Renewable Energy 95 (2016) 53–62

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Role of critical metals in the future markets of clean energy technologies

Leena Grandell [a,*], Antti Lehtilä [a], Mari Kivinen [b], Tiina Koljonen [a], Susanna Kihlman [b], Laura S. Lauri [b]

[a] VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Finland
[b] Geological Survey of Finland, P.O. Box 96, 02151 Espoo, Finland

A R T I C L E I N F O

Article history:
Received 5 February 2015
Received in revised form
27 January 2016
Accepted 26 March 2016
Available online 7 April 2016

Keywords:
Critical metals
Clean energy technologies
TIMES model
Resources
Reserves

A B S T R A C T

The global energy sector is expected to experience a gradual shift towards renewable energy sources in the coming decades. Climate change as well as energy security issues are the driving factors. In this process electricity is expected to gain importance to the cost of fuels. However, these new technologies are in many cases dependent on various metals. This analysis evaluates the need for special metals and compares it with known resources in order to find possible bottlenecks in the market. The time perspective of the analysis reaches to the year 2050.

Following technologies have been selected for evaluation: solar electricity, wind power, fuel cells, batteries, electrolysis, hydrogen storages, electric cars and energy efficient lighting. The metals investigated belong either to the semiconductors, platinum group metals, rare earth metals or are other critical metals like silver and cobalt.

The global transition of the energy sector is modelled with TIMES. According to the results the most critical market situation will be found in silver. Other elements, for which bottlenecks in the market seem possible, include tellurium, indium, dysprosium, lanthanum, cobalt, platinum and ruthenium. Renewable energy scenarios presented by the IPCC Fifth Assessment Report seem partly unrealistic from the perspective of critical metals.

1. Introduction

The European Union has launched a Climate Action with a target to reduce greenhouse gas (GHG) emissions by 80–95% until 2050 when compared to the 1990 level. Until 2030 a reduction of 40% is sought. To achieve these targets Europe should be transformed into a low-carbon economy. A roadmap outlines possible future paths in this process [18]. A recently published report by IPCC addresses the question of climate change mitigation by assessing more than 1200 emission scenarios. The low carbon scenarios of the report emphasise an extensive implementation of either energy efficiency of renewable energy sources.

The promotion of energy efficiency and renewable energy sources relies on related technologies. These technologies unfortunately are often dependent on so called critical metals. A metal is perceived critical if it is crucial for green energy technologies and if it is scarce by its' geological occurrence. A shift in the global energy sector towards low carbon technologies will result in an increased demand of these metals. This article analyses the impacts on the

Abbreviations: Ag, silver; a-Si, amorphous silicon; AZO, aluminium doped zinc oxid; BGS, British Geological Survey; CAT, calcium tungstate; Ce, cerium; CFL, compact fluorescent lamp; CIGS, copper-indium-gallium-selenide solar cell; CIS, copper-indium-selenide solar cell; Co, cobalt; c-Si, crystalline silicon solar cells; CSP, concentrated solar power; DSSC, dye sensitized solar cells; Dy, dysprosium; EDLC, electric double-layer capacitor; EOL-RR, end of life recycling rate; EPIA, European Photovoltaics Industry Association; Eu, europium; EV, electric vehicle; FCEV, fuel cell electric vehicle; FTO, fluorine doped tin oxide; GHG, greenhouse gases; HEV, hybrid electric vehicle; HTS, high temperature superconductivity; In, indium; ITO, indium-tin-oxide; JORC, The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves; La, lanthanum; LAP, lanthanum phosphate; LED, light emitting diode; LFL, linear fluorescent lamp; mc-Si, monocrystalline silicon solar cells; MMTA, Minor Metals Trade Association; Nd, neodymium; NdFeB, neodymium-iron-boron permanent magnet; NiMH, nickel metal hydric battery; pc-Si, polycrystalline silicon solar cells; PEMFC, proton exchange membrane fuel cell; PFSI, perfluorosulfonic; PGM, platinum group metals; PHEV, plug-in hybrid vehicle; PM, permanent magnet; Pr, praseodymium; Pt, platinum; PV, photovoltaics; RC, recycled content; REE, rare earth elements; REO, rare earth oxids; rpm, rotations per minute; Ru, ruthenium; SOFC, solid oxid fuel cell; Tb, terbium; Te, tellurium; USGS, United States Geological Survey; Y, yttrium; YBCO, yttrium-barium-copper-oxid; YSZ, yttrium stabilised zirkonia.

* Corresponding author.
E-mail addresses: leena.grandell@vtt.fi, grandell@t-online.de (L. Grandell).

http://dx.doi.org/10.1016/j.renene.2016.03.102
0960-1481/

metals markets and seeks to find possible bottlenecks resulting from the availability of the critical metals. The evolution of the global energy market is to model by TIMES.

2. Methods – data sources and simulation

We have modelled the global demand for 14 critical metals (Ag, Nd, Pr, Dy, Tb, Yt, La, Ce, Eu, Co, Pt, Ru, In, Te) resulting from a shift towards green energy technologies from present until 2050. In the analysis a broad spectrum of green energy technologies have been chosen. Both technologies producing renewable energy as well as energy efficient technological solutions are taken into account: solar energy, wind energy, electric mobility, fuel cells, batteries, electrolysis and efficient lighting. One important criterion for the selection of the technologies has been the metals needed in the technology, and the technologys' expected future role in the metals markets. For the analysis detailed information on the specific need for metals has been collected. This data together with information on metals resources and reserves as well as annual mining is fed in to the TIMES model.

2.1. Reviewing critical metal dependencies of green energy technologies

In the following chapters the selected technologies are presented in more detail, focus being on material requirements.

2.1.1. Solar energy

2.1.1.1. Crystalline silicon photovoltaics. Crystalline silicon solar cells (c-Si) belong to the first generation of photovoltaic technology and represents still today 80% of the global PV markets [19]. Three types of c-Si cells exist: monocrystalline (mc-Si), polycrystalline (pc-Si), and ribbon silicon (ribbon pc-Si). The efficiency of the cell varies depending on the technology, but is roughly 20% [27].

The bulk material of the cell is silicon, which is one of the most common elements in the earths' crust. The cells are connected electrically to each other with metal strips consisting of an alloy rich in silver. Silver is the metal of choice because of its' superior electrical conductivity. PV manufacturers estimate the current silver content to be in the range of 8 g/m^2 [60]. Currently the technology is based on screen printed silver paste. However there are some technological approaches to reduce the dependence of silver such as the “metal wrap through technology” or “buried contact”, which are discussed by Saga [57]. Further decreases are sought by substituting silver to a large degree by copper. The expected development of the silver content per cell area is shown in Fig. 1.

2.1.1.2. Dye sensitized solar cells, DSSC. Dye sensitized solar cells are organic solar cells and belong to the third generation of photovoltaics. This technology is on the verge of commercialization. The manufacturing process brings many cost advantages, and the efficiency of the cells is in the range of 8–12% [27]. The photoactive material, the dye, can be made of several materials. However a complex based on ruthenium and osmium gives the best cell performance [22]. The metallization of the cell is based on a silver ink. Platinum acts as a catalyst. Fraunhofer ISI has published estimations on the need of critical metals [2] as shown in Table 1.

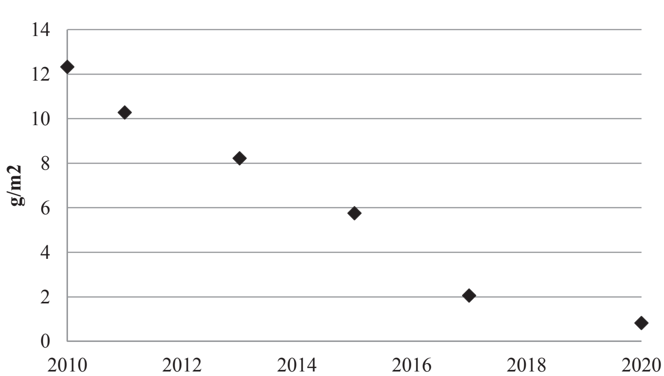

Fig. 1. Silver consumption per area in c-Si cells [4].

