from PV.

The other values concerning the electricity production by means of PV for the different scenarios can be seen in Appendix A.

Figure 20 shows two values: the capacity of thin-film PV modules by yearly installation and that of the total of the cumulated installed capacity. The discontinuity (e.g. for scenario C in the years 2020 and 2030) is caused by the changes in the growth rates in these years. This is in particular prominent in scenario C, since it assumes massive changes in the growth rates in the course of three years. To iron out this discontinuity the moving average of those three years for the calculation of the absolute installed capacities have been taken.

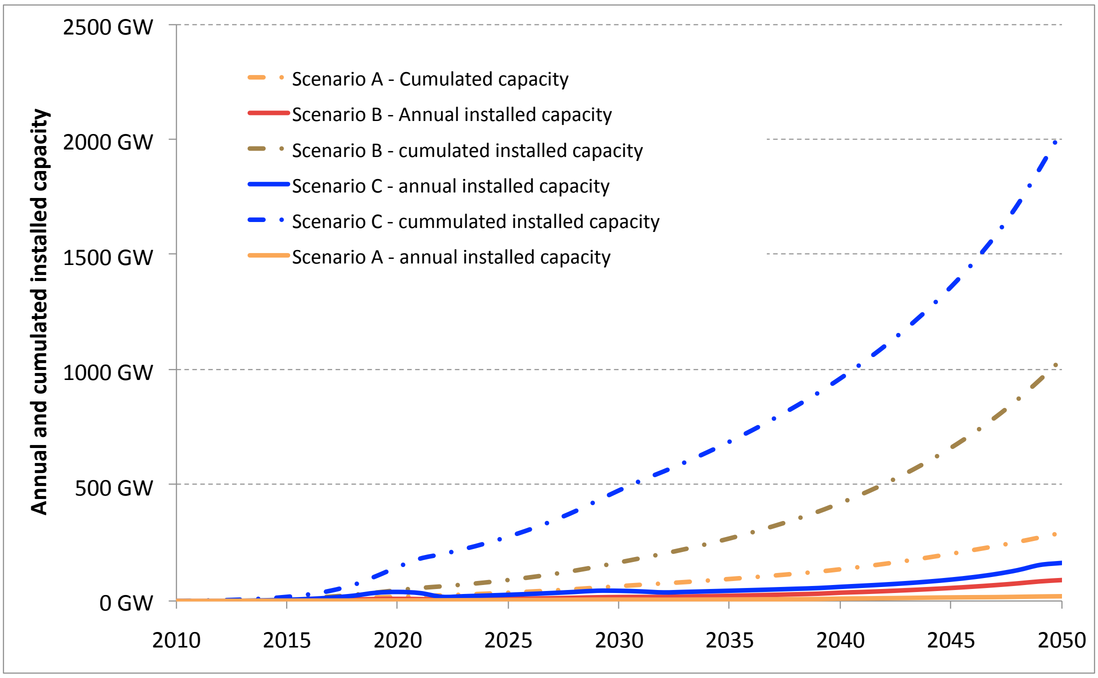

Figure 20: Yearly installed thin-film PV capacity and cumulated installed capacity for scenario A, B and C (source: own illustration)

The lifetime of PV modules is assumed to be 30 years. After the year 2040 the capacity installed annually also includes the replacement of PV modules older than 30 years.

4.2.2 Indium

Figure 21 presents the annual demand for Indium for thin-film production. Scenario A suggests a moderate increase in the demand for the element. In the year 2020 the demand is 44 t and that will rise to 100 t (2030), 160 t (2040) and 310 t (2050). For scenario B considerably higher amounts are required: 160 t in 2020, 280 t in 2030, 560 t in 2040 and 1,380 t in 2050. Scenario C predicts a demand for Indium at about 600 t in the year 2020 (but it will decrease in the following years for reasons of discontinuity outlined above). Nevertheless, according to it, about 700 t in 2030, 960 t in 2040 and 2,520 t in 2050 will be needed respectively.
USGS 2010 stated the figure of 600 t of Indium produced world wide in the year 2009. If we consider the demand for other products (see chapter 3.1.3) the demand for Indium for PV modules (according to scenarios A and B) will have no strong effects on the market for Indium. However, by the year 2050 the demand for Indium for thin-film PV production will require 50% of the actual Indium production (scenario A) or even be even twice as large as the current production of Indium (scenario B).

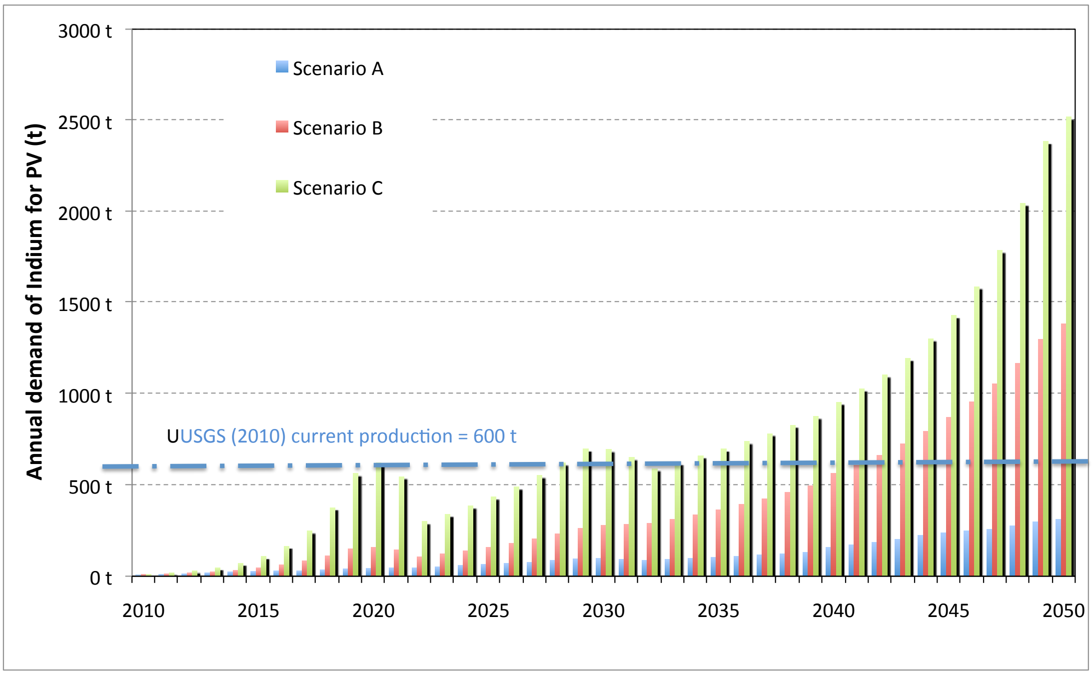

Figure 21: Annual demand of Indium for PV thin-film production for scenarios A, B and C (source: own illustration)

