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sustainable energy for everyone



# Critical materials for the transition to a 100% sustainable energy future

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# EXECUTIVE SUMMARY

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The most critical supply bottlenecks of non-energy raw materials are lithium and cobalt, which are used for batteries in electric vehicles. These bottlenecks can be alleviated by recycling lithium, substituting lithium in other sectors, and by using less cobalt-intensive cathodes.

By contrast indium, gallium and tellurium are not expected to become important bottlenecks. Their use in solar power (photovoltaics) can be substituted by applying technologies requiring less critical materials, such as silicon. The use of indium and gallium for energy efficient lighting is very small compared to production in 2011. Supply bottlenecks are likely to pose less of a problem also for copper, which is used for transition grids and increasingly for more capture wind and solar energy and in energy efficient motors.

So-called 'rare earths', including neodymium and yttrium, and which are needed for wind turbines, are expected to exceed the demand. However, rare earths are nevertheless considered a bottleneck for other, geopolitical reasons. The majority of current production is concentrated in a single country, China. In recent years, rare earths have been the subject of export restrictions, which have given rise to concerns in, for instance, Japan, the United States and Europe. Eliminating these geopolitical constraints in the short term is difficult, but is possible in the longer term as resources become available in other geographical areas as well.

This study examines whether non-energy raw material supply bottlenecks could occur in the transition to a fully sustainable energy system. Such a transition is represented in The Energy Report, published in 2011 by WWF and Ecofys, which shows a way to almost 100% renewable energy by 2050 coupled with strong energy efficiency efforts in all sectors.

The authors of this study used the following approaches: A quick scan was carried out to identify areas where bottlenecks might occur. These bottlenecks were further analysed by taking information from The Energy Report, such as the installed electric capacity, amount of vehicles or building area, and multiplying this with the material intensity of the different technologies, such as the amount of tellurium per GW installed capacity of photovoltaics. These calculations resulted in the maximum material demand for a technology, both on a yearly basis as well as cumulative for the period 2012 to 2050. The maximum material demand per year was compared with the production of that material in 2011. The cumulative demand for the material was compared with the reserves and the resources of that material. Ways of mitigating material scarcities were also investigated.

This study concludes that although the scenario in The Energy Report leads to additional material demand for specific applications, there are also significant material savings related to the high energy and material efficiency pathways chosen for these scenarios. As a result, the overall impact on scarce resources in a highly renewable powered and energy-efficient world is likely to be substantially smaller than in a scenario with more modest sustainable energy ambitions. However, new political legislation in all major economies to promote material recycling and drive substantial technological development is still required to increase material efficiency.

# FOREWORD

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About 3 years ago, WWF launched its energy vision to arrive at a 100% renewable energy powered economy by 2050.



**Dr Stephan Singer,**  
**Director Global**  
**Energy Policy, WWF**  
**International**

Global politics permitting we know that sustainable renewable energy can fuel the world reliably while overcoming threats of climate change, air pollution and high economic costs for the majority of countries from increased import costs of fossil fuels. While a vision for a fossil fuel and nuclear free global energy supply by 2050 is environmentally sound and a key condition to stay well below 2 degree global warming, reduce nuclear risks and substantially diminish air pollution which still kills more than 3 million people annually and mostly in developing countries, such a vision seems to imply that clean renewables have no limits and resource constraints.

It is true that the simple amount of clean energy from sun, wind and geothermal alone can power our global energy demand by more than 100 times. It is, however, not true that the overall renewable energy supply chain and conversion technologies have no limits. We need more grids, more transformers, more batteries, simply more materials, new specialised materials, more rare earth materials, copper, lithium etc. for highly innovative and modern energy technologies that provide a close to zero-emission energy sector. But we also know that mining of materials has a footprint in nature, creates waste, consumes fresh water, and that often practices of these non-energy minerals mined are highly dangerous and extremely polluting in some developing countries. In addition, some of these minerals are limited and not highly concentrated in the Earth crust.

Modern, innovative energy-related technologies often have a high demand for these materials. And they do not stand alone. Modern information technology sectors from computers to TV flat screens and mobile phones, various industrial applications and processes, lighting technologies and transport applications also increasingly require these materials.

For a long-term 100% renewable energy vision powered by modern technologies and assuming substantive growth and demand for all kind of other industrial technologies worldwide, and particular in developing countries, we need to make sure that there are no bottlenecks. Already some authorities and institutions warn of shortages of some rare earth materials before 2020. Though geologically we may not run out of rare earths that easily and that fast, 90% of worldwide production of these materials is presently concentrated in China. And in some cases, such as lithium for electric car drives and batteries, we may see shortages as this report by Ecofys documents.

Hence, a strong focus on energy efficiency and conservation is paramount to reduce non-energy material needs for the emerging renewable energy technologies worldwide. Also, WWF strongly urges all governments to legislate as soon as possible strong incentives and create regulations for enhanced recycling and reuse of precious and rare materials. In parallel, research and development shall be fostered for new materials and high material efficiency. This will not only provide a sufficient flow for materials for highly-innovative technologies and applications both in energy and non-energy usage, but also reduce overall environmental and social impacts of mining non-renewable resources.

We are happy to see the evidence in this Ecofys report that a transition to a 100% sustainable energy supply is possible, in spite of supply chain bottlenecks, which can be mitigated through increased recycling and substitution.

Stephan Singer,  
January 2014



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Lithium being extracted from ore. The demand for lithium, a major component in batteries for cell phones, laptops and electric vehicles, is expected to increase rapidly and is widely regarded as a key bottleneck for the large scale introduction of electric vehicles.

# INTRODUCTION

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There are increasing concerns about the future availability of mined and non-renewable minerals and materials for our society.

This concern focuses especially on rare earth metals, but also includes more common metals such as copper and aluminium. The upcoming material requirements for sustainable energy technologies is crucial in the debate, though non-energy material needs such as for IT and highly specialised manufacturing and modern transport industries also claim an ever larger share of these extractive non-renewable minerals.

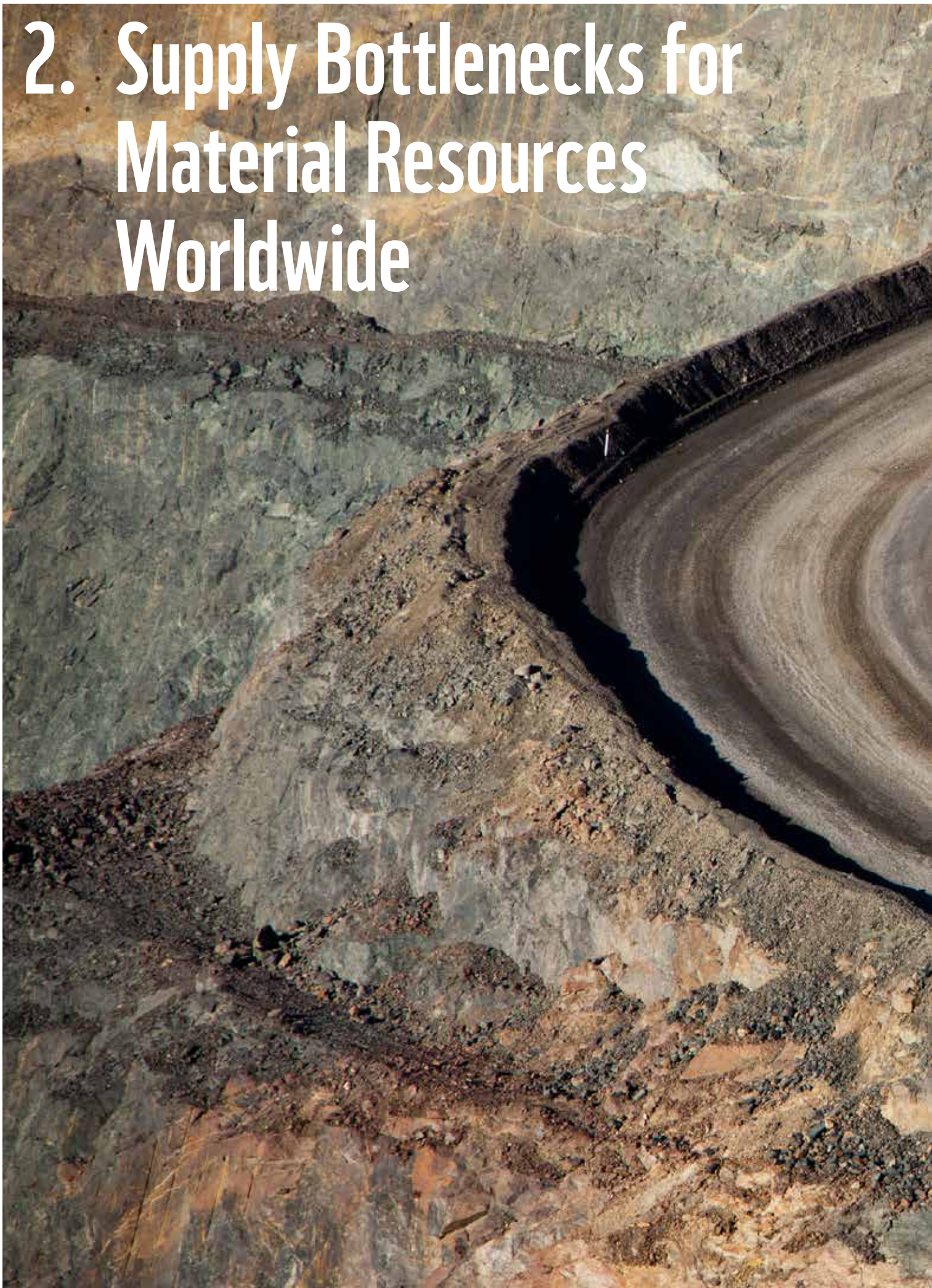
The development of a fully sustainable energy system will definitely lead to a change of material demands compared to a business-as-usual development of the conventional energy system. However, and strongly depending on overall successes in material, resource and energy efficiency, it remains to be seen whether the entire package of technologies belonging to a 100% sustainable renewable energy scenario actually leads to a higher net resource demand.

This study investigates what material supply bottlenecks may occur in a transition to a 100% sustainable energy system, and how these bottlenecks can be overcome. It bases its calculations on the 100% sustainable energy scenario presented in The Energy Report (TER), a study produced by WWF and Ecofys in 2011.

The critical materials report is divided up into five chapters.

- Chapter 1 is this introduction.
- Chapter 2 provides an overview of material production worldwide and a quick scan of materials for which supply bottlenecks may occur in future.
- Chapter 3 describes which critical materials impact on which sustainable energy production technologies utilised in The Energy Report.
- Chapter 4 provides a detailed assessment of ten critical material bottlenecks for TER, including proposed mitigation measures.
- Chapter 5 compares the material demand related to The Energy Report scenario with a business as usual scenario from the International Energy Agency (IEA).

## 2. Supply Bottlenecks for Material Resources Worldwide







# SUPPLY BOTTLENECKS FOR MATERIAL RESOURCES WORLDWIDE

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This chapter contains an overview of non-biomass, non-renewable mineral material production worldwide and a quick scan of materials for which supply bottlenecks may occur in future. Biotic resources, such as fish and timber, and fuel resources, such as coal and oil, are excluded from this analysis. Included are metals, such as copper (Cu), platinum (Pt) and rare earth elements, and industrial minerals such as barite (BaSO<sub>4</sub>) and fluor spar (CaF<sub>2</sub>).

## Materials production, resource and reserves worldwide

This chapter considers current materials production, resources and reserves worldwide. In resource accounting, the distinction between reserves and resources is important:

- ‘Resources’ are everything that is known and expected to exist somewhere. They are defined as materials of economic interest for extraction, which either now or in the future become commercially available (EU, 2010. USGS, 2012).
- ‘Reserves’ are everything for which there is reasonable certainty about where they are located. They are defined as “a subset of resources which are fully geologically evaluated and which can be economically, legally and immediately extracted; reserves are often described as the ‘working inventory’ of a mining company, which is continually updated according to changing economic, technological, legal and political situations” (EU, 2010. USGS, 2012).

In general, these definitions are almost identical to those used with fossil fuels. High commodity prices increase the reserve base while lower ones reduce its size.