2.1.1.3. Thin film photovoltaic panels. Thin film cells, or second generation photovoltaics, comprise several technologies depending on the semiconducting material. The cells can consist of one or several layers of photoactive substance, each of one being very thin (in the range of nanometres or micrometres). This leads to reduced need of material.

CdTe-panels are cost efficient to produce and thus are regarded as the most promising thin film technology. The confirmed measured electricity generation efficiency is as high as 17.5% [78], however in commercial applications somewhat lower, 10–11% [19]. Tellurium is a critical metal. The need of tellurium has been estimated to be 6.5 g/m^2 [1].

CIS or CIGS (copper-indium-selenide or copper-indium-gallium-selenide) yields an efficiency of 15% whereas commercial applications show an efficiency range of 7–12% [19]. Indium and gallium are critical metals. The need of these metals is estimated to be 2.9 g/m^2 (In) and 0.53 g/m^2 (Ga) [1].

Thin film cells based on amorphous silicon (a-Si) have a relatively low efficiency, 4–8%. The cell suffers from light induced degradation, which has a negative impact on the efficiency of the cell. The degradation is not that severe, if the cell is built with a layer structure (a-Si/μc-Si). A layer with microcrystalline silicon gives the cell stability and increases the efficiency to 7–9% [19]. Doping amorphous silicon with germanium has the same effect. The front contact is an ITO layer (indium-tin-oxide), typically 60 nm thick [2]. This means the need of indium is approximately 0.4 g/m^2. The back contact can be either silver or aluminium.

2.1.1.4. Concentrated solar power – CSP. There are various technological approaches to concentrated solar power such as parabolic trough, linear Fresnel reflectors or the solar power tower, but all function according to the same principle. A system of mirrors or lenses concentrates solar irradiation. The concentrated light heats an absorber fluid, which could be water, a molten salt or synthetic oil. The heat is transformed to electricity by conventional turbine technology. Silver has highest optical reflectivity of all elements and is thus used on the surface of the mirrors to obtain high reflectance. The silver content per mirror area is constant for all technologies (1 g/m^2), but since the electrical output varies depending on the choice of technology, the silver requirement with respect to electricity generation capacity is different [2]. Table 2 comprises this information.

2.1.2. Wind energy

The wind energy concept can be classified into two categories: geared and gearless wind mills. Induction generators have high

Table 1
Material consumption of some selected raw materials in dye-sensitized solar cells [2].

Material	Needed mass/area [g/m^2]
Ruthenium	0.07
Platinum	0.03
Silver	1

Table 2
Silver requirement for the various concentrated solar power technologies [2].

	Silver content [kg/m^2]	kg/MW
Fresnel reflector	0.001	13.75
Parabolic trough	0.001	3.75
Solar power tower	0.001	7.57

rotational speed and thus a gear is inevitable, which leads typically to a higher need for maintenance and respective costs. On the other side, this type of generator does not include any critical metals. Permanent magnets based on rare earth elements produce very high magnetic fields, thus even compact and light generators generate high torque. Therefore PM generators can operate with low rotational speeds and are suitable to both gearless and geared concepts.

The permanent magnets used in commercial applications consist of an alloy based on neodymium (NdFeB). The share of neodymium in the magnet varies between 28 and 31% [46]. Other rare earth elements in the magnet are dysprosium (2–3 w-%) and in small quantities praseodymium and terbium. The need for REE is 160–200 kg/MW in gearless applications and 30 kg/MW for generators operating with higher rotation speed and gears [6].

A possible future technical concept might open up through high temperature superconducting materials (HTS generator). The most promising material seems to be YBCO (yttrium-barium-copper-oxid) [39]. This material comprises the rare earth element yttrium and to small quantities also cerium and lanthanide. The estimated need for REE is 2 kg/MW [6].

2.1.3. Electric cars

Electric cars can be classified into full electric vehicles and hybrid cars. An electric vehicle (EV) only has an electric motor whereas a hybrid electric vehicle (HEV) can be run either with an electric motor or a conventional combustion motor. A battery stores excess energy, which is captured by regenerative braking. In a plug in hybrid electric vehicle (PHEV) the batteries can additionally be loaded with grid electricity. A fuel cell electric vehicle (FCEV) comprises a hydrogen tank and a fuel cell as source of energy. Table 3 presents various types of electric cars.

2.1.3.1. Electric motor. An important criterion for electric motors in vehicle technology is light weight and compact size. Motors based on permanent magnets show high power density and are therefore used in mobile applications. The permanent magnet used is based on neodymium (NdFeB). Beside neodymium, the magnet comprises small amount of dysprosium for better heat resistance and to smaller extent praseodymium, terbium and gallium. Table 4 comprises the need for critical metals for two motor sizes: below 50 kW and over 50 kW power [7].

2.1.3.2. Fuel cell and hydrogen storage. The energy source of a fuel cell electric vehicle (FCEV) is hydrogen. A proton exchange membrane fuel cell (PEMFC) has perfluorosulfonic acid ionomer (PFSI) as an electrolyte, which is based on fluoride. Platinum serves as catalysts on both anode and cathode. In the current state the need for platinum is 0.6–0.7 g/kW. A reduction to 0.2 g/kW is sought through various solutions, like alloys with other metals [5].

Table 4
Critical metals in motor technology for two motor sizes. The amount of the metal is expressed per motor [7].

	<50 kW g	≥50 kW g
Nd	150	360
Pr	50	120
Dy	90	210
Tb	9	21
Ga	0.435	1

Hydrogen is comprised to 700 bar for storage. The process consumes approximately 15% of the energy content of the gas [76]. The hydrogen tank can be produced of several materials like steel aluminium, possible glass or carbon fiber; none of them are critical elements [15].

2.1.3.3. Batteries. Batteries are characterised by specific energy (Wh/kg) and specific power (W/kg). For BEV the most critical factor is specific energy, therefore the choice is li-ion battery. For HEV however more important is the continuous charging/discharging cycle and ability to release power, therefore a nickel metal hydride battery (NiMH) is more suitable, in some cases an electric double-layer capacitor (EDLC). Since lithium is not subject of this analysis, it will be not discussed further.

The specific energy for NiMH batteries is low, 50 Wh/kg. It is compensated by a high specific power, over 1000 kW/kg [12]. The negative electrode is a metalhydrid, in automobile applications typically AB_5. A is an alloy containing rare earth metals and B can be nickel, cobalt, mangan or aluminium. Råde estimates the need for rare earth metals to be 1.2 kg/kWh presently and for the future 0.85 kg/kWh [56]. A typical mischmetal A is $La_{5,7}Ce_{8,0}Pr_{0,8}Nd_{2,3}$ [20].

Supercondensators, also called double layer capacitors do not comprise any critical metals [40].

2.1.3.4. Power electronics system and electric recharging point. The power electronics system steers the currency to and from the battery. It converts DC voltage to AC voltage and vice versa. During regenerative breaking the electric motor serves as a generator. In PHEV's the grid electricity needs to be converted into DC currency. The power electronic system as well as the electric recharging point comprise small amounts of critical metals like palladium, gold, germanium, indium and silver as can be seen in Table 5.

2.1.4. Fuel cells and electrolysis

Electricity produced by solar and wind energy is intermittent in nature and thus a need for storage technologies is obvious. One option to store the energy produced by renewable energy sources is hydrogen. Hydrogen is produced through electrolysis and is burned again in fuel cells to produce electricity. Also if fuel cell electric vehicles will penetrate the market in large scale a functioning hydrogen infrastructure is needed.

Table 3
Various types of electric vehicles.

		Motor	Energy source	Battery
HEV	hybrid vehicle	electric and combustion	Liquid fuel	NiMH
PHEV	plug in hybrid vehicle	electric and combustion	Liquid fuel + grid electricity	NiMH
BEV	battery electric vehicle	electric	Grid electricity	Li-ion
FCEV	fuel cell electric vehicle	electric	hydrogen storage and fuel cell	Li-ion

Table 5
Need for critical metals in electric vehicles [7].

