EUROPEAN PARLIAMENT

Science and Technology Options Assessment

S T O A

Future Metal Demand from Photovoltaic Cells and Wind Turbines

Investigating the Potential Risk of Disabling a Shift to Renewable Energy Systems

FINAL REPORT

PE 471.604

EUROPEAN PARLIAMENT

DIRECTORATE GENERAL FOR INTERNAL POLICIES
DIRECTORATE G: IMPACT ASSESSMENT
SCIENCE AND TECHNOLOGY OPTIONS ASSESSMENT

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Since the world cannot afford any further delay in climate change mitigation, this study investigates whether the supply of raw materials may hinder the successful transition to a renewable energy supply by looking at the future metal demand from photovoltaic cells and wind turbines. The findings show that major deployment of photovoltaic cells and wind turbines may have a serious impact on the future demand of 8 *significant elements* - gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium. The current recycling rate of these metals is less than one percent, and material substitution possibilities are found to be very limited. Due to the long lifespan of these technologies, increased demand will have to be met almost exclusively by virgin raw material extraction, which in turn will have major consequences for society and the environment, including large emissions of greenhouse gases.

To tackle these issues and to avoid that the demand for certain raw materials will outstrip supply and cause a delay to any major deployment of photovoltaic cells and wind turbines, technological alternatives will have to be sought and implemented, as well as the concept of raw materials criticality will have to be reassessed and integrated into energy roadmaps and targets. If this is not done, bottlenecks in the future supply of these elements entail a risk of disabling a shift towards low-carbon, and eventually carbon-free, economies - thereby disrupting European and global efforts to tackle climate change.

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About the Study and the Author

This study was carried out by Isak Öhrlund during an internship at the Science and Technology Options Assessment (STOA) unit, European Parliament, in fall 2011. Isak Öhrlund holds a BSc in Environmental Science from the Swedish University of Agricultural Sciences and was (at the time of this study) in his last year of an MSc in Sustainable Development at Uppsala University, Sweden.

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Disclaimer

Note

Within the scope of this study, the author has used and assessed numerous information sources in a carefully neutral fashion, complying all the time with established principles of research. Nevertheless the author cannot guarantee that what is forecasted will actually occur, particularly in the case of supply and demand balance - since there are numerous influencing factors which can change at short notice.

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Abbreviations and Acronyms

AlNiCo	Aluminium Nickel Cobalt
a-Si	Amorphous Silicon
ATO	Antimony Tin Oxide
BGS	British Geological Survey
CdTe	Cadmium Telluride
CIS/CIGS	Copper Indium Selenide / Copper Indium Gallium (di)Selenide
CO_2	Carbon Dioxide
CPV	Concentrator Photovoltaics
c-Si	Crystalline Silicon
DSSC	Dye-sensitized Solar Cell
ECEs	Energy Critical Metals
ECN	Energy research Center of the Netherlands
ELV	End-of-life Vehicles
EM	Electromagnet
EPIA	European Photovoltaic Industry Association
EREC	European Renewable Energy Council
EU & EU-27	European Union (with its current 27 member states)
EU Com	European Commission
GWEC	Global Wind Energy Council
H/M	High/Medium
HREE	Heavy Rare Earth Elements (atomic number 39 and 64-71)
HTS	High-temperature Superconductor
IEA	International Energy Agency
ITO	Indium Tin Oxide
LREE	Light Rare Earth Elements (atomic number 21 and 57-63)
NdFeB	Neodymium-iron-boron
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Co-operation and Development
PM	Permanent-magnet
PV / PVs	Photovoltaic / Photovoltaics
REE	Rare Earth Elements (atomic number 21, 39 and 57-71)
REE-Fe-Nb	Rare Earth Elements-Iron-Niobium
REY	Rare Earths and Yttrium
RICS	Royal Institute of Chartered Surveyors
SET	Strategic Energy Technology
SmCo	Samarium Cobalt
TCO	Transparent Conductive Oxide
UNEP	United Nations Environment Programme
USGS	US Geological Survey
WEEE	Waste Electrical and Electronic Equipment
WWF	World Wildlife Fund

Units

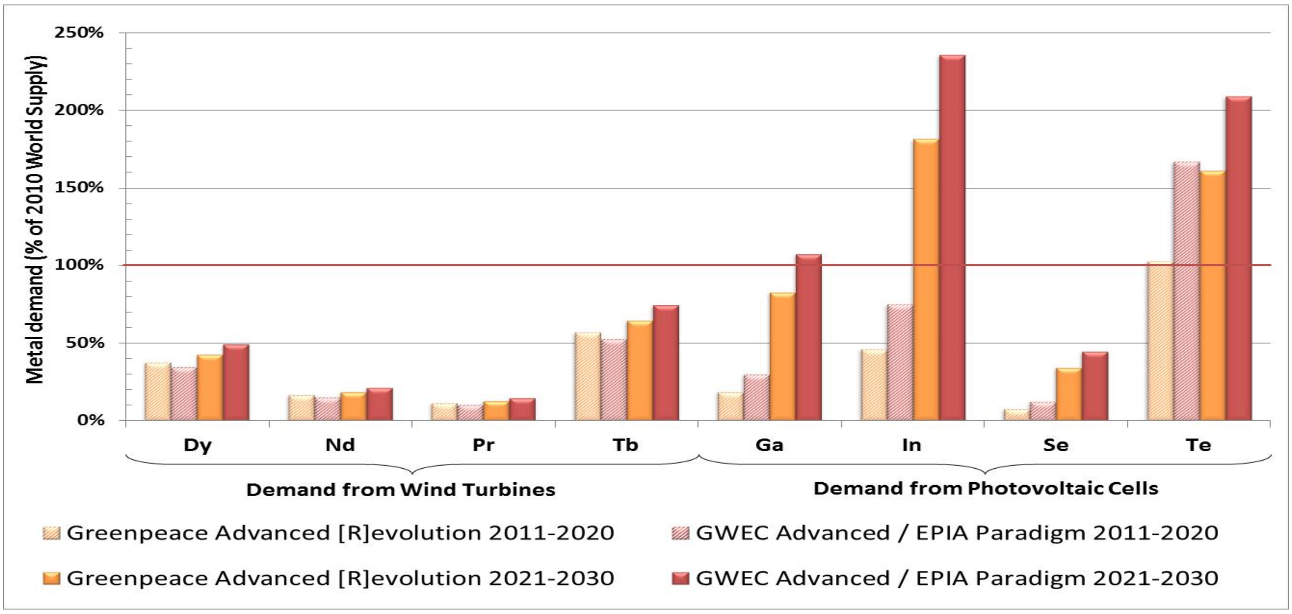
Btu	British thermal unit	**Wh**	watt-hours
g	gram	**Wp**	watt-peak
ppm	Parts Per Million	**t**	tonne
W	watt	**SI prefixes: k, M, G, T**	kilo (10^3), mega (10^6), giga (10^9), terra (10^{12})

Note: W and Wp are used interchangeably in the energy mix scenarios as it has been assumed by EPIA (2011a; 2011b)[17,18] that 1 W = 1 Wp.

Executive Summary

Our climate is rapidly changing, and to lower the risk of crossing a tipping point where dangerous climate change will be irreversible, greenhouse gas emissions must decrease rapidly within the coming decade and eventually be eliminated in a few decades ahead. To accomplish this, we will inevitably have to abandon fossil fuels and shift towards renewable energy systems, such as photovoltaic cells and wind turbines. Recent events have however indicated that the supply of raw materials used in advanced and emerging technologies may not be able to keep up with the rapidly increasing demand.

Since the world cannot afford any further delay in climate change mitigation, this study investigates whether the supply of raw materials may hinder the successful transition to a renewable energy supply by looking at the future metal demand from photovoltaic cells and wind turbines. The findings show that major deployment of photovoltaic cells and wind turbines may have a serious impact on the future demand of 8 *significant elements* - gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium.



Yearly global metal demand from photovoltaic cells and permanent-magnet wind turbines 2011-2030 under the most optimistic deployment scenarios used in the study.

Following the identification of the 8 significant elements, the study looks at recycling rates and practices, as well as potential material and technology substitution options. It is found that current recycling rates of the 8 significant elements are less than one percent, that material substitution possibilities are very limited and that technology substitution options are moderately available. The findings suggest that, if photovoltaic cells and wind turbines continue to rely on the 8 significant elements, demand will increase substantially and has to be met almost exclusively by virgin raw material extraction, due to a relatively low recycling potential during the next two decades. A major increase in virgin raw material extraction will have severe consequences for local communities and the environment, including large emissions of greenhouse gases.

Based on the findings and the experience gained while conducting the study, a set of policy recommendations are given. The recommendations are:

1. **To Integrate Raw Materials Criticality in Energy Strategies and Targets**
   - To prevent potential supply bottlenecks and unsustainable price developments, the European Union and the rest of the world must integrate knowledge on raw material constraints in energy strategies and targets.
2. **To Cooperate on the Management of Raw Materials**
   - To prevent potential supply bottlenecks of important raw materials and to ensure economic, political, social and environmental sustainability, the European Union must work together with the rest of the world on establishing a global framework for cooperation on the management of raw materials and other natural resources.
3. **To Increase Transparency and Research**
   - To improve the reliability of raw material demand forecasts in order to avoid potential supply bottlenecks and to ensure strategic planning and sustainable management of raw materials, the European Union must ensure transparency on raw materials use.
   - Furthermore, the European Union must promote further research in the area of material flow analysis and raw materials use in strategic energy technologies, especially focusing on technologies that are crucial to the fulfillment of long-term strategies and targets.
4. **To Raise Public Awareness**
   - To ensure that research and development promotes technologies that do not heavily rely upon raw materials with potential supply constraints, the European Union must act to raise public awareness about resource constraints.
5. **To Set up Recycling Schemes**
   - To close material loops, to increase supply security of critical raw materials and to ensure the sustainable use of natural resources, the European Union must develop proper recycling schemes for, and eliminate all exports of, products containing critical raw materials.
6. **To Promote Sustainable Mining and Processing**
   - To promote a sustainable supply of critical raw materials that ensures proper environmental standards, safety precautions and human rights, the European Union must step up efforts to promote sustainable mining and processing both within and outside of the EU.

The study stresses the fact that the European Union must actively work to ensure that the demand for certain raw materials will not outstrip supply and cause a delay to any major deployment of photovoltaic cells and wind turbines. To do this, technological alternatives will have to be sought and implemented and the concept of raw materials criticality will have to be reassessed and integrated into energy roadmaps and targets. If this is not done, bottlenecks in the future supply of certain raw materials may entail a risk of disabling a shift towards low-carbon, and eventually carbon-free, economies - thereby disrupting European and global efforts to tackle climate change.

1 Introduction

1.1 Background

Humans have extracted metals from the earth's crust for thousands of years because of their physical and chemical properties. Some metals, such as gold and silver, have been considered valuable for a long time because of their attractive appearance and rareness in nature. Since the industrial revolution, metals have become an integrated part of our daily lives, and today we use far more metals than just gold and silver to support the development of new technologies and our high standards of living. The supply of metals has not been questioned since we have constantly developed better methods to find new deposits and more advanced extraction technologies to retrieve the desired elements, and we have thus developed our society without any real concern for the future.

Our exponentially growing population and the following exponentially growing demand for earth's resources has slowly made us realize that earth and its resources may not be infinite. We received the first proof of earth's finiteness when we first entered into space and were able to see planet earth and its distinct boundaries, separating it from black empty space. Even though we realized this many decades ago, we have continued to use earth's resources as if our trip into space was just a dream. However, reality has caught up on us and during the last decades scientists have been reminding us of that first journey into space by bombarding us with evidence of the increasing pressure we are putting on our planet and its resources. We now know that some of the resources that we so heavily rely upon are going to run out if we continue using them the same way as we have in the past. Crude oil, which is the single most important resource that has powered our society for more than a century, is an excellent example of such a resource. We have been rejecting the possibility of *Peak Oil* for a long time, but the point in time when the production of crude oil starts to decline and prices start to rise may actually already have occurred (*IEA, 2010*)[34].

Crude oil is yet only one of many resources whose production may peak in the near future if we continue to consume them as if they were infinite. During the last decade, numerous reports have been written on what some refer to as "*Peak Minerals*" (*Giurco et al., 2009; Mudd and Ward, 2008*)[23,47], which highlights the fact that even mineral resources are finite and that there will be a point in time when mineral resources are not profitable to extract due to environmental constraints and high economic and societal costs. Some argue this won't happen since minerals are virtually unlimited and lower ore grades will inevitably become profitable to extract if demand is high enough (*Simon, 1996*)[58]. This may have been the truth in the past, but as demand for minerals increases and the global population grows we realize that there are environmental, social and perhaps even physical constraints to mineral extraction, and that we cannot afford mineral extraction at every cost. Instead of continuing the unsustainable practice of mining ores with lower and lower concentrations, it is likely that our society will find alternative ways of accessing minerals such as recycling and *urban mining* (*UNEP, 2011*)[64].

1.2 Recent Events

During the last two years, the world has been reminded of the scarce supply of, and our high dependence on, certain minerals. This time, the focus has been on *rare earth elements* - a group of 17 elements (atomic number 21, 39 and 57-71) that are crucial to advanced technologies such as superconductors, high performance magnets, lasers, catalysts, nuclear power plants, luminescent phosphors, x-ray technologies etc. (*Öko Institute, 2011*)[73]. Numerous alarming articles on the so called "*rare earth crisis*" began to appear as the prices of rare earth elements began to rise steeply when China - the number one extractor and producer of rare earth metals with 97% of world production (*USGS, 2010*)[68] - began to cut their exports in 2008 (*Moran, 2010; Scott & Freedman, 2011; Öko Institute, 2011*)[44,56,74].

Since then, several reports have been written by geological institutes, governments and international organizations in order to assess the future supply of critical raw materials (not only rare earths), and governments and companies are now responding with the development of recycling schemes, material substitution research and political negotiations in order to decrease their dependence on others and secure their future supply of these metals.

1.3 Content, Aim and Scope

The aim of this is to analyze current and future impacts of raw materials supply on the deployment of photovoltaic cells and wind turbines. The main question that this study aims to answer is *if major deployment of renewable energy might be constrained by resource shortages*.

The study will start with an overview of the current situation of raw materials by summarizing the most recent studies on the topic. Following this overview, the focus will be turned to elements that are critical to renewable energy technologies, and later on the future supply and demand of elements that are used specifically in photovoltaic cells and wind turbines will be assessed. Demand scenarios of the specific elements used in these technologies will be modeled based on the best available data on metal supply, technology material compositions and technology- and energy-mix scenarios. Elements that may have significant impact on the future deployment of photovoltaic cells and wind turbines will be identified and followed by a discussion on recycling and substitution possibilities as well as environmental impacts associated with raw materials extraction, processing and refining. Finally, the results will be summarized, discussed and compared with similar studies, and eventually conclude with a set of policy recommendations.

2 Methodology

2.1 Information Gathering

The facts that make up the basis of this study are generally taken from scientific reports published by well-renowned organizations such as the U.S Geological Survey, British Geological Survey, United Nations Environment Programme, Global Wind Energy Council, European Photovoltaic Industry Association, Greenpeace, European Renewable Energy Council and the European Commission.

Additional information about the material composition of photovoltaic cells and wind turbines as well as information about recycling, material substitution and environmental impacts has been taken from Ökopol and Öko-Institute e.V as well as a number of other research papers from industry, universities and renowned researchers. Most reports are publicly available and can be accessed via Internet, but a small portion of the reports used in this paper do however require access to scientific journals.

2.2 Modelling

The modeling carried out in this study is based on facts, scenarios and estimates given in the reports by the sources mentioned above. In a few cases where data has not been available, estimates have been given by the author of this study based on statements or figures presented in the reviewed reports (these cases are clearly stated and explained in the report). Furthermore, the modeling results have been compared with the results of similar modeling scenarios, such as those from a very recent study by the European Commission (2011b)[14], to verify their validity. All calculations have been carried out using simple linear mathematics in Microsoft Excel.

3 Findings

3.1 Earth's Metal Supply

There are 118 known chemical elements out of which the vast majority is categorized as metals. The rest are *non-metals*, *halogens*, *noble gases* and *elements with unknown chemical properties*. Metals are usually elements with high electrical and thermal conductivity, luster, malleability and a tendency to readily lose electrons to form positive ions. The abundance of metals on earth varies enormously, where some metals such as aluminium and iron are very common, while others such silver, gold and platinum are not (see Table 1).

Table 1. Average crustal abundance of most solid elements, measured in ppm (if not specified). Based on data from Rudnick and Gao (2003)[55] and the British Geological Survey (2011)[5]

Element	Upper Crust[55]	Avg. Total Crust[5]	Element	Upper Crust[55]	Avg. Total Crust[5]	Element	Upper Crust[55]	Avg. Total Crust[5]
SiO_2	66,6 (wt%)	-	Er	2,3	2,1	Pb	17	11
TiO_2	0,64 (wt%)	-	Eu	0,1	1,1	Pd	0,00052	0,0015
Al_2O_3	15,4 (wt%)	-	F	557	553	Pr	7,1	4,9
FeOT	5,04 (wt%)	-	Fe		52.157	Pt	0,0005	0,0015
MnO	0,10 (wt%)	-	Ga	17,5	16	Rb	84	49(5)
MgO	2,48 (wt%)	-	Gd	4	3,7	Re	0,000198	0,000188
CaO	3,59 (wt%)	-	Ge	1,4	1,3	Ru	0,00034	0,00057
Na_2O	3,27 (wt%)	-	Hf	5,3	-	S	62	404
K_2O	2,80 (wt%)	-	Hg	0,05	0,03	Sb	0,4	0,2
P_2O_5	0,15 (wt%)	-	Ho	0,83	0,77	Sc	14	21,9(5)
Ag	0,053 (wt%)	0,055	I	1,4	0,71	Se	0,09	0,13
Al	-	84149	In	0,056	0,052	Sm	4,7	3,9
As	4,8	2,5	Ir	0,000022	0,000037	Sn	2,1	1,7
Au	0,0015	0,0013	K	-	15025	Sr	320	320
B	17	11	La	31	20	Ta	0,9	0,7
Ba	628	456	Li	24	16	Tb	0,7	0,6
Be	2,1	1,9	Lu	0,31	0,3	Th	10,5	5,6
Bi	0,16	0,18	Mg	-	28104	Tl	0,9	4136
Br	1,6	0,88	Mn	-	774	Tm	0,3	0,28
Cd	0,09	0,08	Mo	1,1	0,8	U	2,7	1,3
Ce	63	43	N	83	-	V	97	138
Cl	370	244(5)	Na	-	22.774	W	1,9	1
Co	17,3	26,6	Nb	12	8	Y	21	19(5)
Cr	92	135	Nd	27	20	Yb	1,96	1,9
Cs	4,9	-	Ni	47	26,6	Zn	67	72
Cu	28	27	Os	0,000031	0,000041	Zr	193	132
Dy	3,9	3,6	P	-	567	Zr	17	132

Upper Crust refers to the upper 12 km of the continental crust and Avg. Total Crust refers to the average composition of the upper, middle and lower crust (40 km in total depth). - indicates that no data is available.

As society has developed, science has found that some of the more unusual elements on earth have very special physical and chemical properties - properties that have enabled researchers to develop technologies such as nuclear power, x-ray machines, LCD-screens, superconductors and strong permanent magnets. Today, common electronic products may incorporate as many as 60 different metals (*National Research Council, 2008*)[50], and medical equipment and diagnostic tools more than 70 (*Duclos SJ, 2009*)[9]. In other words, some of the rarest elements on earth are also the very basis of high-tech society.

As with other resources (such as oil and coal) we have had to struggle enormously to access metals, and without considering the possibility of supply shortages and future alternatives, we have continued to develop a society that totally relies on these resources. In the case of crude oil, society has slowly realized the situation and is now beginning to shift towards more sustainable energy resources - a shift that has been proven possible and totally necessary with regards to peak oil, climate change, human health and the health of our ecosystems.

In the case of metals, the situation is somewhat different. Since each metal has its own special property and since most of our technologies rely on these - shifting our use from one metal to another may not be straightforward. Substituting one material with another has been proven possible many times in history when materials have become expensive, turned out to be toxic or as better alternatives have emerged. However, as we have continued to develop ever more advanced technologies, we have also become increasingly dependent on the properties of specific elements, and our options for material substitution have rapidly decreased. A secure supply of metals is therefore fundamental.

3.1.1 Rare Earth Elements

Recently, 17 elements that play an important role in advanced technologies have been given major attention (e.g. see *British Geological Survey, 2011; European Commission, 2010; Ökopol, 2011*)[5,13,73]. These elements are called *rare earth elements* (REE) and can be found in the lower parts of the periodic table (Figure 1).