While production figures are generally available, estimating reserves and resources on a global scale involves some uncertainty. Information about materials of strategic importance (e.g. radioactive materials, materials used in weapons production) is often not publically available. In addition, production figures of some of the rarer materials (e.g. many of the rare earth elements) are not always readily available since these materials are often traded directly via long term delivery contracts rather than on the open global market. Further detail is provided in chapter 3 on how these uncertainties should be taken into account when analysing critical materials.

**PRODUCTION RATIOS**  
ARE NOT ALWAYS GOOD INDICATORS FOR THE LIKELIHOOD OF A SUPPLY CHAIN BOTTLENECK, AS THESE CAN ALSO BE AFFECTED BY AN INCREASE IN DEMAND

We distinguish the group of rare earths and the specific group of platinum group metals (PGMs). These groups consist of respectively seventeen and six different metals. Rare earths are: scandium (Sc), yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er) and thulium (Tm). Platinum group metals are: platinum (Pt), osmium (Os), iridium (Ir), ruthenium (Ru), rhodium (Rh) and palladium (Pd). Each is often grouped together because they are generally mined and processed as a group.

Table 1 provides a comprehensive overview of the most important material resources produced worldwide, their annual production rates, the most important sectors and applications for which they are used and, where available, information on reserves, resources and the ratio of reserves and resources to annual production. Reserves and resources are quantified as far as possible. Where quantitative information for a material is limited, the material's status is indicated as either<sup>1</sup>:

- adequate, i.e. needs can be met into the foreseeable future
- abundant, i.e. needs can be more than met into the foreseeable future
- NA, i.e. no information is available.

Table 1 is divided into five sections: minerals (rock type materials obtained by mining), noble metals (metals resistant to attacks by acids and other reagents and non-corrosive), metalloids (semimetals displaying properties of both metals and non-metals), non-metals and metals.

Note that Table 1 excludes materials that are judged to be of low relevance to this study. That is, materials for which:

- supply is very large, and the material is easy to obtain and widely available on a global scale (e.g. nitrogen (N), sand and stone)
- supply may not be very large, but the material can be readily synthesised (e.g. diamonds and quartz)
- the material is used in low-tech applications and can be easily substituted for other materials (e.g. perlite and pumice)
- the material is primarily used as a feedstock for a material already on the list, or the material is the product of a precursor that is already on the list (e.g. bauxite, which is the feedstock for aluminium (Al) and iron (Fe) and steel, which are the products of iron ore)
- the main function of the material is as an energy carrier (e.g. uranium (U) or coal).

As can be seen in Table 1, many of the materials currently in demand worldwide are not considered to have near or long term supply bottlenecks. Many resources are available for over 100 years, sometimes even over 1000 years. There are a few exceptions. Zirconium (Zr) and molybdenum (Mo) resources are only expected to last

<sup>1</sup> Please note that this terminology has been introduced by Ecofys. The USGS does not use standardized terminology in its handbook to indicate quantitative information on materials

for respectively 43 and 56 years at current production levels. Reserves are clearly more constrained than resources, sometimes down to only 20 years. Notably low reserves to production ratios are present for antimony (Sb), strontium (Sr), gold (Au), lead (Pb) and tin (Sn), which are each below 20 years.

Note that the reserves to production and resources to production ratios are not always good indicators for the likelihood of a supply chain bottleneck, as they only are relevant for materials with a stable demand. With rapidly increasing demand, exhaustion may happen much earlier. On the other hand, developments in reuse, recycling and substitution of critical metals can alleviate the exhaustion of materials.

Materials judged to be vulnerable to supply bottlenecks, i.e. critical materials, will now be considered further.

**Table 1 2011 production rates, reserves, resources and key sectors of usage for most important material resources worldwide (USGS, 2012)**

Material	World production (Mt/year)	World reserves (Mt)	Reserves / Production (years)	World resources (Mt)	Resources / Production (years)	Key sectors of usage
<b>Minerals</b>						
Barite(BaSO4)	7.8	240	31	740	95	petroleum industry, paints, plastics, rubber, transport, metal casting, radiation shielding
Fluorspar (CaF2).	6.2	240	39	500	81	processing of aluminum and uranium, steelmaking, glass manufacture
Kyanite (Al2SiO5)	0.00046	NA	NA	Abundant	Abundant	iron making and steel making, manufacture of chemicals, glass, nonferrous metals
Titanium dioxide (TiO2)	6.7	690	103	2,000	299	pigments, aerospace applications, armor, chemical processing, marine, power generation
Wollastonite (CaSiO3)	0.51	180	353	NA	NA	plastics, rubber products, ceramics, metallurgical applications, paint, friction products
<b>Noble metals</b>						
Gold (Au)	0.0027	0.051	19	NA	NA	jewellery, arts, dental, electrical and electronics
Platinum group metals	NA	0.066	NA	100	NA	catalysts, chemicals production, electronics, glass manufacturing, displays, jewelry
Silver (Ag)	0.0238	0.53	22	NA	NA	industrial applications, jewellery, photography, batteries and catalysts, electronics, bearings, mirrors, solar cells
<b>Metalloids</b>						
Antimony (Sb)	0.169	1.8	11	NA	NA	flame retardants, transportation, batteries, chemicals, ceramics and glass
Arsenic (As)	0.052	1.0	20	11	212	ammunition, batteries, bearings, fertilisers, pesticides, electronics, solar cells
Boron (B)	0.0043	210	48,837	Adequate	Adequate	glass, ceramics, soaps, detergents, bleaches, agriculture, enamels and glazes
Germanium (Ge)	0.000118	NA	NA	Adequate	Adequate	fiber-optic systems, infrared optics, polymerisation catalysts, electronics, solar energy
Silicon (Si)	8	Abundant	Abundant	Abundant	Abundant	aluminum and aluminum alloys, chemical industry, semiconductor, solar industry
Tellurium (Te)	0.000115	0.024	209	NA	NA	steel, copper and lead alloys, chemical industry, solar cells, photoreceptor, thermoelectric electronic devices, thermal cooling devices
<b>Non Metals</b>						
Bromine (Br)	0.46	Abundant	Abundant	1,000	2000	flame retardants, drilling fluids, pesticides, water treatment, pharmaceuticals, chemicals
Graphite	0.925	77	83	800	865	refractory applications, crucibles, foundry operations, steelmaking, batteries, lubricants

Material	World production (Mt/year)	World reserves (Mt)	Reserves / Production (years)	World resources (Mt)	Resources / Production (years)	Key sectors of usage
Helium (He) (in million cubic meters)	NA	7,500	7,500	31,300	31,300	cryogenic applications, pressurising and purging, controlled atmospheres, welding cover gas
Iodine (I)	0.029	15	517	34	1,172	nutrition, industrial purposes
Selenium (Se)	0.002	0.093	47	Adequate	Adequate	glass manufacturing, agriculture, metallurgy, solar cells
Sulfur (S)	69	Abundant	Abundant	600,000	8,696	agricultural chemicals (fertilisers), petroleum refining, metal mining, industrial products
<b>Metals</b>						
Aluminum (Al)	44.1	6,525	148	65,000	1,474	transportation, packaging, buildings, electrical, machinery, consumer durables
Beryllium (Be)	0.00024	NA	NA	0.08	333	electronics, telecommunication, defence, industry, aerospace, energy, medicine
Bismuth (Bi)	0.0085	0.32	38	NA	NA	pharmaceuticals, chemicals, metallurgical additives, fusible alloys, solders, ammunition
Cadmium (Cd)	0.0215	0.64	30	NA	NA	alloys, coatings, nickel-cadmium batteries, pigments, plastic stabilisers.
Caesium (Cs)	NA	0.070	NA	NA	NA	oil and gas industry, chemical, electronics, pyrotechnic industry, clocks, (bio)medical
Chromium (Cr)	24	480	20	12,000	500	superalloys, pigments, leather processing, catalysts, surface treatments, refractories
Cobalt (Co)	0.098	7.5	77	15	153	superalloys, aircraft, cutting and wear-resistant applications, chemical applications
Copper (Cu)	16.1	690	43	3,000	186	building construction, electronics, transport, consumer products, industrial machinery
Gallium (Ga)	0.000216	NA	NA	1	4,630	integrated circuits, optoelectronic devices, LEDs, photodetectors, and solar cells
Hafnium (Hf)	NA	NA	NA	NA	NA	nuclear control rods, nickel-based superalloys, metal cutting, high-temperature ceramics
Indium (In)	0.00064	NA	NA	NA	NA	flat-panel devices, solders and alloys, compounds, electrical components, semiconductors
Iron (pig iron) (Fe)	1100	80,000	73	230,000	209	steel production, construction, transportation, cans and containers
Lead (Pb)	4.5	85	19	1,500	333	batteries, ammunition, glass and ceramics, casting metals, sheet lead
Lithium (Li)	0.034	13	382	30	882	ceramics and glass, batteries, lubricants, air treatment, polymers, aluminum production, pharmaceuticals
Magnesium (Mg)	0.78	Abundant	Abundant	Adequate	Adequate	refractories, agricultural, chemical, construction, environmental and industrial applications
Manganese (Mn)	14	630	45	Abundant	Abundant	construction, machinery, transportation, iron and steel applications
Mercury (Hg)	0.00193	0.093	48	0.6	311	chlorine-caustic soda production, fluorescent lights, dental amalgam, neon lights
Molybdenum (Mo)	0.25	10	40	14	56	iron and steel production, superalloys
Nickel (Ni)	1.8	80	44	130	72	transportation, metallurgy, electrical equipment, petroleum industry, chemical industry, construction, household appliances, industrial machinery

Material	World production (Mt/year)	World reserves (Mt)	Reserves / Production (years)	World resources (Mt)	Resources / Production (years)	Key sectors of usage
Niobium (Nb)	0.063	3	48	Abundant	Abundant	steel industry, alloys, aerospace industry
Rare earths	0.13	110	846	NA	NA	catalysts, metallurgical applications and alloys, glass polishing, ceramics, permanent magnets, ceramics, rare earth phosphors for computer monitors, lighting, radar, televisions
Rhenium (Re)	0.000049	0.0025	51	0.006	122	crucibles, electronics, electromagnets, heating elements, metallic coatings, semiconductors
Rubidium (Rb)	NA	NA	NA	NA	NA	biomedical research, electronics, specialty glass, pyrotechnics
Scandium (Sc)	NA	NA	NA	Abundant	Abundant	aluminum alloys, metallurgical research, high-intensity metal halide lamps, electronics
Strontium (Sr)	0.38	6.8	18	1,000	2,632	pyrotechnics and signals, ferrite ceramic magnets, master alloys, pigments, fillers
Tantalum (Ta)	0.00079	0.12	152	Adequate	Adequate	alloys, capacitors, automotive electronics, pagers, personal computers, portable telephones
Thallium (Tl)	0.000010	0.00038	38	0.017	1,700	medical purposes, gamma radiation detection equipment, wireless communications, infrared applications, various specialty electronics
Thorium (Th)	NA	1.4	NA	0.5	NA	catalysts, high-temperature ceramics, alloys, welding electrodes, nuclear fuel
Tin (Sn)	0.253	4.8	19	Adequate	Adequate	coating of metals, alloys, glass making, cans and containers, construction, transportation
Tungsten (W)	0.072	3.1	43	NA	NA	construction, metalworking, mining, oil- and gas-industry, electronics, heating, lighting, chemicals
Vanadium (V)	0.06	14	233	63	1,050	alloys, catalysts
Yttrium (Y)	0.0089	0.54	61	Adequate	Adequate	ceramics, metallurgy and phosphors, magnets, electronics, lasers
Zinc (Zn)	12.4	250	20	1,900	153	galvanising, alloys, agriculture, chemical, paint, rubber
Zirconium (Zr)	1.41	52	37	60	43	ceramics, foundry applications, opacifiers, refractories, abrasives, chemicals, metal alloys



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Molybdenum (Mo), a rare earth mineral, resources are only expected to last for 56 years at current production levels.