	Power electronics		Cables		Recharging point
	<50 kW	>50 kW	<50 kW	>50 kW	
	g	g	g	g	g
Pd	0.064	0.08			
Au	0.16	0.2			
Ag	4	6	1	1	0.001
Ga	0.03	0.05			0.001
Ge	0.03	0.05			0.001
In	0.03	0.05			0.001

2.1.4.1. Alkaline water electrolysis. Alkaline water electrolysis is a traditional technology which is used in industrial hydrogen production. Several materials can be used as catalysts [77]. The need for the typical catalyst cobalt on anode is 6.2 mg/cm^2 (anode 3.4 mg/cm^2, cathode 2.8 mg/cm^2) [61]. Assuming a currency density of 0.3 mA/cm^2 and a potential of approximately 1.7 V, the need for cobalt is 8.9 mg/W.

2.1.4.2. Polymer electrolyte membrane (PEM) electrolysis. PEM electrolysis represents a new technology, which can be used with an altering power level and thus is suitable for solar and wind energy applications.

The electrolyte is a solid polymer membrane. The catalysts are PGM metals: ruthenium and iridium on anode and platinum on cathode. In the current state no catalysts outside of the PGM group are known to be suitable [3]. The need for catalysts on anode is 2 mg/cm^2 and on cathode 0.5 mg/cm^2 [34]. It is possible to reduce the need for catalyst material by one order of magnitude by applying catalyst particles in nanosize scale on a supporting structure [3]. The cell needs a potential of 1.6 V [3], whereas the current density is 0.3 A/cm^2 [34]. Thus the needed for electrical power to run the process is 0.5 W/cm^2. The cell operates with 93% efficiency (the needed potential to split water is 1.48 V).

2.1.4.3. Solid oxid fuel cell SOFC. SOFC technology finds its' application mainly in combined heat and power production. The operating temperature is very high, 600–850 °C. Therefore the process does not need a catalyst the PGM group. Suitable fuels are hydrocarbons, carbonmonoxid and hydrogen [31].

Critical metals lanthanum, cerium, yttrium and cobalt are present in the structures of SOFC. The electrolyte is yttrium stabilized zirconia (YSZ). The anode is based on the same compound YSZ together with nickeloxid. Nickel functions as a catalyst. Cathode is an alloy of lanthanum and cobalt. Himanen has estimated the need for critical metals in the present state as well as in the future. The data is presented in Table 6.

2.1.5. Lighting

Energy efficient lighting applications based on fluorecence are LED lamps (light emitting diode), organic LED lamps and fluorescent lamps. In fluorescence an atom or a molecule absorbs a photon and emits it again. The wavelength of the emitted photon is dependent on the atom emitting it. Thus by varying the elements one can produce light with different wavelengths and therefore colours. Some REE metals like Dy, Ce, Eu, or Tb are suitable elements [53]. Also La and Y are used [54].

The lighting phosphor used in compact fluorescent lamps (CFL) for domestic applications is Calcium Tungstate (CAT), approximately 1.5 g are needed per one lamp. The phosphor contains several rare earth elements: La, Ce, Eu, Tb and Y, the weight being on Ce (20%) and Y (62%). In linear fluorescent lamps (LFC), common in offices and public buildings, a phosphate called Lanthanum Phosphate (LAP) is used. It contains the same REE metals with the exception, that the main elements are La (22%) and Y (62%) [14].

LED (light emitting diode) comprises a light emitting semiconductor, typically based on indium and gallium (InGaN). The monochromatic light is then converted into white light with the help of above mentioned phosphates. According to Fraunhofer, the need for semiconducting material per LED lamp is 0.17 mg In and 0.53 g Ga [2]. The phosphor contains cerium and yttrium (Ce^{3+}:YAG) [63]. DOE estimates the need for the phosphor in a 12.5 W LED lamp to be 1 g [58]. This means 0.7 mg Ce and 450 mg Y per one lamp [42].

Organic LED technology, which is currently being researched, does not contain any critical metals.

Table 6
The need for critical metals in SOFC in the present state and in 5–10 years [31].

	Need for metals g/kW	
	Present state	Future (5–10 years)
Ce	2	0.1
La	20	4
Co	30	3
Y	40	10

2.2. Resources and mine production of critical metals

To estimate a potential future supply of critical metals, we have used two approaches in this study: calculations based on information over 1) global reserves and 2) global resources.

2.2.1. Data sources and reliability

Information on global resources, reserves and annual mining of the critical metals used for this study is presented in Tables 7 and 8. Used data sources can have inconsistencies in reporting reserve and resource classes due the various methods. USGS uses its own classification system [64] while the other dataset are provided by commercial actors Minor Metal Trade Association and Lenntech. In addition, there are several regional classification systems used by exploration and mining companies, for example, JORC in Australia [33] and National Instrument 43–101 in Canada [9].

Table 7 comprises the data for rare earth elements (REE). The aggregated data for all REO (RE-oxide) was obtained from USGS. Commercial actors provide estimations on how the aggregate REE resources and reserves can be split between the individual metals [37,44]. The data on reserves and resources of dysprosium and cerium are rough estimations based on the aggregate REE resource [72] and the information on rare earth contents in the major source minerals bastnäsite and monazite [67]. We used 1% metal content for Dy and 45% for Ce. Almost half of the known REE-reserves are estimated to situate in China [72], which has dominated the trade of RE-metals in the recent years. In addition, USA, India and Australia have marked REE resources. US Geological Survey has also estimated that the amount of undiscovered REE resources can be very large [72].

Table 8 represents the information on metals outside the REE-group. USGS was the most important source for information for these metals in addition to commercial actors and the British Geological Survey (BGS). USGS estimation for silver reserves on national level show high variations depending on the reporting year. Such is the case for Australia, China and Peru, where reserves have grown substantially in 2011. This might have been caused by silver prices, which have increased 10 fold from 5 US$/oz in 2001 to 50 US$ in 2011 shifting parts of the resources to the reserve category. The countries included in the aggregated resource estimation

Table 7
Global mineral resources and annual mining of selected rare earth elements [14,37,44,67,72].

	REO (including all rare earth elements)	Nd	Pr	Dy	Tb	Y	La	Eu	Ce
Resources, tons	150,000,000	11,200,000	2,800,000	670,000	420,000	12,600,000	8,400,000	210,000	57,000,000
Source	USGS	MMTA	MMTA	USGS	Lenntech	Lenntech	MMTA	MMTA	USGS
Reserves, tons	140,000,000	8,000,000	2000,000	480,000	300,000	9,000,000	6,000,000	150,000	41,000,000
Source	USGS	MMTA		USGS	Lenntech	Lenntech	MMTA	MMTA	USGS
Annual mining, tons		20,000	5900	1600	320	10,500	31,000	370	42,000
Source		DOE	DOE	DOE	DOE	DOE	DOE	DOE	DOE

Table 8
Global mineral resources and annual mining of selected metals [65,66,68,69,23,55,71,73,4,43,44,75,11].

	Ag	Co	Pt	Ru	In	Te
Resources, tons	770,000	25,000,000	47,000	5000	65,000	48,000
Source	USGS, Rundqvist, Geoscience Australia	USGS	BGS	MMTA	Mikolajczak	USGS
Reserves, tons	599,000	7,200,000	8500	5000	65,000	24,000
Source	USGS + Rundqvist	USGS	BGS	MMTA	Mikolajczak	USGS
Annual mining, tons	26,000 (2013)	82,200 (2011)	192 (2013)	12 (2010)	782 (2012)	500 (2010)
Source	USGS	CDI	USGS	MMTA	USGS	USGS

also vary by year. We have used information from five reports [65,66,68,69,71]. USGS excludes data on Russian deposits, which are estimated to constitute 10% of the global silver reserves and resources [55]. According to the Australian government/Geoscience Australia, the silver resources of this important silver producer are 125,000 tonnes [23]. This data is included in the estimation of global resources. Silver is a metal commonly mined as a by-product, especially from zinc and lead deposits. Silver-bearing deposits and production is widely spread internationally, and at least 62 silver productng countries [52]. The increases in silver production are currently restricted by its nature as a by-product.