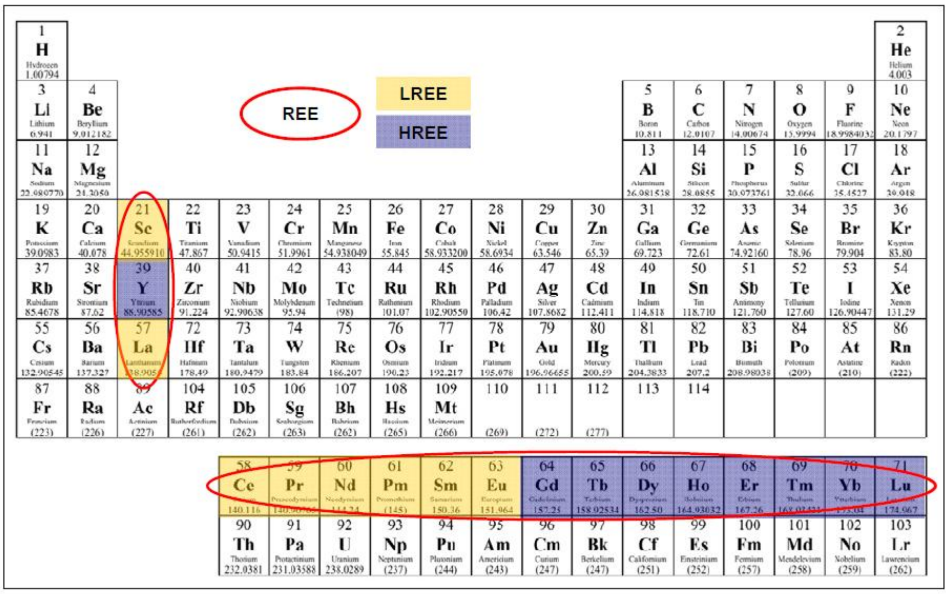


Figure 1. Rare earths elements and their position in the periodic table. Source: Öko-Institut e.V. (2011)[73]

The recent attention has been given due to the high technological and economical importance of rare earth elements combined with severe supply cuts followed by an average price increase of 1700 percent during the last two years (*Metal Pages and Core Consultants, 2011*)[43].

These events have mainly been caused by Chinese export restrictions, and since China has as much as 97% of world production (*USGS, 2010*)[68] and both the EU-27 and USA import about 90% of rare earth elements from China (*Öko-Institute e.V., 2011*)[73] - industries and governments have desperately been trying to reduce their dependence on and secure the future supply of these metals by looking into substitution alternatives and potential mining sites.

Rare earth elements are not the rarest elements considering their crustal abundance (see Table 1), but considering the amount of discovered minable concentrations, they are still quite rare (*USGS, 2010*)[68]. According to the U.S. Geological Survey (2011)[68], world production of all rare earth oxides combined was about 130000 tonnes in both 2009 and 2010, while the total estimated reserves that could be economically extracted in the future amount to about 110 million tonnes.

Even though current world production of rare earth elements is quite small compared to estimated reserves, the British Geological Survey came out with a risk list in September 2011 saying that rare earth elements have a very high supply risk (see Table 2), taking into account the abundance in Earth's crust, the location of current production and reserves as well as the political stability in those regions (*BGS, 2011*)[5].

Table 2. Current supply risk index for chemical elements or element groups which are of economic value. Based on data from British Geological Survey (2011)[5]

Element or element group	Symbol	Risk	Leading producer	Element or element group	Symbol	Risk	Leading producer
antimony	Sb	8,5	China	cadmium	Cd	5,5	China
platinum group elements	PGE	8,5	South Africa	lithium	Li	5,5	Australia
mercury	Hg	8,5	China	calcium	Ca	5,5	China
tungsten	W	8,5	China	phosphorous	P	5,0	China
rare earth elements	REE	8,0	China	barium	Ba	5,0	China
niobium	Nb	8,0	Brazil	boron	B	4,5	Turkey
strontium	Sr	7,5	China	zirconium	Zr	4,5	Australia
bismuth	Bi	7,0	China	vanadium	V	4,5	Russia
thorium	Th	7,0	India	lead	Pb	4,5	China
bromine	Br	7,0	USA	potassium	K	4,5	Canada
carbon (graphite)	C	7,0	China	gallium	Ga	4,5	China
rhenium	REE	6,5	Chile	flourine	F	4,5	China
iodine	I	6,5	Chile	copper	Cu	4,5	Chile
indium	In	6,5	China	selenium	Se	4,5	Japan
germanium	Ge	6,5	China	carbon (coal)	C	4,5	China
beryllium	Be	6,5	USA	zinc	Zn	4,0	China
molybdenum	Mo	6,5	Mexico	uranium	U	4,0	Kazakhstan
helium	He	6,5	USA	nickel	Ni	4,0	Russia
tin	Sn	6,0	China	chlorine	Cl	4,0	China
arsenic	As	6,0	China	sodium	Na	4,0	China
silver	Ag	6,0	Peru	carbn (diamonds)	C	4,0	Russia
tantalum	Ta	6,0	Rwanda	sulphur	S	3,5	China
manganese	Mn	5,5	China	iron	Fe	3,5	China
magnesium	Mg	5,5	China	chromium	Cr	3,5	Canada
cobalt	Co	5,5	DRC	aluminium	Al	3,5	Australia
gold	Au	5,5	China	titanium	Ti	2,5	Australia

Supply risk index runs from 1 (green - very low risk) to 10 (red - very high risk)

The risk list does not however take into account factors that may influence demand, which means that elements that are critical to a particular technology and/or are difficult to substitute may face a higher supply risk and become scarce depending on the future production of such technologies. This means that the supply of rare earth elements (among others) - which is already identified as having a very high risk, may become a serious issue depending on what type of technologies we chose to develop and on their future demand. Worth noticing is that rare earth elements are not the only elements with a high supply risk. In fact, most metals that are crucial to advanced technologies have a supply risk of 6 or more. Some of these metals, their use and importance to advanced technologies will be introduced and discussed in the following sections.

3.2 The "Energy Metals"

As mentioned in the previous section, some of the rarest elements and/or elements with a high supply risk are crucial to advanced technologies, and depending on what technologies we want to use in the future, the supply of these elements may become an issue.

It is therefore reasonable to ask how potential supply shortages of such elements may affect our societal development. Some of the technologies that rely on these elements have already been mentioned, and a supply shortage of the elements that we use in our LCD-screens, computers and Smartphones will certainly make the rich part the world dissatisfied. It would be a bit more worrying if the production of x-ray machines, catalysts and metallurgical alloys was affected, but these technologies are still not the biggest issue. The major issue is that the elements that are used in the mentioned technologies are also used in our energy systems, and unfortunately also in the renewable energy technologies that we need to stop global warming, urban air pollution, ocean acidification and other types of environmental destruction. More specifically, some of these elements are used in the cleaning systems of coal plants and oil refineries, in nuclear power plants, in modern wind turbines and in solar panels.

In the beginning of 2011, Thomas E. Graedel, a well-known researcher on metal stocks and flows, did a study on the future availability of the so called "energy metals" (*Graedel, 2011*)[27]. This study looked at "*metals utilized in the energy industry...with particular emphasis on the elements whose use is deemed desirable or essential for the major deployment of renewable energy*". The identified metals and rough estimates of their major use are presented in Table 3.

Table 3. Principal uses of the energy metals. Based on data from Graedel (2011)[27]

Metal	Major applications	Use (%)	Metal	Major applications	Use (%)
Cobalt (Co)	Superalloys	22	Indium (In)	Flat-panel displays	83
	Batteries	22		Metallurgical alloys	12
	Catalysts	11	Tellurium (Te)	Metallurgical alloys	60
Copper (Cu)	Construction	50		Chemicals	25
	Electrical	21		Photovoltaics	8
	Transportation	11	Lanthanum (La)	Batteries	37
	Industrial machinery	8		Magnets	29
Gallium (Ga)	Integrated circuits	67		Metallurgical alloys	12
	Optoelectronics	31	Neodymium (Nd)	Magnets	33
Selenium (Se)	Glass	25		Catalysts	26
	Metallurgical alloys	22		Optical	18
	Agricultural	19	Dysprosium (Dy)	Magnets	100
	Chemicals	14	Hafnium (Hf)	Ceramics	Unavailable
Cadmium	Batteries	83		Superalloys	Unavailable
	Pigments	8		Nuclear	Unavailable
	Coatings/platings	7		Electronics	Unavailable

The metals presented in Table 3 have been called "energy metals" because copper (Cu) is the backbone of electrical generation and distribution systems; cadmium (Cd), cobalt (Co) and lanthanum (La) are used in batteries that are vital to new vehicle technologies (among other applications); gallium (Ga), selenium (Se), indium (In) and tellurium (Te) are crucial to thin-film photovoltaics; neodymium (Nd) and dysprosium (Dy) are key metals in high-strength magnets; and hafnium (Hf) is an essential component of nuclear control rods (Graedel, 2011)[27].

3.2.1 Metals and Renewable Energy Technologies

The "energy metals" suggested by Graedel (*Graedel, 2011*)[27] included metals that are crucial to modern energy systems in general - including electric and hybrid vehicles as well as nuclear power. Graedel's assessment of "energy metals" gives us a general idea of how important certain metals are to renewable energy systems. But how will the supply of these metals be affected if (or when) major worldwide deployment of renewable energy kick-starts as a response climate change and to the very recent findings showing that climate change is happening faster than previously thought? Dangerous climate change will be irreversible if we do not start taking strong action to reduce greenhouse gas emissions in the next five years (*IEA, 2011*)[33] and eventually they will have to be reduced to zero or even become negative (e.g. through carbon capture and storage) if we are to meet the global climate goal of maximum 2 °C increase in global average temperature this millennium (*Friedlingstein et al, 2011*)[22].

Major deployment of renewable energy must be therefore be realized, not only with regard to climate change, but also with regards to increased costs of, and pollution from, fossil fuels. If we look at energy mix scenarios in the EU and the rest of the world, it becomes obvious that renewable energy technologies are expected to dominate our future energy supply.

Having recognized this, this report will focus on metals used in two renewable energy technologies that have been proven to have major potential and are expected to gain significant market shares in the world energy supply during the coming decades - photovoltaic cells and wind turbines (*EPIA, 2011b; EREC, 2010; GWEC, 2010; Greenpeace & EREC, 2011*)[18,19,24,28]. These two technologies are not only relevant in this respect, but also highly relevant with regard to their reliance on metals (many that are not included in Table 3), ranging from common ones to "*precious metals*" and rare earths. The specific use of metals in these two technologies and their potential future demand will be analyzed in the following chapters.

3.2.1.1 Photovoltaic Cells

Photovoltaic cells have been developing rapidly since the 1970's when research got a boost and previously high production costs dropped significantly. The first generation of photovoltaic cells that were based on crystalline silicon is now accompanied by more than a dozen of other types of cells. The classification of photovoltaic technologies is fuzzy and based on several factors such as manufacturing techniques, physical structure, the main use and/or type of materials used. Table 4 summarizes three generations of photovoltaic cells, their most common names and abbreviations.

Table 4. Photovoltaic technologies (PVs)

1st Generation "crystalline silicon" PVs
Crystalline Silicon (c-Si)
Ribbon sheet c-Si
Mono c-Si (m-Si/mono-Si)
Poly/multi c-Si (poly-Si/pc-Si/mc-Si)
2nd Generation "Thin-film" PVs
Amorphous Silicon (a-Si)
Multi-junction thin silicon film (a-Si/μc-Si)
Cadmium Telluride (CdTe)
Copper Indium Gallium Selenide (CIS or CIGS)
Concentrator photovoltaics (CPV), substrate can be Si or GaAs/GaInAs/GaInP2/Ge
3rd Generation "emerging" PVs
Advanced inorganic Thin-Films, e.g. spherical CIS and Thin-Film polycrystalline silicon
Hybrid dye-sensitized solar cells (DSSC)
Fully organic photovoltaic cells (OPV)
Thermo-photovoltaic cells (TPV)

The diversity of photovoltaic cell technologies shown in Table 4 has resulted in an even higher diversity of materials used in their manufacturing. The diversity of metals that can be found primarily within 1st and 2nd generation cells, as well as in the emerging 3rd generation dye-sensitized cells are summarized in Table 5. The table does not only include metals that are crucial to the functioning of photovoltaic cells, but also metals that have been found present in small quantities (by research laboratories etc.), and information about their function may be poorly documented or simply not publicly available (as far as this study is concerned). The table only includes elements found within the photovoltaic cells and omits those found in frames, cables, inverters and possible batteries. The table should not be considered as exhaustive as some metals may have been missed due to limited availability of information and the limits of this study.

Table 5. Elements found and used in common photovoltaic cell technologies

Metal	Class	Photovoltaic technology use	Other uses
Aluminium (Al)	N	a-Si, CIS, CIGS, CdTe(20,74)	construction, transportation, packaging, electrical transmission lines, heat sinks, coins, magnets
Antimony (Sb)	M, S	CdTe*, PV cover glass**(51,49)	ATO, micro capacitors[12]
Arsenic (As)	M, S	CdTe*, CPV(51,60)	alloys, biocides, medical treatments, animal food
Barium (Ba)	S	CdTe*(51)	cathode ray tubes, electrodes, alloys, fireworks, drilling mud
Boron (B)	S	a-Si, CdTe(74)	glass & ceramics, NdFeB magnets, detergents, insecticides, semiconductors, shielding
Cadmium (Cd)	S	CdTe, CIS*, CIGS*(20,51,74)	batteries, pigments, coatings/platings[27]
Cerium (Ce)	R, S	PV cover glass**(49)	automotive catalysts, polishing powders[32]
Chromium (Cr)	F	CdTe*(51)	Seawater desalination, marine technologies[12]
Cobalt (Co)	S	DSSC electrolyte(7)	superalloys, catalysts[27]; Li-ion batteries, synthetic fuels[12]
Copper (Cu)	N	c-Si, CIS, CIGS, CdTe(74)	construction, electrical, transportation, industrial machinery[27]; efficient electric motors, RFID[12]
Gallium (Ga)	S	CIS/CIGS, CPV, CdTe (13,74)	integrated circuits, optoelectronics[27]; IC, WLED[12]
Germanium (Ge)	M, S	a-Si, CPV(13)	fibre optic cable, IR optical technologies[12]
Gold (Au)	P	CIS**, OPV**(57,59)	jewelry, investment money, medical applications, analytical equipment, soldering, electronics, chemistry
Indium (In)	S	a-Si, CIS, CIGS, CPV, CdTe, DSSC, ITO-glass(13,20,74,61,42)	flat-panel displays, metallurgical alloys[27]
Lead (Pb)	N	c-Si*, CdTe*(51,74)	lead-acid batteries, ballast keels, radiation shielding, solders, electrodes
Mercury (Hg)	S	CdTe*(51)	fluorescent lamps, drugs, medical appliances, chemistry
Molybdenum (Mo)	F	CIS, CIGS, CdTe*(51,20,74)	high temperature alloys, special fertilizers, solid lubricants
Nickel (Ni)	F	CdTe*(51)	NiMH batteries, alloys, alnico magnets
Osmium (Os)	P	DSSC sensitizer(30)	alloys, electrical contacts, fountain pens, instrument pivots
Platinum (Pt)	P	DSSC glass coating(3)	fuel cells, catalsts[12]
Ruthenium (Ru)	P	DSSC sensitizer(30)	industrial catalytic converters, alloys, resistors
Silicon (Si)	M	c-Si, a-Si, CIGS	semiconductors (high-grade silicon), alloys, construction compounds
Silver (Ag)	P	c-Si, CIS, CIGS, CdTe, DSSC(74, 48)	RFID, lead-free soft solder[12]
Selenium (Se)	Nm,S	CIS, CIGS(74)	glass, metallurgical alloys, agricultural chemicals, chemicals general[27]
Tellurium (Te)	M, S	CdTe(74)	metallurgical alloys, chemicals[27]
Tin (Sn)	N	c-Si, a-Si, CdTe, ITO-glass(74)	solders, platings, special alloys, chemistry
Titanium (Ti)	N	DSSC(30)	seawater desalination, implants[12]
Zinc (Zn)	N	CdTe, CIGS (20,74,51)	anti-corrosion coatings, batteries, alloys, pigments, chemistry

Metal classification by UNEP (2011)(64): F - "ferrous metal"; N - "non-ferrous metal"; P - "precious metal"; S - "specialty metal". Superscripted numbers refer to sources of information listed in the reference list ("other uses" without references are taken from Wikipedia and should be regarded as examples). M or Nm - The element is classified as a "metalloid" or "non-metal" respectively, since it has somewhat different physical and chemical properties from metals. * The metal is present, but the metal may not be primarily used in production or there is no information about the use of this metal. ** It is unclear to what extent these metals are used and according to PV experts at ECN Solar Energy Netherlands[79] and the National Renewable Energy Laboratory[75], almost no cerium or antimony is currently used in the glass covers of photovoltaic cells.

Table 5 shows that the study by Graedel (2011)[27] on the general use of "energy metals" (Table 3) excluded the majority of metals specifically used in photovoltaic cells. The supply and demand of the additional metals presented in Table 5 as well as those investigated by Graedel (2011)[27] will be assessed and discussed in section 3.3.2 and onwards.

3.2.1.2 Wind Turbines

The modern wind power industry started around the 1980's, and since then wind turbines have evolved rapidly - from being able to produce 20 kW per turbine in the beginning to 7.5 MW per turbine today (*European Commission, 2011b*)[14].

Just as with photovoltaic cells, different technologies have evolved for harvesting the wind's energy. These differences can be found both on the outside in their different types of blades and rotational axes, but also on the inside in terms of the type of technology that is used to convert the blades' movements to electricity. In terms of materials use, the latter makes the biggest difference between different turbine technologies. Table 6 gives a general summary of the different turbine technologies.

Table 6. Summary of wind turbine technologies. Based on data from the European Commission (2011b)[14]

System Types	Available generator types	Available speeds
Geared transmission	Electromagnetic (EM) Permanent magnet (PM)	
Gearless transmission (direct-drive)	Electromagnetic (EM) Permanent magnet (PM) Permanent magnet (PM)	Low Low High/medium speed
High temperature superconductor (HTS)*	High temperature superconductor	

* Not yet commercially available

Table 6 shows that there are several types of technology combinations that are currently used in wind turbines. Generally speaking the technologies that are used are a mix of geared / gearless transmission turbines with electromagnetic or permanent magnet generators. On top of this, there are several different speeds for gearless turbines that use permanent magnets. The emerging high temperature superconductor technology is also included in the table, even though it is not yet commercially available.

Depending on the combination of technologies that is used, different amounts of different metals are used in the manufacturing of a wind turbine. When looking at metal use in wind turbines, those that have permanent magnet generators are of special interest since they incorporate a wider range of metals - some that are quite rare. The reason for this is that permanent magnets have to be very strong in order to work as substitute for electromagnets (which is most commonly used), and the strongest magnets available today are NdFeB-magnets that incorporate several unusual metals. These magnets are (as the name implies) based primarily on neodymium, iron and boron - but they also contain other metals. The metals that can be found in different parts of different wind turbine technologies are summarized in Table 7.

Table 7. Elements found and used in different types of wind turbines.

Metal	Class	Use	Other uses
Aluminium (Al)	N	NdFeB-magnets[(11)], turbine body[(14)]	construction, transportation, packaging, electrical transmission lines, heat sinks, coins, magnets
Boron (B)	S	NdFeB-magnets[(11,14,8)]	glass & ceramics, NdFeB magnets, detergents, insecticides, semiconductors, shielding
Cobalt (Co)	S	SmCo-magnets*[(66)]	superalloys, catalysts[27]; Li-ion batteries, synthetic fuels[12]
Copper (Cu)	N	Electromagnets & wires[(14)]	construction, electrical, transportation, industrial machinery[27]; efficient electric motors, RFID[12], photovoltaics[(see Table 5)]
Chromium (Cr)	F	Turbine body steel alloy[(14)]	Seawater desalination, marine technologies[12], photovoltaics[(see Table 5)]
Dysprosium (Dy)	R, S	NdFeB -magnets [(11,14,8)]	NdFeB magnets (for computers, audio systems, automobiles, household app. & MRI)[8]
Iron (Fe)	F	NdFeB-magnets, Turbine body [(11,14,8)]	construction, transport, tools, alloys
Molybdenum (Mo)	F	Turbine body steel alloy[(14)]	high temperature alloys, special fertilizers, solid lubricants, photovoltaics[(see Table 5)]
Manganese (Mn)	F	Turbine body steel alloy[(14)]	steel alloys, aluminium alloys, fuel additive, batteries, chemistry, pigments
Nickel (Ni)	F	Turbine body steel alloy[(14)]	NiMH batteries, alloys, alnico magnets, photovoltaics[(see Table 5)]
Neodymium (Nd)	R, S	NdFeB-magnets[(11,14,8)]	NdFeB magnets (for computers, audio systems, automobiles, household app. & MRI)[8]; catalysts, optical glass[27]; lasers[12]
Niobium (Nb)	F	NdFeB-magnets[(11)]	steel production, superalloys, supermagnets, electroceramics, hypoallergenic applications, numismatics
Praseodymium (Pr)	R, S	NdFeB-magnets [(11,8)]	NdFeB magnets (for computers, audio systems, automobiles, household app. & MRI)[8]
Samarium (Sm)	R, S	SmCo-magnets*[(66)]	military equipment, catalysts, nuclear reactors[(66)]
Terbium (Tb)	R, S	NdFeB-magnets [(8)]	NdFeB magnets (for computers, audio systems, automobiles, household app. & MRI)[8]

Metal classification by UNEP (2011)[(64)]: F - "ferrous metal"; N - "non-ferrous metal"; P - "precious metal"; S - "specialty metal". Superscripted numbers refer to sources of information listed in the reference list ("other uses" without references are taken from Wikipedia and should be regarded as examples). * The U.S. Department of Energy (2010)[66] has said that SmCo-magnets are/can be used in permanent magnets for wind turbines, but this has not been confirmed by any other report reviewed in this study.