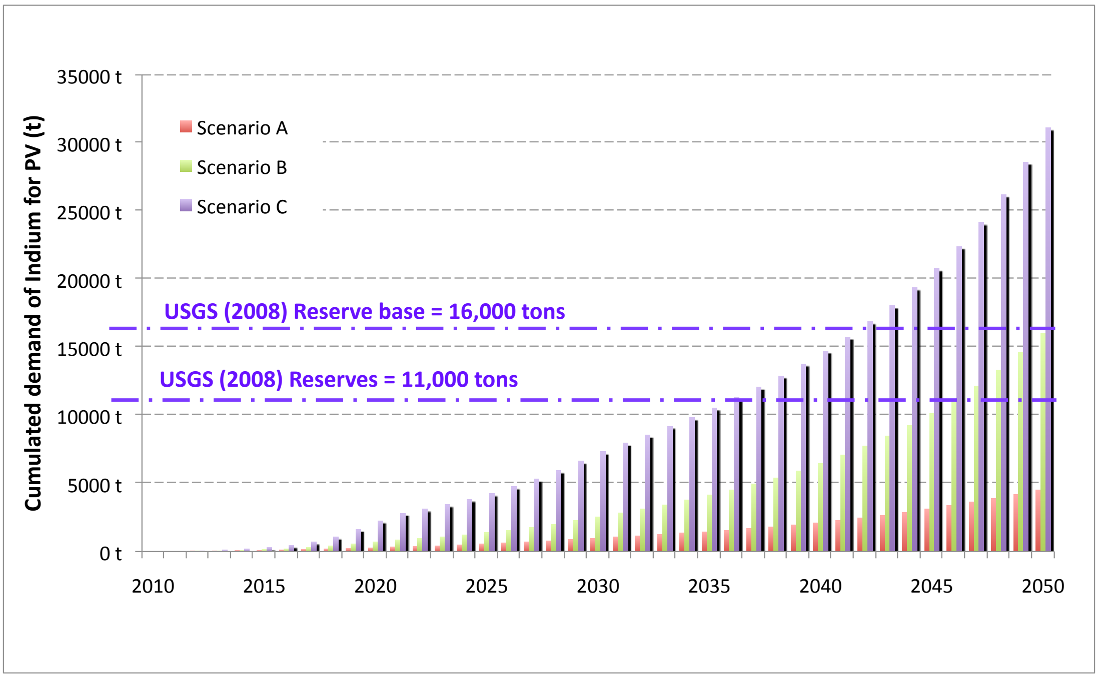

Figure 22: Cumulated demand of Indium for thin-film production for scenarios A, B and C (source: own illustration)

Figure 22 shows the cumulated demand for Indium for the period from 2010 to 2050. For the different scenarios the cumulated demand is:

- Scenario A: 980 t in 2030 and 4,520 t in 2050

- Scenario B: 2,550 t in 2030 and 16,010 t in 2050
- Scenario C: 7,330 t in 2030 and 31,130 t in 2050

By comparison scenario B requires about 3.5 times the amount of Indium that is requested in scenario A. Scenario C assumes an amount 6.9 times higher than that of scenario A.

Figure 22 shows both the indium reserves and the reserve base according to the USGS 2008. For scenario B the total amount of Indium available including to the reserve base will be needed to produce the PV systems until 2050. In scenario C the Indium necessary exceeds the available quantities as early as the year 2042. But as detailed in chapter 3.2.2 the prediction data for the reserves vary vastly between the different sources. If the quantity of Indium globally available is estimated at about 50.000 t (according to the sources of the Lithium Company), the demand for all scenarios up to the year 2050 can be met. However, if this prediction is taken, it means, that on the base of scenario C 62% of the global Indium reserves would have already been used for PV production until 2050. If one just briefly think that other sectors of industry could also require some Indium, it is very unclear, whether enough Indium will be available.

The diagram stating the cumulated Indium demand furthermore indicates the quantity of Indium stored in PV systems. Therefore the extraction of Indium from used PV panels might prove an invaluable source for future availability. However, in a short term perspective it must be seen, that until 2020 this question is of minor relevance (in particular for scenarios A and B). By 2020 only 1,8% (scenario A), 4,5% (scenario B) or 14,2% (scenario C) of the actual reserve base will have been used for thin-film PV systems.

4.2.3 Tellurium

A similar picture can be drawn for the demand for Tellurium:
Scenario A states the annual demand for that element (see Figure 23) at 90 t for 2020 and then at 200 t (2030), 340 t (2040) and 660 t (2050) respectively. Scenario B on the other hand already requests 330 t of Tellurium in the year 2020. This demand rises then to 590 t in the year 2030, to 1,180 t in 2040 and to 2,910 t in the year 2050. Scenario C assumes the highest demand for the material. By the year 2030 it predicts that 1,460 t will be needed, 2005 t in the year 2040 and 5,290 t in

2050. Since data for the current production of Tellurium could not be attained, the projected quantities needed in the different scenarios cannot compare with the actual realities.