The USGS reports were also used as main information source for cobalt resources. The world-wide cobalt resources are estimated to be app. 25 Mt and the main producer for this metal during the 21st century has been the Democratic Republic of Congo. Known resources of cobalt are mainly concentrated in the Democratic Republic of Congo, Canada, Australia and Russia [73].

The global resources of platinum group metals (PGM) are estimated to be more than 100,000 tons [74]. PGM consist of six metals, of which platinum and ruthenium are considered in this study. Most of the PGM resources are found in four geological areas: The Bushveld Complex in South Africa, the Great Dyke in Zimbabwe, the Stillwater complex in USA, and the Norilsk area in Russia. Of these, the Bushveld complex hosts 75% of known global platinum resources. The proven and probable reserves and potential resources in the Bushveld complex have been estimated to be 35,000 tons [4]. Most of the global ruthenium production also comes from South Africa and the estimation for the global ruthenium resource was adopted from Minor Metals Trade Association [44].

Indium is a by-product from base metal, especially zinc and copper concentrates [59]. According to Mikolajczak [43]; only 30% of the indium in these concentrates is currently utilized due the lack of indium collection technology on smelters. China is currently the World's largest producer of indium in addition to Canada, Japan and South-Korea [70]. Indium Corporation [43] has estimated the indium resources in ores to be 65,000 t with additional resources in tailings and other mining-based mineral wastes.

Tellurium is another metal that is produced solely as a by-product, with the most important carrying metal being copper. There is no information available for the global resources of tellurium, but USGS [75] has estimated the reserves of tellurium to be 48,000 tonnes, including only tellurium reserves present in copper ores. Other possible sources for tellurium might be in conjunction with gold or lead and zinc deposits. The biggest reserves are estimated to be in Peru and USA. Tellurium can be produced in any country smelting copper ores if the technology needed for tellurium collection is available, but there is a lack of exact information available for the actual production figures. However, according to USGS [75] the most important producers in recent years have been Canada, Japan, Russia, Peru and USA.

3. Modelling critical metals demand

The global energy system is modelled with TIMES, a modelling framework, which has been developed under IEA Energy Technology System Analysis Program (ETSAP). The model seeks equilibrium between supply and demand for commodities. The price of the commodities is derived endogenously based on price elasticities. Optimization is based on maximizing the cumulative surplus of consumers and producers therefore assuming a financially rational decision making [35].

All relevant energy commodities are included in the model: fossil energy carriers, hydro power, biomass and the new clean energy technologies. The need for critical metals per unit of technology, which is given as exogenous data for the model. Also the expected future development of the metals need per unit of installed capacity is given to the model as input data.

3.1. Metals market

The amount of metal, which can be used for clean energy technologies, is constrained by metals markets. Clean energy technologies compete with other end-uses of the metal. This is explained in detail in the case of silver for solar applications [26]. The market share of the green energy technologies in each metals market in the initial state is based on literature. This data is comprised in Table 9 The calculated evolution of the metals demand is based on the metals need per technology unit and the annual installations estimated by the TIMES model. However competing end-uses for the metals exist as well. We expect the metals demand from competing end-uses to be in correlation with GDP. The global economy is divided in 17 subareas with individual GDP projections, same values as used generally in other IEA baseline future scenarios. An aggregated value is calculated based on these. The estimation is a very rough one, not taking into account that for some metals and some end-use markets there might be a

Table 9
Market share of various market segments in the current state based on literature.

	Nd	Pr	Dy	Tb	Y	La	Eu	Ce
Market share (year)	76% (magnets)	70% (magnets)	100% (magnets)	100% (magnets, phosphors)	54% (phosphors)	16% (batteries); 2% (phosphors)	100% (phosphors)	10% (batteries); 2% (phosphors)
Source	[25]	[25]	[25]	[25]	[25]	[25]	[25]	[25]

	Ag	Co	Pt	Ru	In	Te
Market share (year)	2% (PV); 3% (mirrors)	30% (Batteries); 9% (catalytes)	6% (catalysts)	16% (catalyst)	3% (CIS panels, LED lamps)	40% (CdTe panels)
Source	[21]	[10]	[8]	[8]	[49]	[62]

far stronger demand. This might for example be the case for REE used in light weight magnesium alloys, which are increasingly used in the automotive and aeronautical sectors. Another example might be silver in the medical and hygiene sectors. However a more comprehensive approach of the competing markets goes beyond the scope of this article.

Annual mining, reserves and resources potentially coming into production in the future set further boundaries to the metals availability in the markets. We use USGS data presented in Tables 7 and 8for current annual mining. Possible changes in the mining in the future are estimated by the TIMES model by taking into account the calculated demand for the metal as well as recycled metal flows.

3.2. Recycling

Recycling is included in the model. The term “recycled content (RC)” also called “recycling input rate” refers to the share of recycled metal in relation to total metal input. End-of-life recycling rate (EOL-RR) describes the share of the metal that is recovered after the life time of the products.

Recycled content (RC) and end-of-life-recycling rate (EOL-RR) in the global metals market in the current state are based on literature estimations, which are listed in Table 10 for the metals in the TIMES model. RC is lower than EOL-RR for two reasons. The recycled metal input is limited partly because of long lifetimes of many products but also since the metals markets show high growth rates and thus primary input from mining industry is dominating. The EOL-RR varies in the current state, but we expect, that it will increase significantly in the future by increasing scarcity and prices of the metals. Our estimations for the evolution of the EOL-RR are also given in Table 10. The estimations reflect current knowledge of technical possibilities. In the case of rare earth elements recycling is almost absent currently. Recycling technologies and schemes exist, particularly for magnets and motors and other applications, where the metal is not dispersed. However there are several challenges such as costly and extensive dismantling of the magnet [51]. However it is a reasonable assumption that with increasing scarcity the in-use stocks will be regarded as future mines and increasing prices will allow building up a recycling infrastructure [29].

The amount of recycled metal flowing into the market depends not only on the recycling rate but also on the life expectancy of the technologies. We assume a general life expectancy of 20 years and a processing time period for the scrap of one year resulting in a flow speed of 21 years. In the case of the modelled green energy technologies we use individual life expectances varying between the technologies and the time. Table 11 presents the data for some selected technologies.

Table 11
Life expectances of some selected green energy technologies.

	2010	2050
PV	21	31
CSP	23	31
Windmills	21	21
Electric vehicles	15	15

4. Results

We have modelled one possible path for the evolution of the global energy system. Global GDP is expected to grow annually approximately 2% resulting in an increase of 130% from 2010 to 2050. The growth in GDP is related to a respective growth in global primary energy production, more than 40% in the same time period. Fig. 2 presents the modelled primary energy production with the distribution between the various energy sources. Data for the year 2010 as initial state is based on IEA statistics [32].

The global electricity production, presented in Fig. 3, shows an even higher growth of almost 150% from 2010 to 2050 when compared to the growth in primary energy consumption and GDP. This reflects the assumed shift of the energy sector from fuels to electricity. Nuclear and hydro power is expected to grow 240% and 120% respectively.

In 2010 solar and wind power are minor sources for electricity production constituting together only 2% of the global electricity. However over the time period of 40 years these technologies show the highest growth rates: wind power will grow 24fold and solar power 86fold in absolute terms according to the model. Thus in 2050 they form 17% and 6% of the global electricity production respectively. This is comparable with nuclear electricity, which is assumed to be responsible for one fifth of the global electricity consumption in 2050.

We expect the internal combustion engine technology to be replaced partly by electric vehicles. ICE passenger vehicles will come down from the current level of 700 million cars to 400–450 million cars. Until 2030 new car sales will shift more towards hybrid cars (HEV and PHEV), but after 2040 full electric vehicles will gain market share. In 2050 we expect 12% to be BEV, 26% ICE and the remainder hybrid cars. Fuel cells are not expected to gain any significant market share. Fig. 4 illustrates the situation.