## Materials which are vulnerable to supply bottlenecks

The scarcity of a particular material and whether or not it can lead to a supply chain bottleneck depends on a lot of factors. First of all, the total amount of material and the part of this which is potentially recoverable. Secondly, the development of demand in the future and to which extent supply can be adjusted to meet changes in demand. This is also affected by the possibilities of recycling and substituting the material. Thirdly, the geological distribution of the material supply, which can lead to trade disruptions and supply risks. This last factor is up for debate. When the transition to a sustainable energy system is looked at from a global perspective, the distribution of the material over individual countries is not relevant and geopolitical factors do not play a role.

This section considers which materials from Table 1 are vulnerable to supply bottlenecks. This is done by analysing six recent reports which identify critical materials for various sectors:

- **Ad-hoc Working Group on defining critical raw materials – Critical raw materials for the EU (2010).** The Working Group has identified 14 critical materials at the EU level based on supply risk and economic importance. These include platinum group metals (PGMs) and the rare earths.
- **The Hague Centre for Strategic Studies – Scarcity of Minerals: A strategic security issue (2010).** The HCSS has identified 15 individual elements, as well as the rare earths and PGMs, as critical materials using the following criteria: the importance of the metals for the high tech industrial sector, the limited availability of substitutes and the elements which are essential to emerging technologies and ‘green technologies’ in particular.
- **Joint Research Centre Institute for Energy and Transport – Supply chain bottlenecks in the Strategic Energy Technology Plan (2010).** This study identifies supply chain bottlenecks based on technologies included in the Strategic Energy Technology Plan, focusing on a wide range of renewable energy technologies, including wind power, onshore and offshore, solar photovoltaics (PV), concentrated solar power (CSP), carbon capture and storage (CCS), advanced biofuels, nuclear power generation, fuel cells and hydrogen in transport, solar thermal, electricity networks.
- **Joint Research Centre Institute for Energy and Transport – Critical Metals in Strategic Energy Technologies (2011).** This study assesses 14 metals which are used in large quantities in technologies presented in the Strategic Energy Technology Plan, considering market and political factors to divide the metals into three groups: high risk, medium risk and low risk. For our analysis, Ecofys focuses on materials considered high and medium risk, with low risk metals considered where relevant to the deployment of renewable and energy efficient technologies.
- **APS Panel on Public Affairs & The Materials Research Society – Energy Critical Elements: Securing Materials for Emerging Technologies (2011).** This report considers ‘energy-critical elements’, which are defined as elements for which scarcity can significantly hamper the introduction of game-changing energy technologies, with energy-critical

**Table 2 Critical materials identified in recent reports**

European Commission Raw Materials Supply group	The Hague Centre for Strategic Studies	JRC Study	JRC Study 2	American Physical Society	United Nations Environment Program
Antimony (Sb)					
Beryllium (Be)					
		Caron Fibre			
Cobalt (Co)				Cobalt (Co)	Cobalt (Co)
	Copper (Cu)	Copper (Cu)			
			Dysprosium (Dy)		
Fluorspar (CaF <sub>2</sub> )					
Gallium (Ga)	Gallium (Ga)	Gallium (Ga)	Gallium (Ga)	Gallium (Ga)	Gallium (Ga)
Germanium (Ge)				Germanium (Ge)	Germanium (Ge)
Graphite					
	Hafnium (Hf)				
				Helium (He)	
Indium (In)		Indium (In)	Indium (In)	Indium (In)	Indium (In)
				Lanthanum (La)	
	Lithium (Li)			Lithium (Li)	Lithium (Li)
Magnesium (Mg)					
	Manganese (Mn)				
	Molybdenum (Mo)				
			Neodymium (Nd)		
	Nickel (Ni)				
Niobium (Nb)	Niobium (Nb)		Niobium (Nb)		
					Palladium (Pd)
PGM	PGM	Platinum (Pt)		Platinum (Pt)	Platinum (Pt)
Rare Earths	Rare Earths			Rare Earths	Rare Earths
				Rhenium (Re)	
					Ruthenium (Ru)
			Selenium (Se)	Selenium (Se)	
		Silver (Ag)		Silver (Ag)	
Tantalum (Ta)	Tantalum (Ta)				Tantalum (Ta)

European Commission Raw Materials Supply group	The Hague Centre for Strategic Studies	JRC Study	JRC Study 2	American Physical Society	United Nations Environment Program
		Tellurium (Te)	Tellurium (Te)	Tellurium (Te)	Tellurium (Te)
	Tin (Sn)		Tin (Sn)		
Tungsten (W)	Tungsten (W)				
			Vanadium (V)		
	Zinc (Zn)				
	Zirconium (Zr)	Zirconium (Zr)			

elements grouped according to their usage. For the rare earths, specifically dysprosium (Dy), neodymium (Nd), praseodymium (Pr), samarium (Sm), gadolinium (Gd), europium (Eu), terbium (Tb) and yttrium (Y) are mentioned.

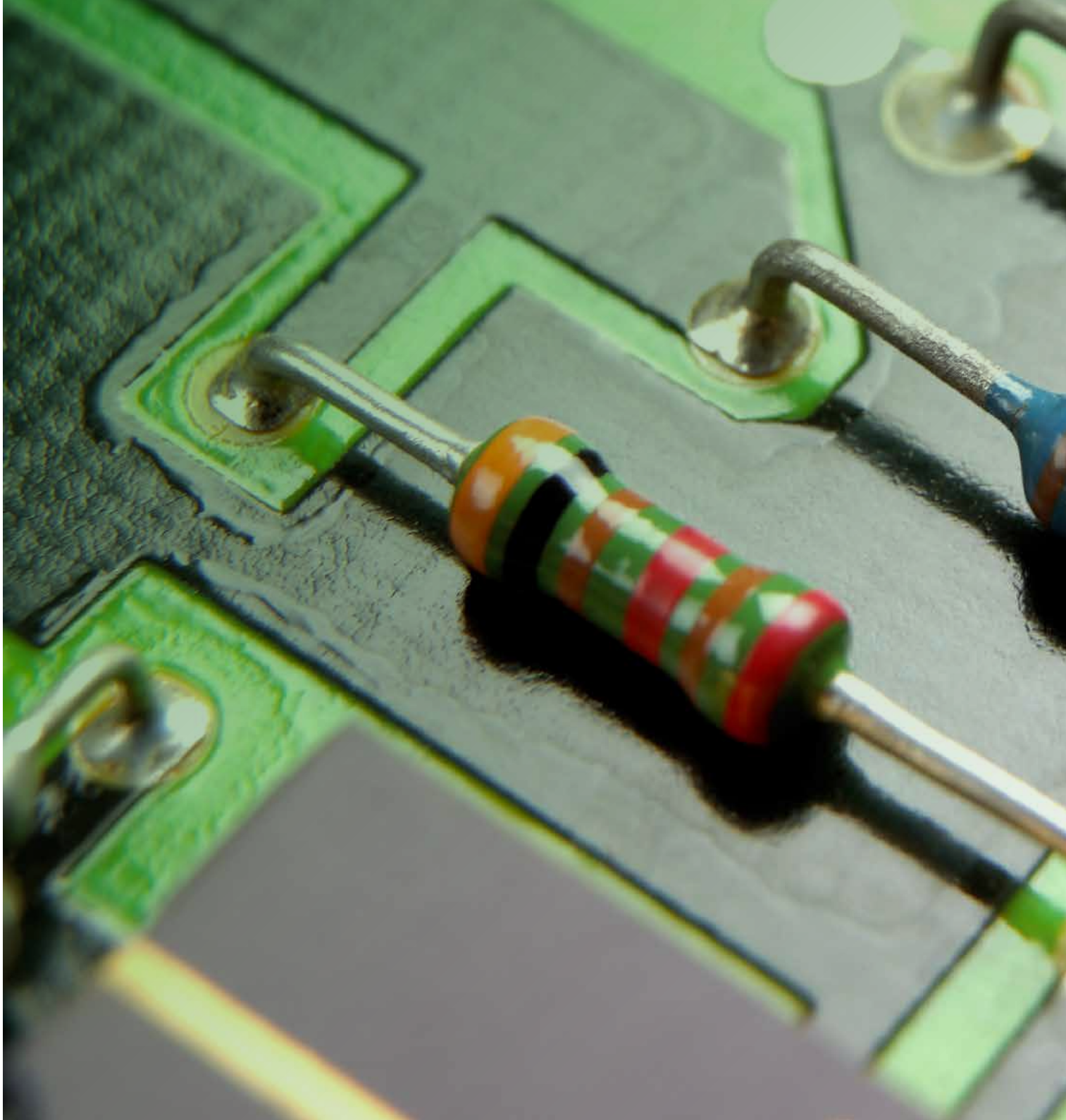
- **United Nations Environment Programme – Critical Metals for Future Sustainable Technologies and their Recycling Potential (2009).** This report identifies critical metals for future sustainable technologies such as renewable energy production and energy efficiency technologies, based on demand growth, supply risks and recycling restrictions and classifying metals according to whether they will be critical on the short, medium or long term.

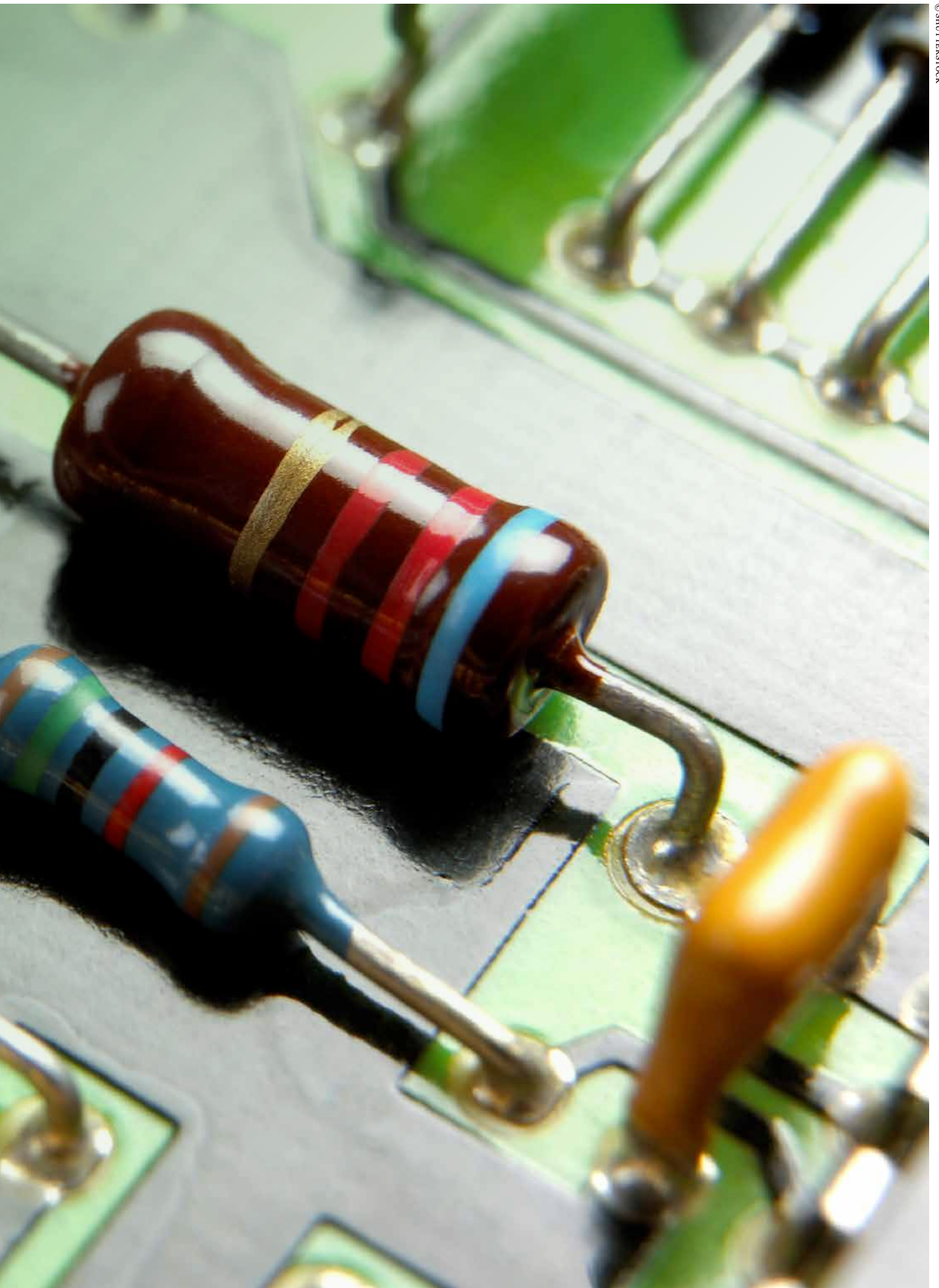
Table 2 below shows the subset of materials from Table 1 which are identified in the six reports as vulnerable to supply bottlenecks.