Just as with photovoltaic cells, there is no consensus on what metals are used in different wind turbine technologies. Some studies have reported the use of SmCo-magnets (*U.S. Department of Energy, 2010*)[66], and some have reported that praseodymium and terbium are commonly used in NdFeB-magnets (*Du and Graedel, 2011*)[8] while others say they are only used occasionally or in very small quantities (*European Commission, 2011b*)[14]. The supply and demand of the metals presented in Table 5 and Table 7 for which data is available will be assessed and discussed in the following sections.

3.3 Renewable Energy Deployment and Impacts on Metal Demand

3.3.1 Background Data

Many organizations and research institutes have been trying to foresee the future development and deployment of photovoltaic cells and wind turbines. As the industry is developing rapidly, and new technologies are constantly being developed, resulting in increased uncertainty and large differences between studies done in different years and by different organizations. The common picture is however that photovoltaic cells and wind turbines will play a major role in the future energy supply both in Europe and globally, depending primarily on the political support (*EPIA, 2011b; EREC, 2010; GWEC, 2010; Greenpeace & EREC, 2011*)[18,19,24,28]. In this section we will assess the future metal demand from photovoltaic cells and wind turbines over the coming decades by combining recent deployment forecasts with scenarios of future technology mixes and material compositions.

3.3.1.1 Future Deployment of Photovoltaic Cells and Wind Turbines

Starting with the future deployment of photovoltaic cells and wind turbines, Table A 1 and Table A 2 (Annex A) summarizes the latest forecasts under several different scenarios given by EPIA (2011b)[18], GWEC (2010)[24] and Greenpeace & EREC (2011)[28]. As can be seen in the tables, there are some differences between the scenarios modeled by the different organizations - illustrating the degree of uncertainty related to energy technology forecast. The main differences are that EPIA (2011b)[18] expects a higher penetration of photovoltaic cells in the energy system (mainly in the "paradigm shift"-scenario) than Greenpeace & EREC (2011)[28], just as GWEC (2010)[24] is slightly more optimistic on the deployment of wind turbines than Greenpeace & EREC (2011)[28]. Taking into account the recent findings and recommendations by the International Energy Agency (2011)[33] and Friedlingstein et al. (2011)[22] discussed in section 3.2.1, it is not unlikely that even the most optimistic scenarios may come true. The metal demand modeling in this study is therefore based on all scenarios presented by Greenpeace & EREC (2011)[28] (since these are the latest estimates) as well as the "Paradigm shift" and "Advanced" scenarios by EPIA (2011b)[18] and GWEC (2010)[24] respectively. The scenarios and their key characteristics are summarized in Table 8.

Table 8. Key characteristics of the energy deployment scenarios used in the metal demand modeling

Scenario	Key Characteristics
Greenpeace & EREC[28] "Reference"	*This scenario is based on the reference scenario published by the International Energy Agency (IEA) in World Energy Outlook 2009. It only takes existing international energy and environmental policies into account.*
Greenpeace & EREC[28] "Energy [R]evolution"	*In this scenario, a key target is to reduce worldwide carbon dioxide emissions down to a level of around 10 Gigatonnes per year by 2050. A second objective is the global phasing out of nuclear energy. To achieve its targets, the scenario is characterised by significant efforts to fully exploit the large potential for energy efficiency, using currently available best practice technology. At the same time, all cost-effective renewable energy sources are used for heat and electricity generation as well as the production of bio fuels.*
Greenpeace & EREC[28] "Advanced [R]evolution"	*This scenario aims at an even stronger decrease in CO_2 emissions by incorporating stronger efforts to develop better technologies to achieve CO_2 reduction. It assumes a lower energy demand from the transport sector by a change in driving patterns and a faster uptake of efficient combustion vehicles and – after 2025 – a larger share of electric and plug-in hybrid vehicles. More geothermal heat pumps are also used, which leads – combined with a larger share of electric drives in the transport sector – to a higher overall electricity demand. A faster expansion of solar and geothermal heating systems is assumed as well as a shift in the use of renewables from power to heat.*
GWEC[24] "Advanced"	*This scenario is the most optimistic scenario for wind power and it examines the extent to which this industry could grow in a best case 'wind energy vision'. The assumption here is a clear and unambiguous commitment to renewable energy, along with the political will necessary to carry it forward. It takes into account all policy measures to support renewable energy either already enacted or in the planning stages around the world. It also assumes that the targets set by many countries for either renewables, emissions reductions and/or wind energy are successfully implemented, as well as the modest implementation of new policies aimed at pollution and carbon emission reduction, and increased energy security.*
EPIA[18] "Paradigm Shift"	*This scenario is the most optimistic scenario for photovoltaic power and it represents the real technical potential of PV as a reliable and clean energy source, in all parts of the world. In this scenario, PV would produce up to 12% of the electricity needs in European countries by 2020 and in many countries from the Sunbelt (including China and India) by 2030. It is ambitious, but also feasible, providing some boundary conditions are met before 2020, especially in the EU. The assumption is that current support levels will be strengthened, deepened and accompanied by a variety of instruments and administrative measures that will push the deployment of PV forward.*

3.3.1.2 Technology Mix Scenarios

Assessing future trends of photovoltaic and wind turbine technologies is less straightforward. Technology trends are difficult to estimate due to rapid developments (especially of photovoltaic technologies), but some estimates have been given recently by EPIA (2011b)[18], the European Commission (2011b)[14] and Oakdene Hollins (2010)[52] (Table A 3, Table A 4 and Table A 5 in Annex A). For photovoltaic cells, the metal demand modeling in this study is based on the figures given by EPIA for the years 2010, 2015 and 2020 as well as estimated figures for 2030 done by the author of this study - based on the trends given by EIPA (2011b)[18] and the European Commission (2011b)[14]. For wind turbines, there are several technology mix scenarios that can be used, but we chose to use the two technology mix scenarios given by the European Commission (2011b)[14] (i.e. "Dominance of EM systems" and "Take-up of PM and HTS systems"). Worth noticing is that the modeling scenarios wind turbines focuses solely on permanent-magnet wind turbines using NdFeB-magnets, since these are the turbines that are most relevant with regards to metals use. The choice of scenarios is further explained in section 6.2 (Annex A).

3.3.1.3 Material Compositions of Photovoltaic Cells and Wind Turbines

To model future metal demand, detailed information about the composition of photovoltaic cells and wind turbines is needed. Table 5 and Table 7 listed all the metals that are used and/or have been found in different photovoltaic and wind turbine technologies according to the reports reviewed in this study. However, detailed information about the amount of each metal present in these technologies is largely unavailable, especially with regards to photovoltaic cells (see table Table A 6). The reason for this is partly that different manufacturers use different compositions, making average composition data uncertain and difficult to determine. However, the main reason is that manufacturers keep this information secret - something that has been a major issue in conducting this study, since not even research laboratories such as NREL[75] or major photovoltaic recycling organizations such as PV Cycle[79] has any detailed information at hand.

The information that has been found in this study thus only covers a fraction of the metals listed in Table 5 and Table 7. The modeling results of metal demand from photovoltaic cells should be seen as first estimates of the potential metal demand from common photovoltaic technologies, while the modeling results of permanent-magnet wind turbines can be considered slightly more representative since the diversity of metals is lower. Information about the detailed material composition used in the metal demand modeling is given in Table A 6, Table A 7 and Table A 8 and is further explained in Annex A.

3.3.2 Modelling Results

Based on the data that was briefly discussed above and more thoroughly presented in Annex A, modeling of the future metal demand from photovoltaic cells and permanent-magnet wind turbines has been carried using simple linear mathematics in Microsoft Excel. The formula used to calculate the data presented in this section can be simplified as: (a*b*c)/d, where:

a = average total deployment of wind turbines or photovoltaic cells per year (MW/year)
b = specific technology mix during the same period (%)
c = the corresponding metal content of the technologies used in the mix (tonnes/MW)
d = world production of corresponding metal in 2010 (tonnes/year)

3.3.2.1 Metal Demand from Photovoltaic Cells 2011-2030

The modeled metal demand for photovoltaic cells is presented in Figure 2 and Figure 3 below.

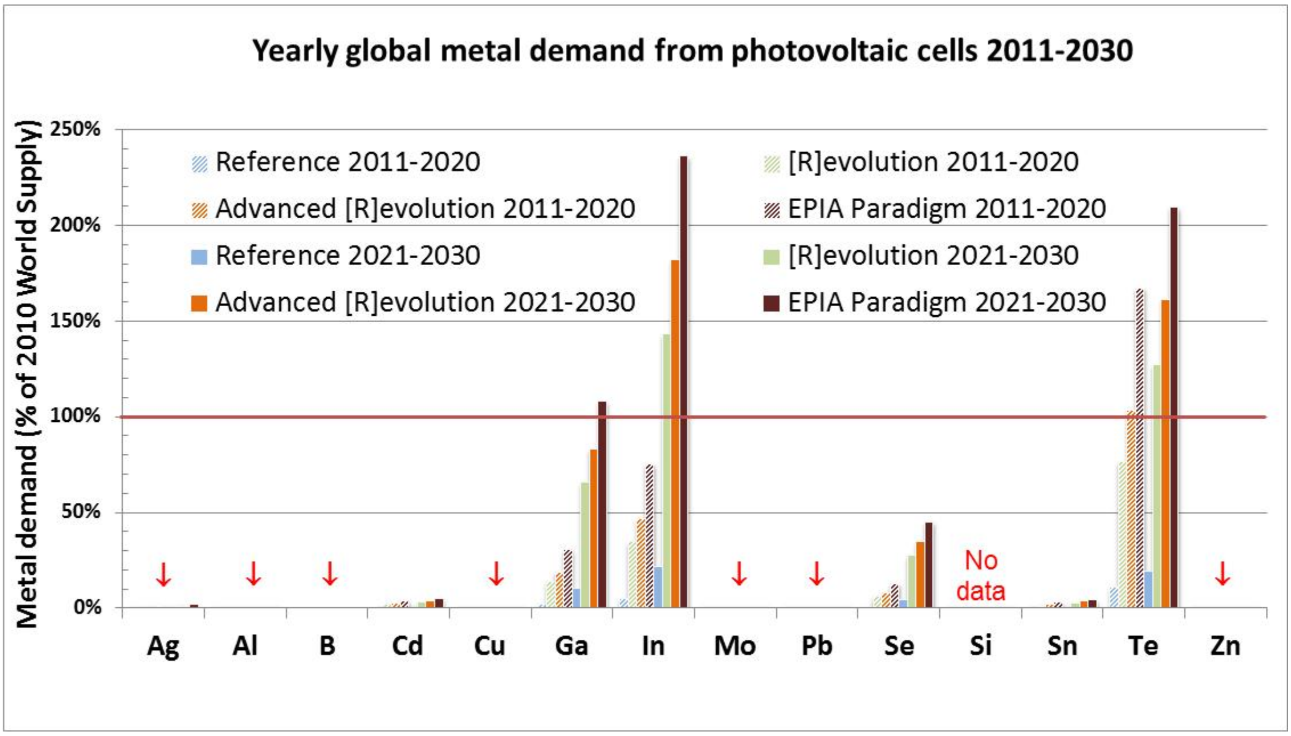


Figure 2. Yearly global metal demand from photovoltaic cells 2011-2030. All elements for which no data is available have been omitted (except for Si - see discussion below). Bars with diagonal stripes represent the period 2011-2020 and filled bars represent 2021-2030. Arrows denote that demand is very low. The red line highlights the point where future demand is equal to the 2010 world supply.

Figure 2 shows the yearly global metal demand from photovoltaic cells for the period 2011-2030 under four different deployment scenarios (discussed in section 3.3.1.1). As mentioned, the metal demand data presented in Figure 2 only represents a fraction of all the metals that are used in photovoltaic cells, and it is therefore impossible to draw any conclusions on the full future metal demand. Elements for which no data is available have been omitted from the figure, except for silicon with the purpose of highlighting the fact that silicon is an important element for both c-Si and a-Si photovoltaics and is used in rather large quantities - however, no detailed data on the average amount has been found.

Figure 2 show that the global metal demand from photovoltaic cells may have a notable impact on the future supply of at least four metals - gallium, indium, selenium and tellurium.

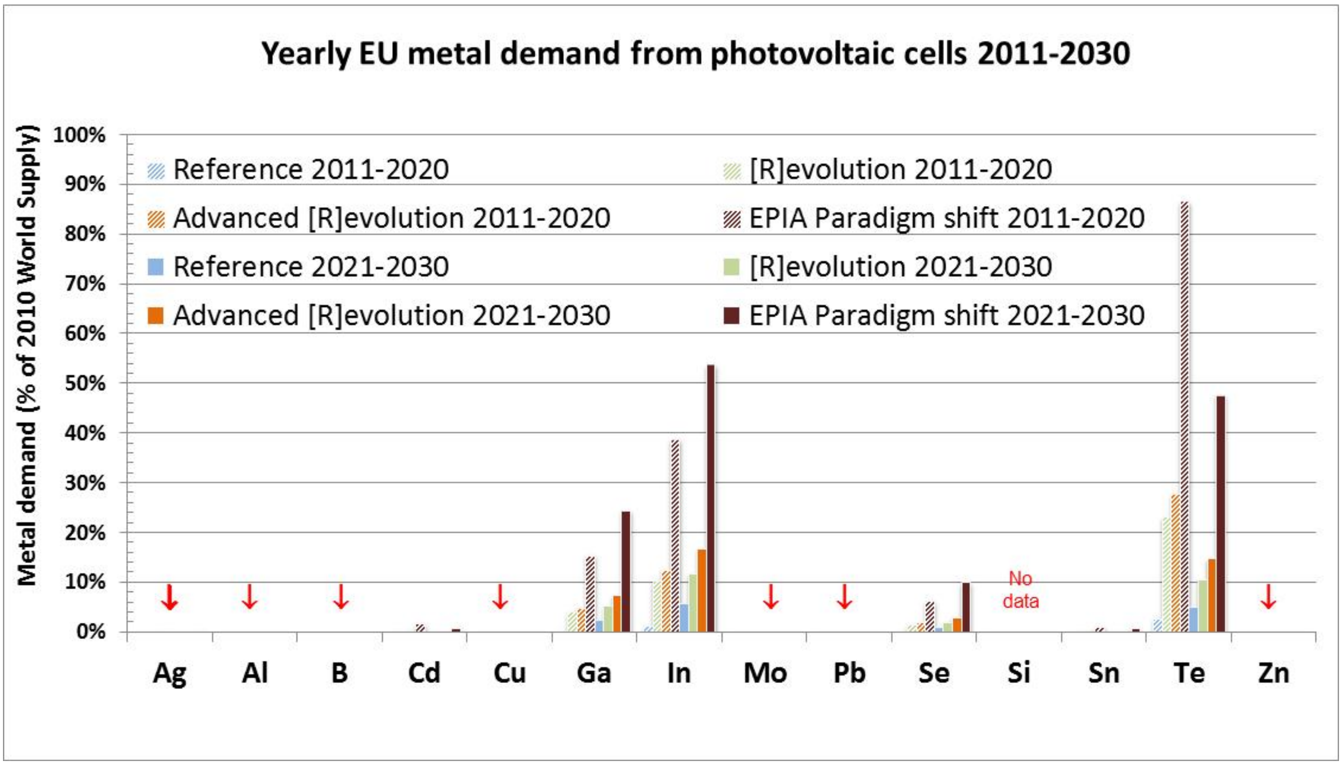


Figure 3**. Yearly EU metal demand from photovoltaic cells 2011-2030. All elements for which no data is available have been omitted (except for Si - see discussion below Figure 2). Bars with diagonal stripes represent the period 2011-2020 and filled bars represent 2021-2030. Arrows denote that demand is very low.**

Figure 3 shows the corresponding figures for the yearly metal demand from photovoltaic cells in the EU. The only difference between the modelings in Figure 2 and Figure 3 is the deployment scenarios (see Table A 1), and the demand for metals is therefore similar, with notable supply impacts for gallium, indium, selenium and tellurium. Please note that the scales are different between Figure 2 and Figure 3.

Figure 3 shows that even the EU alone may require notable shares of current world supply of gallium, indium, selenium and tellurium if the deployment of photovoltaic cells during the next two decades follows any of the more advanced scenarios.

3.3.2.2 Metal Demand from Permanent-Magnet Wind Turbines 2011-2030

The modeled metal demand for permanent-magnet wind turbines is presented in Figure 4 and Figure 5. To simplify and limit the length of this section, only the most interesting scenario from a metal demand point-of-view has been included (i.e. the "Take-up of PM & HTS Systems"-scenario). The metal demand modeling under the "Dominance of EM Systems"-scenario can be found in Figure A 1 and Figure A 2 (Annex A).

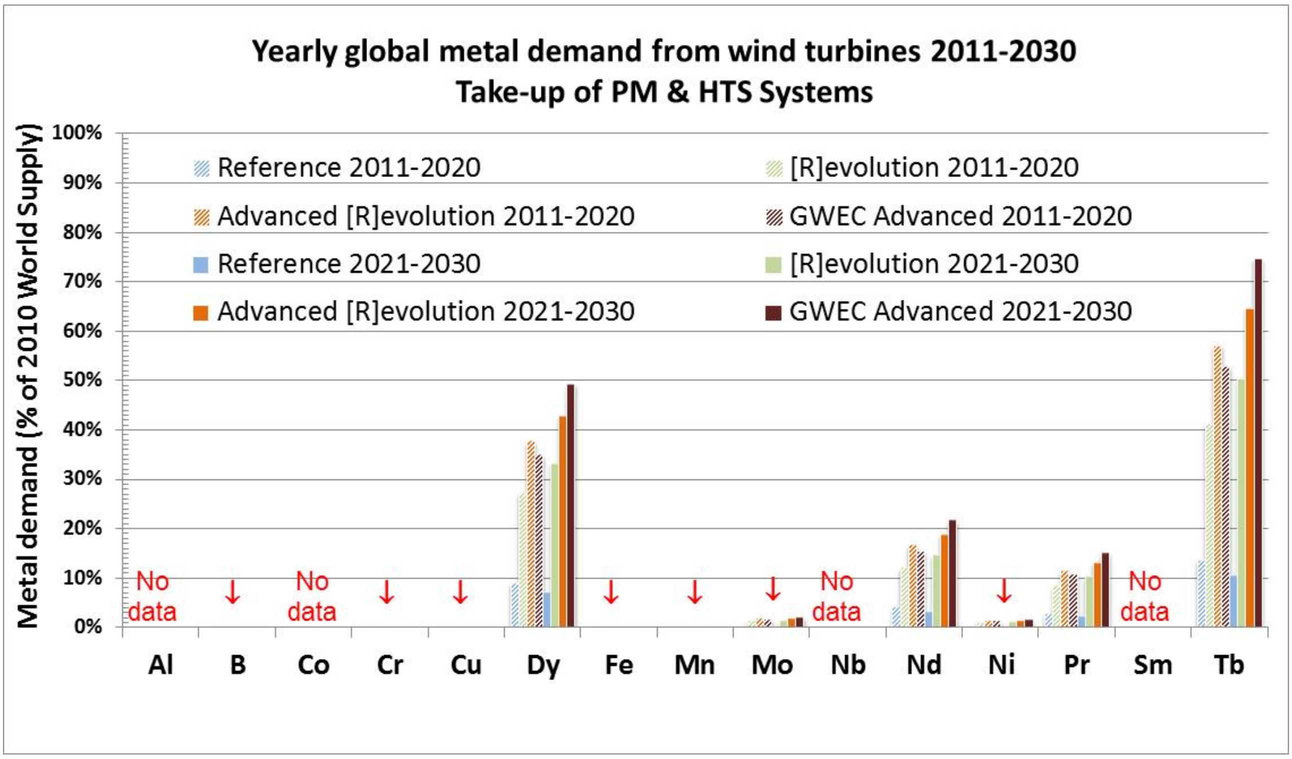


Figure 4. Yearly global metal demand from permanent-magnet wind turbines 2011-2030 under the "Take-up of PM and HTS Systems"-scenario. **Bars with diagonal stripes represent the period 2011-2020 and filled bars represent 2021-2030. Arrows denote that demand is very low.**

Figure 4 shows the yearly global metal demand from permanent-magnet wind turbines under the "Take-up of PM & HTS Systems"-scenario for the period 2011-2030 under four different deployment scenarios (discussed in section 3.3.1.1). As mentioned, the data presented in Figure 4 does not include all metals that may be used in wind turbines due to limited data availability, but it includes the majority of the most important metals from a demand-supply point-of-view. Cobalt, niobium and samarium are likely to be used very seldom in permanent magnets for wind turbines, and even though aluminium may be present in the magnets as well as substantially used in the body of the turbine - the demand for aluminium from permanent-magnet wind turbines is most likely negligible compared to current production.

Figure 4 shows that the global metal demand from permanent-magnet wind turbines under the "Take-up of PM & HTS Systems"-scenario may have a notable impact on the future supply of at least four metals - dysprosium, neodymium, praseodymium and terbium.