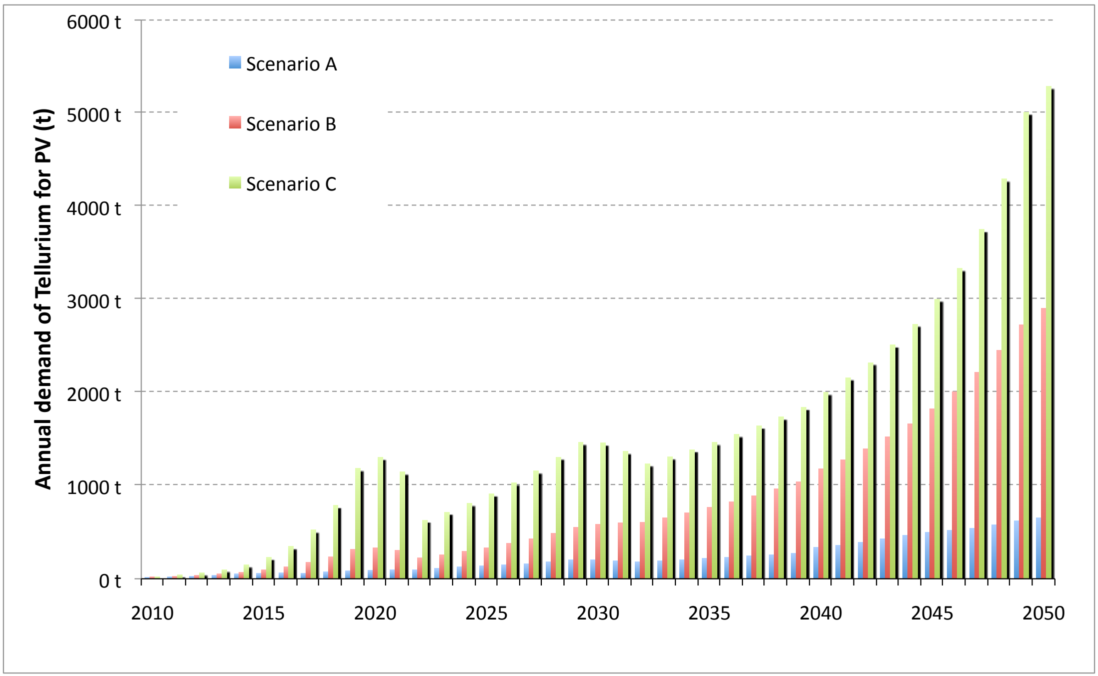

Figure 23: Annual demand of Tellurium for PV thin-film production for scenarios A, B and C (source: own illustration)

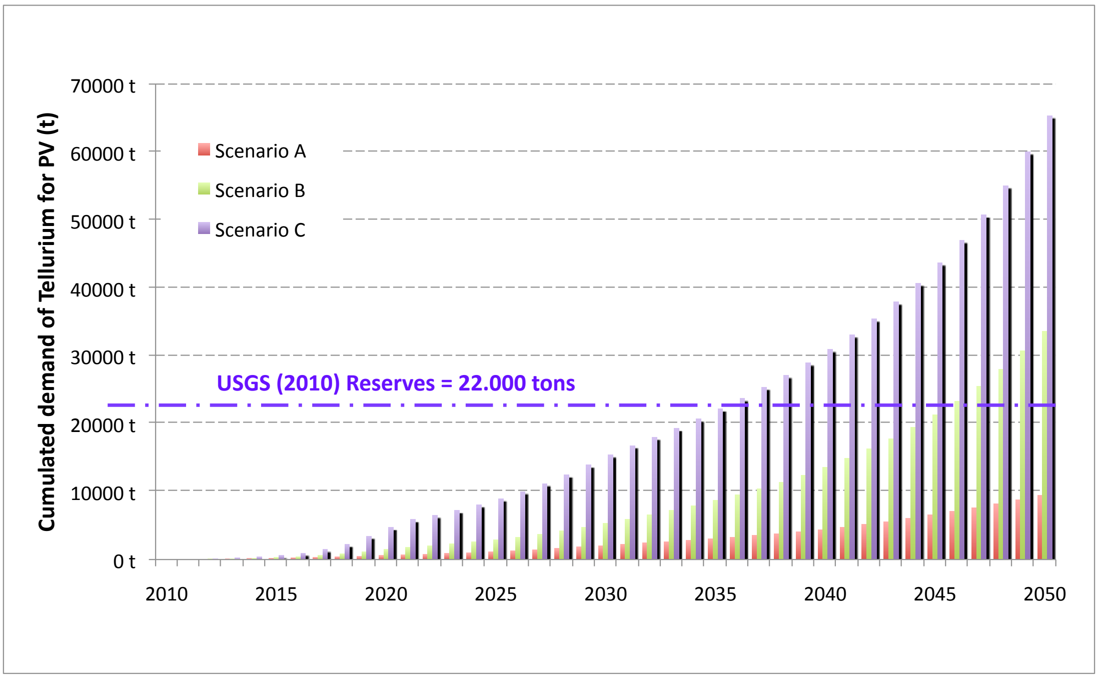

Figure 24: Cumulated demand of Tellurium for thin-film production for scenarios A, B and C (source: own illustration)

Table 8: Assumptions and Results from the scenarios I.

	years	2010	2015	2020	2025	2030	2035	2040	2045	2050
General assumption	grwoth rate electricity demand [%]	2,489	2,489	2,489	2,489	2,489	2,489	2,489	2,489	2,489
	global electricity demand [TWh]	17692	20006	22623	25582	28929	32713	36991	41830	47301
	growth rate car stock [unit]	3,025	3,025	3,025	3,025	3,025	2,5	2	1,5	1
	gloabl car stock [million units]	879	1021	1185	1375	1596	1823	2033	2212	2348
PV usage Scenario A	growth rate PV electricity production [1+%/100]	1,383	1,383	1,169	1,112	1,101	1,06	1,06	1,06	1,06
	PV electricity generation [TWh]	9,230	44,318	100,825	173,640	278,807	377,968	505,806	676,882	905,821
	growth rate installed PV capacity [1+%/100]	1,248	1,248	1,140	1,097	1,085	1,060	1,060	1,060	1,060
	Installed Capacity [GW]	14,343	42,187	82,707	132,605	198,875	268,263	358,996	480,418	642,907
	yearly installed capacity [GW]	3,000	7,380	9,227	11,292	14,203	15,185	23,321	34,574	45,618
	Market share thin film [%]	18,0	24,8	31,5	38,3	45,0	45,0	45,0	45,0	45,0
	yearly installed thin film PV [GW]	0,540	1,827	2,907	4,319	6,391	6,833	10,494	15,558	20,528
	cumulated installed thin fim PV [GW]	0,540	6,816	18,563	36,382	64,508	95,733	137,913	205,082	296,436
	yearly needed indium [t]	8,231	27,844	44,306	65,838	97,424	104,158	159,966	237,157	312,916
	cummulated Indium in PV stock [t]	8,231	103,901	282,956	554,583	983,311	1459,269	2102,226	3126,103	4518,635
	yearly needed Tellurium [t]	17,280	58,453	93,012	138,214	204,522	218,659	335,816	497,864	656,904
	cummulated Tellurium in PV stock [t]	17,280	218,119	594,010	1164,236	2064,265	3063,443	4413,202	6562,625	9485,967
PV usage Scenario B	growth rate electricity production [1+%/100]	1,317	1,317	1,317	1,138	1,138	1,080	1,080	1,080	1,080
	PV electricity generation [TWh]	9,145	36,290	137,467	276,265	518,525	775,546	1139,531	1674,345	2460,162
	growth rate installed PV capacity [1+%/100]	1,285	1,285	1,285	1,098	1,098	1,08	1,08	1,08	1,08
	Installed Capacity [GW]	15,643	54,747	182,301	306,842	486,079	718,078	1055,092	1550,276	2277,864
	yearly installed capacity [GW]	4,000	12,133	33,159	27,271	40,828	53,191	82,155	126,968	201,890
	Market share thin film [%]	18,0	24,8	31,5	38,3	45,0	45	45	45	45
	yearly installed thin film PV [GW]	0,720	3,003	10,445	10,431	18,373	23,936	36,970	57,136	90,850
	cumulated installed thin fim PV [GW]	0,720	9,600	46,986	91,266	167,469	271,868	425,324	665,754	1050,568
	yearly needed indium [t]	10,975	45,775	159,216	159,004	280,059	364,860	563,536	870,932	1384,848
	cummulated Indium in PV stock [t]	10,975	146,336	716,216	1391,188	2552,755	4144,133	6483,295	10148,212	16014,001
	yearly needed Tellurium [t]	23,040	96,094	334,239	333,793	587,921	765,942	1183,020	1828,328	2907,182
	cummulated Tellurium in PV stock [t]	23,040	307,201	1503,536	2920,491	5358,944	8699,688	13610,242	21303,922	33617,846
PV usage Scenario C	growth rate electricity production [1+%/100]	1,47071314	1,47071314	1,47071314	1,12981507	1,12981507	1,05826875	1,05826875	1,05826875	1,05826875
	PV electricity generation [TWh]	9,230	63,5099205	403,235777	816,988702	1472,26976	1998,23108	2652,31787	3520,50878	4672,49159
	growth rate installed PV capacity [1+%/100]									
	Installed Capacity [GW]	15,7872732	95,8116278	534,748061	907,414118	1380,14459	1850,16241	2455,78145	3259,63953	4326,26056
	yearly installed capacity [GW]	4	29,0086226	129,326264	74,5862275	101,332847	101,87077	139,216425	208,485834	367,186019
	Market share thin film [%]	18,0	24,8	31,5	38,3	45,0	45	45	45	45
	yearly installed thin film PV [GW]	0,720	7,180	40,738	28,529	45,600	45,842	62,647	93,819	165,234
	cumulated installed thin fim PV [GW]	0,720	19,104	148,738	280,433	481,164	692,672	967,000	1364,747	2042,248
	yearly needed indium [t]	10,975	109,442	620,979	434,881	695,093	698,782	954,955	1430,108	2518,712
	cummulated Indium in PV stock [t]	10,975	291,206	2267,255	4274,737	7334,539	10558,625	14740,307	20803,298	31130,668
	yearly needed Tellurium [t]	23,040	229,748	1303,607	912,935	1459,192	1466,938	2004,715	3002,193	5287,473
	cummulated Tellurium in PV stock [t]	23,040	611,321	4759,595	8973,855	15397,224	22165,474	30943,979	43671,874	65351,880