Some of the studies from Table 2 mention the platinum group metals as a group, while others mention them individually (platinum (Pt), palladium (Pd) and ruthenium (Ru)). The same holds for rare earths, which are mentioned as a group in some studies and as individual elements in others.

The next chapter considers the implications of these critical metals for transitioning to a 100% sustainable energy system.

# 3. Critical Materials for Transitioning to a 100% Sustainable Energy System





# CRITICAL MATERIALS FOR TRANSITIONING TO A 100% SUSTAINABLE ENERGY SYSTEM

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This chapter assesses which critical materials will impact on the sustainable energy production technologies utilised in a fully sustainable energy system.

This fully sustainable energy system is as represented in The Energy Report (TER) and identifies which material supply bottlenecks are recommended for more detailed analysis in the following chapter. In that chapter, a full analysis will be given of the expected material requirement for building a fully sustainable energy system. That material requirement will then be compared to the long-term availability of materials. The first part of this chapter describes the technologies from the TER and gives a general indication of their material requirements. The second part lists the most important bottlenecks, based on the technologies from the TER and information on critical materials.

## Critical materials for sustainable energy production technologies

The six studies used to make the overview of critical metals in Chapter 2 each have their own basis for determining whether a material is critical or not. For this study, only the materials which might lead to a bottleneck for the TER scenario are of interest.

The 100% renewable energy scenario which forms the basis for TER contains many different renewable energy supply technologies and energy efficiency technologies across the transport, built environment and industrial sectors. However, not all of these technologies are dependent on the materials identified in Chapter 2 and not all are vulnerable to materials supply bottlenecks.

- **Solar energy** - Solar energy is an important consumer of critical materials. In the TER scenario, solar energy supplies half of our total electricity demand in 2050, half of our building heating and 15% of industrial heat and fuel. Solar energy can be subdivided into photovoltaics, concentrated solar power, low-temperature heating and 'concentrating solar heat'. Photovoltaics can be further subdivided into silicon-based crystalline cells and thin film cells. Especially for thin film cells photovoltaics, which require several types of scarce materials,

## SOLAR ENERGY IS AN IMPORTANT CONSUMER OF CRITICAL MATERIALS

bottlenecks can occur. In addition, a large increase in photovoltaics will cause an increase in demand for silver, tin and silicon.

- **Wind energy** - If wind energy is deployed on a large scale, as is foreseen in the TER, it could become a significant consumer of critical materials, particularly for the production of permanent magnets for direct-drive solutions. An additional 1,000,000 onshore and 100,000 offshore wind turbines could meet a quarter of the world's electricity needs in 2050 (Ecofys, 2011). In addition to scarce materials, copper is also required for the transformers needed for the wind turbines. How a large scale increase in wind energy affects supply and demand of these materials, is elaborated upon further on in the report.
- **Wave and tidal energy** - Wave and tidal energy, which make a relatively small contribution to the TER scenario, will not be significantly affected by a scarcity of critical materials, with the possible exception of copper for generators.
- **Hydropower** - Hydropower is not anticipated to be significantly affected by critical material bottlenecks despite the use of copper, since the amount of copper required per MW electricity is relatively low due to the large scale of hydropower stations.
- **Geothermal power** - Geothermal power requires copper for heat exchangers. Especially with the increase in installed capacity of geothermal power, this could affect future copper demand. However, no reliable quantitative data is available.
- **Efficiency in industry** - Improving energy efficiency in the industrial sector includes a wide variety of measures (Ecofys, 2009). On the one hand this will involve integration of processes and process intensification, which will lead to a reduction in material usage. On the other hand, there will be add-on technologies, like heat exchangers and power speed control. Heat exchangers require materials with a large thermal conductivity, such as copper and aluminium. Power speed control equipment requires power semiconductors. In addition, lightweight and more durable alloys can improve the efficiency of machinery, such as motors and drives, making them useful for process improvements.

For chemical processes, catalysts are important. Improvements in catalysts, which often include critical materials such as PGMs, can lead to energy efficiency improvements in industry. The materials used in catalysts, however, are so diverse, that not one specific critical material stands out. In addition, since their usage is already widespread in industry, the projected increase in demand for these materials due to additional energy efficiency measures in TER will not be exceptional. Finally, in comparison with other industrial energy efficiency improvements, catalysts are only a small aspect. New catalysts are not critical for achieving the TER scenario and will therefore not become a material bottleneck.

With the exception of control equipment, which composes only a small part of efficiency improvements in industry, efficiency improvements in industry do not require critical materials.

- **Low carbon transport** – Low carbon transport involves improving energy efficiency, fuel switching to biofuels and electric vehicles. Improving energy efficiency includes measures such as using lighter materials, improving aerodynamics and making more efficient engines. This requires lightweight materials such as carbon fibre and super alloys, which are stronger, lighter and

**WAVE  
& TIDAL  
ENERGY  
WILL NOT BE  
SIGNIFICANTLY  
AFFECTED BY  
A SCARCITY OF  
CRITICAL MATERIALS.**

more durable than conventional alloys and require scarce materials such as molybdenum and tungsten. Switching from fossil fuels to electricity will see increased demand for materials to produce, for example, electrical engines, batteries, loading stations for fuels. High density energy storage devices, which are mainly batteries containing lithium or cobalt, will be required for electric vehicles.

- **Energy efficiency in the built environment** - Energy efficiency in the built environment is dominated by two main measures: insulation and installations.
  - Insulation is of key importance in the TER. Heating and cooling of new buildings should require virtually no energy by 2030 and existing buildings should have energy demands for heating and cooling reduced by 60%. Most of the materials used for insulation, such as mineral wool and foam, do not require critical materials.
  - Installations include the energy-using infrastructure within buildings, including heat pumps, air conditioning and lighting. A heat pump contains a heat exchanger, which contains high conductivity materials such as copper and aluminum, as well as less common materials such as selenium and chromium. Energy efficient lighting consists of light-emitting diodes (LEDs) and fluorescent lamps, which require critical materials such as gallium, indium and rare earths. Energy efficient homes also make use of smart electronics which help save energy in households and offices, for example by turning off equipment that isn't used, regulating temperature and preventing the waste of food. These smart electronics contain semiconductors, which contain scarce materials such as indium and gallium. Scarce materials for semiconductors are discussed further on in this report.
- **Infrastructure** - In order to switch to a 100% renewable energy scenario, the energy transport, distribution and storage infrastructure has to adapt to a more flexible, decentralised energy system. This will result in additional material demand, most notably copper for instance for the enlarged transmission grid infrastructure.

Semiconductors, which are used for a wide variety of purposes, are included in many applications in for instance the built environment and industry. Depending on their purpose, semiconductors are designed using different materials. Further on in the report, a brief assessment is included on whether materials for semiconductors can become a bottleneck for the implementation of a fully sustainable energy system as represented in The Energy Report (TER).

Biomass is used in TER for specific purposes where no other renewable energy sources are available. An increased production of biomass will result in an increased demand of both organic and artificial fertilisers. The total amounts, however, may differ based on selection and use of crops, plant materials and their products, management practices, regions and technological progress as well as specific demand for biofuels. The three main components of artificial fertilisers are nitrogen, phosphorus and potassium. This study contains a concise assessment of whether the supply of these materials can become a bottleneck for the implementation of the TER scenario.



**Table 3 Critical materials required by technologies from The Energy Report. Highlighted cells indicates a potentially critical material for a technology.**

	Solar (photo-voltaics)	Wind	Low carbon transport	Efficiency in the built environment	Efficiency in industry	Energy infrastructure
Beryllium						
Cobalt						
Copper						
Fluorspar						
Gallium						
Germanium						
Graphite						
Helium						
Indium						
Lithium						
Magnesium						
Manganese						
Molybdenum						
Nickel						
Niobium						
PGM						
Rare earths						
Rhenium						
Selenium						
Silver						
Tantalum						
Tellurium						
Tin						
Tungsten						
Vanadium						
Zinc						
Zirconium						

## COPPER IS NOT CRITICAL FOR ONE PARTICULAR TECHNOLOGY BUT FOR THE SYSTEM AS A WHOLE

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Identifying technologies that suffer from specific critical material bottlenecks is complex. In this study, Ecofys has drawn on a broad range of sources including the six studies listed in chapter 2, as well as scientific publications and Ecofys' informed expert opinion. Table 3 lists the critical materials identified for the TER technology sectors which are most likely to be affected by supply bottlenecks.

### Critical materials bottlenecks for detailed assessment

This section identifies critical materials bottlenecks for achieving a fully sustainable energy system as represented in The Energy Report (TER) that will be the focus of the more detailed analysis in the following chapter. These have been selected on the basis of:

- the number of studies that emphasise the critical material for the technology
- the expected quantities of the material required for the technologies, relative to other critical materials (informed expert judgement)
- having representation across as many TER technologies that will be impacted by critical materials as possible.

Using these selection criteria, the critical materials bottlenecks to be the focus of the detailed analysis are proposed to be:

- tellurium, indium and gallium specifically for thin film **photovoltaics** and silver for photovoltaics
  - These first three critical materials are identified from literature review as the three critical materials of greatest importance for thin film photovoltaics. In addition, silver, which is used in several types of photovoltaics, is also expected to be critical.
- indium and gallium for **energy efficient lighting**
  - Additional critical materials, such as rare earths, were identified for energy efficient lighting, however assessing two materials only will still allow for representation of the key issues and challenges associated with critical materials for this technology (and allow resources for this project to be deployed between a greater number of TER technologies).
  - Indium and gallium were selected as the two materials to analyse in more detail, but it would have been equally valid to have selected alternative materials.
- rare earths, used for magnets in **wind turbines**, in particular neodymium and yttrium
  - Rare earths are one of the most important bottlenecks for wind turbines, being mentioned in almost all the studies on critical materials.
  - Other materials such as cobalt, manganese and molybdenum are also potential material bottlenecks for wind turbines.

# ENERGY EFFICIENT LIGHTING

REQUIRES CRITICAL  
MATERIALS SUCH AS  
GALLIUM, INDIUM  
AND RARE EARTHS

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- materials used in **smart electronics in the built environment** and **power electronics in industry**
  - Smart electronics and power electronics in the built environment and industry require semiconductors, which contain different types of scarce materials, depending on their purpose. Examples are arsenic, germanium, indium and gallium. Semiconductors are a complicated topic which requires further research. During this study, more information on materials required for semiconductors will be collected and where bottlenecks occur, these will be explained.
- cobalt and lithium for high energy density **batteries for electric transport**
  - Demand for lithium, a major component in batteries for cell phones, laptops and electric vehicles, is expected to increase rapidly and is widely regarded as a key bottleneck for the large scale introduction of electric vehicles.
  - Cobalt is another important component of lithium ion batteries; it is also used for making super alloys and in wind turbines.
- copper for **electricity distribution and energy supply**
  - Copper is a main component of electricity distribution networks and could become a bottleneck for developing the flexible, decentralised energy system required to realise the TER scenario. In addition, copper is used in many other renewable energy technologies such as wind and solar energy but also in transformers and motors.
  - It stands apart from the previously mentioned materials because it is not critical for one particular technology but for the system as a whole. A more detailed analysis on copper is presented further on in this report.
- nitrogen, phosphorus and potassium for **biomass**
  - In the TER scenario, biomass is used where no other renewable energy sources are available. The enhanced production of biomass requires organic and artificial fertilizers, which have nitrogen, phosphorus and potassium as their main components. This study will contain a brief assessment on whether material bottlenecks will occur for biomass in the TER scenario.