Table 10
Data on recycling used in the TIMES model. Present state data is based on literature [28,29].

	Nd	Pr	Dy	Tb	Y	La	Eu	Ce	Ag	Co	Pt	Ru	In	Te
RC, present state	<1%	<1%	<1%	<1%	0%	<1%	<1%	<1%	32%	32%	50%	50%	<1%	<1%
EOL-RR, present state	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	45%	60%	>50%	5–25%	<1%	<1%
EOL-RR, 2050	80%	70%	95%	50%	50%	70%	60%	50%	90%	90%	90%	90%	90%	90%

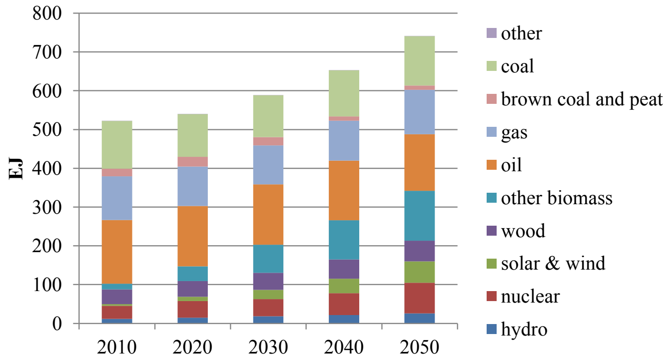

Fig. 2. Global primary energy production from 2010 to 2050.

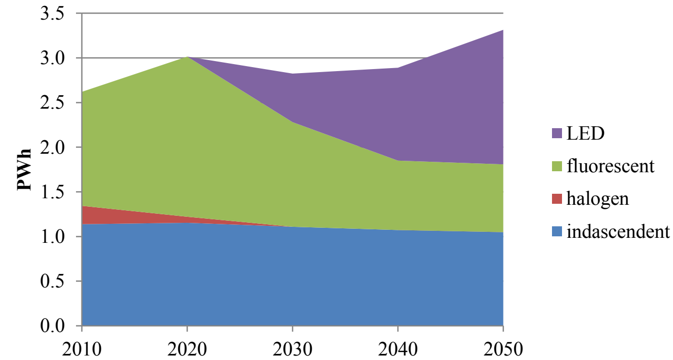

Fig. 5. Electricity demand for lighting by lamp technology.

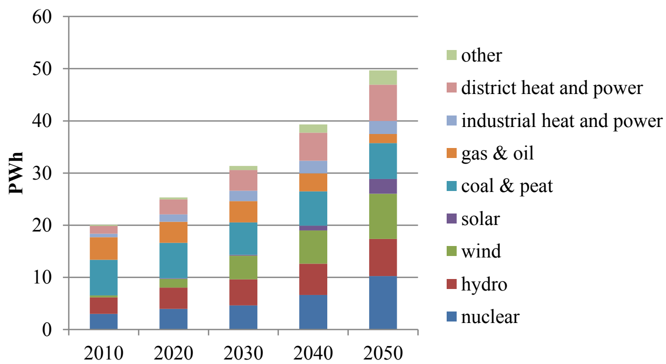

Fig. 3. Global electricity production by source.

In the case of lighting the current energy efficient lamps – halogen lamps and fluorescent lamps will be replaced by more efficient LED technology. In 2050 already 45% of lighting electricity will be used by LED lamps. The number of incandescent lamps will remain flat. Fig. 5 presents the modelled evolution of lighting electricity.

The metals demand for a number of chosen critical metals is calculated by the model assuming the described global shift. Below two sets of data are presented. The need of metal which is resulting from the market expansion of the clean energy technologies, is compared to the global reserves and global resources, known in the present state. The blue bar in the chart indicates the share of the known metals reserves (or resources) which need to be mined until 2050 in order to realize this global energy scenario. The red bar shows the cumulative need of the respective metal until 2050, also in relation to the known global reserves (or resources). The cumulative need of the metal is higher than the need for mining. The difference can be explained in most cases through recycling as the same metal atoms circulate in the material loop between the in-use stock and recycling. Figs. 6 and 7 present the results.

The direst situation can be found for silver, which is needed especially in solar energy technologies: several PV technologies as well as CSP. Silver is also consumed in electronics and therefore the expanding EV stock results in further demand of silver. The demand will exceed known global resources by more than 300% and currently classified reserves by almost 450%.

Indium and tellurium are two other metals essential for solar energy technologies. Additionally indium is used in electronics in electric vehicles and in LED lamps. The modelled cumulative demand until 2050 will be 170% (In) or 270% (Te) with respect to known global reserves or 130% (Te) with respect to global resources. Almost 70% of the currently known resources or both metals will be mined until 2050; the remaining cumulative need will be covered through recycling of the metal.

Ruthenium is another critical metal needed in solar technology. The cumulative consumption until 2050 is 73% of currently known resources. PGM metals are recycled already in the present state and therefore only 35% of the known resources need to be mined until 2050. For platinum the cumulative consumption is almost three times as high as the present reserves, however through an extensive recycling already today in place this need can be covered. Also the platinum resources are far higher than current reserves. In the case of rare earth metals neodymium, dysprosium and lanthanum

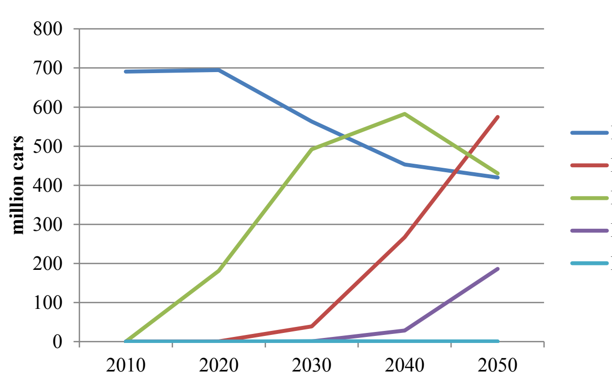

Fig. 4. Private cars in use.

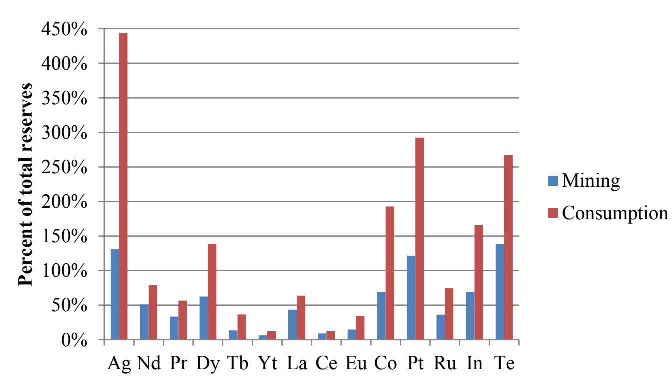

Fig. 6. Metals cumulative need for clean energy technologies until 2050 in relation to global mineral reserves.

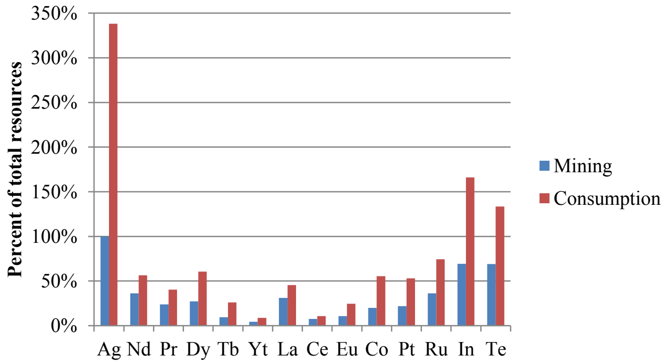

Fig. 7. Metals cumulative need for clean energy technology until 2050 in relation to global mineral resources.

are most critical according to the model. Neodymium and dysprosium are needed in permanent magnets in motors and generators, whereas lanthanum is needed in fuel cells and lighting applications. Only in the case of dysprosium does the cumulative need exceed the presently known reserves, but not presently known resources. The only market for dysprosium is permanent magnets and for magnets it is reasonable to assume an effective recycling infrastructure. Therefore only some 60% of the presently known reserves need to be mined until 2050. The share of the known resources mined until 2050 will be 37% (Nd), 29% (Dy) and 30% (La) according to the model.