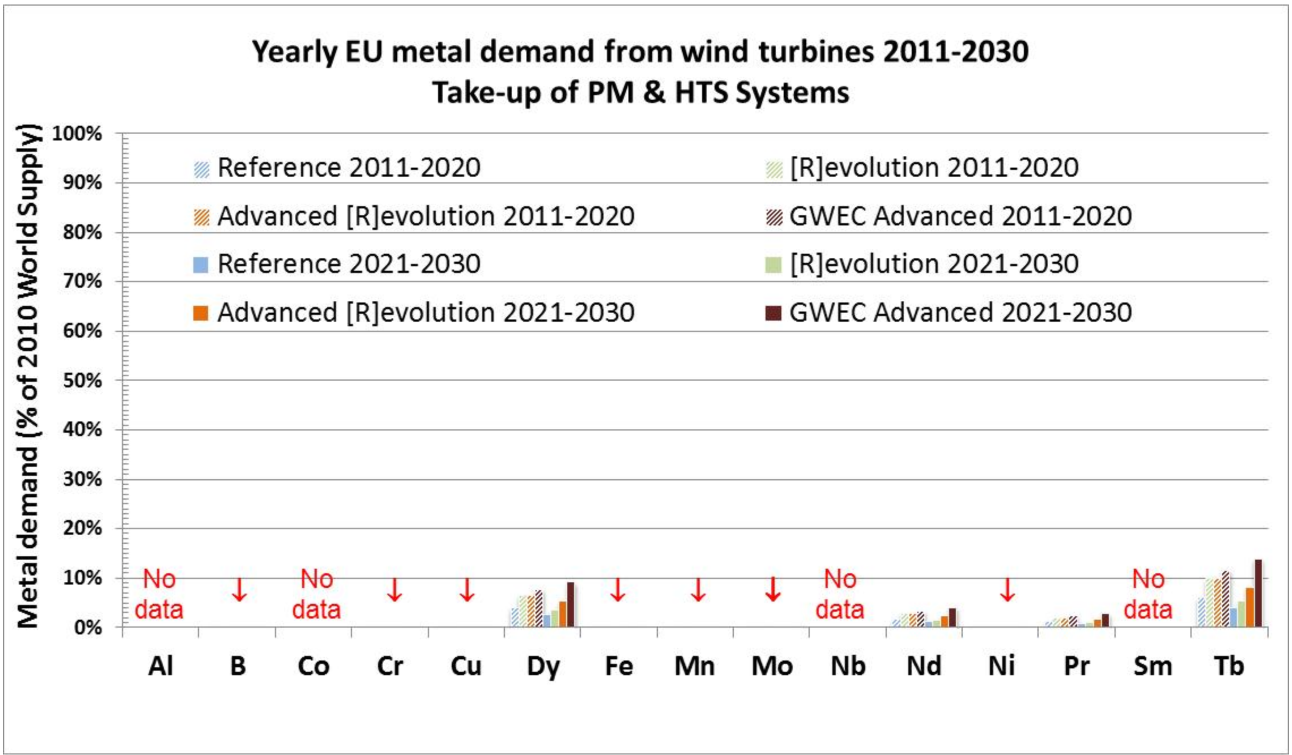


Figure 5. Yearly EU metal demand from permanent-magnet wind turbines 2011-2030 under the "Take-up of PM and HTS Systems"-scenario. **Bars with diagonal stripes represent the period 2011-2020 and filled bars represent 2021-2030. Arrows denote that demand is very low.**

Figure 5 shows the corresponding figures for the yearly metal demand from permanent-magnet wind turbines under the "Take-up of PM & HTS Systems"-scenario in the EU. The only difference between the modeling in Figure 4 and Figure 5 is the deployment scenarios (see Table A 2), and the demand for metals is therefore similar, with notable supply impacts for dysprosium, neodymium, praseodymium and terbium

Figure 5 shows that the EU alone is expected to require moderate shares of the current world supply of these elements if the deployment of permanent-magnet wind turbines during the two coming decades follows any of the more advanced scenarios.

3.3.3 Identification of Significant Elements

Out of all the elements that were assessed in the metal demand modeling, 8 elements have been identified for which the global deployment of photovoltaic cells and permanent-magnet wind turbines will require at least 10% of current world supply per annum in any of the different scenarios. The European Commission (2011b)[14] choose a 1% limit when they identified elements of significance to the European Union and the 10% limit used in this study was therefore considered reasonable with regards to the more optimistic deployment scenarios and the global scale. This limit also proved to be appropriate with regards to the modeling results. The 8 identified elements are henceforth referred to as the "significant elements" since their supply may have a significant effect on the future deployment of photovoltaic cells and permanent-magnet wind turbines.

Gallium, indium, selenium and tellurium may negatively affect the future deployment of photovoltaic cells, while dysprosium, neodymium, praseodymium and terbium may negatively affect the future deployment of permanent-magnet wind turbines. Considering that most of these metals are primarily used in other applications than photovoltaic cells and wind turbines (see Table 3), demand conflicts may arise.

Since major deployment of photovoltaic cells and wind turbines is inevitable in order to limit the effects of dangerous climate change, environmental destruction and urban pollution as well as securing our future energy supply - we simply cannot afford any demand conflicts that may lead to supply constraints. It is therefore of major importance to investigate options for alternative technologies and materials. In order to assess the seriousness of potential supply constraints, we must look at recycling rates and practices as well as potential options for material and technology substitution.

3.4 Recycling

Recycling of materials is fundamental in creating a sustainable management of natural resources. The physical properties of metals and the large environmental burden that the extraction and processing of metals entail, make metals convenient and desirable to recycle. For most of the major industrial metals that we have used for decades we have had time to develop recycling technologies and to achieve rather good recycling rates (compared to other metals). However, for most of the metals that are used in advanced and emerging technologies, recycling schemes are not in place and recycling rates are poor. Figure 6 and Figure 7 shows the most recent estimates of the global end-of-life recycling rates and average recycled content for sixty metals.

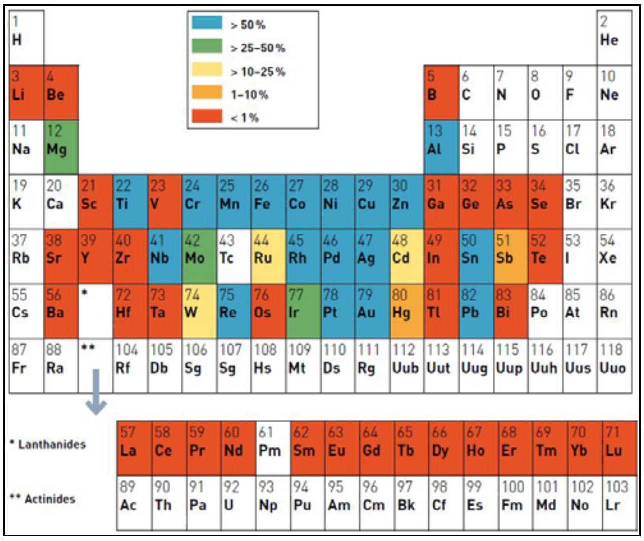


Figure 6. The periodic table of global average end-of-life functional recycling for sixty metals. Source: UNEP (2011)[64].

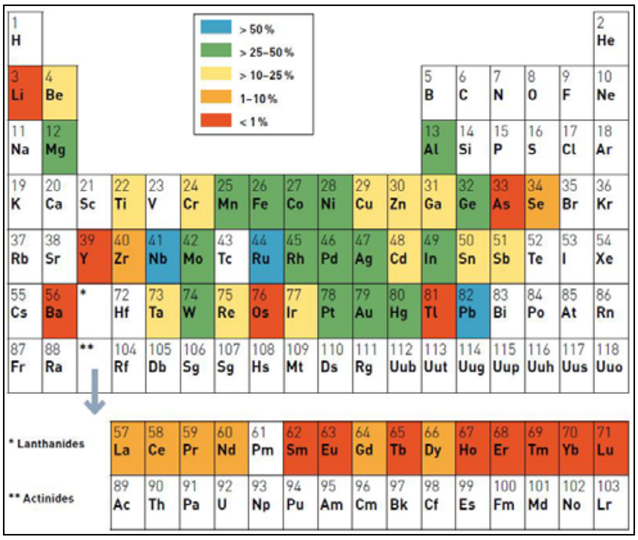


Figure 7. The periodic table of global average recycled content for sixty metals. Recycled content is the fraction of secondary metal (scrap) in the total metal input to metal production. Source: UNEP (2011)[64].

Figure 6 shows that current recycling rates of the 8 elements that were identified as significant to the deployment of photovoltaic cells and permanent-magnet wind turbines are less than 1 percent, while Figure 7 shows that the old scrap ratio of these metals ranges from less than 1 percent up to 20-50 percent.

3.4.1 The Recycling Potential

The extremely low recycling rates and general scrap ratios of the 8 significant elements show that there are great opportunities for improvement. The question is whether recycling will be able to compensate for any significant part of the metals needed in the future, that otherwise would have to come from virgin raw materials extraction. Figure 8 and Figure 9 show recent estimates of the expected amount of waste from photovoltaic cells and the amount of global in-use stocks of rare earth elements in permanent-magnet wind turbines.

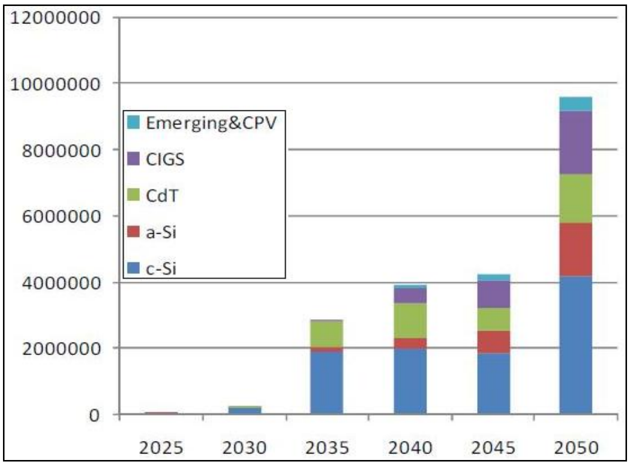


Figure 8. Photovoltaic waste generated by technology annually in the EU-27 (in tonnes). Source: European Commission (2011)[13]

Stocks (Gg)	*Nd*	*Pr*	*Dy*	*Tb*	***Total***
Computers	21.2	5.3	5.3	1.1	**32.8**
Audio systems	15.1	3.8	3.8	0.8	**23.4**
Wind turbines	10.1	2.5	2.5	0.5	**15.7**
Automobiles	9.8	2.5	2.5	0.5	**15.2**
Household appliances	3.3	0.8	0.8	0.2	**5.1**
MRI	3.0	0.8	0.8	0.2	**4.7**
Total	**62.6**	**15.7**	**15.7**	**3.1**	**97.0**

Figure 9. Estimated global in-use stocks of rare earth elements in NdFeB permanent-magnets in 2007. Source: Du and Graedel (2011)[8]

With a life expectancy of at least 25 years, waste from photovoltaic cells is expected to increase significantly within the coming decades (*European Commission, 2011a*)[13]. For permanent-magnet wind turbines, the situation is similar. With an estimated life expectancy of 20 years, waste from wind turbines is expected to increase significantly within the coming decades. Du and Graedel (2011)[8] have estimated that the global in-use stocks of neodymium, praseodymium, dysprosium and terbium in 2007 were almost four times the 2007 annual extraction rate (including the stock of NdFeB-magnets in all major applications - see Figure 9). This suggests that recycling of rare earth elements incorporated in permanent-magnets may have the potential to substitute a significant part of rare earths virgin extraction in the future (*Du and Graedel, 2011*)[8].

The amount of secondary raw materials from photovoltaic cells and permanent-magnet wind turbines, as well as from other technologies that use the same materials, will be significant in the future, and developing recycling schemes and technologies will be important. However, most of these materials will only be available in a few decades ahead when products have reached their end-of-life. This suggests that recycling will not be able to compensate for any significant part of the raw material supply needed for the successful deployment of photovoltaic cells and permanent-magnet wind turbines up to 2030. In other words, the demand for the 8 significant elements up to 2030 will largely have to be met by virgin raw material extraction.

3.4.2 Recycling Targets and Practices

Even though recycling will not be able to compensate for any significant part of the raw material supply needed for the successful deployment of photovoltaic cells and permanent-magnet wind turbines up to 2030 - tapping the full potential of urban mining and closing material cycles with appropriate global infrastructures is essential to establishing a green economy and to secure sustainable development (*UNEP, 2011*)[64].

As described in section 3.4.1, recycling has not been commonly practiced for most of the elements that we use in modern technologies (such as rare earths). In fact 32 out of 37 "specialty metals" have an end-of-life recycling rate of less than 1 percent (*UNEP, 2011*)[64]. Products containing these metals, such as waste electric and electronic equipment (WEEE) have so far been insufficiently recycled, burnt or landfilled. One reason for this has been that the prices of many metals have been too low to run an economical recycling process (e.g. in the case of rare earths), particularly when considering costs of collection, dismantling and treatment as well as energy requirements (*Öko-Institut e.V, 2011; UNEP, 2011*)[73,64]. Stable and adequate prices of metals is a pre-condition for economical recycling processes (*Öko-Institut e.V, 2011*)[73], and unfortunately, economics has so far been the main priority, regardless of the evident benefits that recycling brings in terms of environmental sustainability.

The fact that only 18 metals have an end-of-life recycling rate of above 50%, and that the majority of these are commonly used metals like steel, aluminium and copper, proves that there is a learning curve for recycling (UNEP, 2011)[64], and it is therefore important to set up recycling schemes today for the metals that will be available for recycling tomorrow.

Investing in recycling research and development is becoming increasingly important as our demand for, and dependence on, "specialty metals" (such as rare earths) as well as sustainability concerns continue to rise. One of the most important categories of waste to consider in this aspect is WEEE, as it often contains higher concentrations of metals than the ores we currently mine. Up to date, much of the WEEE has been inadequately treated, landfilled or illegally exported to developing countries (UNEP, 2011)[64]. This unsustainable management must come to an end by looking at WEEE as a valuable resource of raw materials instead of waste, and this has to be done through the implementation of proper and efficient regulation.

3.4.2.1 European Legislation and Targets

In the European Union, the treatment of many relevant wastes containing valuable raw materials is already regulated by the *Waste Electrical and Electronic Equipment Directive* (WEEE-Directive), the *End of Life Vehicles Directive* (ELV) and the *Battery Directive*. Currently, these directives do however not include any targets on the collection and recycling of specific raw materials, nor any targets regarding photovoltaic panels or rare earths containing wastes. The WEEE-Directive is nevertheless being recast and is expected (as of beginning of December 2011) to include targets on the collection and recycling of photovoltaic panels - if agreed.

Rare earths containing wastes are currently not mentioned in the recast, but Öko-Institut has pointed out the importance of doing so in its recent report (ordered by the European Parliament), by saying that the "*potential relevant Directives which should be verified in terms of modification for the support of a rare earth recycling scheme are the Ecodesign Directive, the WEEE Directive, the ELV Directive and the Battery Directive*" (*Öko-Institut e.V, 2011*)[73]. The Royal Institute of Chartered Surveyors (RICS) has also stressed the need for including rare earth containing products in Directives such as the WEEE-Directive, and it quite likely that rare earth elements will soon be integrated in a number of Directives (*Jones, 2011*)[36].

On top of existing Directives regulating product design, waste collection and treatment, the European Commission published a *Raw Materials Initiative* strategy document 2 February 2011, proposing improvements of recycling markets through the possible development of best practices in collection and treatment of waste, improvement in the availability of certain statistics on waste and materials flows, and support for research on economic incentives for recycling (*European Commission, 2011c*)[15]. The strategy also reaffirms the need for action to improve enforcement of waste rules, in particular to tackle illegal shipments of waste from Europe to non-OECD countries. Furthermore, many of these objectives have been incorporated in the *2020 Flagship Initiative on Resource Efficiency* (published 26 January 2011) as well as in the *Roadmap to a Resource Efficient Europe* (published 20 September 2011).

The Raw Materials Initiative strategy document was largely based on the findings of the report *Critical Raw Materials for the EU* (European Commission, 2011)[12], and thus recognizes the need for management of critical raw materials such as rare earth elements. The *Roadmap to a Resource Efficient Europe* does not mention rare earths or metals used in photovoltaic cells specifically, but it does mention the need to "*ensure security of supply of critical raw materials (for renewables and electrification)*" (*European Commission, 2011d*)[16].

3.4.2.2 Recycling of Photovoltaic Cells

PV Cycle, a not-for-profit organization founded by PV manufacturers, proposed a voluntary recycling scheme for the photovoltaic industry to the European Commission in December 2010, but the proposal was rejected due to a number of concerns, including financing and target setting (*European Commission, 2011a*)[13]. After that, the European Commission decided to analyze the option of including photovoltaic panels in the scope of the WEEE-Directive to provide a solid ground for the ongoing discussions. The Commission found that the environmental impacts were reduced by a factor of 6 when comparing the inclusion of all PVs in the WEEE Directive to a baseline scenario with no recycling of photovoltaic panels (*European Commission, 2011a*)[13]. The net benefits of including photovoltaics and their recycling in the WEEE Directive would annually amount to about 16,6-16,5 billion Euros in 2050 compared to baseline scenarios (*European Commission, 2011a*)[13]. The Commission further found that the main environmental risks associated with improper disposal of photovoltaic cells were leaching of lead and cadmium (two toxic metals) as well as loss of conventional resources such as aluminum and glass and rare metals such as silver, indium, gallium and germanium (*European Commission, 2011a*)[13].

Even though there is currently no legislation that regulates the collection and recycling of photovoltaic cells, and even though end-of-life photovoltaic cells are not expected to hit the market in any significant amount before 2025-2030 (see Figure 8), collection and recycling schemes are already being developed. PV Cycle started its own voluntary recycling scheme which turned out to be successful, and they recently announced the collection of 1020 tonnes of end-of-life photovoltaic modules (*PV Cycle, 2011*)[53]. PV Cycle is cooperating with several recycling industries and is currently able to recover glass, cadmium, selenium, tellurium and indium (*Beyer, 2011*)[4].

PV Cycle is however not the only one setting up recycling schemes. Deutsche Solar has its own recycling scheme for crystalline silicon panels and can recover glass, silicon, aluminium, steel, silver, copper, lead and cadmium (*European Commission, 2011a*)[13]. First Solar has a recycling scheme for CdTe panels and is testing its methods on CIS/CIGS (*European Commission, 2011a*)[13]. Umicore, a metals refining and recycling company, has also developed recycling schemes for photovoltaics and is able to recycle CdTe, CIS/CIGS and ITO-glass to recover metals like copper, indium, gallium, selenium and tellurium. Some of the mentioned recycling schemes can recover up to 90-95% of the input material (*Beyer, 2011*)[4] - showing that photovoltaic recycling is feasible and will be possible to run on commercial scales in the near future.

3.4.2.3 Recycling of Permanent Magnets

As mentioned in section 3.4.2.1, recycling of rare earths containing products is not currently regulated and to include these products in Directives such as the WEEE Directive is not as straightforward as for photovoltaic cells, since rare earth elements and permanent magnets are used in a wide range of products, and not necessarily electric or electronic ones.

Recycling of rare earth elements is very uncommon, and the only recycling practice currently known is pre-consumer recycling of permanent magnet scrap (*Öko-Institut e.V, 2011*)[73]. The reasons for this lack of proper recycling has been the "*quite dissipative applications, quite low prices of rare earths and a tendency of REE to move in the slags of smelter plants*" (*Öko-Institut e.V, 2011*)[73]. However, the sharp increase of rare earth prices and the high media coverage have put the issue of recycling on the agenda worldwide and numerous research activities are now being conducted on both pre- and post-consumer recycling in China and other countries (*Öko-Institut e.V, 2011*)[73].

Öko-Institut found that there is a range of possible ways to recycle pre-consumer permanent-magnet scrap, such as re-melting the scrap and recovering it in an un-oxidized state, recovering rare earths as oxides and selectively extracting neodymium and dysprosium by using selective extracting agents (*Öko-Institut e.V, 2011*)[73]. There are however issues such as low yields, contamination, expensive re-processing (e.g. of rare earth oxides) and chemistry adjustment needs that must be solved (*Öko-Institut e.V, 2011; Goodier, 2005*)[73,26]

Recycling of post-consumer magnets, which has the greatest potential in terms of material amounts, is however more complex. Except for the costly recycling process and difficulty of product collection and dismantling, there are technical issues connected to contamination (due to platings, glues, plastics etc.), highly variable magnet compositions (whose mixing may destroy the desired material properties) and magnet corrosion (especially of NdFeB, requiring additional refining processes to remove oxides and hydroxides)(*Goodier, 2005*)[26]. Recent progress in research however shows that high recovery rates of rare earths as well as automatic dismantling processes are possible (*Öko-Institut e.V, 2011, p. 105-106*)[73]. Currently, end-of-life products containing NdFeB-compounds are usually not recycled, instead the "*unwanted NdFeB is often used in hardcore for road construction*" (*Goodier, 2005*)[26].