# 4. Detailed Assessment of Bottleneck Areas





# DETAILED ASSESSMENT OF BOTTLENECK AREAS

This chapter provides a detailed assessment of the potential bottleneck areas identified in the previous chapter.

It calculates the maximum annual material demand and the cumulative material demand for each bottleneck to 2050 and then compares both these figures with the production, reserves and resources of the material in 2011.

As explained in chapter 2, the distinction between reserves and resources is:

- **Resources** - are everything that is expected to exist. They are defined as materials of economic interest for extraction, either now or in the future (EU, 2010. USGS, 2012).
- **Reserves** - are everything for which there is reasonable certainty about where they are located. They are defined as “a subset of resources which are fully geologically evaluated and which can be economically, legally and immediately extracted; reserves are often described as the ‘working inventory’ of a mining company, which is continually updated according to changing economic, technological, legal and political situations” (EU, 2010. USGS, 2012).

**29%**  
OF TOTAL  
ELECTRICITY  
PRODUCTION IS  
FROM PHOTOVOLTAIC  
ENERGY

The basis for the calculations is the data from The Energy Report (TER). The sources for the data used in the calculations and the reasoning behind the assumptions made for the calculations are explained in each chapter. The only exception is the bottleneck for semiconductors, which is explained qualitatively rather than quantitatively.

For each of the bottlenecks, the results of the calculations are shown in a graph and further analysed in a separate paragraph. A brief supply forecast and some information on supply risks is also included. For each of the bottlenecks, mitigation measures, e.g. options for recycling and substitution, are mentioned.

## Indium, gallium, tellurium and silver for photovoltaics

The two main technologies in photovoltaics are thin film photovoltaics and crystalline photovoltaics. For thin film photovoltaics, indium, gallium and tellurium are potential material bottlenecks. For crystalline photovoltaics, silver is a potential material bottleneck. In 2050, The Energy Report (TER) assumes that around 29% of total electricity production is from photovoltaic energy. With an estimated annual electricity production of 127.4 EJ, this means 37 EJ is produced by photovoltaics in TER.

For thin film photovoltaics, four different technologies exist. It has been assumed that each of these technologies will have a market share of 25% in 2050. These thin film photovoltaics are the following:

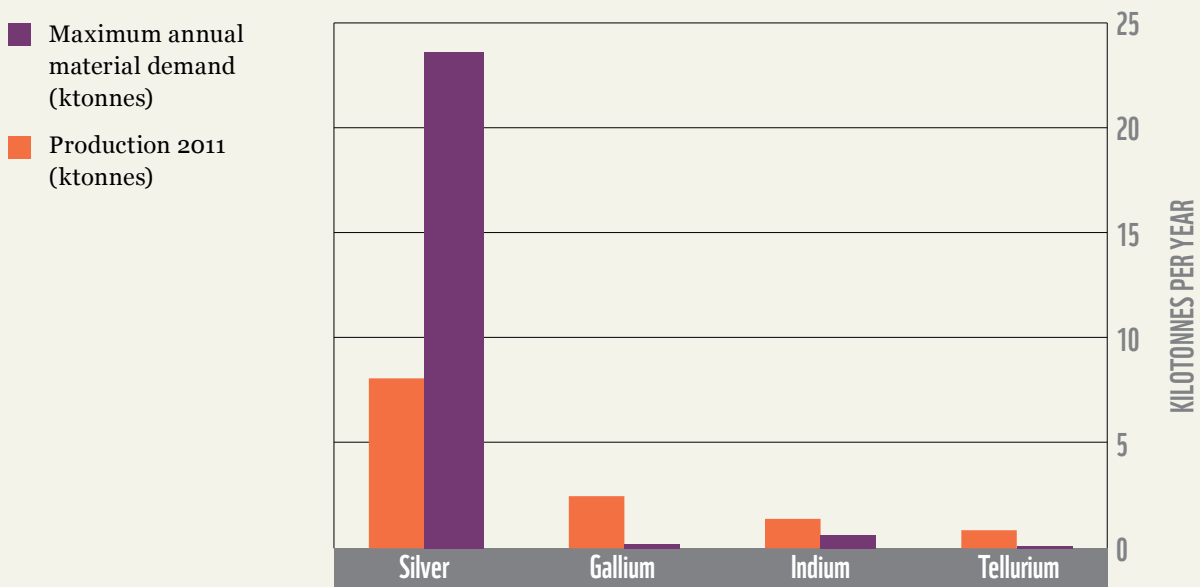
- CdTe – cadmium and telluride, with tellurium as a potential bottleneck
- CI(G)S - copper, indium, selenium and optionally gallium, with indium as a potential bottleneck
- GaAs - gallium, arsenic (and optionally germanium), with gallium as a potential bottleneck
- aSi – silicon, with no bottlenecks identified.

The material intensities for each of these technologies and for silver in crystalline photovoltaics are taken from Wild - Scholten (2007) and Fraunhofer (2009). For all four materials, a progress ratio<sup>1</sup> of 85% is assumed. This progress ratio is used to calculate the decrease in material intensity over time. For the material calculations, it was assumed that the 37 EJ produced by photovoltaics in 2050 is either met by 100% crystalline photovoltaics or by 100% thin film photovoltaics.

### Analysis of materials in photovoltaics

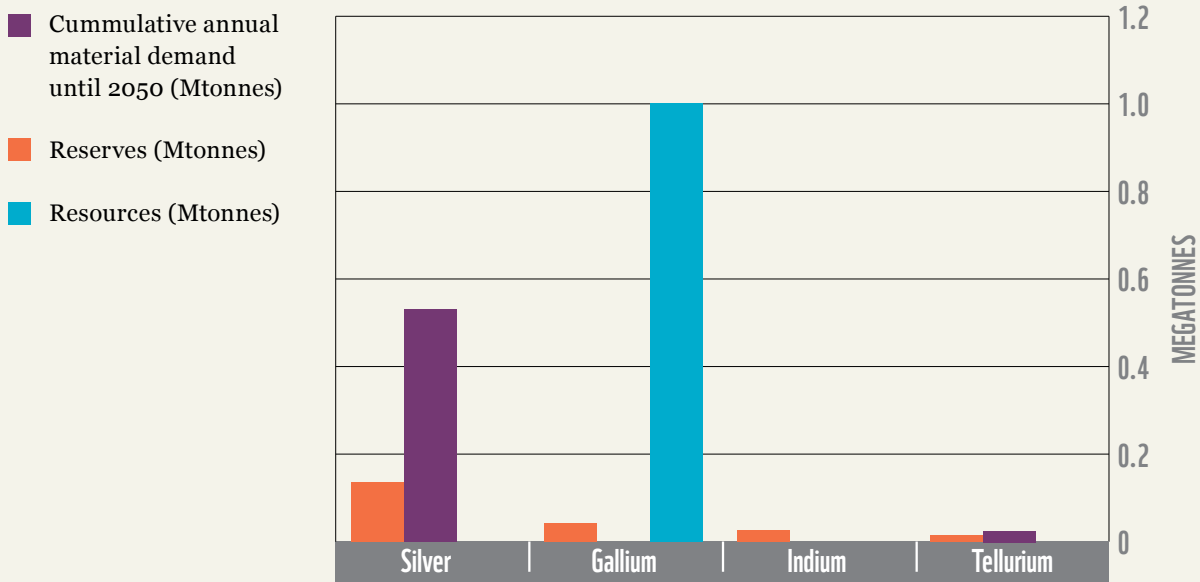
The annual capacity increase of photovoltaics until 2050, and hence also the annual material demand attributed to photovoltaics, were calculated based on annual energy production figures in the TER scenario. Figure 1 shows a comparison between the maximum material demand for one year and production of that material in 2011.

**Figure 1 Comparison of maximum annual material demand for photovoltaics in the period 2010 – 2050 with production in 2011 for silver, gallium, indium and tellurium. All numbers are in kilotonnes per year (Source: Ecofys).**



<sup>1</sup> For each doubling in capacity, the material intensity is multiplied by 0.85

**Figure 2 Comparison of cumulative material demand for photovoltaics until 2050 with reserves and resources. All numbers are in megatonnes (Source: Ecofys).**



The TER scenario was also used to calculate the cumulative material demand for deploying the photovoltaics capacity up to 2050. Figure 2 shows a comparison of cumulative material demand with the reserves and resources of the materials in 2011.

As can be seen in Figure 1, with silver being the notable exception, the maximum annual demand for gallium, indium and tellurium exceeds current production by far. On the other hand, in spite of the lack of information on reserves and resources of many of the materials, Figure 2 shows us that current reserves and resources are in principle able to accommodate the cumulative material demand for photovoltaics until 2050. As can be seen in Figure 2, reserves for silver are currently sufficient to meet cumulative silver demand for photovoltaics, even in a 100% crystalline scenario.

When looking at the material requirements in Figure 1 and Figure 2, one should take into account that in reality, it is most likely a mix of crystalline and thin film photovoltaics will be used. This means that total material requirements will be spread over crystalline and thin film photovoltaics. In addition, economic principles will cause a shift to a different technology when material scarcity drives up prices for a certain materials. This will cause the shift to technologies with less material restrictions.

In addition to the demand from photovoltaics, material demand arising from other technologies can put additional strain on the market for these materials. An example is the increase in demand for smart phones and light emitting diodes (LEDs), both containing gallium. Currently, the main application of gallium (66%) is in integrated circuits, used in computers and telecommunications. 18% of gallium is used for laser diodes and LEDs and 14% is used in R&D activities. At the moment, only 2% of gallium is used in photovoltaics (UNIA, 2011). An increased demand for gallium for



integrated circuits and LEDs can put additional strain on the supply of gallium for photovoltaics.

In addition to bottlenecks caused by a mismatch between supply and demand, bottlenecks can also occur because of geopolitical constraints. An example is the fact that over 50% of refined indium production is controlled by China (UNIA, 2011). Disruptions in trade routes could result in short term material bottlenecks.

### Key mitigation measures

For the three thin film photovoltaic technologies containing indium, gallium and tellurium, substitution can take place with silicon, for which no bottlenecks are expected (USGS, 2012)

#### Indium

- Indium is currently considered an impurity in the production process of zinc (JRC, 2011). When an increase in demand for indium causes prices for indium to increase, this will be an economic incentive to produce indium as a co-product of zinc production.
- Research into the substitution of indium in Liquid Crystal Displays (LCDs) is underway and is estimated to become commercially available in the next three years. This could free up additional indium for photovoltaics. Gallium arsenide can substitute for indium phosphide in solar cells, but this is a scarce material as well. (USGS, 2012).
- Recycling of indium from flat panel displays will become an important aspect of maintaining an adequate indium supply, noting that 74% of total indium consumption is for flat panel displays (JRC, 2011) and hence increasing demand for flat screen displays can put additional strain on the supply of indium for photovoltaics.

#### Gallium

- Recycling from electronic scrap is currently non-existent and is difficult because the waste stream is small and dissipative.
- There is little research put into the substitution of gallium in solar cells, but substitution will probably lead to lower efficiencies (UNIA, 2011). Possibilities for substituting gallium in LEDs and lasers are being researched (USGS, 2012).
- Current gallium production mainly takes place as a by-product of the production of other metals, such as zinc and aluminium. Currently, less than 10% of gallium in bauxite is recovered, mainly due to a lack of refining equipment (JRC, 2011). This means that a gallium bottleneck might be prevented by increasing gallium production by constructing additional refining equipment. This will be more attractive when the economics for recovering gallium become more favourable.

**50%+**  
OF REFINED INDIUM  
PRODUCTION IS  
CONTROLLED BY  
CHINA

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## Tellurium

- Recycling rates are currently very small, but could increase when PV cells are being recycled. Recovery of tellurium from electronic scraps is difficult due to its dissipative use in small electronics.
- For most of its uses, tellurium can be substituted for a different material, although this does lead to production efficiency losses or product characteristics (USGS, 2012).