Figure 24 shows the cumulated demand for Tellurium. For the different scenarios the cumulated demand is:

- Scenario A: 2,060 t in 2030 and 9,490 t in 2050
- Scenario B: 5,360 t in 2030 and 33,620 t in 2050
- Scenario C: 15,400 t in 2030 and 65,350 t in 2050

Comparing these results with the reserves the USGS 2010 shows, scenario A does not predict any shortage of Tellurium. However, the demand foreseen by scenario B will have exhausted the reserves by the year 2046. According to scenario C this situation will already have to be faced in the year 2035.

4.3 Scenarios for electrical vehicles

Two scenarios dealing with the usage of electrical vehicles have been calculated. Both of them assume the car stock to increase yearly by about 3% for the years between 2003 and 2030. For the following two decades this figure is supposed to decrease steadily, until it will settle on a base of 1% in the year 2050. The lifetime of a car is assumed to be 13 years. The same span is accepted for both electrical vehicles and their batteries.

On the base of these premises the amount of vehicles sold per year has been calculated. This sum includes both cars to be replaced and cars actually increasing the global car stock. So all cars older than 13 years that have to be replaced will not be included in the calculation as a growth factor. Only those cars that have a new owner (or are the base for a new form of communal ownership) will contribute to the growth rates described above. [2].

In Figure 23 the annual numbers of vehicles sold can be seen. In the year 2010 about 70 million cars have been sold on the global market. This figure is seen to rise until 2050 to about 170 million units per year. Those cars replacing old ones will see an ever-growing number among the total of cars sold. And this share will even increase in the course of time, since the number of overall stock is growing steadily and therefore more older cars will have to be replaced in the future. If furthermore it is assumed that the growth rate of the car stock will be decreasing anyway, then the share of those cars sold per year that represent a genuine addition to the existing car stock is shrinking even more.

[2] If a average car runs 15,000 km per year, the cars (including the battery) have to be replaced after 200,000 km. With the assumed distance range of the battery of about 100 km this means that the battery has a life time of about 2,500 cycles if the battery is not emptied to more than 80% per each cycle.

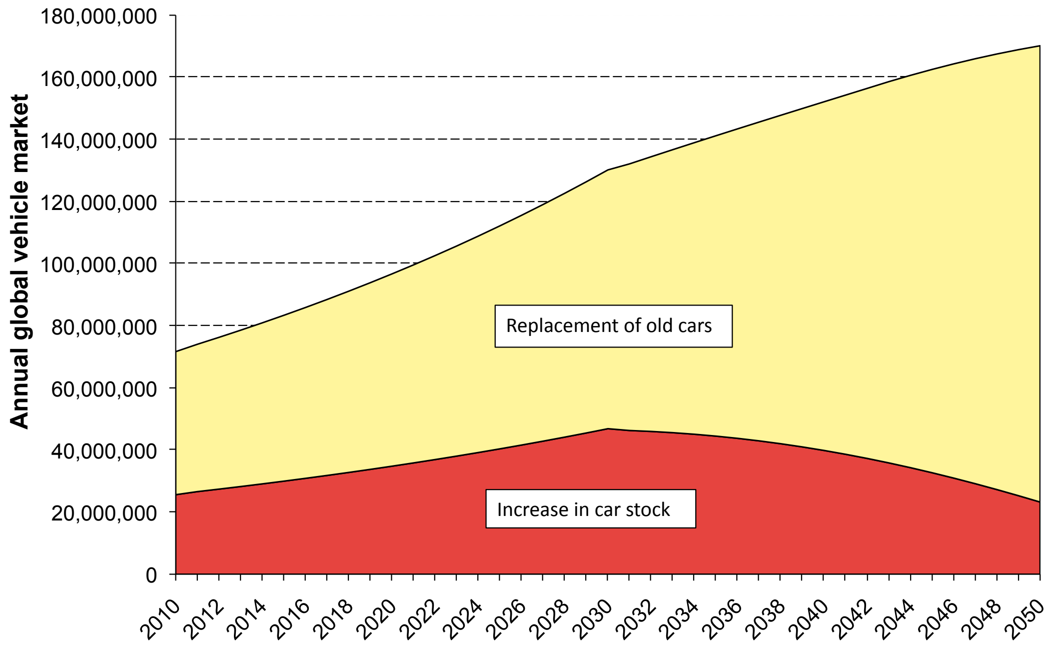

Figure 25: Composition of annual vehicle market

Despite these restrictions the global car market is still expected to grow significantly. The two formulated scenarios describe the possible future usage of electrical vehicles in terms of market share for EV's and PHEV's:

- *Scenario I:* The market share of EV's and PHEV's increases from 2010 to 2020 to 4% and rises further to 8% until 2030, to 15% in 2040 and to 20% in 2050. In the beginning this market share has 95% PHEV's and only 5% EV's. But this division changes steadily. By 2030 the ratio will be 75% to 25%. An even distribution of 50% both will have been achieved by 2040 and settle on this level for the following decade.