5. Discussion

5.1. Geological data accuracy

The data used for modelling in this study represent the global reserves and resources of the modelled metals. Hence two sets of modelling results are presented in this work. The data quality varies thus from high to low level of certainty. Information from USGS was used as primary information for most of the metals. USGS information is a collection from different sources, and cannot be compared in reliability to company reports made after established reporting codes e.g. JORC ([33]). The strength of the USGS data in the modelling perspective is, however, that it's providing an estimate over global production and resources of critical metals that individual company reporting cannot provide.

The results based on present global mineral reserve data form a basis for the analysis. Due to the ongoing exploration and probable future increase in the prices for critical metals, parts of the currently known resources will likely turn out to be mineable during the coming decades. The use of information over resources in modelling gives an estimate of the time the currently known critical metal resources would last, if all these resources turn out to be mineable. In real terms the known resource changes according to the amount of mined ore (reducing effect) and new resources discovered through exploration (increasing effect). In addition, local conditions (environmental, social and legal) may prevent the utilization of some resources, notably the very low-grade deposits [17,24,41,47,50]. The amount of resources and their currently mineable part, reserves, are thus changing in time, which creates uncertainty on any estimation that attempts to determine how long the resources will last. However, by using the information on the currently known resources we can estimate theoretical future bottlenecks which could hinder the technical development and streamlining of new energy technologies.

5.2. Recycling and substitution

According to our modelling the cumulative demand for silver will be 2.6 million tons until 2050, which is 340% (440%) with respect to the currently known global resources (reserves). Less than 30% of the cumulative demand can be covered by mining resources. Since solar applications is one important market area for silver, and solar devices generally have a life expectancy of 20–30 years, and we have even in the present state a well functioning recycling system for silver, a significant part of the cumulative consumption can be satisfied by secondary silver sources. According to the model 55% of the demand could be recycled metal, and the remainder, some 15% should be a substitute. A minor part of the recycled metal is from the substituting metals.

Silver constitutes already now a significant part of the production cost of c-Si panels, 6–14%, and any significant rise of the silver price would have a significant effect on the c-Si producing industry [36]. Higher silver prices should be expected in the case of the extra demand occurring through an intensive building up of the green energy infrastructure. There are currently known various possibilities for substitution such as the “metal wrap-through” technology or substitution to a large degree by copper. These approaches are already taken into account in the decreasing silver content of c-Si panels as indicated in Fig. 1. Therefore a further need for substitution of 15% needs to come from other technologies. Another important silver demand is expected to occur through CSP technology, where silver is needed as reflecting coating on the mirrors. As Phil states [48] there exists a possibility of changing from silver to aluminium. However since the maximum reflectivity of 95% would be decreased to 90% a scale up of the reflector area is needed, which influences the plant economy. If this new approach is economically feasible goes behind the scope of this article.

Other sources of possible material restrictions for solar energy applications are indium, tellurium and ruthenium. Tellurium is part of the active semiconducting layer of the CdTe. According to IEA a possibility to reduce tellurium intensity by 75% could exist by reducing the respective layer thickness, however it is unclear if this approach is technically feasible [36].

Indium is needed in ITO layers (indium-tin-oxide), which is used as conducting layer in several thin film technologies. As alternatives FTO (fluorine doped tin oxide) and AZO (aluminium doped zinc oxid) could be used. Another green energy technology relying on indium is LED lighting. Zinc oxid (ZnO) has been investigated as a possible substitute for the semiconducting material. However due to stability aspects currently no feasible substitute exists [38].

Generators and motors based on permanent magnets (NdFeB) have several advantages over conventional technologies: high torque, light weight and compact size. Dysprosium, which is more critical than neodymium, is needed for temperature resistance. To reduce the dependency on REE some substituting technologies exist, such as the HTS generator [39] or induction generators for wind applications. For electric vehicles SmCo motor could be an alternative [30]. CRM Innonet has analysed several possible future technologies to reduce the dependency on REE metals: REE free switch reluctant motors, brushless permanent magnet machine construction, Ce-TM magnet for electric traction motors and motor topology based on hardmagnetic ferrites. However, all these technologies are still not rife for the market and it remains unclear whether the market introduction will be successful [CRM [13]].

The recently published IPCC Fifth Assessment Report, addresses the question of climate change mitigation [16] by modelling an adaptation of the global energy system. IPCC defines technical potentials for renewable energy sources, which do not take into account any specific barriers such as economical factors, land-use questions, social barriers or material constraints. The technical

Table 12
Technical potentials for some selected renewable energy sources by IPCC [45].

EJ/a	Low estimation	High estimation
Solar photovoltaics	1338	14,778
Solar CSP	248	1791
Wind power	85	580

potentials for solar energy and wind energy, even the low estimations, are very high, as indicated in Table 12.

Within these technical potentials the report presents a broad range of scenarios. The report assesses more than 1200 emission scenarios, which are categorized according to their climate impact. Our interest lies in the low-stabilisation scenarios, which aim at atmospheric GHG levels in the range of 430–530 ppm CO_2eq. Within this group the scenarios are further divided into high energy demand and low energy demand scenarios, depending on whether the emphasis is on energy efficiency (low energy scenarios) or renewable energy (high energy scenarios). In the low energy demand scenarios the solar electricity generation varies very much with a median value of approximately 22 EJ/year. The median for the high energy scenarios is 30 EJ/year. For wind power the respective median values are ~20 EJ/year and ~32 EJ/year by 2050.

According to our model the wind energy generation could be 31 EJ/year. The calculations show, that from the perspective of global REE resources there seem not to exist any serious long term bottlenecks, provided a sufficient mining capacity. However, in the case of solar energy our study shows severe material restrictions. Even the build-up of a solar infrastructure for a modest solar energy supply of 10 EJ/year (comprising both photovoltaics and CSP) will face serious material constraints with the technologies currently known. Doubling or tripling the solar generation capacity to the range of 20–30 EJ/year, which would refer to the IPCC low and high energy median case, would require a whole new set of technologies, not dependent on critical metals.

5.3. Concluding remarks

The global energy sector is expected to undergo a shift towards green technologies such as solar and wind energy, electromobility and energy efficiency in the coming decades. Often these technologies rely on critical metals. This article analysis possible bottlenecks arising from the availability of critical metals during the global change of the energy sector. According to the analysis most serious problems can arise in the solar energy sector through the availability of silver, which is used in photovoltaics and CSP. Other possible material restrictions could be caused by indium, tellurium or ruthenium. It is therefore highly recommendable to concentrate efforts in developing substitutions for the critical metals or even new solar energy technologies, which are not dependent on critical elements.

The future renewable energy projections presented by IPCC do not consider material availability aspects. According to our analysis solar energy future projections presented in the IPCC Fifth Assessment Report [16] do not seem to be realizable with the currently known technologies and metals resources.

Acknowledgements

The article is part of a larger research project called "Low Carbon Finland 2050 platform" primarily funded by Tekes. Valuable comments to the article have been provided by Prof. Mikael Höök, Uppsala University and Simon Davidsson, Uppsala University.