To promote recycling of end-of-life rare earth components such as permanent-magnets, Öko-Institut proposes that the Ecodesign Directive, the WEEE Directive, the ELV Directive and the Battery Directive should be verified in terms of modification for the support of a rare earth recycling scheme (*Öko-Institut e.V, 2011*)[73]. Öko-Institut argues that rare earth recycling should be addressed by specific requirements such as the compulsory quotas of the WEEE Directive, the ELV Directive and the Battery Directive, e.g. through the obligation for dismantling of selected rare earth containing components (*Öko-Institut e.V, 2011*)[73]. The first priority of setting up an appropriate legal framework for the recycling of rare earths will be "*a screening in order to identify the sectors where the collection and treatment is already regulated and sectors where no regulation takes place"* (*Öko-Institut e.V, 2011*)[73]. Wind turbines are currently unregulated, and they will be very important to include in the mentioned directives since permanent-magnet wind turbines use huge amounts of rare earth elements that can be easily separated from the turbine.

3.5 Substitution

3.5.1 Material Substitution

As concluded in the previous section, recycling will not be able to compensate for any significant part of the raw material supply needed for the successful deployment of photovoltaic cells and permanent-magnet wind turbines up to 2030, which suggests that the demand will largely have to be met by virgin raw material extraction. Recycling is however not the only way of securing the future deployment of photovoltaic cells and permanent-magnet wind turbines. Material and technology substitution may be equally, or even more important in this respect.

The reason that certain elements are used in certain technologies is that they have certain chemical and/or physical properties that are needed in order for the technology to function properly and/or effectively. Usually a technology is developed using a certain set of materials, but, as time passes - new advantages of new materials are discovered, and the technology is further refined by altering the original set of materials. These refining processes many times involve and require elements and materials that are more unusual and rare than the original ones.

This has proved to be the case with both photovoltaics - where the initial silicon-based technologies are slowly being replaced by CIS/CIGS, CdTe, CPV and others, as well as for wind turbines - where the original electromagnets are slowly being replaced by rare earth magnets. The driver behind this increase in technology and material complexity is price and performance.

What then are the possibilities of substituting these new materials to reduce these technologies' dependence on materials that have potential sustainability issues? To answer that, we must define what we require from potential substitute materials. If possible, we want a substitute to provide similar performance at a satisfactory cost and with no major new technology challenges (*Graedel, 2011*)[27]. With these requirements, our options automatically become limited to elements that have similar properties to those that we want to substitute and furthermore to elements that are available at largely the same cost.

Looking at possible elements with regard to their chemical and physical properties, we realise that our options are very limited. To illustrate this, Figure 10 shows the potential substitution options in optoelectronics.

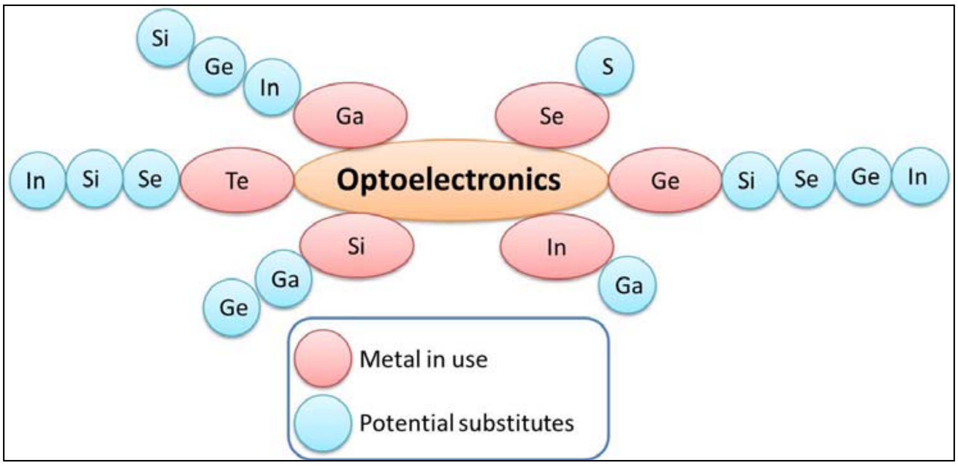


Figure 10. Potential substitute elements in optoelectronics. Adapted from Hagelüken & Meskers (2010)[31]

If we compare the potential substitutes presented in Figure 10 with the position of these elements in the periodic table (Figure 1), we see that the potential substitutes lie very close to each other. This makes sense, since the periodic table is constructed in such a way that elements with similar chemical and physical properties lay close to each other. In fact, many metals not only lay close to each other in the periodic table, but also in geological formations. Elements with very low crustal abundances (less than approximately 1 ppm) seldom form useable deposits of their own - instead they tend to occur interstitially in the ores of other metals with similar physical and chemical properties (*Graedel, 2011*)[27]. In practice, this means that most unusual elements are not mined separately, but are rather recovered when other more common, large-scale industrial metals, are extracted. The metals that occur in smaller quantities are termed 'daughter metals' (if recovered), and their hosts - 'parent metals'. Figure 11 and Figure 12 show how this "major and minor metal production" is linked.

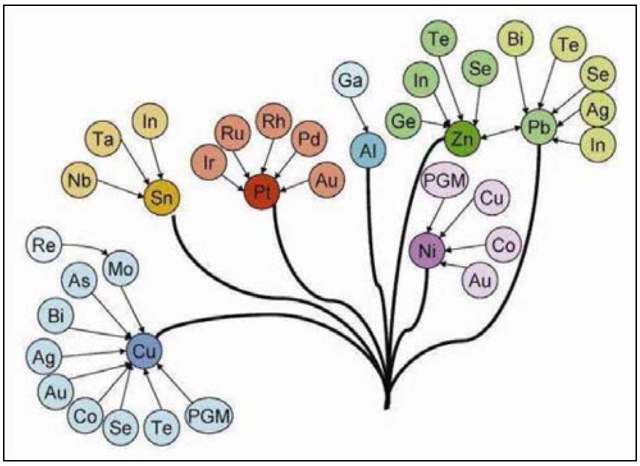


Figure 11. Coupling of major and minor metal production. The figure indicates which minor metals are produced as by-products of major metals. Source: Hagelüken & Meskers (2010)31

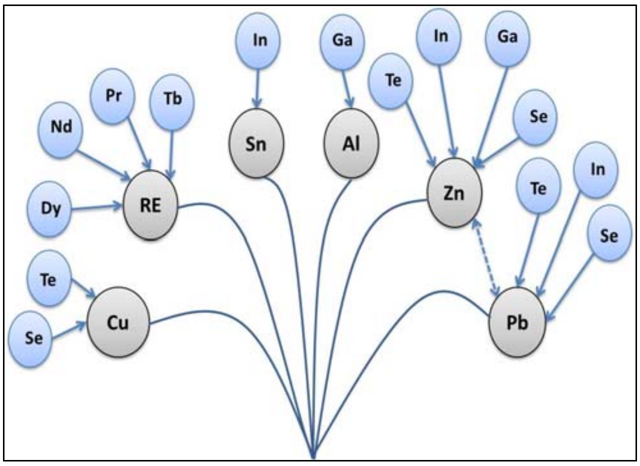


Figure 12. Coupling of the 8 significant elements and their parent elements. The parent metals shown often have other daughter metals as well, but those are omitted here for clarity. RE denotes rare earth. Adapted from Hagelüken & Meskers (2010)31

In the example of optoelectronics, we see that the potential substitutes are all daughter elements (compare Figure 10 with Figure 11 and Figure 12) - many of them even from the same parent. This means that the potential substitutes are very likely to have similar long-term sustainability concerns as the original elements (*Graedel, 2011*)[27]. This is a dilemma for most technologies that rely on daughter elements.

Following this brief introduction of the general complexity behind material substitution, we will now look more closely at our options for substituting the 8 significant elements used in photovoltaic cells and permanent-magnet wind turbines.

3.5.1.1 Photovoltaic Cells

Gallium

The projected gallium demand comes from photovoltaic cells based on the CIS/CIGS technology, where it is used directly as an absorber of sunlight. Substituting gallium in this light-absorbing compound has not been discussed widely as far as this study is concerned. A ratio of 70% CIS and 30% CIGS is normal in CIS/CIGS photovoltaics (*Ökopol, 2007*)[74], meaning that gallium only makes up a small fraction of the CIS/CIGS compound. Further lowering the fraction of CIGS could be a way to reduce gallium content, but the feasibility of this has not been covered by this study.

Gallium supply risk is low/medium (see Table 2) and gallium is theoretically abundant compared to current production (1 million tonnes in estimated reserves vs. 106 tonnes produced per year), but in reality only a small fraction of this supply is economically recoverable (*U.S. Geological Survey, 2011, p. 59*)[68]. If gallium cannot be substituted in the near future and gallium supplies do not expand significantly within the two coming decades, CIS/CIGS photovoltaic cell manufacturing may suffer.

Indium

The projected indium demand comes from photovoltaic cells based on a-Si, CdTe and CIS/CIGS. CIS/CIGS is the only technology which uses indium directly as an absorber of sunlight, while a-Si and CdTe only involve the use indium if the substrate- and cover-glass is indium-tin-oxide glass (ITO). It is not clear to what extent ITO is used compared to other substrates, but in this study we have assumed that ITO is used in all technologies except c-Si, as suggested by the European Commission (2011b)[14].

Substituting indium in the CIS/CIGS technology has not been discussed as far as this study is concerned, and according to our findings, substitution of indium in the CIS/CIGS compound would not have much of an effect on the overall indium demand from CIS/CIGS, since two thirds of the indium is used in the ITO-glass. Thus, substituting ITO-glass in all photovoltaic applications seems to be the single most important measure to reduce the use of and dependence on indium.

Substituting ITO-glass may not be that difficult, since there are already alternatives such as SnO_2 (used by the largest CdTe manufacturer First Solar)(*European Commission, 2011b*)[14] and ZnO:Al (used by a wide range of CIS/CIGS manufacturers)(*Ullal and von Roedern, 2007*)[62]. Other alternatives to ITO, such as antimony tin oxides (ATO), carbon nanotube coatings, poly 3,4-ethylene dioxythiophene (PEDOT), graphene quantum dots, zinc oxide nanopowders and silver nanotubes, have also been explored (*U.S. Geological Survey, 2011, p. 75; Lamontagne, 2011*)[68,38], but they are not yet commercially available. However, ATO does not seem to be a future alternative considering antimony's extremely high supply risk (see Table 2), plastics have a tendency to deteriorate in sunlight, and the possible health implications of nanotechnologies is not yet fully understood.

Considering that the global demand for indium already exceeded production in 2008 and 2009 (*U.S Department of Energy, p 177*)[66], it is quite likely that manufacturers will develop alternatives to ITO if indium prices continue to rise due to a rapidly increasing demand.

Selenium

The projected selenium demand comes from photovoltaic cells based on the CIS/CIGS technology, where it is used directly as an absorber of sunlight. Substituting selenium in this light-absorbing compound has not been discussed widely as far as this study is concerned. Selenium makes up about 50% of the CIS/CIGS compound weight and is therefore a crucial component in the technology.

Selenium supplies do not have a high risk (see Table 2) according to the British Geological Survey (2011)[5], which is a bit surprising since estimated reserves (not all economically extractable) are not very abundant compared to current production (88000 tonnes vs. 2260 tonnes/year). On top of that, selenium is recovered entirely as a byproduct of copper, and to a lesser extent nickel (*U.S. Geological Survey, 2011, p. 59*)[68] - meaning that the production is dependent on the supply and demand of other metals.

These facts, in combination with a potential demand for selenium from CIS/CIGS of as much as 45% of the 2010 world supply (Figure 2), suggest that if selenium cannot be substituted in the near future and supplies do not expand significantly within the two coming decades, CIS/CIGS photovoltaic cell manufacturing may suffer.

Tellurium

The projected tellurium demand comes from photovoltaic cells based on the CdTe technology, where it is used directly as an absorber of sunlight. Substituting tellurium in this light-absorbing compound has not been discussed widely as far as this study is concerned, but substitution possibilities in other applications have. According to the U.S Geological Survey (2011)[68], "*several materials can replace tellurium in most of its uses, but usually with losses in production efficiency or product characteristics*". In the example of many free-machining steels - bismuth, calcium, lead, phosphorus, selenium and sulphur can be alternatives to tellurium (*U.S Geological Survey, 2011*)[68]. Since tellurium's major use is as an alloying additive in steel, the current demand for tellurium could perhaps be offset by substitution - something that might be necessary in order to allow for further use of CdTe photovoltaics, provided that tellurium is not substituted in CdTe photovoltaics in the near future and supplies do not expand significantly within the next two decades.

The supply risk of tellurium has not been assessed by the British Geological Survey (2011)[5] due to a lack of data, but considering the potential demand from CdTe photovoltaics (Figure 2) in the next two decades, low tellurium supply is very likely to inhibit the deployment of CdTe photovoltaics unless "*the copper industry can optimise extraction, refining and recycling yields*" (EPIA, 2011b)[18] (since tellurium is a by-product of copper processing).

3.5.1.2 Permanent-Magnet Wind Turbines

Dysprosium

The projected dysprosium demand comes from permanent-magnet wind turbines using NdFeB-magnets. Dysprosium is used in NdFeB-magnets to increase high-temperature performance (*European Commission, 2011b*)[14], and as far as this study is concerned dysprosium is present in the majority of all high-performance NdFeB-magnets.

Potential supply shortages of dysprosium have already been identified by various organisations, and, according to the European Commission (2011b)[14], "*considerable research effort is underway to reduce the quantity of dysprosium required to achieve the necessary performance over a motor's operating temperature*". The Japanese government is at the forefront of this research and has sponsored research efforts targeting dysprosium minimisation and substitution (*European Commission, 2011b*)[14].

So far, no feasible replacement strategies have been identified for dysprosium (*European Commission, 2011b*)[14]. The best substitute for dysprosium is currently terbium, but since terbium is even more rare and expensive, large-scale substitution using terbium is unlikely (*European Commission, 2011b*)[14].

Reducing the dysprosium content in NdFeB-magnets used in wind turbines may be a way forward (as some NdFeB-magnets do not contain dysprosium), but whether this is feasible with regard to the operating conditions in wind turbines is not within the scope of this study.

Neodymium

The projected neodymium demand comes from permanent-magnet wind turbines using NdFeB-magnets. Neodymium is the main constituent in NdFeB-magnets after iron with a content of 20-30% in magnets used in wind turbines (see Table A 7). Small fractions of the neodymium NdFeB-magnets are currently being substituted by other rare earths to modify the magnets' performance under different operating conditions, but neodymium still makes up 20-30% of NdFeB magnets. Substituting neodymium in NdFeB-magnets on a larger scale would not be possible without completely changing the type of magnet. This will be further discussed in section 3.5.2.2.

Praseodymium

The projected praseodymium demand comes from permanent-magnet wind turbines using NdFeB-magnets. Praseodymium can be used in NdFeB-magnets to substitute a portion of the neodymium, but at the loss of performance (*European Commission, 2011b*)[14]. As discussed in section 6.3.2, it is not clear to what extent praseodymium is used in NdFeB-magnets, and it is therefore not clear if it is needed in NdFeB-magnets used in wind turbines at all. However, in this study it has been assumed that praseodymium is present in NdFeB-magnets to analyse a possible "worst-case"-scenario of rare earths demand, and we will therefore discuss other possibilities of reducing dependence on praseodymium supplies in section 3.5.2.2.

Terbium

The projected terbium demand comes from permanent-magnet wind turbines using NdFeB-magnets. Terbium can be used as an alternative to dysprosium to increase high-temperature performance, but it is less well suited due to its scarce supply, high price and performance losses (*European Commission, 2011b*)[14]. According to Oakdene Hollins (2010)[52], terbium also has less impact on the remanence of a magnet (i.e. the magnetisation left after an external magnetic field has been removed, which should be low in order to achieve a high performance) than dysprosium.

According to European magnet experts, terbium could probably be substituted entirely with dysprosium in most applications which do not require extreme performance (*Öko-Insitut e.V, 2011, p. 96*)[73]. Furthermore, it is unclear to what extent terbium is used in NdFeB-magnets (discussed in section 6.3.2), and it is not clear if it is needed in NdFeB-magnets used in wind turbines at all.

In this study it was however assumed that a small portion of terbium is present in NdFeB-magnets in order to analyse a possible "worst-case"-scenario of rare earths demand, and we will therefore discuss other possibilities of reducing wind turbine dependence on terbium supplies in section 3.5.2.2.

3.5.2 Technology Substitution

As we have seen, material substitution is difficult and most often requires a totally new product design (*European Commission, 2011*)[12], involving "*significant research, reengineering, retooling, and recertification with attendant delays*" (*American Physical Society, 2011*)[1]. But material substitution is fortunately not the only way of reducing or eliminating the use of a material. Substituting a technology with another technology that serves the same purpose may many times prove to be a far more efficient alternative.

3.5.2.1 Photovoltaic Cells

As described in section 3.5.1.1, the possibilities of substituting gallium, selenium and tellurium in photovoltaic cells is poorly studied, and currently no satisfactory substitutes are known. Fortunately, these elements are only used in CIS/CIGS (gallium and selenium) and CdTe (tellurium) photovoltaics, leaving several other technology options.

Most PV technologies that are, or may become, available are presented in Table 4, but not all of them may be seen as feasible alternatives to CIS/CIGS and CdTe. Generally, the feasibility of an alternative technology must be assessed with regard to the conditions under which it will operate. Generally speaking, the strength of the CdTe technology is that it is tolerant to high temperatures and performs well in low-light conditions, while the CIS/CIGS technology performs worse in high temperatures, but also good in low-light conditions. Unfortunately, CdTe and CIS/CIGS could be seen as substitution alternatives to each other, but as mentioned both technologies have identified raw material supply constraints.

The best alternative to CdTe and CIS/CIGS with regard to technology characteristics seems to be multi-junction amorphous silicon - a technology that is very tolerant to high temperatures and also performs very well in low-light conditions (*Jardine et al, 2001*)[35]. Other types of amorphous and crystalline silicon technologies can also work as alternatives, depending on the operating conditions. Furthermore, emerging technologies such as dye-sensitised solar cells are evolving rapidly and recently reached cell efficiencies of 12,3% (*Lamontagne, 2011b*)[39], meaning that they may soon be competing with already commercialised technologies and thus prove to be a feasible alternative to CdTe and CIS/CIGS in the future.

3.5.2.2 Permanent-Magnet Wind Turbines

As described in section 3.5.1.2, the possibilities of substituting rare earth elements in NdFeB-magnets is poorly studied, and currently no satisfactory substitutes are known. Altering the magnet composition, at the cost of possible performance losses, is one way to at least reduce the reliance on some of the more scarce rare earths such as terbium. However, neodymium will inevitably remain a main component in NdFeB-magnets, so we need to think of other ways of removing potential supply bottlenecks. Fortunately, technology substitution seems to offer far more possibilities than material substitution in the sense that there are several alternatives to NdFeB permanent-magnet wind turbines.

Permanent-magnet wind turbines were initially introduced because to their high efficiency, low weight and low maintenance costs, but so far they have only been able to gain a small share of the total wind capacity (about 14% according to *Fairley, 2010*)[21]. Most wind turbines use electromagnets - a mature technology that does not rely on rare earths. Up until recently, turbines with electromagnets have been using gearboxes to convert the slow rotation of the blades to fast rotations in the generator, which has made them subject to frequent maintenance - increasing the overall costs as well as lowering their life-time. However, Enercon (a large German manufacturer of wind turbines) has recently developed gearless turbines using "*separately excited annular generators*" (a low speed synchronous generator based on electromagnetic fields), a technology that looks very promising as a substitute for permanent-magnet generators.

A second alternative to permanent-magnet turbines is the "classic" geared turbines which currently have the largest share of the total wind turbine capacity. The disadvantage with these is their high need for maintenance (and thus cost), as well as their size and weight (making transport and assembly more difficult).

A third alternative is permanent-magnet turbines using other types of magnets. SmCo-magnets (based on samarium and cobalt) are the second best commercially available magnets (about half as powerful as NdFeB), but they are expensive and unfortunately also dependent on metals with potential supply risks. According to Morcos (2009)[45], sintered ferrite magnets (the most common magnet type, based on iron) could also be an alternative to NdFeB-magnets. They are about 30 times less expensive than NdFeB-magnets and can provide slightly better efficiency at higher generator speeds, but unfortunately they can only provide a tenth of the energy product of NdFeB-magnets and thus have to be very large and heavy in order to offer similar performance (*Morcos, 2009*)[45]. AlNiCo-magnets (based on aluminium, nickel and cobalt) offer slightly better performance than ferrite magnets, but cobalt may have potential supply issues and the magnets have a very low coercivity - meaning that they demagnetise easier.

Another magnet that is under development is the iron nitride ($Fe_{16}N_2$) magnet - a very promising magnet which has a theoretical energy product of more than twice the maximum reported for NdFeB-magnets (*University of Minnesota, 2011*)[65]. The production is also said to be "*environmentally friendly and compatible with mass production techniques*" (*University of Minnesota, 2011*)[65], but currently "*the material is metastable and exhibits relatively low coercivity*" (*Dvorak, 2011*)[10] and that will have to be solved before it can challenge the NdFeB-magnets.