- *Scenario II:* The market share of EV's and PHEV's increases from 2010 to 2020 to 16%, climbing up to 28% by the year 2030, 34% in 2040 and 50% in 2050. The ratio of distribution between the two classes is assumed to be the same as for scenario I.

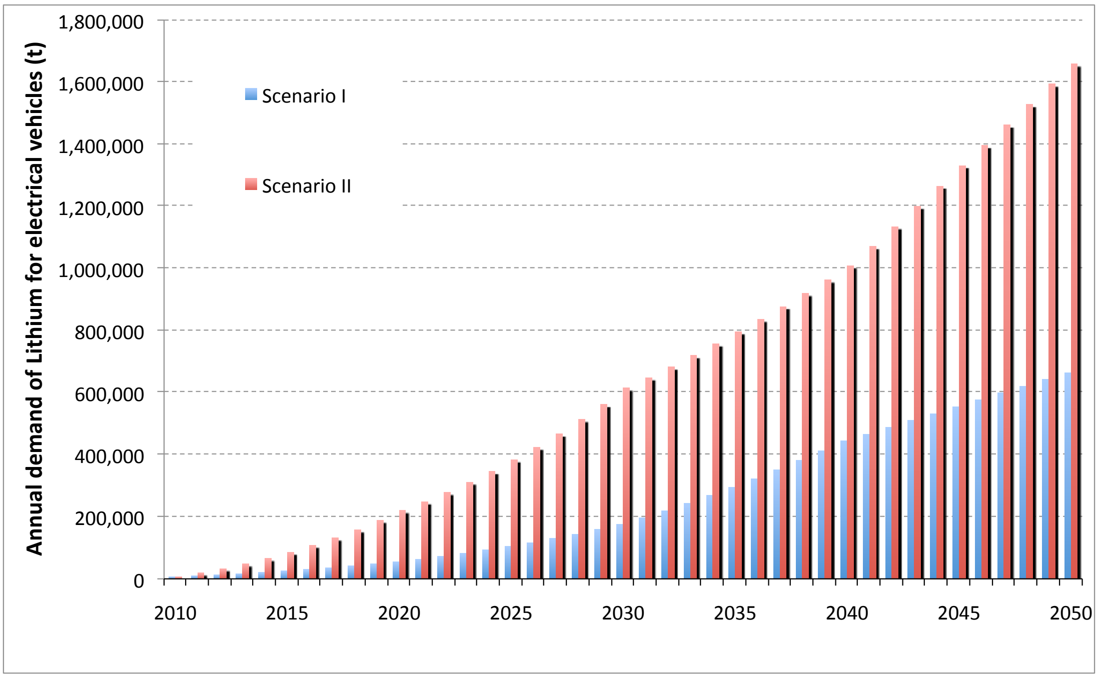

Figure 26: Annual demand for Lithium for the production of batteries for electrical vehicles for scenarios I and II (source: own illustration)

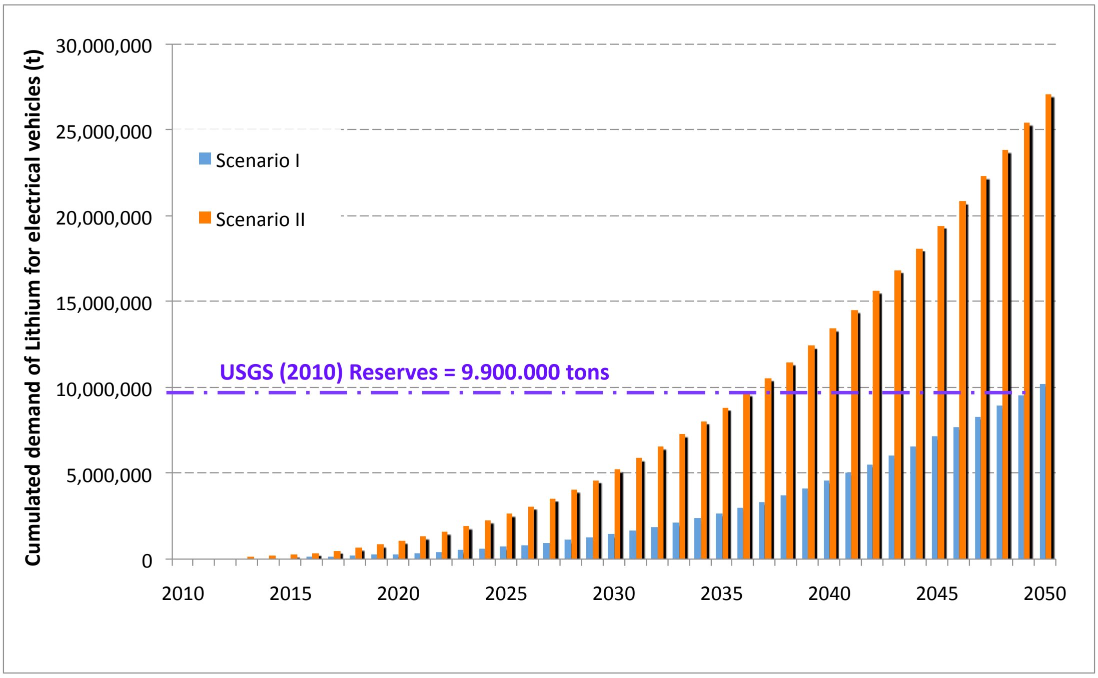

Figure 27: Cumulated demand for Lithium for the production of batteries for electrical vehicles for scenarios I and II (source: own illustration)

Figure 26 shows the annual demand for Lithium resulting from the two scenarios. It is clear that it rises constantly until 2050. Scenario I predicts an annual demand at 55,000 t of the element for the year 2020, and subsequently 176,000 t in 2030, 445,000 t in 2040 and culminating at 664,000 t in the year 2050. Scenario II, which is considerably more optimistic, assumes an annual demand to have reached 220,000 t by 2020, 615,000 t by 2030, 1,009,000 t by 2040 and 1,659,000 t by 2050.