References

[1] B.A. Andersson, Materials availability for large-scale thin-film photovoltaics, Prog. Photovolt. 8 (2000) 61–76.
[2] G. Angerer, L. Erdmann, F. Marschneider-Weidemann, M. Scharp, A. Lüllmann, V. Handke, M. Marwede, Rohstoffe für Zukunftstechnologien. Einfluss des branchenspezifischen Rohstoffbedarfs in rohstoffintensiven Zukunftstechnologien auf die zukünftige Rohstoffnachfrage, Stuttgart: Fraunhofer IRB Verlag, Germany, 2009.
[3] A.S. Arico, S. Siracusano, N. Bruguglio, V. Baglio, A.D. Blasi, V. Antonucci, Polymer electrolyte membrane water electrolysis: status of technologies and potential applications in combination with renewable power sources, J. Appl. Electrochem. 43 (2013) 107–118.
[4] BGS., Mineral Profile Platinum, 2009 (accessed 13.03.13.), https://www.bgs.ac.uk/mineralsuk/statistics/mineralProfiles.html.
[5] A. Brouzgou, S.Q. Song, P. Tsiakaras, Low and non-platinum electrocatalysts for PEMFCs: current state, challenges and prospects, Appl. Cat. B Env. 127 (2012) 371–388.
[6] M. Buchert, Rare Earths – a Bottleneck for Future Wind Turbine Technologies? Wind Turbine Supply Chain & Logistics, 2011. Berlin 29th August 2011, http://www.oeko.de/oekodoc/1296/2011-421-en.pdf (accessed 15.03.13).
[7] M. Buchert, W. Jenseit, S. Dittrich, F. Hacker, E. Schueler-Hainsch, K. Ruhland, S. Knöfel, D. Goldmann, K. Rasenack, F. Treffer, Resourceneffizienz und resourcenpolitische Aspekte des Systems Elektromobilität, in: Arbeitspaket 7 des Forschungsvorhabens OPTUM: Optimierung der Umweltlastungspotentiale von Elektrofahrzeugen; 2011, 2011. http://www.oeko.de/oekodoc/1334/2011-449-de.pdf.
[8] J. Butler, Platinum, 2012. http://www.platinum.matthey.com/publications/pgm-market-reviews/market-review-archive/platinum-2012 (accessed 15.3.13).
[9] CIM Canadian Institute of Mining, Metallurgy and Petroleum, National Instrument 43-101, 2013. http://web.cim.org/standards/MenuPage.cfm?sections=177,181&menu=229 (accessed 15.04.13.).
[10] CDI, Cobalt Development Institute, 2013. http://www.thecdi.com/ (accessed 25.02.13).
[11] CDI, Cobalt Development Institute. Cobalt Supply and Demand 2012, 2012. http://www.thecdi.com/cdi/images/documents/Cobalt%20Facts%20-%20Supply%20%20Demand%20-%2012.pdf (accessed 15.03.13).
[12] F.V. Conte, Battery and battery management for hybrid electric vehicles: a review, Elektrotechnik Inf. 123 (10) (2006) 424–431.
[13] CRM Innonet, Roadmap to the Substitution of Critical Raw Materials in Electric Motors and Drives, 2015. http://www.isi.fraunhofer.de/isi-wAssets/docs/v/en/publikationen/CRM-InnoNet-Roadmap-for-CRM-substitution_Electric_Motors_And_Drives.pdf.
[14] DOE, US Department of Energy. Critical Materials Strategy, 2011. http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf (accessed 15.04.13).
[15] U. Eberle, B. Mueller, R. von Helmholt, Fuel cell electric vehicles and hydrogen infrastructure: status 2012, Energy Environ. Sci. 5 (2012) 8780–8798.
[16] O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, I. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, J.C. Minx (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
[17] W.G. Ernst, Sustainable energy and mineral resource extraction and consumption—can a viable biosphere be preserved?, in: J.P. Richards (Ed.), Mining, Society, and a Sustainable World, Springer-Verlag, Berlin, 2009.
[18] EC, in: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Roadmap for Moving to a Competitive Low Carbon Economy in 2050, 2011. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0112.
[19] EPIA, Solar Generation 6. Solar Photovoltaic Electricity Empowering the World, 2011. http://www.epia.org/index.php?id=18 (accessed 15.4.13).
[20] M.A. Fetchenko, S.R. Ovshinsky, B. Reichman, K. Young, C. Fierro, J. Koch, A. Zallen, W. Mays, T. Ouchi, Recent advances in NiMH battery technology, J. Power Sources 165 (2007) 544–551.
[21] Fortis Bank Nederland, VM Group, Silver Book, 2010. http://www.virtualmetals.co.uk/pdf/FBNSB0610.pdf (accessed 15.10.12).
[22] F. Gao, Y. Wang, J. Zhang, D. Shi, M. Wang, R. Humphrey-Baker, P. Wang, S.M. Zakeeruddin, M. Grätzel, A new heteroleptic ruthenium sensitizer enhances the absorptivity of mesoporous titania film for a high efficiency dye-sensitized solar cell, Chem. Commun. 23 (2008) 2635–2637.
[23] Geosience Australia/Australian Gouvernment, Australia's Identified Mineral Resources, 2013. http://www.ga.gov.au/corporate_data/78988/78988_AIMR_2013.pdf (accessed 13.3.13).
[24] D. Giurco, C. Cooper, Mining and sustainability: asking the right questions, Miner. Eng. 29 (2012) 3–12.
[25] T. Goonan, Rare Earth Elements – End Use and Recyclability, 2011. USGS Scientific Investigations Report 2011-5094, http://pubs.usgs.gov/sir/2011/5094/.
[26] L. Grandell, A. Thorenz, Silver supply risk analysis for the solar sector, Renew.