## Silver

- For several of its current applications, silver could be substituted by other materials. Hence, if supply constraints would arise; silver supply could shift from other applications, such as cutlery and jewellery, to photovoltaics.
- Current recycling rates are between 30 and 50%. Good candidates for increasing the recycling rate are jewellery, coinage, catalysts and electronics (UNIA, 2011). A further increase in the price of precious metals will make additional recycling more attractive (UNEP, 2011).

## Conclusion

For some photovoltaics technologies, supply bottlenecks can be expected, but in all cases there are ways to at least partly overcome them. But it is anyway possible to continue with currently dominant crystalline silicon technology, for which no real bottlenecks exist.

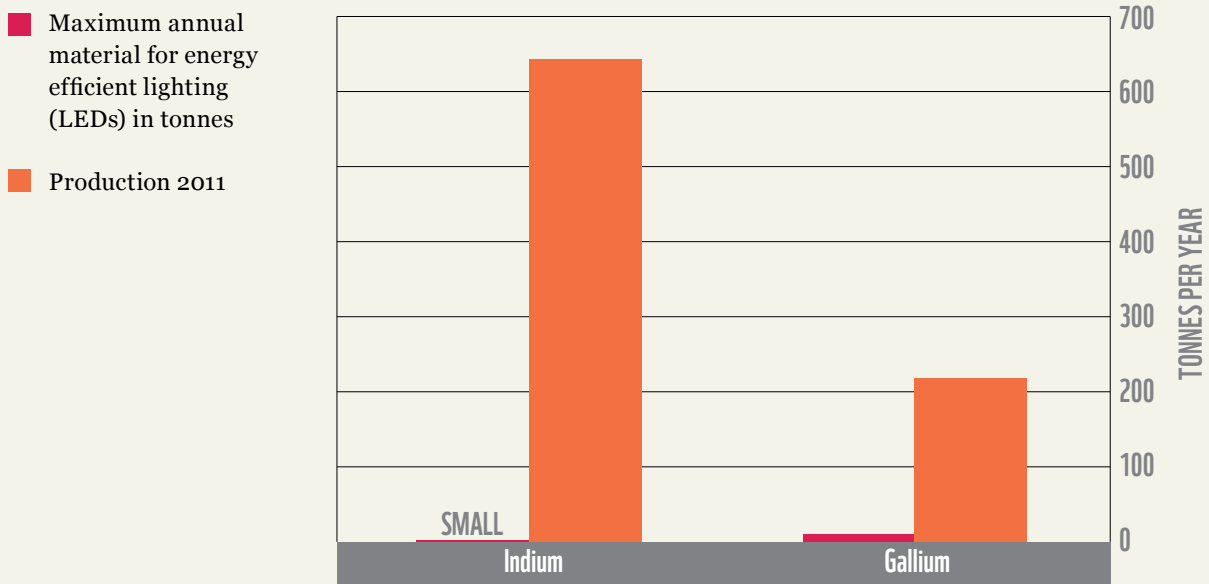
## Indium and gallium for energy efficient lighting

Indium and gallium are important materials for the manufacturing of light emitting diodes (LEDs). LEDs will become the dominant technology for energy efficient lighting in the following decades (McKinsey, 2011). Material demand for indium and gallium in LEDs was calculated using:

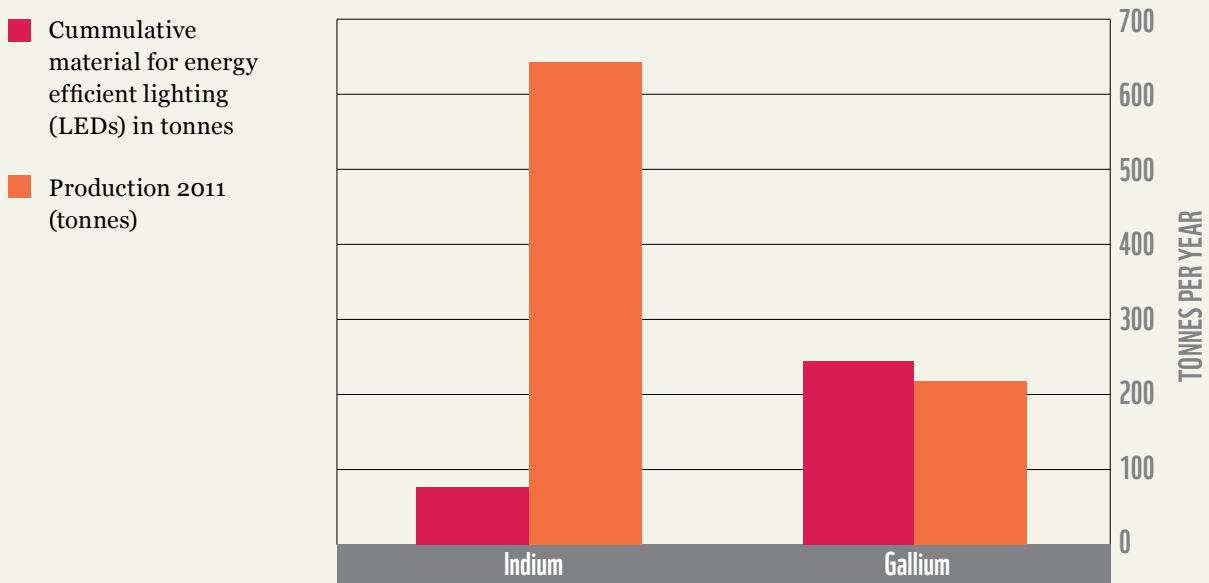
- the total floor surface area of buildings in 2050 (square meters), taken from The Energy Report (TER) scenario
- the amount of LEDs per square meter (1 LED per square meter has been assumed)
- the material demand per LED, taken from a Fraunhofer study on resources for future technologies (Fraunhofer, 2007) whereby the material demand for a high performance WLED (White LED), an efficient LED type, was taken by Ecofys as the primary source of energy efficient lighting up to 2050.

### Analysis of indium and gallium in energy efficient lighting

**Figure 3** Comparison of maximum annual material demand for energy efficient lighting in the period 2010 – 2050 with production in 2011 for indium and gallium. All numbers are in tonnes per year (Source: Ecofys).



**Figure 4** Comparison of cumulative material demand for energy efficient lighting until 2050 with production in 2011. A comparison with production instead of reserves and resources was made, in order to provide an indication of the magnitude of demand and information on reserves and resources is difficult to obtain. All numbers are in tonnes (Source: Ecofys).



Even though the demand for LEDs is expected to increase significantly over the coming decades, Figure 3 shows that the indium and gallium demand per LED is so small that the maximum annual material demand is insignificant compared to production in 2011. As shown in Figure 4, the cumulative material demand for energy efficient lighting for indium is several magnitudes smaller than production in 2011 and for gallium this is about equal. It should be noted that this cumulative demand is spread out over about 40 years. The comparison with production, instead of with reserves and resources has been made, because figures on reserves and resources are not available for indium and gallium.

### Key mitigation measures

- The development of **liquid crystals from organic compounds could become substitutes** for indium and gallium in LEDs, although the adjustments of colours might still require indium.
- If, in the unlikely event, materials for LEDs become scarce, energy efficient **fluorescent lighting could be used as a substitute for LEDs**. Fluorescent lighting requires rare earths, however (JRC, 2011).
- The paragraph on indium and gallium in photovoltaics explains further options for expanding supply and recycling and substitution for indium and gallium.

### Conclusion

Even though our assumptions on the material demand for LEDs is uncertain, it is clear from the results that neither indium nor gallium is likely to become a bottleneck for the production of LEDs. In the unlikely scenario that this would be the case, substitution by other materials and the development of organic LEDs will alleviate the problem.

## Rare earths for wind turbines (neodymium and yttrium)

Rare earths are used in a number of technologies from The Energy Report (TER) scenario, such as wind turbines, electric vehicles (magnets and batteries) and energy efficient lighting. The supply constraints of rare earths for wind energy are frequently mentioned in studies on critical materials for renewable energy and are therefore selected for a detailed analysis in this study. This requires calculating the maximum annual material demand for wind turbines and the cumulative material demands for wind turbines and comparing them with current production, reserves and resources.

Offshore turbines must be able to withstand harsh conditions at sea, such as stronger winds and a salty environment, compared to onshore wind turbines.

# RARE EARTHS

ARE ONE OF THE MOST IMPORTANT BOTTLENECKS FOR WIND TURBINES

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In addition, maintenance for offshore turbines is more difficult than maintenance for onshore turbines. For these reasons, offshore turbines may profit more from direct drive and superconductivity, which are less prone to technical failures and require less frequent maintenance. Since onshore turbines do not suffer from harsh environments and costly maintenance, it has been assumed that onshore wind turbines consist of conventional gearbox turbines, which do not require rare earths. Onshore wind turbines are therefore excluded from this analysis. In the future, if costs for direct drive and superconductive turbines are less prohibitive, onshore wind turbines could also benefit from this technology. This is, however, not included in this analysis. In addition, if serious material constraints would occur, the current technology (without direct drive and use of superconductivity turbines) can be used to avoid these constraints.

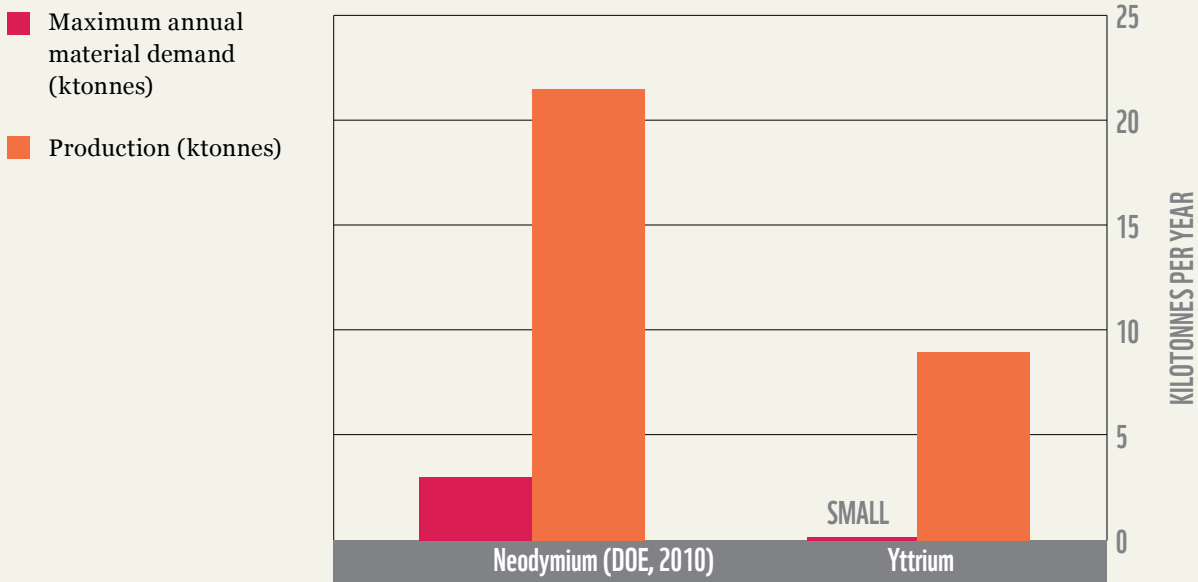
Direct drive and superconductive turbines require the rare earth elements neodymium and yttrium, respectively, and are therefore included in this analysis. The share of direct drive turbines in 2050 is assumed to be 90% and the share of superconductive turbines is assumed to be 10%. Estimates on the material intensity of neodymium and yttrium for direct drive and superconducting wind turbines have been taken from Fraunhofer (2009). Just as with solar energy, a progress ratio of 85% is assumed.

It should be noted that reliable information on rare earths is difficult to obtain (APS, 2011). Information on yttrium is available as a separate entry in the USGS commodities summary. Neodymium, however, only appears as part of the rare earths group. Production statistics for neodymium for 2010 have been obtained from DOE (2010). The reserves of neodymium are assumed to be equal to the reserves of rare earths. For neodymium and yttrium as well as for rare earths in general, information on resources is not available.