A fourth alternative which is currently under development is generators based on high-temperature superconductor magnets (HTS). HTS magnets have the potential to offer better magnetic performance than NdFeB-magnets, but they currently need low temperatures to operate and thus need to be cooled (*European Commission, 2011b*)[14].

Furthermore, HTS technologies currently involve the use of elements such as yttrium, tungsten and silver - something which has to be considered before HTS can be seen as a sustainable alternative to NdFeB-magnets (*Öko-Insitut e.V, 2011, p. 96*)[73]. At the moment it is not yet clear whether HTS will be able to replace NdFeB-magnets, but the company AMSC has announced plans of commercialising turbines with HTS in the future (*Öko-Insitut e.V, 2011, p. 96*)[73].

Table 9 summarises all technological substitution options discussed above in descending order according to their current potential - based on the author's evaluation of the available information.

Table 9. NdFeB permanent-magnet turbine substitution options

#	Technology	Pros	Cons
1	Gearless EM (separately excited annular generator)	No gears	New technology, (performance relative to NdFeB PM and maintenance needs?)
2	"Classic" geared EM	Mature technology	High maintenance & weight
3	Iron nitride PM	No gears, high potential performance	Not yet commercially available
4	Sintered ferrite PM	No gears, inexpensive	Low energy product, high weight & large size
5	AlNiCo PM	No gears, less expensive than NdFeB	Low energy product, high weight & large size, partly dependent on scarce raw materials
6	SmCo PM	No gears, fairly high energy product	Expensive, dependent on scarce raw materials
7	High temperature superconductor (HTS)	No gears, high potential performance	Not yet commercially available, dependent on scarce raw materials

EM - Electromagnet, PM - Permanent magnet

3.6 Environmental Impacts

In order to meet the rapidly increasing demand for rare earth elements and other metals from photovoltaic cells, permanent-magnet wind turbines and a wide range of other technologies - virgin raw material extraction and processing will most likely have to increase. Since mining and refining operations are among the most energy-intensive and polluting activities there are, the increased production and opening of new mines will inevitably have large environmental impacts. This section will briefly summarise those impacts and discuss the consequences of increased demand.

3.6.1 Increasing Environmental Impacts

When mining explorations began on an industrial scale, extraction technologies were much less advanced and only the highest ore grades were profitable and/or possible to mine. As demand has grown, we have begun to mine lower and lower ore grades (Figure 13).

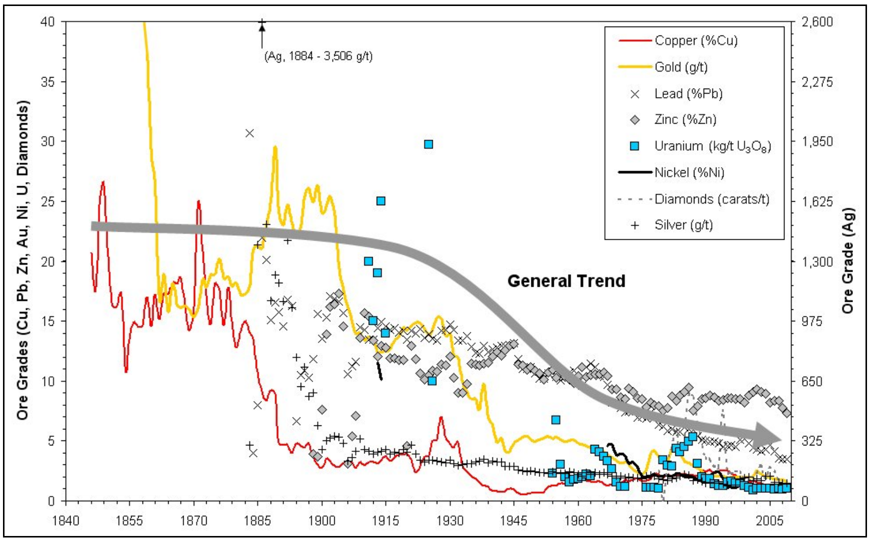


Figure 13. Combined Average Ore Grades Over Time for Base and Precious Metals in Australia. Source: Mudd (2009)[46].

This development has had major implications for the environment, since a lowering of the average ore grade means that more rock has to be processed in order to obtain the same amount of refined metal. The result is that the amount of waste rock has increased dramatically during that same period (Figure A 3, section 6.6), just as the amount of tailings and the use of energy and chemicals for processing and refining.

3.6.2 Environmental Risks

The number of environmental risks and impacts associated with metals extraction, processing and refining is large and will not be dealt with in detail in this study, but the most important risks in the example of rare earths are summarized in Figure 14 and further explained in Figure A 4, section 6.6.

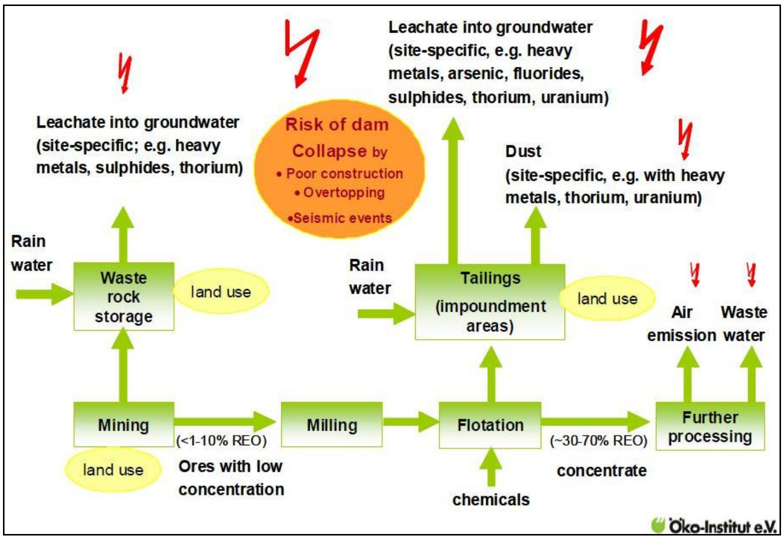


Figure 14. Risks of rare earth mining without or with insufficient environmental protection systems. Source: Öko-Institut e.V. (2011)[73].

The main environmental risks normally associated with mining activities are connected to the enormous amounts of tailings - a toxic slurry of chemically reactive particles (due to their small size and large surfaces), waste water and flotation chemicals (*Öko-Institut e.V., 2011*)[73]. The tailings are usually stored in artificial ponds surrounded by tailings dams, and due to their toxicity, biodiversity is likely to get wiped out in that area.

If a tailings dam fails, as they have about 50-60 times per decade during 1960-1990 and 20 times per decade during 1990-2010 (*Azam and Li, 2010*)[2], site-specific emissions such as thorium, uranium, heavy metals, acids and fluorides are flushed into the environment (*Öko-Institut e.V., 2011*)[73]. If a dam is located near a river these site-specific emissions may spread and cause major environmental, social and economic damage in several countries. Due to past industrial spills, such as the dam failure in Hungary 2010 where approximately 700,000 m^3 of tailings were released (*Azam and Li, 2010*)[2], this is what many fear would happen to the river Danube (connecting Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Moldova, Ukraine and Romania) if a large accident occurs (*WWF, 2010*)[72].

It has been shown that one of the main reasons for tailings dam failures has been extreme weather events, and it is therefore likely that climate change may increase the risk of tailings dam failures. Researchers have therefore argued that the "*inclusion of climate change effects in the initial design and of the observational method during construction, maintenance, and monitoring are highly desirable*" (*Azam and Li, 2010*)[2].

Furthermore, it is important to mention that "*most rare earth deposits contain radioactive materials which impose the risk of radioactive dust and water emissions*" (*Öko-Institut e.V., 2011*)[73]. Research has shown that plants and soil have been contaminated with radioactive elements near rare earth extraction sites, that groundwater has been polluted by leakage from tailings dams (affecting wells, livestock, agriculture and human health in nearby villages) and that the mortality rate from lung cancer for workers has increased by the long-term exposure to radioactive dust (*Öko-Institut e.V., 2011*)[73]. This shows that mining, except for impacts on the natural environment, also entails social impacts which have to be carefully considered when planning and realising mining projects (*Öko-Institut e.V., 2011*)[73].

3.6.3 Mining Activities

Except for the potential risks mentioned above, mining activities inevitably destroy the natural habitat and wipe out biodiversity by utilising and polluting vast land areas. The Bayan Obo mining district (the largest discovered REE-Fe-Nb resource in the world located in Inner Mongolia, China) covers an area of 48 km^2, and the tailings impoundment/reservoir at Bayan covers an area of 11 km^2, even though only 35% of the Main and East ore bodies have been exploited after more than 40 years of mining (*Öko-Institut e.V., 2011*)[73].

If fast growing emerging economies are going to use similar technologies and lifestyles as developed countries, "*global in-use metal stocks required would be 3-9 times those existing at present*" (*UNEP, 2011*)[64]. To meet such a demand for conventional and "specialty" metals, as well as to break unsustainable monopolies (such as the Chinese rare earths monopoly), new mines will have to be opened in the near future (Figure 15).

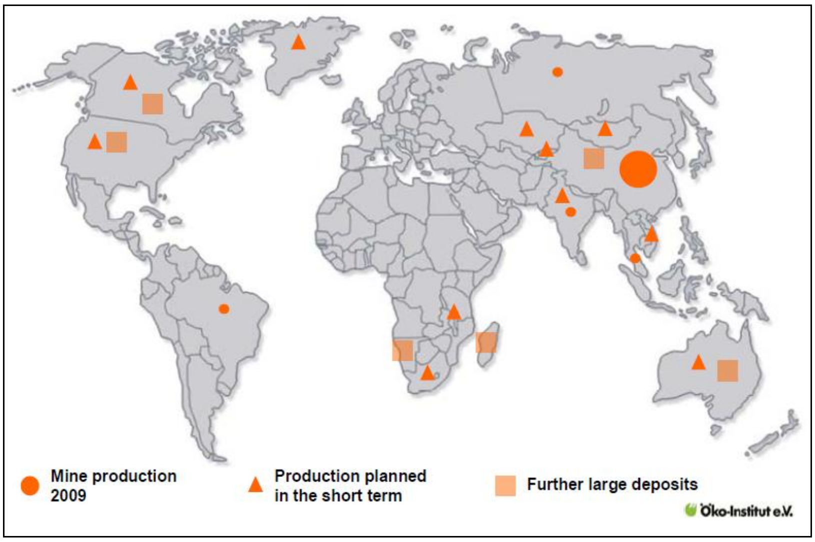


Figure 15. The spatial distribution of current and planned short-term rare earth mines as well as further large deposits. Source: Öko-Institut e.V. (2011)[73].

Figure 15 shows that current rare earth mines only represent a fraction of all the mines that are planned in the short term and that even more deposits may become exploited in the future. Additionally to those mines shown in the figure, there are numerous illegal mines in China, most of them without any environmental protection systems (*Öko-Institut e.V., 2011*)[73]. Figure 15 also shows that there are currently no mines operating or planned in the European Union, and the reason is that very little information is available on rare earth deposits in the EU (*Öko-Institut e.V., 2011*)[73].

On top of rare earth mines, new mines for other metals such as tellurium and indium may be opened to meet future demand. One concern is that the pressure on the opening of new mines outside of China (in the case of rare earths) to meet the steeply increasing demand may lead to the opening of mines that do not keep minimum environmental standards (*Öko-Institut e.V., 2011*)[73]. One such case could be the Kvanefjeld deposit in Greenland where they plan to store the tailings in a natural lake with connection to the sea (*Öko-Institut e.V., 2011*)[73]. To make sure that new mines are not opened without proper environmental protection systems, "*environmental aspects should be monitored attentively by the authorities and the public*" (*Öko-Institut e.V., 2011*)[73]. However, if a large number of new mines are opened to meet increasing demand, vast land areas will inevitably become destroyed and polluted, regardless of environmental protection measures (exemplified in Figure 16 and Figure 17).

Figure 16. Copper mining pits, in Pima County, Arizona, United States. Courtesy of Airphoto - Jim Wark

Figure 17. An iron-ore tailings pond in Maquette County, Michingan, United States. Courtesy of Airphoto - Jim Wark

As stated in section 3.1.1, the U.S. Geological Survey (2011)[68] estimates that the total reserve of rare earth oxides that could be economically extracted in the future amount to about 110 million tonnes - to be compared with the current world production of 130 000 tonnes. If those 110 million tonnes would be extracted in the future, the environmental and social impacts from land use, energy use and pollution would be immense. It is therefore of outmost importance to reduce virgin raw material extraction by increasing recycling, reducing material use and by substituting metals whose ore grades are low with other metals that are more abundant.

3.6.3.1 Recent Discoveries

Except for the mining prospects shown in Figure 15, it was recently discovered by Japanese researchers that deep-sea muds contain high concentrations of rare-earth elements at numerous sites throughout the eastern South and central North Pacific (Figure 18) (*Kato et al., 2011*)[37]. They estimate that an area of just one square kilometre, surrounding one of the sampling sites, could provide one-fifth of the current annual world consumption of rare earth elements, and that the total amount of rare earths contained in the mud could exceed the world's current land reserves (*Kato et al., 2011*)[37]. The mud has also been shown to be enriched in transition metals such as V, Co, Ni, Cu, Zn, Mo, and Mn by up to two orders of magnitude greater than average continental crustal contents, making the resource value of the mud even greater if the metals can be recovered together (*Kato et al., 2011*)[37]. Moreover, the mud does not require extensive processing such as crushing and milling (since it is already made up of fine particles), it contains lower amounts of radioactive thorium and uranium and the metals are recoverable with a simple acid leaching method (*Kato et al., 2011*)[37].

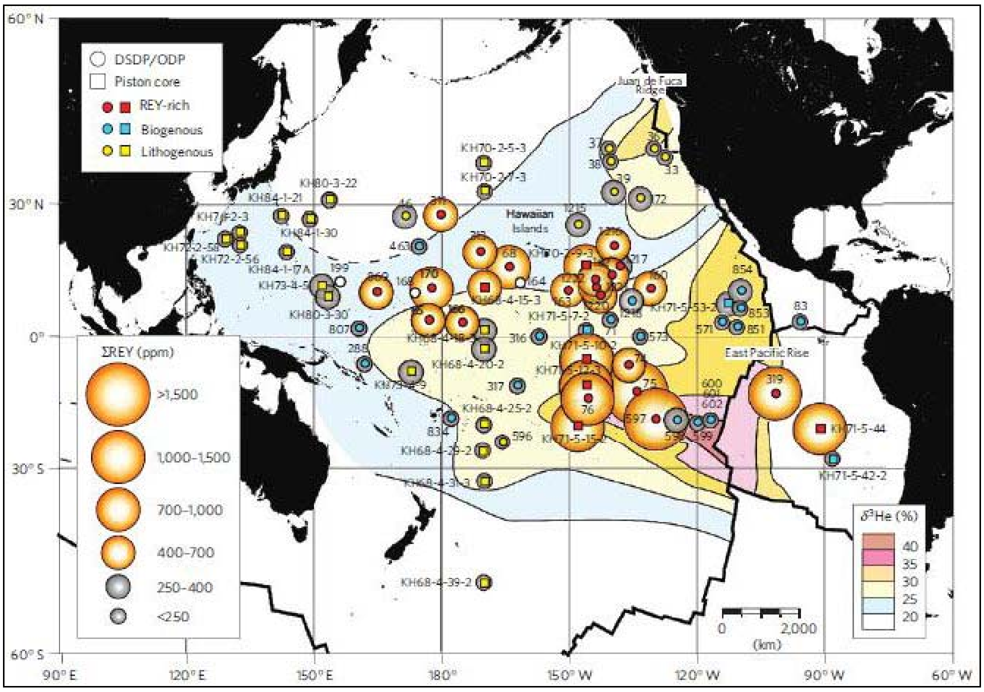


Figure 18. Distribution of average ∑REY content for surface sediments (<2m in depth) in the Pacific Ocean. **Reprinted by permission from Macmillan Publishers Ltd: [*Nature Geoscience*] Kato et al., 2011[37]: Deep-sea mud in the Pacific Ocean as a potential resource for rare-earth elements. Nature Geoscience, Vol 4, 535-539. Copyright 2011**

The findings mentioned suggest that "*REY-rich mud*" (i.e. mud containing rare earths and yttrium) may constitute a highly promising REY resource for the future "*unless the great water depths have a significant impact on the technological and economic viability*" (*Kato et al., 2011*)[37]. However, before these potential resources can be utilised, it is highly important to assess the environmental impacts of such activities, as well as to solve the apparent issue of property rights connected to the use of global commons.

3.6.4 Energy Use and Climate Change

Except for the environmental risks and impacts associated with pollution and land-use, another serious issue is energy use. Mining, processing and refining of metals is extremely energy-intensive, and depending on what energy carriers are used, high CO_2 emissions may arise and contribute to climate change (*Öko-Institut e.V., 2011*)[73].

In 2007 it was estimated that the metals industry in the U.S. consumed about 550 TBtu/year, corresponding to about 33,5 Mt of CO_2 emissons (*U.S Department of Energy, 2007*)[67]. A quick calculation shows that this amount of energy corresponds to that produced by 28 average nuclear power plants (assuming 436 nuclear power plants with an average production of 2558 TWh in 2009) and the CO_2 emissons correspond to the total of New Zeeland's or a third of Belgium's (data from 2008; *World Bank, 2011*)[71].

Another example is Iceland which by far has the highest energy use per capita in the world of 16.9 kg Oil equivalents in 2010 (compared to the U.S. which had 7,2 kg) (*World Bank, 2011*)[71]. This extreme energy consumption comes from aluminium smelting industries on Iceland. Iceland does not have any aluminium resources, but it has been targeted by the aluminium smelting industry as an "*energy paradise*" where they can supply their operations with cheap energy. This has resulted in major exploitation of Iceland's water resources and large environmental and social impacts (*Magnason, 2008*)[41].

These two examples highlight how energy-intensive the metals industry is, and how it significantly contributes to CO_2 emissions and climate change. They also highlight the potential impact on energy use and CO_2 emissions that a rising demand for metals may have. Looking at Figure 15, we see that 11 rare earth mines are planned in the short-term and that an additional 6 large deposits may be exploited in the future. These exploitation activities will indeed require large amounts of energy and contribute to global warming.

4 Conclusions

This study has shown how major deployment of photovoltaic cells and permanent-magnet wind turbines may have a serious impact on the future demand of 8 *significant elements* - gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium. Based on these findings, the recycling and substitution potential of these metals as well as potential technology substitution options have been assessed. Finally, the main environmental impacts associated with metals extraction, processing and refining have been summarized and discussed in the light of a potential increase in demand.

4.1 Main Findings

The main findings can be summarized in the following points.

- **Major deployment** of photovoltaic cells and permanent-magnet wind turbines may have a serious impact on the future demand of 8 *significant elements* - gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium.
- **The current recycling rate** of the 8 *significant elements* is less than 1 percent.
- **Recycling will not be able to offset any significant part of the raw material supply** needed for the successful deployment of photovoltaic cells and permanent-magnet wind turbines up to 2030. Demand will have to be met by virgin raw material extraction.
- **Material substitution** options for the 8 *significant elements* are very limited.
- **Technology substitution** options can be considered fairly available for photovoltaic cells dependent on gallium, indium, selenium and tellurium; and available for permanent-magnet wind turbines dependent on dysprosium, neodymium, praseodymium and terbium.
- **The environmental risks and impacts** associated with metals extraction, processing and refining are many, and a rising demand for metals will inevitably have major environmental and social impacts, including significant contribution to climate change. Environmental risks are expected to grow if new mines with sub-standard environmental protection are opened in a hurry to meet demand, and as extreme weather events become more frequent.

4.2 Discussion

This study set out to analyze current and future impacts of raw materials supply on the deployment of photovoltaic cells and wind turbines. The main question was *if major deployment of renewable energy might be constrained by resource shortages*. Our findings suggests that this may be the case, depending on how we choose to adapt our technologies and to tackle potential resource constraints. The results will now be briefly discussed by comparing them with the most recent and relevant studies on the topic of critical and strategic metals.

The most important finding of this study is that the future supply of 8 *significant elements* may be adversely affected by any major deployment of photovoltaic cells and permanent-magnet wind turbines. This further suggests that any shortage of these 8 significant elements may inhibit a successful transition to renewable energy systems.

This conclusion is supported by a number of similar studies, such as a recent report on *energy critical elements (ECEs)* by the American Physical Society (2011)[1], the *Critical Materials Strategy* by the U.S. Department of Energy (2010)[66], two reports by the European Commission (2011; 2011b)[12;14] and a report by Öko-Institut e.V. (2011)[73]. Each study has identified a different set of critical or significant elements depending on the methodology used, but a common conclusion is that potential supply shortages of these "critical" or "significant" elements could "*significantly inhibit the adoption of otherwise game-changing energy technologies*" (*American Physical Society, 2011*)[1]. The elements that were identified as critical or significant in the mentioned studies are summarized in Table A 10 for an easy comparison.