Energy 69 (2014) 157–165.
[27] M. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables (version 39), Prog. Photovolt. Res. Appl. 20 (2012) 12–20.
[28] T.E. Grädel, J. Allwood, J.-P. Pirat, M. Buchert, C. Hagelüken, B.K. Reck, S.F. Sibley, G. Sonnemann, What do we know about metal recycling rates? J. Ind. Ecol. 15 (2011) 355–366.
[29] T.E. Grädel, M. Buchert, B.K. Reck, G. Sonnemann, Assessing Mineral Resources in Society: Metal Stocks and Recycling Rates, 2011. ISBN 978-92-807-3182-0, http://www.unep.org/resourcepanel/Portals/24102/PDFs/Metals_Recycling_Rates_110412-1.pdf.
[30] O. Gutfleisch, M.A. Willard, E. Brueck, C.H. Chen, S.G. Sankar, J.P. Liu, Magnetic materials and devices for the 21st century: stonger, lighter and more energy efficient, Adv. Mater. 23 (2011) 821–842.
[31] Himanen Olli, VTT. Personal. Commun. 14.5.2013.
[32] IEA, World Energy Statistics and Balances http://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en. Accessed in 15.2.2014.
[33] JORC, Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (The JORC Code), 2012 [online], http://www.jorc.org (The Joint Ore Reserves Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia).
[34] Kauranen P, VTT. Personal communication 14.2.2013.
[35] T. Koljonen, A. Lehtilä, The impact of residential, commercial, and transport energy demand uncertainties in Asia on climate change mitigation, Energy Econ. 34 (2012) S410–S420.
[36] F. Lehner, A. Rastogi, S. Sengupta, F. Vuille, S. Ziem, Securing the Supply Chain for Wind and Solar Energy (RE-SUPPLY), 2012. Final Report, E4tech and Avalon Consulting for IEA-RETD, 2012, http://iea-retd.org/wp-content/uploads/2012/11/RE-SUPPLY-final-report.pdf.
[37] Lenntech, http://www.lenntech.com/periodic/elements/, (accessed 15.04. 13).
[38] J.S. Liu, C.X. Shan, H. Shen, B.H. Li, Z.Z. Zhang, L. Liu, G. Zhang, D.Z. Shen, ZnO light-emitting devices with a lifetime of 6.8 hours, Appl. Phys. Lett. 101 (2012), 011106.
[39] J. Lloberas, M. Sumper A,Sanmarti, X. Granados, A review of high temperature superconductors for offshore wind power synchronous generators, Renew. Sustain. Energy Rev. 38 (2014) 404–414.
[40] C. Lämmel, M. Schneider, M. Weiser, A. Michaelis, Investigations of electrochemical double layer capacitor (EDLC) materials – a comparison of test methods, Mat.-wiss. U. Werkst. 44 (No 7) (2013) 641–649.
[41] L. Mason, T. Prior, G. Mudd, D. Giurco, Availability, addiction and alternatives: three criteria for assessing the impact of peak minerals on society, J. Clean. Prod. 19 (2011) 958–966.
[42] Y. Masui, H. Hurikawa, M. Iwasuki, W. Park, Preparation of YAG: Ce nanochrystals by an environmentally friendly wet process. Effect of Ce3+ concentration on photoluminescent property, J. Ceram. Process. Res. 12 (No. 3) (2011) 348–351.
[43] C. Mikolajczak, Availability of Indium and Gallium, Indium Corporation, 2009. http://www.commodityintelligence.com/images/2010/jan/11%20jan/availability_of_indium_and_galliumwhite_papermikolajczak_sept09.pdf (accessed 12.05.13).
[44] Minor Metals Trade Association MMTA, http://www.mmta.co.uk/metals, accessed 15.4.2013.
[45] W. Moomba, F. Yomba, M. Kami moto, L Nyberg Maurice, K. Urata, T. Weir, Introduction: renewable energy and climate change, in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Marschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechon (Eds.), .IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, 2011.
[46] R.L. Moss, E. Tzimas, H. Kara, P. Willis, J. Kooroshy, Critical Metals in Strategic Energy Technologies, JRC SETIS, 2011. ISBN 978-92-79-20698-6.
[47] G.M. Mudd, The environmental sustainability of mining in Australia: key mega-trends and looming constraints, Resour. Policy 35 (2010) 98–115.
[48] E. Pihl, D. Kushnir, B. Sanden, F. Johnsson, Material constraints for concentrating solar thermal power, Energy 44 (2012) 944–954.
[49] Polinares, Fact Sheet: Indium, 2012. Polinares Working Paper Nr. 39, http://www.polinares.eu/docs/d2-1/polinares_wp2_annex2_factsheet5_v1_10.pdf (accessed 15.03.13).
[50] T. Prior, J. Daly, L. Mason, D. Giurco, Resourcing the future: using foresight in resource governance, Geoforum 44 (2013) 316–328.
[51] Jelle H. Rademaker, René Kleijn, Yongxiang Yang, Recycling as a strategy against rare earth element criticality: a systemic evaluation of the potential yield of NdFeB magnet recycling, Environ. Sci. Technol. 47 (18) (2013) 10129–10136.
[52] C. Reichl, M. Schatz, G. Zsak, World Mining Data. Welt Bergbau Daten, vol. 28, Minerals Production, Wien, 2013. http://ec.europa.eu/eip/raw-materials/en/system/files/ged/20%20WMD2013.pdf.
[53] E. Riedel, in: C. Janiak, T.M. Klapötke, H.-J. Meyer (Eds.), Moderne Anorganische Chemie, second ed., De Gruyter Verlag, 2007. ISBN 3110178389.
[54] C.R. Ronda, Phosphors for lamps and displays: an applicational view, J. Alloys Compd. 225 (1995) 534–538.
[55] Rundqvist DV, Cherkasov SV. Infrastructure corridors in Russia - pros and cons: a mineral resources approach http://www.google.de/url?sa=t&rct=j&q=&esrc=s&frm=1&source=web&cd=3&ved=0CDQQFjAC&url=http%3A%2F%2Fwww.schillerinstitute.org%2Fmedia%2FCherkasov-Rundqvist.ppt&ei=8inJU6-CH7HY4QTr94DYDQ&usg=AFQjCNFEXpYVzFfyJ5a9iwBuGk-x205pYg&sig2=zok_vAXJh2puQnjZYcZKTQ. (accessed 13.03.13).
[56] I. Råde, B.A. Andersson, Requirement for metals of electric vehicle batteries, J. Power Sources 93 (2001) 55–71.
[57] T. Saga, Advances in crystalline silicon solar cell technology for industrial mass production, NPG Asia Mater. 2 (3) (2010) 96–102.
[58] M.J. Scholand, H.E. Dillon, Life-cycle Assessment of Energy and Environmental Impacts of LED Lighting Products Part 2: LED Manufacturing and Performance, 2012, http://dx.doi.org/10.2172/1044508.
[59] U. Schwarz-Schampera, P.M. Herzig, Indium: Geology, Mineralogy, and Economics, Springer-Verlag, Berlin, 2002.
[60] Semi PV Group Europe, International Technology Roadmap for Photovoltaics (ITRPV.net) Results 2011, 2011. http://www.itrpv.net/doc/roadmap_itrpv_2012_full_web.pdf (accessed 3.03.13).
[61] R.N. Singh, D. Mishra, A.S.K. Anindita Sinha, A. Singh, Novel electrocatalysts for generating oxygen from alkaline water electrolysis, Electrochem. Commun. 9 (2007) 1369–1373.
[62] STDA Selenium Tellurium Development Association. www.stda.org, (accessed 25.02.13).
[63] S. Tanabe, S. Fujita, S. Yoshihara, A. Sakamoto, S. Yamamoto, YAG glass-ceramic phosphors for white LED (II): luminiscence characteristics, Proc. SPIE 5941 (2005), 594112–1.
[64] USGS, Principles of a Resource/Reserve Classification for Minerals, Circular 831; 1980, 1980. http://pubs.usgs.gov/circ/1980/0831/report.pdf.
[65] USGS, Mineral Commodity Summaries, Silver; 2006, 2006. http://minerals.usgs.gov/minerals/pubs/commodity/silver/silvemcs06.pdf (accessed 13.03.13).
[66] USGS, Mineral Commodity Summaries, Silver; 2009, 2009. http://minerals.usgs.gov/minerals/pubs/commodity/silver/mcs-2009-silve.pdf (accessed 13.03.13).
[67] USGS, 2010 Mineral Yearbook, Rare Earths (Advanced Release); 2012, 2012. http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2010-raree.pdf (accessed 15.04.14).
[68] USGS, Mineral Commodity Summaries, Silver; 2012, 2012. http://minerals.usgs.gov/minerals/pubs/commodity/silver/mcs-2012-silve.pdf (accessed 13.03.13).
[69] USGS, Mineral Commodity Summaries, Silver; 2013, 2013. http://minerals.usgs.gov/minerals/pubs/commodity/silver/mcs-2013-silve.pdf (accessed 13.03.13).
[70] USGS, Mineral Commodity Summaries, Indium; 2013, 2013. http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2013-indiu.pdf (accessed 13.03.13).
[71] USGS, Mineral Commodity Summaries, Silver; 2014, 2014. http://minerals.usgs.gov/minerals/pubs/commodity/silver/mcs-2014-silve.pdf (accessed 13.03.14).
[72] USGS, Mineral Commodity Summaries, Rare Earths; 2014, 2014. http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2014-raree.pdf (accessed 15.04.14).
[73] USGS, Mineral Commodity Summaries, Cobalt; 2014, 2014. http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2014-cobal.pdf (accessed 13.03.14).
[74] USGS, Mineral Commodity Summaries, Platinum Group Metals; 2014, 2014. http://minerals.usgs.gov/minerals/pubs/commodity/platinum/mcs-2014-plati.pdf (accessed 13.03.14).
[75] USGS, Mineral Commodity Summaries, Tellurium; 2014, 2014. http://minerals.usgs.gov/minerals/pubs/commodity/selenium/mcs-2014-tellu.pdf (accessed 13.03.14).
[76] R. von Helmholt, U. Eberle, Fuel cell vehicles: status, J. Power Sources 165 (2007) 833–843.
[77] K. Zeng, D. Zhang, Recent progress in alkaline water electrolysis for hydrogen production and applications, Prog. Energy Consum. Sci. 36 (2010) 307–326.
[78] Martin A. Green, Emery Keith, Hishikawa Yoshihiro, Warta Wilhelm, D. Ewan, Dunlop: Solar cell efficiency tables (version 44), Prog. Photovolt: Res. Appl. 22 (2014) 701–710, http://dx.doi.org/10.1002/pip.2525.