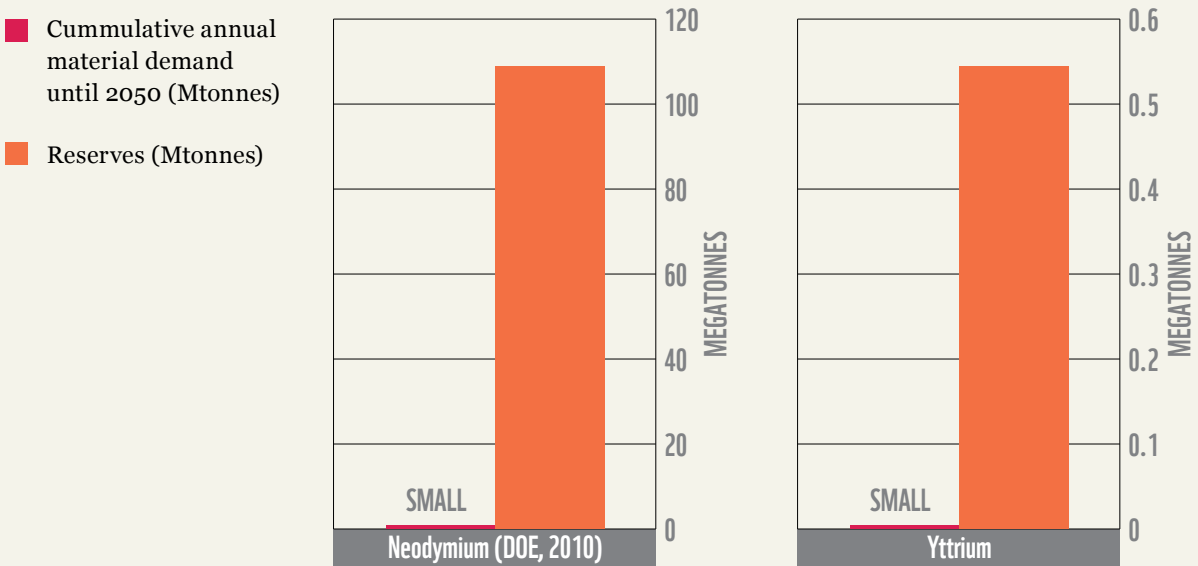
## Analysis of rare earths in wind turbines

In 2050, the TER scenario assumes that 5% of global electricity production comes from off-shore wind turbines. With an estimated annual electricity production of 127 EJ, this means that around 6.4 EJ is produced by off-shore wind turbines annually. Based on this figure, assumptions have been made for the annual growth of offshore wind turbines and the total capacity of turbines required to produce this electricity in 2050. Using these data, the maximum annual material demand has been calculated. The cumulative material demand for offshore wind turbines has also been determined. This has been compared with figures for production, reserves and resources in 2050, see Figure 5 and Figure 6. Even if offshore wind energy supply is higher, such as around 10-20 EJ eventually by 2050, constraints for both elements, neodymium and yttrium, are unlikely.

**Figure 5 Comparison between maximum annual material demand for offshore wind turbines and production in 2011. All numbers are in megatonnes per year (Source: Ecofys).**



**Figure 6 Comparison between cumulative material demand until 2050 for offshore wind turbines and reserves in 2011. The material demand is so small in comparison with reserves that it doesn't show up on the graphs. All numbers are in megatonnes (Source: Ecofys).**



As can be seen in Figure 5, the maximum yearly demand of neodymium and yttrium for wind technologies is a lot lower than the current production of neodymium and yttrium. Furthermore, Figure 6 shows that the cumulative demand for neodymium and yttrium required for offshore wind turbines is a lot smaller than reserves in

## 2030 THE MAXIMUM ANNUAL MATERIAL DEMAND FOR LITHIUM AND COBALT OCCURS IN 2030

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2011. Additional demand due to wind turbines is so small that it hardly shows up in the figure. This means that, even though demand growth for rare earths due to requirements for other applications is expected to rise sharply in the next five to ten years, rare earths will most likely not be a bottleneck for the implementation of wind energy in TER. (JRC, 2011)

The reason that these rare earths are considered a bottleneck is not because the quantities of the material are not enough to meet demand, but for other, geopolitical reasons. The main reason is that the majority of production is concentrated in a single country, namely China (APS, 2011). In recent years, rare earths have been the subject of export restrictions, which has given rise to concerns in for instance Japan, the United States and Europe. Eliminating these geopolitical constraints on the short term is difficult.

In some cases, rare earths elements are the by-products of iron, zirconium, tin, thorium, or uranium production (APS, 2011). Projects to expand rare earth production are underway, but opening new mines requires large investments and time and almost a decade goes by before they are up and running. This means that even though reserves are more than enough to accommodate demand until 2050, increasing supply on the short run might be difficult. In addition, the exploitation of rare earth reserves can lead to severe environmental problems, which makes it difficult to open new mines in areas with strict environmental regulations.

### Key mitigation measures

- **Recycling** of rare earths from pre-consumer magnets **requires further research**. Recycling from post-consumer waste, such as rare earths found in hard-drives is a possibility, although it can take some time before significant quantities enter the waste stream.
- The substitution of rare earths used in permanent magnets, which are used in wind turbines, is difficult and has a negative effect on performance. **Using other types of wind turbines**, such as those using conventional gearboxes, however, can be a solution to eventual remaining bottlenecks (JRC, 2011).

### Conclusion

The material demand for wind turbines is so small compared to annual production and reserves and resources that no supply bottlenecks are expected. In addition, it is possible to use conventional gearboxes instead of permanent magnets.

## Cobalt and lithium for high density batteries

The Energy Report (TER) scenario assumes a complete shift to plug-in hybrids and/or electric vehicles for light duty vehicles. Light duty vehicles include personal two-wheelers, city cars and non-city cars. It is assumed that these vehicles will each have a battery that contains lithium and cobalt. In 2050, the TER scenario contains close to 3.3 billion light-duty vehicles.

For these calculations, it is assumed that the batteries for light duty vehicles in the TER scenario will be the same as for plug in hybrid vehicles as presented in DOE (2010). The vehicles in the DOE report have a range of 40 miles (64 kilometres). The DOE provides a high and a low figure for the amounts of lithium and cobalt contained in these batteries. The high figure for lithium in batteries is 5.07 kg and the low figure is 1.35 kg. For cobalt this is 3.77 and 0 kg respectively. In order to calculate the material demand, the average of these low and the high figures have been used. This makes the amount of lithium and cobalt in a battery 3.2 and 1.9 kg, respectively.

In a study on batteries from 2010, Boston Consulting Group (BCG) has estimated the cost developments of batteries from 2010 to 2020. Almost all of the cost reduction comes from increased production volumes, which are economy of scale effects. In contrast, almost no cost reductions are expected from production-volume-independent costs, which mainly consist of material costs. From this information it can be deduced that the material demand per battery is not expected to decrease much over time. For this reason, no technological learning has been taken into account for batteries. The fact that 'limited' material learning will occur is not unexpected. For batteries, the capacity is to a large extent determined by the amount of active materials. This means that material use cannot be reduced substantially without reducing battery capacities.

For each 5 year period from 2000 to 2050, TER contains figures for the amount of new light duty vehicles. The amount of new vehicles per period is multiplied by the material intensity of that period to arrive at total material demand for that period. The sum of these amounts is the total material demand for batteries in new electric and hybrid vehicles from 2000 until 2050. The maximum annual material demand for lithium and cobalt occurs in 2030. These figures are compared to current production of lithium and cobalt and shown in Figure 7. The cumulative material demand for lithium and cobalt is compared to current reserves and resources and shown in Figure 8.

The results presented in Figure 7 and Figure 8 have been calculated without taking into account the limited lifetime of batteries for electric vehicles. This means that the actual amount of batteries required for vehicles from 2000 until 2050 in the TER scenario is likely to be higher than shown in Figure 7 and Figure 8. It is difficult to include the lifetime of batteries in these calculations, because very little information is available on this issue, due to limited hands on experience with electric vehicles. Another complicating factor is the fact that the lifetime is largely dependent on the usage of the battery, such as kilometres driven and how it is charged. A lot of research is being poured into the development of more efficient and durable batteries.

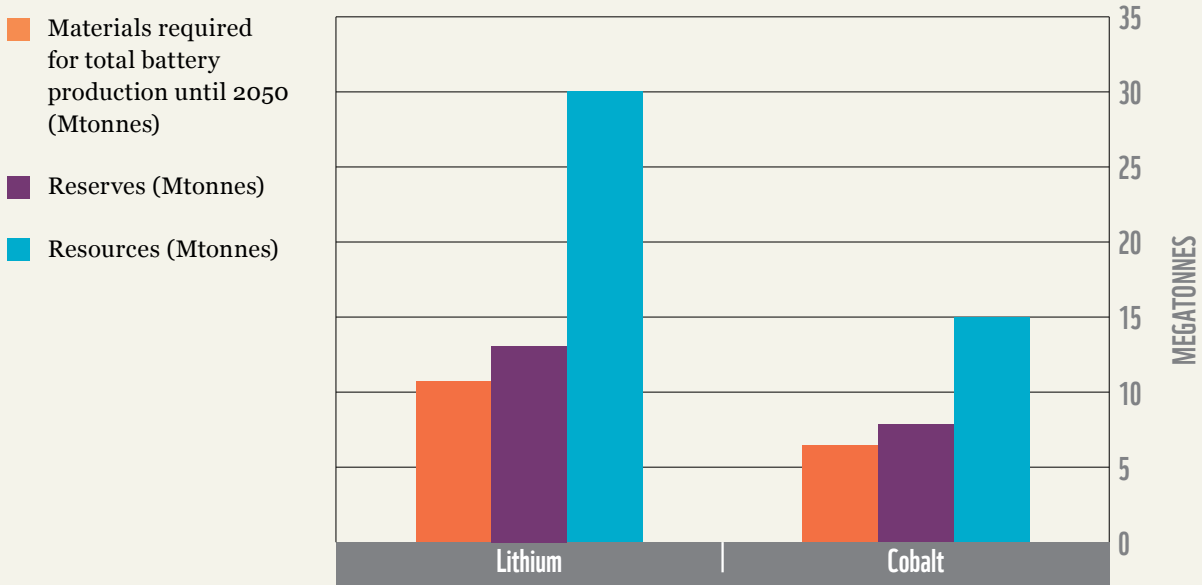
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Skutterudite is mined as an ore of cobalt and nickel with a by-product of arsenic.



**Figure 7 Comparison between maximum material demand for batteries and production in 2011. All numbers are in megatonnes (Source: Ecofys).**



**Figure 8 Comparison between cumulative lithium and cobalt demands for total battery production until 2050 and reserves and resources in 2011. All numbers are in megatonnes (Source: Ecofys).**

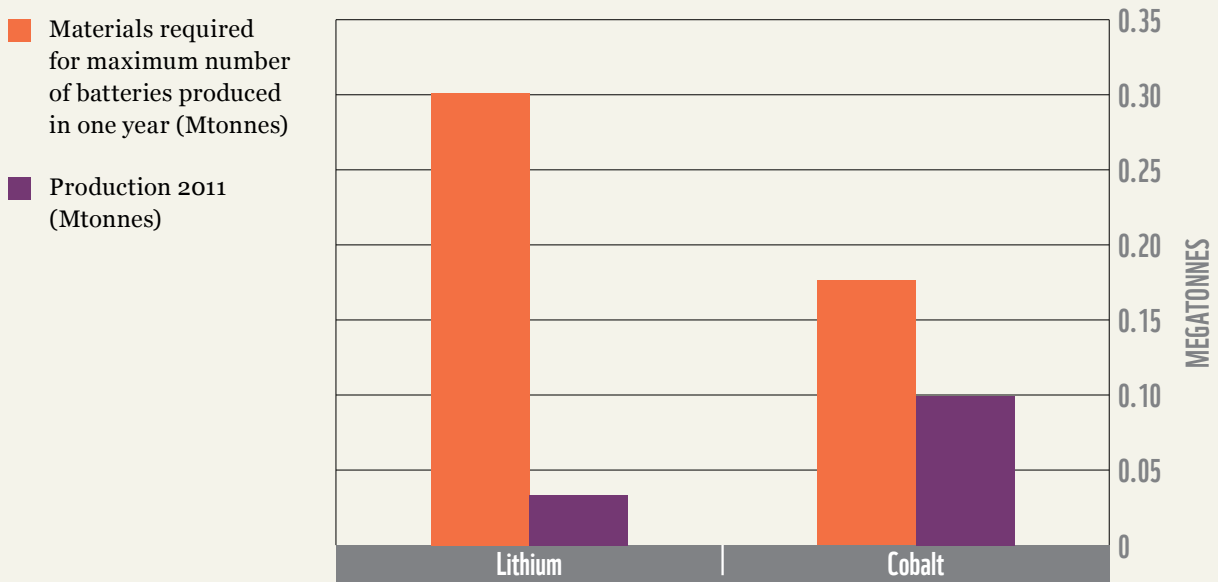


Figure 7 shows that current production levels of lithium and cobalt are not sufficient to meet the yearly peak material demand for batteries in the TER report. Especially for lithium the difference is large. In addition, Figure 8 shows that expected material requirements for both materials are large compared to reserves and resources. If

the limited lifetime of batteries would be taken into account, this shortage would be even more pronounced. Also, if more than the assumed 3.3 billion electric vehicles are on the road eventually or in case electrification expands into other transport areas in the future such as freight vehicles and/or aviation and shipping there may be further shortages. However, reductions in material intensity for batteries used in the calculations is conservative compared to the estimates made for wind and solar.