Furthermore, the studies conclude that "*Chinese HREE production will probably not rise and eventually even decrease*" (*Öko-Institut e.V., 2011*)[73] and "*the lag time between increased demand and the availability of new supplies can be extensive*" (*American Physical Society, 2011*)[1]. Due to the current lack of data, and the importance of certain elements to strategic and renewable energy technologies (energy critical elements - ECEs), the American Physical Society (2011)[1] has suggested that the U.S. "*should gather, analyze, and disseminate information on ECEs across the life-cycle supply chain, including discovered and potential resources, production, use, trade, disposal, and recycling*". These suggestions are just as relevant to the European Union, and researchers have stressed the importance of including a number of energy critical metals in the *critical raw materials list* of the European Commission (*Graedel, 2011*)[27].

Finally, to highlight the most important characteristics and findings of this study, a short comparison with the most relevant studies on the topic of critical and strategic metals will be made.

4.2.1 Critical Raw Materials for the EU

In 2010, the European Commission (2010)[12] identified 14 elements (and element groups) as critical to the European Union. The study assessed criticality by looking at supply risks, "*taking into account the political-economic stability of the producing countries, the level of concentration of production, the potential for substitution and the recycling rate*" as well as the "environmental country risk" "*assessing the risks that measures might be taken by countries with weak environmental performance in order to protect the environment and, in doing so, endanger the supply of raw materials to the EU*" (*European Commission, 2010*)[12]. The study did not assess geological availability "*as geological scarcity is not considered as an issue for determining criticality of raw materials within the considered time horizon of the study, e.g. ten years*" (*European Commission, 2010*)[12].

Comparing the results of the European Commission (2010)[12] with the findings of this study as well as with others, we see that the choice of methodology and how we choose to define "criticality" is crucial to our understanding of the situation. A simple comparison of methodologies and results are presented in Table A 11 and Table A 10 respectively.

As an example, this study has concluded that the supply of gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium may be critical for the major deployment of photovoltaic cells and permanent-magnet wind turbines. Since major deployment of photovoltaic cells and wind turbines is expected as the EU and the rest of the world is moving towards low carbon, and eventually carbon free, economies - these metals can, and should therefore, be seen as "critical". In the example of selenium and tellurium, none of them have been identified as critical by the European Commission (2010)[12].

Moreover, the European Commission (2010)[12] aggregated the individual rare earth elements into one group, most likely since several rare earths are mined together, and since the production is concentrated to 97% in China. This approach is unfortunately blind to the supply and demand of the individual rare earth elements, and may therefore result in a misleading interpretation of criticality. Not all rare earth elements may be "critical" or have the same level of "criticality", as has been shown in the case of permanent-magnet wind turbines (Figure 4).

The list of critical raw materials given by the European Commission (2010)[12] is currently being revised[76], and the results of this study, as well as others (e.g. *European Commission, 2011b; Graedel, 2011*)[14,27], strongly suggest that the methodology used to identify "critical" raw materials should be carefully re-assessed and put in the perspective of policy targets and roadmaps, such as the *Europe 2020* targets and the upcoming *Roadmap for moving to a competitive low-carbon economy in 2050*.

4.2.2 Critical Metals in Strategic Energy Technologies

In a more recent report, carried out by the Joint Research Centre of the European Commission and two external consultants, critical metals in strategic energy technologies were assessed (*European Commission, 2011b*)[14]. The findings are similar to those in this report (compare Figure A 5), since much of the data and several deployment scenarios are the same - but there are some important differences:

1. This study investigates critical metals on a global scale and focuses on photovoltaic cells and permanent-magnet wind turbines - as opposed to a European scale with a focus on all major "SET-plan technologies". Due to the different scopes of the studies, the findings are different regarding:
    a. The identified critical elements and their criticality on a global scale
    b. Material compositions and substitution options of photovoltaic cells and permanent-magnet wind turbines
2. This study is based on a wider range of deployment scenarios, both on a European and a global scale

3. This study includes additional information on the implications that metals production and demand has on the environment and climate

The narrower scope of this study has allowed for a deeper analysis of the material compositions of photovoltaic cells and permanent-magnet wind turbines as well as of material and technology substitution options. This, together with the choice of scale, has resulted in a different set of identified *significant elements*. The differences highlighted above suggest that the findings of this study may add some additional insights to the ongoing debate on critical metals and renewable energy technologies.

4.3 Policy Recommendations

Based on the findings of this study and the experience gained while conducting it, the need for several policy actions has been identified. These needs are explained and summarized in comprehensible recommendations below.

Recommendation 1. Integrating Raw Materials Criticality in Energy Strategies and Targets

This study has shown how a major shift towards renewable energy systems, using photovoltaic cells and permanent-magnet wind turbines, may have a great impact on the supply of several elements. These findings further suggest that the future supply of these elements may impose a risk of disabling a shift towards low carbon, and eventually carbon free economies - potentially disrupting European and global efforts to tackle climate change.

→ To prevent potential supply bottlenecks and unsustainable price developments, **the European Union and the rest of the world must integrate knowledge on raw material constraints in energy strategies and targets.**

Failing to do so may result in supply shortages of important elements, rising prices of renewable energy systems and further delays in climate change mitigation.

Recommendation 2. Global Cooperation on the Management of Raw Materials

The findings of this study have again highlighted what it means to live in globalized world. No nation has access to all elements needed in modern societies, and the export cuts imposed by the Chinese government on rare earth elements in 2008 clearly reminded us of our interdependence. Global cooperation on the management of raw materials (as well as other natural resources) is therefore key in assuring economic, political, social and environmental sustainability.

→ To prevent potential supply bottlenecks of important raw materials and to assure economic, political, social and environmental sustainability, **the European Union must work together with the rest of the world on establishing a global framework for cooperation on the management of raw materials and other natural resources.**

Failing to do so will promote continued unsustainable development and increase the risk of economic, political, social and environmental instability.

Recommendation 3. Increasing Transparency and Research

When conducting this study, it became increasingly obvious that the availability and quality of data related to raw material composition of different technologies is extremely poor. The main reason for this seems to be a lack of transparency on raw materials use among manufacturers, as the detailed compositions of products are the secret of every producer[78]. Not even experts at organisations[78] and research centers[75,79] have the information because there is a wide range of available compositions and a lack of research. The poor availability of data forces studies such as this one to rely on average compositions, assumptions and simplifications. The result is that we are forced to rely on rough estimates to foresee potential supply bottlenecks of materials that are crucial to our society, and that we may spend a lot of money and effort on developing technologies whose potential may be limited (such as CdTe photovoltaics). Therefore, there is an urgent need for increased transparency among those who use raw materials, such as manufacturers of photovoltaic cells and wind turbines. Öko-Institut e.V. (2011)[73] has also pointed out that "*precise analyses and reliable demand forecasts require a comprehensive material flow analysis to be undertaken*".

For manufacturers, increased transparency could likely be achieved without threatening business confidentiality or fair competition since only the amount of each element is of interest in this context (not the manufacturing techniques or technology designs). In fact, making such information publicly available may even foster further technological and sustainable development, since is in the interest of manufacturers to keep raw materials use and costs at a minimum. The same can however not be said with regard to the mining industry, as giving out information about the production capacity of a company may cause investors to search for other companies with higher extraction rates and thus probability of future profits.

> → To improve the reliability of raw material demand forecasts in order to avoid potential supply bottlenecks and to ensure strategic planning and sustainable management of raw materials, **the European Union must ensure transparency on raw materials use.**
>
> → Furthermore, **the European Union must promote further research in the area of material flow analysis and raw materials use in strategic energy technologies,** especially focusing on technologies that are crucial to the fulfillment of long-term strategies and targets.

Failing to do so will result in continued reliance on best estimates, thereby obstructing the possibility to accurately assess the full range of materials used in the most crucial technologies to our society and to foresee potential supply shortages.

Recommendation 4. Raising Public Awareness

The findings of this study show that we have been developing technologies that may not be compatible with our long-term goals and targets. The reason for this has most likely been a lack of knowledge and public awareness. One example of this is the development of wind turbines, where several large manufacturers (such as GE and Siemens) are relying on rare earth permanent-magnets for gearless turbines, while, as far as this study is concerned, only one manufacturer (Enercon) has developed gearless turbines without permanent magnets. Having realised the potential supply constraints of several raw materials now shows that holistic thinking and integrative planning must be strongly encouraged if we are to tackle the challenges of the 21st century. Raising public awareness about resource constraints is therefore key to promote research and development of new technologies that do not rely upon raw materials with potential supply constraints.

> → To ensure that research and development promotes technologies that do not heavily rely upon raw materials with potential supply constraints, **the European Union must act to raise public awareness about resource constraints.**

Failing to do so will result in the continued development of technologies that may not be compatible with our long-term strategies and targets.

Recommendation 5. Setting up Recycling Schemes

This study has shown that the recycling potential of the materials used in strategic energy technologies is very large, and that the amount of waste from these technologies will be vast in the future. To close material loops, increase supply security and ensure the sustainable use of natural resources, it is important to develop efficient recycling schemes as well to stop exporting products containing critical raw materials. Recycling research and development "*should be started now without further delay as it will take a minimum of five to ten years for the first large-size implementation to take place*" (*Öko-Institut e.V., 2011*)[73].

> → To close material loops, to increase supply security of critical raw materials and to ensure the sustainable use of natural resources, **the European Union must develop proper recycling schemes for, and eliminate all exports of, products containing critical raw materials.**

Failing to do so will result in increased reliance on virgin raw materials extraction, continued loss of valuable and critical raw materials, as well as increased risk of potential supply shortages.

Recommendation 6. Promoting Sustainable Mining and Processing

Finally, this study has highlighted the environmental risks and impacts associated with raw materials extraction, processing and refining. The increased demand for raw materials such as "specialty metals" is expected to grow significantly within the coming decades, and there is a risk that new mines will be opened without meeting minimum environmental standards. Since the majority of these materials are consumed by the EU, US and Japan (besides China), it is up to them to contribute to the sustainable supply of raw materials. There are a number of initiatives for sustainable mining worldwide, including certification schemes addressing different issues such as environmental aspects, small-scale mining, safety issues and human rights (*Öko-Institut e.V., 2011*)[73]. The interest for certified minerals is increasing, and "*today's mining companies could be interested in certification schemes or similar co-operations with EU participation in order to highlight their environmental efforts*" (*Öko-Institut e.V., 2011*)[73].

> → To promote a sustainable supply of critical raw materials that ensures proper environmental standards, safety precautions and human rights, **the European Union must step up efforts to promote sustainable mining and processing both within and outside of the EU.**

Failing to do so will force us to question the sustainability aspects of technologies that are using critical raw materials - including renewable energy systems. A shift towards renewable energy systems must be accompanied by a shift towards sustainable mining and processing.

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6 Annex A

6.1 Energy Scenarios

Table A 1. Future scenarios of the deployment of photovoltaic cells

Year		Ref 2010	2020	2030
EU installed capacity (GW)	[18]	29.3[17]	30[r]/ 140[a]/ 366[p]	38[r]/ 280[a]/ 631[p]
	[28]		41[r]/ 120[re]/ 138[a]	70[r]/ 179[re]/ 221[a]
Global installed capacity (GW)	[18]	39.5[17]	77[r]/ 345[a]/ 688[p]	156[r]/ 1081[a]/ 1845[p]
	[28]		80[r]/ 335[re]/ 439[a]	184[r]/ 1036[re]/ 1330[a]

Table based on data from EPIA (2011b)[18] and Greenpeace & EREC (2011)[28] except for year 2010 where data is from EPIA (2011a)[17]. [r], [a] and [p] in the rows based on EPIA (2011b)[18] refers to the Reference, Accelerated and Paradigm shift scenarios respectively. [r], [re] and [a] in the rows based on Greenpeace & EREC (2011)[28] refers to the Reference, [R]evolution and Advanced [R]evolution deployment scenarios respectively.

Table A 2. Future scenarios of the deployment of wind turbines

Year		Ref 2010	2020	2030
EU installed capacity (GW)	[24]	86[25]	184[r]/ 251[m]/ 279[a]	234[r]/ 447[m]/ 515[a]
	[28]		185[r]/ 249[re]/ 249[a]	252[r]/ 340[re]/ 386[a]
Global installed capacity (GW)	[24]	194[25]	415[r]/ 832[m]/ 1071[a]	573[r]/ 1778[m]/ 2342[a]
	[28]		417[r]/ 878[re]/ 1140[a]	595[r]/ 1733[re]/ 2241[a]

Table based on data from GWEC (2010)[24] and Greenpeace & EREC (2011)[28] except for year 2010 where data is from GWEC (2011)[25]. [r], [m] and [a] in the rows based on GWEC (2010)[24] refers to the Reference, Moderate and Advanced deployment scenarios respectively. [r], [re] and [a] in the rows based on Greenpeace & EREC (2011)[28] refers to the Reference, [R]evolution and Advanced [R]evolution deployment scenarios respectively.

6.2 Technology Mix Scenarios

Table A 3. Trend scenarios of PV technology market shares (%)

	2010	2015	2020	2030	2011-2030	2011-2030
Technology	**EPIA[18]**	**EPIA[18]**	**EPIA[18]**	**Author***	**EU Com[14] "c-Si dominant"**	**EU Com[14] "Thin film uptake"**
c-Si	80	67	61	55	80	59
a-Si	3	7	8	12	10	15
CdTe	15	15	12	8	5	8
CIGS	2	8	14	18	5	18
CPV & emerging tech.	0	3	5	7	-	-
Total (%)	100	100	100	100	100	100

Table based on data from EPIA (2011b, Figure 12)[18] and the European Commission (2011b, p. 57)[14]. Figures from EPIA (column 2-3) are visually derived from Figure 12 in EPIA (2011b)[18]. The two columns with data from the European Commission (2011b)[14] refer to the two different technology mix scenarios presented in the report - the "c-Si dominant"-scenario where c-Si is continually dominant and the "Thin film uptake"-scenario where thin film technologies gain market shares. * The values in the Author column are example values by the author of this report based on the trends given by EPIA (2011b)[18] and the "Thin film uptake"-scenario by the European Commission (2011b, p. 57)[14].

As shown in Table A 3, EPIA forecasts that c-Si will gradually lose market shares while Thin-Film technologies will gain. This technology shift has to do with the constantly decreasing cost of Thin-Film technologies and their higher ability to absorb diffuse sunlight - something which makes them more suitable in countries further to the north where direct sunlight is less frequent. The European Commission has a different approach and has given two different scenarios - one "c-Si dominant"-scenario where c-Si technologies are dominant and one "Thin film uptake"-scenario where Thin-film technologies gain market shares.

Table A 4. General trend estimates of permanent-magnet (PM) wind turbine market shares (in %)

Area	2009	2015	2020	2030
EU			15*[14,p.34]	20*[14,p.34]
	2009	**2010-2015**	**2015-2020**	**2021-2030**
Globally	14**[21]	10[14,p.99]	20[14,p.99]	25[14,p.99]

* The number refer to Low speed PM wind turbines only (i.e. it is assumed that 100% PM market is low speed turbines). ** The number may be based on a confusion between gearless turbines and permanent-magnet turbines (see discussion below). Superscripted numbers refer to references in the reference list.

As shown in Table A 4, PM wind turbines had a market share of 14% globally in 2009 according to Fairley (2010)[21] - a number that has also been cited in a recent report on rare earths by Öko-Institute e.V. (2011)[73] for the European Parliament. This perception is however not shared by Oakdene Hollins (2010)[52] who say that the market share is expected to be 10% in the period 2010-2015. The study by Oakdene Hollins (2010)[52] which was based on a survey of wind turbine companies (produced by an independent wind energy consultant) further estimated that 20% of global wind turbine installations between 2015 and 2020 were likely to use permanent magnets, rising to 25% for 2021-2030. The inconsistency of the numbers cited in these reports could perhaps lie in a confusion between gearless turbines and permanent-magnet turbines (gearless turbines do not necessarily have to be based on permanent magnets: see Table 6). Furthermore, the European Commission (2011b)[14] has based their latest report "*Critical metals in strategic energy technologies*" on yet another set of wind turbine technology mix scenarios (see Table A 5).

Table A 5. Estimated trends of permanent-magnet wind turbine market shares under the two scenarios "Dominance of EM Systems" and "Take-up of PM and HTS systems" given by the European Commission (2011b)[14]

Scenario	2011-2020 H/M speed	2011-2020 Low speed	2021-2030 H/M speed	2021-2030 Low speed
Dominance of EM systems	10%	10%	5%	5%
Take-up of PM and HTS systems	15%	20%	10%	20%

The general scenarios of permanent-magnet wind turbines presented in Table A 4 are a simplified reality. As can be seen in Table A 8, the weight of the permanent magnets used in wind turbines is quite different between low-speed PM turbines (700kg) and H/M speed PM turbines (80kg) and the deployment of PM wind turbines is uncertain. Therefore, the European Commission (2011b)[14] has proposed two different technology mix scenarios, taking into account different take-up scenarios of PM wind turbines (the "Dominance of EM systems" and "Take-up of PM and HTS systems"), as well as shares of H/M and low-speed PM turbines.

The metal demand modeling in this report is based on the "Dominance of EM systems" and "Take-up of PM and HTS systems" scenarios, since these are the latest and most detailed scenarios available and since this will allow for comparison between the modeling in this study with that of the European Commission (2011b)[14]. Furthermore, it is assumed that these scenarios are applicable on both a European and a global scale.

6.3 Detailed Material Compositions and Assumptions

6.3.1 Photovoltaic Cells

Table A 6. Material composition of common photovoltaic cells in kg/MWp. Metals within frames, cables and batteries etc. are not included - only the metals present in the cells.

Metal	c-Si(74)	a-Si(74)	CdTe(74)	CIGS / CIS(14,74)	CPV	DSSC
Ag	5,17		*(48)	*(48)		*(48)
Al		102,00	*(74)	*(74)		
As			*(51)		*(60)	
Au						
B		0,0008	*(74)			
Ba			*(51)			
Cd			83,51	0,93		
Ce	**(49)	**(49)	**(49)	**(49)	**(49)	**(49)
Co						*(7)
Cr			*(51)			
Cu	589,38		24,41	16,97		
Ga			*(13)	6,17		*(13,60)
Ge		*(60)			*(60)	
Hg			*(51)			
In		5,32	7,95	83,79	*(60)	
Mo				36,78		
Ni			*(51)			
Os						*(30)
Pb	72,38		*(51)			
Pt						*(30)
Ru						*(30)
Sb	**(49)	**(49)	**(49)	**(49)	**(49)	**(49)
Se			*(51)	84,41		
Si	0,00	18,40				
Sn	124,08	103,08	83,86	5,95		* (30)
Te			90,38			
Ti						
Zn			*(74,51)	29,99		

References are within superscripted brackets. * There are reports indicating that the metal is present, but there is no data on the amount. ** It is unclear to what extent cerium or antimony is used in PV cover glass and what kind of PV technologies that may use such glass. According to PV experts at ECN Solar Energy Netherlands[79], (almost) no cerium or antimony is currently used in the glass of photovoltaic cells, and according to experts at National Renewable Energy Laboratory[75], there may be an increase in the use of antimony-doped glass for future PV use, but it appears to be very little in use at the present.

The figures presented in Table A 6 were calculated by using information from Ökopol (2007)[74], the European Commission (2011b)[14] and Q Cells (2011)[70]. Except for the information given on each PV technology below, standard atomic weights were used to derive weights of individual metals from the metal compounds given by Ökopol (2007)[74]. Table A 6 shows that information about the metal content of c-Si and CIS/CIGS is fairly available while information about CdTe is somewhat available and information about a-Si, CPV and DSSC is largely unavailable. For cerium and antimony, reports have been indicating their use (NREL, 2009)[49], but according to experts, almost no cerium or antimony is currently used[79]. However, there may be an increase in the use of antimony-doped glass in the future[75]. Considering the supply risk of antimony (Table 2), large-scale use of this metal may not be feasible due to resource constraints.

c-Si

All figures have been derived from data given by Ökopol (2007)[74], multiplying the compositional data (%) with the module weight per Wp (103,4 kg/kWp). Compared to the data presented by the European Commission (2011b)[14], which is based on the same data from Ökopol (2007)[74], the figures in this report are much lower (e.g. 5,17 vs. 24 kg Ag per MW). The authors responsible for the report by the European Commission (2011b)[14] have been contacted about this issue, but no explanation has been given[77]. The reason is therefore uncertain, but with regard to the available information from Ökopol (2007)[74], it seems like the figures in Table A12 in the report by the European Commission (2011b)[14] may need to be checked.

a-Si

All figures have been derived from data given by Ökopol (2007)[74], except for data on indium and tin. The tin content has been calculated by adding data from Ökopol (2007)[74] (assuming the use of SnO_2 TCO, and tin as oxide) with data given by the European Commission (2011b)[14] (assuming that ITO-glass is used). Thus, it is assumed that both TCO (SnO_2) and ITO is used, which may be the case for some manufacturers but not for others. This assumption was made in order not to underestimate the use of indium, with the consequence that the use of tin may be slightly overestimated. The module size was not used in the calculations since the data was given in g/Wp in both studies, and, since all data was from Ökopol (2007)[74] except for the ITO-glass, the data was assumed compatible (assuming that the thickness of the ITO-glass is not dependent on the size of the panel).