Figure 27 calculates the cumulated demand for Lithium from the year 2010 for every year of the following four decades. The scenarios figure out this cumulated demand:

- Scenario I: 1.4 million t in 2030 and 10.2 million t in 2050
- Scenario II: 5.2 million t in 2030 and 27.1 million t in 2050

If these cumulated material demands as depicted by the two scenarios are compared to the available deposits as stated by the USGS from 2010 (see Figure 27), one see that in the next years no shortage is to be expected. In the case of scenario I the cumulated demand for Lithium for the production of batteries for electrical vehicles is only slightly exceeding the reserves stated in the USGS from 2010. However, in scenario II, the reserves available according to our source will have been exhausted by the year 2037.

Table 9: Assumptions and Results from the scenarios II.

	years	2010	2015	2020	2025	2030	2035	2040	2045	2050
E-mobility Scenario	yearly increase in car stock	25.612.422	29.968.326	34.783.686	40.372.786	46.859.951	44.471.869	39.861.300	32.685.078	23.243.599
	yearly replacement of old cars	46.061.634	53.398.058	61.902.985	71.797.366	83.333.884	96.724.110	112.265.899	129.862.637	146.926.954
	yearly car market	71.674.056	83.366.384	96.686.671	112.170.151	130.193.836	141.195.979	152.127.199	162.547.714	170.170.553
	grwoth rate of car market [%]		3,01	3,01	3,03	3,02	1,61	1,44	1,19	0,74
E-mobility Scenario I	market share of EV+PHEV [%]	1	2,5	4	6	8	11,5	15	17,5	20
	share of EV on (EV+PHEV)	5	15	25	31,25	37,5	43,75	50	50	50
	share of PHEV on (EV+PHEV)	95	85	75	68,75	62,5	56,25	50	50	50
	annual sold EV	35.837	312.624	966.867	2.103.190	3.905.815	7.103.923	11.409.540	14.222.925	17.017.055
	annual sold PHEV	680.904	1.771.536	2.900.600	4.627.019	6.509.692	9.133.615	11.409.540	14.222.925	17.017.055
	annual sold EV + PHEV	716.741	2.084.160	3.867.467	6.730.209	10.415.507	16.237.538	22.819.080	28.445.850	34.034.111
	lithium demand for EV [tons]	1.075	9.379	29.006	63.096	117.174	213.118	342.286	426.688	510.512
	lithium demand for PHEV [tons]	6.128	15.944	26.105	41.643	58.587	82.203	102.686	128.006	153.153
	lithium demand for PHEV + EV [tons]	7.203	25.323	55.111	104.739	175.762	295.320	444.972	554.694	663.665
	cumulated lithium demand [tons]	7.203	93.662	304.195	721.212	1.448.207	2.673.315	4.586.506	7.138.524	10.240.760
E-mobility Scenario II	market share of EV+PHEV [%]	1	8,5	16	22	28	31	34	42	50
	share of EV on (EV+PHEV)	5	15	25	31,25	37,5	43,75	50	50	50
	share of PHEV on (EV+PHEV)	95	85	75	68,75	62,5	56,25	50	50	50
	annual sold EV	35.837	1.062.921	3.867.467	7.711.698	13.670.353	19.149.705	25.861.624	34.135.020	42.542.638
	annual sold PHEV	680.904	6.023.221	11.602.400	16.965.735	22.783.921	24.621.049	25.861.624	34.135.020	42.542.638
	annual sold EV + PHEV	716.741	7.086.143	15.469.867	24.677.433	36.454.274	43.770.753	51.723.248	68.270.040	85.085.277
	lithium demand for EV [tons]	1.075	31.888	116.024	231.351	410.111	574.491	775.849	1.024.051	1.276.279
	lithium demand for PHEV [tons]	6.128	54.209	104.422	152.692	205.055	221.589	232.755	307.215	382.884
	lithium demand for PHEV + EV [tons]	7.203	86.097	220.446	384.043	615.166	796.081	1.008.603	1.331.266	1.659.163
	cumulated lithium demand [tons]	7.203	261.230	1.068.842	2.638.364	5.221.189	8.824.747	13.430.194	19.433.015	27.075.362

Section 3.3.2 has demonstrated that the data regarding the resources and reserves for Lithium vary significantly among the different sources. If we rely upon the upper bound of the bandwidth for the resources and reserves (reserves: 39.4 million t, and

resources: 64 million t) predicted, one can also assume that the cumulated demand for Lithium up to 2050 as foreseen by scenario II, should be available.

4.4 Summary of the scenarios and indicators

This section evaluates the results from the scenarios and the indicators that have been introduced concerning the importance of the availability of Tellurium and Indium for thin-film-PV systems and that of Lithium for batteries for electrical vehicles. One indicator shows a rough estimate of the cost share of the considered materials for the technologies. The second indicator states the proportion between the projected demand and the global reserves and the last shows the distribution of the global deposits among the different countries. If these three values are put together, we receive a picture that tells us whether limits in the availability of the metals needed might prove a bottleneck for the development of the different technologies.

Table 10: Overview of the results of the scenarios and indicators

	CIGS - Indium			CdTe - Tellurium			Electrical Vehicle - Lithium	
	Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C	Scenario I	Scenario II
Price of metal on total technology price	0.6% *			0.72% **			0.46% ***	
Annual demand 2030 / Reserves USGS	0.9%	2.5%	6.4%	0.9%	2.7%	6.6%	1.8%	6.2%
Annual demand 2050 / Reserves USGS	2.8%	12.6%	22.9%	3.0%	13.2%	24.0%	6.7%	16.8%
Cumulated demand up to 2030 / Reserves USGS	8.9%	23.2%	66.7%	9.4%	24.4%	70.0%	14.6%	52.7%
Cumulated demand up to 2050 / Reserves USGS	41.1%	145.6%	283.0%	43.1%	152.8%	297.1%	103.4%	273.5%
Geographic concentration (biggest producer/total production)	50.0%			-			41.1%	
Geographic concentration (biggest reserves/total reserves)	75.0%			13.6%			75.8%	
Competition for Material****	•••			••			•	

* Assumptions: 45.73 g/kW Indium demand; 525 €/kg Indium price; 4,000 €/kWp PV system price
** Assumptions: 96 g/kW Tellurium demand; 300 €/kg Indium price; 4,000 €/kWp PV system price
*** Assumptions: 600 g/kWh Lithium carbonate demand (Aul and Krause 2010); 4.60 €/kg Lithium carbonate price; 600 €/kWh battery price
**** The valuation is based on the market developments, ••• strong competition, •• medium competition, • low competition

If it is considered that the total prices for the different technologies against the initial costs of providing the scarce metal, it can be seen that this latter factor is very low indeed. On the one hand this is positive, because increasing prices of Indium, Tellurium and Lithium will not affect the prices for PV and batteries for electrical vehicles to a very big extent. On the other hand, this also means, that improvements or an increase in recycling will not be caused the prices for the scarce metals.