CdTe

All figures have been derived from data given by Ökopol (2007)[74], except for data on indium and tin. For indium and tin, it was assumed that 50% of the glass was TCO and 50% ITO to compromise between Ökopol (2007)[74] who only reported the use of TCO and the European Commission (2011b)[14] who only reported the use of ITO. This assumption might underestimate the use of tin and indium if only TCO-glass is used, and overestimate it if only ITO-glass is used. The module size was not used in the calculations since the data was given in g/Wp in both studies, and, since all data was from Ökopol (2007)[74] except for the ITO-glass, the data was assumed compatible (assuming that the thickness of the ITO-glass is not dependent of the size of the panel).

CIGS/CIS

The module size used in the calculations was 0,94 m^2 and 115 Wp, based on the size and Wp of a Q-Cells UF L 95-115 CIGS panel (Q Cells, 2011)[70]. A composition of 70% CIS and 30% CIGS was assumed, according to estimates given by Ökopol (2007, p. 55)[74]. Furthermore, all figures have been derived from data given by Ökopol (2007)[74], except for data on indium and tin. It was assumed that ITO-glass is used, as proposed by the European Commission (2011b)[14], and thus the tin content is given by the European Commission (2011b)[14] and the indium content was calculated by adding the indium content from CIGS/CIS (given by Ökopol) with that from the ITO-glass.

6.3.2 Permanent-magnet Wind Turbines

Table A 7. Chemical composition of NdFeB-magnets (% weight)

#	Source	Fe	Nd	Dy	B	Pr	Tb
1	European Commission(14) (Shin Etsu)	66	29	3	1	-	-
2	European Commission(14) (Great Western Minerals Group)	68	31		1	-	-
3	European Commission(14) (Technology Metals Research)	69	28	2	1	-	-
4	European Commission(14) (Avalon Rare Metals)	-	30	-	-	-	-
5	European Commission(14) average	68	29	2	1	-	-
6	Du and Graedel(8)	-	20	5	-	5	1
7	**Du and Graedel(8) / EU Com.(14) mix**	**65**	**24,5**	**3,5**	**1**	**5**	**1**

"-" no data

Table A 7 shows a number of different compositions of NdFeB-magnets reported by magnet manufacturers and researchers. The table only includes compositions reported in scientific studies, although other sources have indicated slightly different compositions (E-magnets UK Limited)[11], as well as the use of "*cobalt (Co), niobium (Nb), gallium (Ga), aluminum (Al), copper (Cu) and other elements*" (Permanent-magnet.net, 2011)[54].

In a very recent study by the European Commission (2011b)[14] the average composition of permanent magnets (based on data from four permanent-magnet manufacturers shown as #1-4 in Table A 7) used in wind turbines was estimated to be 68% iron, 29% neodymium, 2% dysprosium and 1% boron (see #5 in Table A 7). Unlike a recent study by Du and Graedel (2011)[8], the study by the European Commission (2011b)[14] did not quantify the presence of praseodymium (Pr) and terbium (Tb) in the permanent magnets. The reason for this was that these metals are used "only occasionally or in very small quantities" (European Commission, 2011b)[14]. However, according to Du and Graedel (2011)[8], praseodymium coexists with neodymium in rare earth minerals naturally and also co-exists with neodymium in the alloy made into magnets from the minerals. Terbium and dysprosium is also commonly added to magnets to improve their high-temperature performance (Du and Graedel, 2011)[8]. Furthermore, Lynas Corporation[40] claims that neodymium and praseodymium are the main rare earths used in hybrid vehicles electric motors (using permanent magnets) along with terbium and dysprosium that may be added in smaller quantities.

As we can see in Table A 7 Du and Graedel (2011)[8] have estimated that the relative presence of praseodymium and terbium in permanent magnets may actually be in the same order of magnitude as dysprosium and boron respectively. This suggests that these two metals should not be neglected when looking at the future metal demand from permanent-magnet wind turbines, especially not when considering that all rare earth metals have a high supply risk (see Table 2) and that the relative upper crustal abundance of these metals is as follows (see Table 1): neodymium (27ppm) > praseodymium (7ppm) > dysprosium (4ppm) > terbium (1ppm).

In this study, we chose to address the future demand of all the metals that have been found likely to be present in permanent magnets by combining the composition data estimated by Du and Graedel[8] with that by the European Commission[14]. The composition that we assumed is shown as #7 in Table A 7. The content of Nd and Dy is the average between the two studies, the content of B is the same as was found by the European Commission (2011b)[14], the content of Pr and Tb is the same as assumed by Du and Graedel (2011)[8] and the content of Fe has been adjusted downwards to make up for the increased content of the other metals. This "made-up" composition allows us to make reasonable estimates of the future demand of all metals that have been found likely to be present in permanent-magnet wind turbines, even though it might slightly overestimate the total content of rare earth metals. The assumed metal composition and the corresponding metal weights for H/M and low-speed PM wind turbines are presented in Table A 8.

Table A 8. Material composition of high/medium and low speed permanent-magnet (PM) wind turbines

Metal	Composition* (%)	H/M speed PM weight (kg/MW)	Low speed PM weight (kg/MW)
Al	-	-	-
B	1,0	0,8	7,0
Co	-	-	-
Cr	-	789.3*	789.3
Cu	-	1142.9*	1142.9
Dy	3,5	2,8	24,5
Fe	65,0	52,0	455,0
Mn	-	32.5*	32.5
Mo	-	116.1*	116.1
Nb	-	-	-
Nd	24,5	19,6	171,5
Ni	-	557.1*	557.1
Pr	5,0	4,0	35,0
Tb	1,0	0,8	7,0
Sm	-	-	-
Total	100,0	80	700

* The composition is only given for the NdFeB-magnets due to a lack of data. The total weights of the elements in the NdFeB-magnets are calculated by multiplying the composition data with the magnet weights in the last row of the table. The other weights are those used in the report by the European Commission (2011b)[14], obtained through personal communication[77]. * Due to a lack of information, it was assumed that the weights of Cr, Cu, Mn, Mo and Ni in H/M speed PM are equal to those in low speed PM.

Due to a lack of information, it was assumed that the weights of Cr, Cu, Mn, Mo and Ni in H/M speed PM are equal to those in low speed PM. This assumption may result in an overestimation of the demand for these metals, but as can be seen in the results (section 3.3.2.2 and 3.3.3), none of these metals have been identified as *significant*, so the main conclusions remain the same.

6.4 World Production of Investigated Elements 2010

Table A 9. World production of elements investigated in this study, based on data from U.S. Geological Survey (2007 and 2011b)[69,68] and U.S. Department of Energy (2011)[66].

Element	Tonnes/year	Reference	Element	Tonnes/year	Reference
Ag	22200	USGS 2011, p. 147	Mn	13000000	USGS 2011, p. 101
Al	41400000	USGS 2011, p. 17	Mo	234000	USGS 2011, p. 107
As	54500	USGS 2011, p. 21	Nd	21307	US DoE (table 7-2)
Au	2500	USGS 2011, p. 75	Ni	1550000	USGS 2011, p. 109
B	3500000	USGS 2011, p. 33	Os	no data	USGS 2011
Ba	no data	USGS 2011	Pb	4100000	USGS 2011, p. 91
Cd	22000	USGS 2011, p. 37	Pr	6292	US DoE (table 7-2)
Ce	49935	US DoE (table 7-2)	Pt	183	USGS 2011, p. 121
Co	88000	USGS 2011, p. 47	Ru	no data	USGS 2011
Cr	22000000	USGS 2011, p. 43	Sb	135000	USGS 2011, p. 19
Cu	16200000	USGS 2011, p. 49	Se*	3500*	USGS 2007, p. 65.3
Dy	1337	US DoE (table 7-2)	Si	6900000	USGS 2011, p. 145
Fe	2400000000	USGS 2011, p. 86	Sn	261000	USGS 2011, p. 71
Ga	106	USGS 2011, p. 59	Tb	252	US DoE (table 7-2)
Ge	120	USGS 2011, p. 65	Te*	500*	USGS 2007, p. 65.3
Hg	1960	USGS 2011, p. 103	Ti	132000	USGS 2011, p. 173
In	574	USGS 2011, p. 75	Zn	12000000	USGS 2011, p. 189

* The supply of Se and Te are estimates of 2007 word production given by USGS (2007)[69]. The estimates in the table are the highest ones given by USGS (2007)[69], and also the ones used in the metal demand modeling, with the purpose of compensating for the likelihood of a higher world production in 2010. These are also the figures that were used in the latest study by the European Commission (2011b)[14].

6.5 Additional Modelling Scenarios

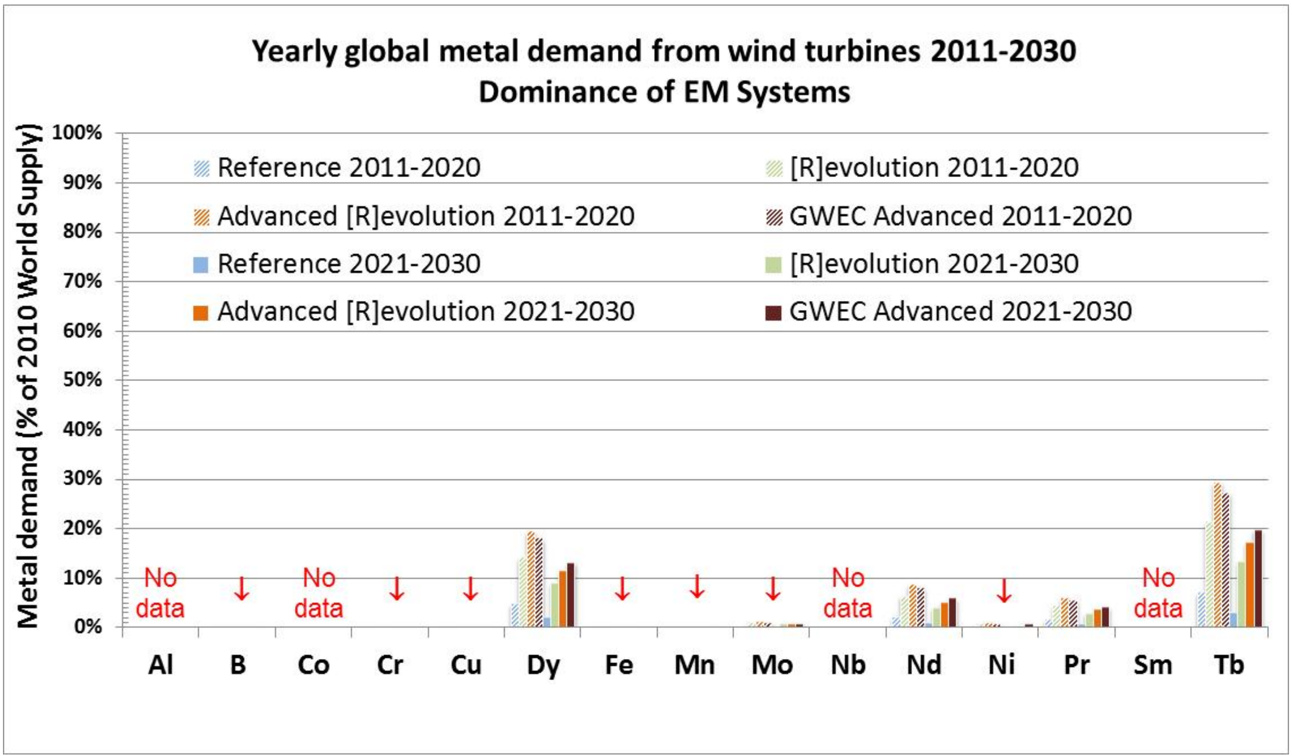

Figure A 1. Yearly global metal demand from permanent-magnet wind turbines 2011-2030 under the "Dominance of EM Systems"-scenario. **Bars with diagonal stripes represent the period 2011-2020 and filled bars represent 2021-2030. Arrows denote that demand is very low.**

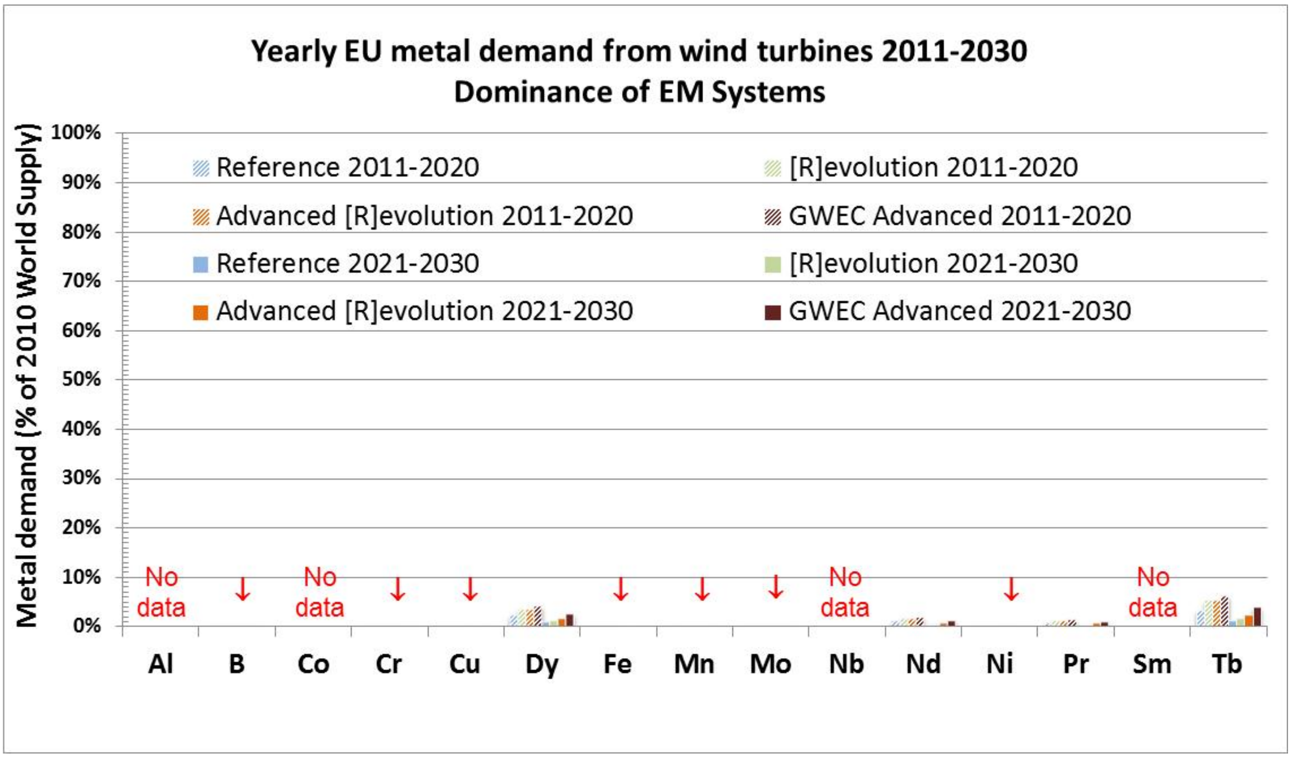

Figure A 2. Yearly EU metal demand from permanent-magnet wind turbines 2011-2030 under the "Dominance of EM Systems"-scenario. **Bars with diagonal stripes represent the period 2011-2020 and filled bars represent 2021-2030. Arrows denote that demand is very low.**

6.6 Additional Figures and Tables

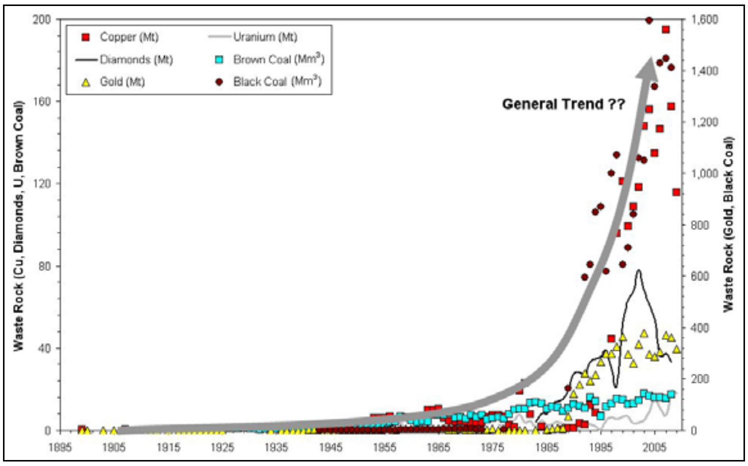

Figure A 3. Combined average increase of waste rock for base and precious metals in Australia. Source: Mudd (2009)[46].

Risk	Affected compartments	Relevant toxic compounds
Overtopping of tailings dam	groundwater, surface water, soil	**Water emissions:** • in most cases radionuclides, mainly thorium and uranium; • heavy metals; • acids; • fluorides; **Air emissions:** • in most cases radionuclides, mainly thorium and uranium; • heavy metals; • HF, HCl, SO_2 etc.
Collapse of tailings dam by poor construction	groundwater, surface water, soil	
Collapse of tailing dam by seismic event	groundwater, surface water, soil	
Pipe leakage	groundwater, surface water, soil	
Ground of tailing pond not leak-proof	groundwater	
Waste rock stockpiles exposed to rainwater	groundwater, surface water, soil	
Dusts from waste rock and tailings	air, soil	
No site-rehabilitation after cease of mining operation	land-use, long-term contaminated land	
Processing without flue gas filters	air, soil	
Processing without waste water treatment	surface water	

Figure A 4. Major risks of rare earth mining and processing with insufficient environmental techniques. Source: Öko-Institut e.V. (2011)[73]

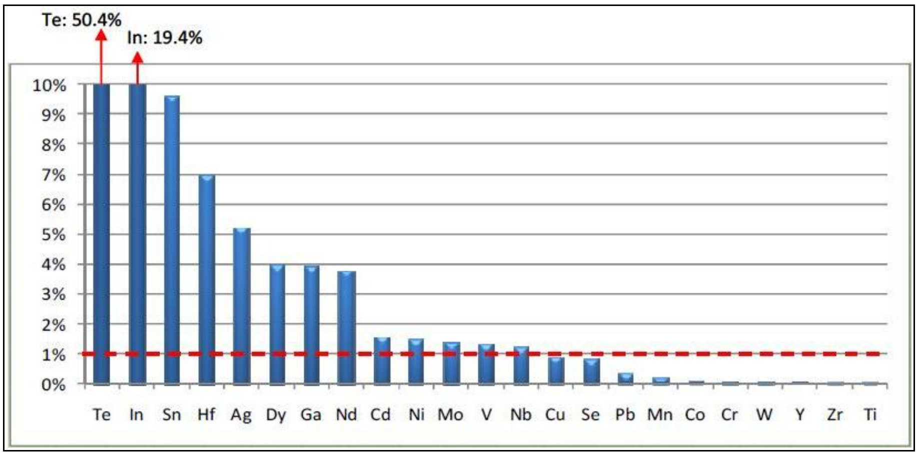

Figure A 5. Metals Requirements of SET-Plan in 2030 as % of 2010 World Supply. Source: European Commission (2011b)[14]

Table A 10. Comparison of identified significant or critical elements

Element	APS[1]	US DoE[66]	EU Com[12]	EU Com[14]	Öko[73]	This Study
Ag	•			•		
Be			•			
Cd				•		
Co	•		•			
Dy	•	•		•	•	•
Eu		•				
Ga	•		•	•		•
Ge	•		•			
Hf				•		
In	•	•	•	•		•
Mg			•			
Mo				•		
Ni				•		
Nb			•	•		
Nd	•	•		•	•	•
Pr	•				•	•
Sb			•			
Se	•			•		•
Sm	•					
Sn				•		
Ta			•			
Tb		•			•	•
Te	•			•		•
V				•		
W			•			
Y		•				
Groups/ compounds						
C (graphite)			•			
Flourspar			•			
Rare Earths			•			
PGMs			•			

APS - American Physical Society (2011)[1], US Doe - U.S. Department of Energy (2010)[66], EU Com - European Commission (2010)[12] and (2011b)[14], Öko - Öko-Institut e.V. (2011)[73]

Table A 11. Simplified summary of methodologies used in similar studies

Methodology	APS[1]	BGS[5]	US DoE[66]	EU Com[12]	EU Com[14]	Öko[73]	This Study
Choice of elements	ECEs	All	Green ECEs	Those important to EU Economy	"ESCEs"	REE	Green "ESCEs"
Supply	•	•	•	•	•	•	•
Basic demand assessment	•		•	•		•	
Demand modeling			•		•		•
Substitution/recycling	•		•	•	•	•	•
Political factors	•	•	•	•	•		
Main geographical focus	US	Global	US	EU	EU	Global	Global

APS - American Physical Society (2011)[1], BGS - British Geological Survey (2011)[5], US Doe - U.S. Department of Energy (2010)[66], EU Com - European Commission (2010)[12] and (2011b)[14], Öko - Öko-Institut e.V. (2011)[73]. ECEs (Energy Critical Elements) - Elements used in energy systems and electricity-using applications that are especially important to society. Green ECEs - Elements used in all types of "green" energy systems and electricity-using applications (e.g. renewable energy systems and electric vehicles and energy efficient lightning etc.). "ESCEs" (Energy system critical elements) - Same as ECEs but not including electricity-using applications. Green "ESCEs" - Same as "ESCEs" but including only elements that are crucial to renewable energy technologies. REE - Rare earth elements.