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The resources available according to the USGS cannot cover the resulting cumulated demand for Indium, Tellurium and Lithium up to the year 2050 in the cases of scenarios B, C, I and II (indicated by orange in Table 10). It is important to note that these results are based on the reserves stated by that source. If the size of the assumed depots from other sources are fed into the projections one will receive different results.

Another critical issue is the geographical distribution. Both for Indium and Lithium 50% or more of the production or the reserves are located in only one country.

For the evaluation of the problems resulting from the competition for the metals, the market description given in chapters 3.2.3, 3.3.3 and 3.4.3 has be used. The competition for Indium is therefore seen as very critical, due to the increased demand resulting from LCD applications.

If the results which the examination has yielded for Indium and Tellurium will be compared with those from Angerer et al. 2009 the following turns out:

- The annual demand for Indium in the year 2030, as predicted in scenario B (280 t), is similar to that for thin-film PV's calculated by Angerer et al. (285 t). For the year 2050 Angerer et al. request 580 t of Indium. This quantity is lower than that anticipated by our scenario B (1,384 t), however, it is higher than the demand claimed by scenario A (313 t). In addition to Indium required for thin-film PV's Angerer et al. calculate a further demand of that element of 1580 t for the year 2030 for ITO's for displays. This points to possible competitions between two technologies both needing the scarce resource in the near future.

- The Tellurium demand for thin-film PV's given by Angerer et al amounts to 148 t in 2030 and to 302 t in 2050. These values are much lower than predicted by scenarios B and C and a little lower than in scenario A: 204 t in 2030 and 657 t in 2050 respectively. Table 3 shows that the specific demand for Tellurium per kW given by Angerer et al. (2009) is much lower in comparison to the other sources.

And Angerer et al. does not publish any values for the cumulated demand for Indium and Tellurium resulting from thin-film PV production.

4.5 Discussion of the scenarios

The results from the scenarios above must be viewed as being no more than rough calculations of the developments under the given assumptions. The following aspects have to be considered when interpreting the results:

- The metal demand is based on the sources described in 2.2.2 and 2.3.3. These values have been calculated to remain constant in the course of time. Improvements in the resource efficiency of the production may lead to a significant reduction of the material demand. Furthermore the efficiency of the products might improve in the course of time, and therefore the demand for raw material may shrink.
- The resources and reserves seen to be available currently, are taken from the sources described in 3.1.2, 3.2.2 and 3.3.2. And these data are only approximations at best: Among them contradicting accounts can allready be found. Furthermore new deposits of the scarce metals might be discovered in the future. A big depot of rare earth metals has been found at the bottom of the Pacific Ocean recently (see http://www.bbc.co.uk/news/world-asia-pacific-14009910).

5 Recycling – Challenges

Recycling happens at two different stages. One is the pre-consumer recycling, where the scrap of the production process is being recycled. The other possibility implies the post-consumption recycling process, denoting the recycling of the used products. The first one is by far easier to achieve, since the generation and composition of the scrap is known, it does not have to be collected and a continuous flow of scrap can be expected which makes its processing much more economical.

The following section briefly surveys the processes available and estimates the recovery rate. The possible effects of recycling will be shown by a calculation based on scenarios B, C and Scenario I.

5.1 Recycling of PV –modules

The booming years of PV started only some ten years ago. Therefore large quantities of PV-modules ready for recycling are still yet another decade away. This is especially true for thin-film PV systems. In the RESOLVED-Project (Berger et al. 2010) two different strategies for recycling of modules whose life-span had expired, have been examined: one for modules which are complete and the other for broken modules (see Figure 28).

The complete modules are heated. The EVA-layer will be destroyed at a certain temperature and thus the components of the modules can be separated. For the recovering of the thin-film materials a vacuum blasting method has been used (a blast medium hits the surface triggered by a vacuum created on the surface). The broken modules on the other hand are crushed even further to a particle size of < 20mm. The material then is treated in a wet-mechanical way in an intensive batch mixer. Now the semiconductor layer can be separated from the glass due to the shear and friction forces.

For both strategies the semiconductor material is separated from the glass using a flotation process.

The recovered materials are purified in a chemical process so that they can be re-used in the PV production. The recovery rate for the CdTe was 78.7% and for CIS modules 54% (Berger et al. 2010).

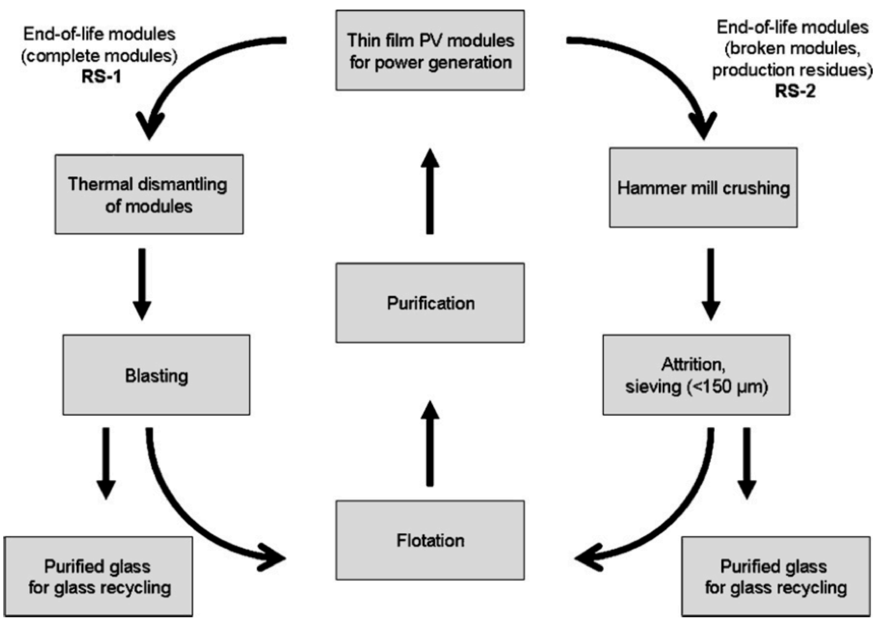

Figure 28: Recycling strategies for thin-film modules (Berger et al. 2010)

For the following calculation a total recovery factor (including the share of PV modules which can be collected and the recovery factor of the recycling process) from 25% has been assumed:

If 25% of the Indium and Tellurium bound in PV modules can be recycled, the first recovery from old PV modules can be performed by 2040. In scenario B this would mean that in that year 1.2% of both the annual demand for Tellurium and for Indium could be supplied by recycled metals. (The shares for Indium and Tellurium are similar due to the identical assumptions.) The coverage of recycled metals on the total metal demand for PV production increases to 2.4% by the year 2045 and to 4.11% by 2050. For Scenario C these shares will be 0.7% in 2040, 3.5% in 2045 and 8.8% in 2050.

5.2 Recycling of Lithium based batteries for electrical vehicles

The recycling of batteries is better known, because lead-acid batteries have a high recycling rate due to their valuable ingredients. Lithium Ion batteries are also already being recycled, because the materials Cobalt and Nickel are precious. At the present Lithium is mostly not recovered by recycling processes, because so far that is not economical. But currently some new recycling plants are starting to recover Lithium as well (see UNEP 2009). Gaines and Nelson (2010) describe two possible paths for recycling:

"Recycling can recover materials at different production stages, all the way from basic building blocks to battery-grade materials. At one extreme are smelting processes that recover basic elements or salts. These are operational now on a large scale and can take just about any input, including different battery chemistries (including Li-ion, Ni-MH, etc.) or mixed feed. Smelting takes place at high temperature, and organics, including the electrolyte and carbon anodes, are burned as fuel or reductant. The valuable metals (Co and Ni) are recovered and sent to refining so that the product is suitable for any use. The other materials, including lithium, are contained in the slag, which is now used as an additive in concrete. The lithium could be recovered by using a hydrometallurgical process, if justified by price or regulations.

At the other extreme, recovery of battery-grade material has been demonstrated. Such processes require as uniform feed as possible, because impurities in feed jeopardize product quality. The components are separated by a variety of physical and chemical processes, and all active materials and metals can be recovered. It may be necessary to purify or reactivate some components to make them suitable for reuse in new batteries. Only the separator is unlikely to be usable, because its form cannot be retained. This is a low-temperature process with a low energy requirement." (Gaines and Nelson 2010)

Since the technology of Lithium recycling is new, no data regarding the recovery rate for such processes have been found in the literature. For the calculation a moderate recovery factor embracing the whole system (including the share of batteries which can be collected and the recovery factor of the recycling process) of 25% has been assumed.

If 25% of the Lithium bound in the batteries can be recycled, the first recovery from old batteries will be in the year 2023. According to scenario I 2.2% of the annual demand for Lithium can be covered by recycled Lithium in the year 2023. This share increases steadily to 5.1% in the year 2030, to 7.3% in 2040 and to 13.2% in 2050.

These results show, that recycling can cover a significant share of the metal demand. But due to the time lag caused by life times of the systems, big quantities cannot be obtained before at least two more decades have elapsed. However, the setting up of the recycling infrastructure and regulation for the designs of the products that allow recycling must be introduced now.

6 Conclusion

Thin-film PV technologies are a modern technology that may have a promising future and can contribute substantially towards establishing a sustainable energy system. According to the view among the industrial producers further improvements in the production processes will decrease the specific production costs for thin-film PV systems as well as a diminishing amout of the material required. Furthermore improvements regarding the efficiency are expected in the near future for CIGS and CdTe, the two dominant thin-film technologies. The specific metal demand is between 22-109 g Indium per kW PV module, 31-279 g Tellurium per kW PV module.

Lithium-based batteries are currently the most promising technology for energy storage systems for electrified vehicles. They have a high energy capacity, high energy density and are low in cost. The specific metal demand for Lithium-based batteries is between 100 and 423 g Lithium per kWh battery storage.

Using assumptions of different sources for thin-film PV usage three scenarios have been calculated. According to them it can be assumed that although PV and especially thin-film PV have huge annual market growth rates, their contribution towards all the electricity produced, will remain on a modest level due to the very low actual utilization and because of the immense growth of the overall demand for electricity. The contribution of PV to the total electricity demand in the year 2050 is predicted to amount to 2% (scenario A), to 5% (scenario B) and to 10% (scenario C). For all scenarios it is assumed, that the share of thin-film on the total PV market increases from 18% to 45% until 2030. This share is kept constant between 2030 and 2050.

For the usage of electrified vehicles two scenarios have been calculated. In scenario I the market share of EV’s and PHEV’s are seen to rise from 2010 to 2020 to 4% and then further to 8% until 2030, 15% in 2040 and 20% in 2050. Scenario II estimates the market share of EV’s and PHEV’s to increase from 2010 to 2020 by 16%. Then it will rise to 28% until the year 2030, to 34% in 2040 and to 50% in 2050.

For the three technologies (CIGS, CdTe and Lithium ion batteries) metals are needed (Indium, Tellurium and Lithium) that are not available in huge amounts.

Furthermore both deposits and the production industries are concentrated in a few countries. The data regarding the resources differ among the various sources. The USGS is the source most widely used. However, discontinuities have been found in the data and some countries do not report their resource data and therefore the data published by the USGS are incomplete.

The material demand in the year 2050 among the different scenarios varies between 4,518–31,130 t Indium, 9,486–65,352 t Tellurium and 20–27 Million t Lithium. The metal demand resulting from the scenarios shows that for

- *Indium* the demand resulting from scenario A can be covered. For scenario B the total amount of Indium available (according to the reserve base stated in the USGS) is needed to produce the PV systems until 2050. For scenario C the Indium required will have exceeded the amount available already by the year 2042 (according to data given in the USGS).
- *Tellurium* scenario A does not predict any shortages. However, the demand for Tellurium calculated with in scenario B will have exceeded the known reserves by the year 2046. Scenario C assumes, that already by the year 2035 the Tellurium reserves (on the base of the amounts stated in the USGS) will be exhausted.
- *Lithium scenarios* give no shortage in the next years. In the case of scenario I the cumulated demand in the year 2050 for Lithium for the production of batteries for electrical vehicles is only slightly exceeding the reserves stated in the USGS from 2010. However, in scenario II, the reserves available according to our source will have been exhausted by the year 2037.

On the other hand improvements in production efficiency as well as the discovery of new depots, which might be found, may yield a changed picture in the course of time.

The specific material demand regarding Indium for CIGS-modules, Tellurium for CdTe PV modules and Lithium for Lithium ion batteries shows that the needed amounts for each unit of the technology is very small. The share of the scarce raw materials in the overall costs for the different technologies is below 1% for all three technologies. Therefore, the prices for these metals themselves may not produce a stimulus sufficient for introducing an environmentally efficient usage management, since they have too little impact on the total cost for the technology. It appears also that recycling might not result from economic pressure, since the recyclable yields are quite low. Therefore binding legal obligations regarding the efficient usage of metals in the production process as well as such obligations pertaining to the recycling of these metals might prove a good policy. Especially countries or regions without resources of these metals themselves might benefit from implementing such obligations. They could increase their own metal production and therefore lower their dependency on countries exporting these metals.

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