Current lithium production mainly takes place in Chile, Australia, China and Argentina. Lithium batteries power the majority of cell phones and laptops. Demand for lithium has grown continuously over the last ten years and is expected to continue growing by 5 to 10% annually during the next decade. Therefore, recycling of lithium is a key issue.

Cobalt is usually produced as a by-product of the production of other metals, such as copper or nickel. It is primarily produced in the Democratic Republic of Congo (DRC), Australia and Cuba. Instability in the DRC could lead to short term supply bottlenecks. The majority of cobalt is refined in China, making cobalt subject to the same insecurities as rare earths. In addition to batteries, cobalt is also used in superalloys, cutting tools and catalysts. Additional demand for these applications could put additional strain on the availability of cobalt for batteries. UNEP reports moderate expected growth rates for cobalt (UNEP, 2011).

## Key mitigation measures

### Lithium

- At this moment lithium prices are not high enough to make recycling profitable. Expected price increases, technological developments and legal measures making battery recycling compulsory, could result in higher recycling rates for lithium (UNEP, 2009).
- Substitution of lithium for other materials in the non-energy sector, which is at present still substantial, is often possible. This could free up additional lithium for batteries (UNIA, 2011).

### Cobalt

- On a positive note, a switch in materials to less cobalt intensive cathodes for batteries could greatly reduce the demand for cobalt in the future.
- Although at present not as effective as cobalt containing batteries, substituting lithium batteries containing cobalt for those that do not contain cobalt could circumvent bottlenecks (BCG, 2010).
- Recycling, which is already taking place in for instance rechargeable batteries, can be expanded without a lot of effort. Current recycling rates are at 25% (UNIA, 2011).

## Conclusion

The large material demand for cobalt and lithium compared with annual production and reserves and resources indicates that these materials might become a bottleneck for a fully sustainable energy system as represented in The Energy Report (TER).

## Copper for infrastructure, energy supply and energy efficient electric motors

Copper is one of the most widely used metals on earth. In addition to usage in roofing, plumbing and industrial machinery, it is used primarily in electrical wires (USGS, 2011). Copper is used for long and short distance electricity transport and distribution, e.g. from the power plant to the consumer. In addition, copper is used in many of the renewable energy supply technologies in The Energy Report (TER), such as transformers in wind turbines and in solar energy. Copper is also used in electric motors. In general, more efficient electric motors require more copper.

A key aspect of TER is the large expansion of supply-driven renewable energy sources; wind energy, solar photovoltaics and wave energy. To accommodate the integration of a large share of these variable renewables, there are several options. Expansion of the electricity infrastructure is one of them, as it provides more flexibility to match supply and demand on a continental scale.

Even though copper has not been highlighted as a critical metal by many of the critical material studies, the combined projected increase in copper demand as a result of several of the technologies included in the TER scenario could make it a bottleneck after all. In order to determine whether this is the case, the maximum and total copper demand for solar and wind energy over the years was calculated, as well as the copper required for energy efficient electric motors and copper attributed to the expansion of infrastructure:

- For **solar energy**, it was assumed that the 37 EJ electricity production in 2050 attributed to photovoltaics is met by a mix of 60% crystalline PV and 40% thin film PV. Copper requirements for concentrating solar power (CSP), which is expected to have an annual electricity production of 21.6 EJ by 2050, is also taken into account. For **wind energy**, copper demands for both on- and offshore wind turbines were taken into account, with an expected annual electricity production of 25.3 and 6.7 EJ respectively.

For each of these technologies, assumptions were made on the annual growth in capacity and the associated copper demand. The peak in copper demand for energy production technologies is expected to occur in 2045.

- In order to calculate the additional copper requirements for **energy efficient electric motors**, figures on the electricity consumed by electric motors in 2006 were extrapolated to 2050 using the expected GDP growth as presented in TER (IEA, 2011, p. 39). The electricity consumption in 2050 was used to calculate installed capacity in 2050. It was assumed that copper requirements for current electric motors (class IE2) are 1000 ton per GW installed capacity. It was also assumed that by 2050, all electric motors are of the IE3 class and energy efficient electric motors are of the IE4 class. It was assumed that for each improvement in efficiency class, roughly 1.2 times more copper is required (Ecofys Estimate), 2012).

By assuming a lifetime of 20 years for electric motors, the annual copper requirements for energy efficient electrical motors in 2050 have been calculated (IEA, 2011).

- The annual copper demand for an **expansion of existing electricity infrastructure** to accommodate renewable energy sources was calculated

taking the approach described in Appendix A. Note that these calculations used conservative assumptions, resulting most likely in an overestimate of copper demand for infrastructure.

### Analysis of copper demand in the TER scenario

Figure 9 shows a comparison of the maximum annual material demand for copper in the period 2012 to 2050 for additional energy infrastructure, wind and solar energy and energy efficient electrical motors with copper production in 2011.

**Figure 9 Comparison of maximum annual material demand for copper in the period 2010 – 2050 with production in 2011 for copper. All numbers are in megatonnes (Source: Ecofys).**

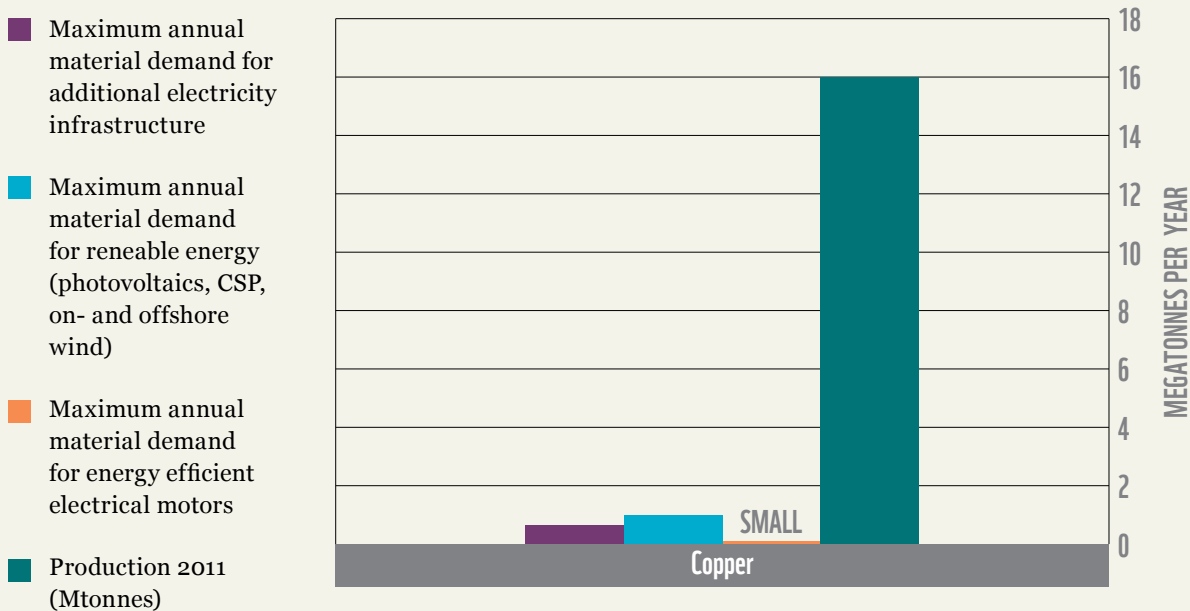


Figure 10 shows a comparison of the cumulative copper demand for the expansion of the electricity distribution infrastructure, wind and solar energy and energy efficient electrical motors with copper reserves and resources in 2011.

**Figure 10 Comparison of cumulative material demand for infrastructure for renewable energy, renewable energy production and energy efficient electrical motors until 2050 with copper reserves and resources in 2011. All numbers are in megatonnes (Source: Ecofys).**

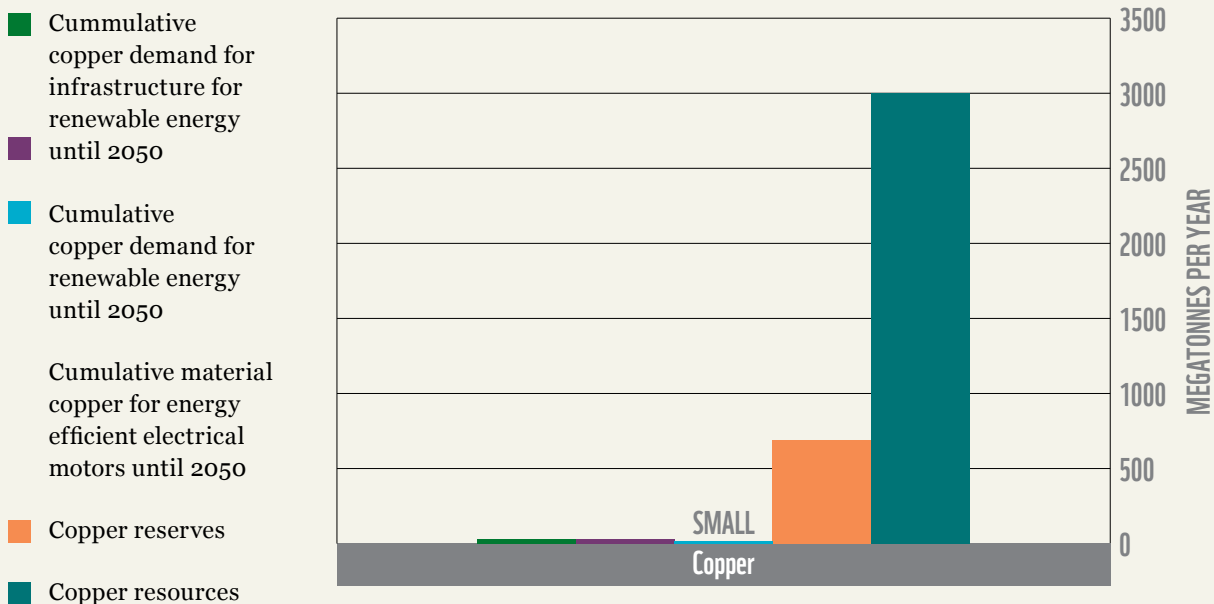


Figure 9 shows that the combined additional copper demand due to the expansion of the electricity infrastructure, solar and wind energy and energy efficient electrical motors is small compared to copper production in 2011. Figure 10 shows that cumulative copper demand for these developments until 2050 is marginal compared with reserves and resources in 2011. These results show that from a technical point of view, copper will most likely not be a bottleneck for a fully sustainable energy system as represented in The Energy Report (TER).

However, an increase in copper demand, also due to technologies not included in the TER, will lead to companies expanding production by using lower quality ores. This leads to increased energy requirements for copper production and increased copper prices (Harmsen, 2011).

### Key mitigation measures

- **Recycling of copper** from old infrastructure and other applications is possible, although it is hindered by the sometimes long use phase of copper and the different waste flows that contain copper, often ending up in landfills. In addition, copper is often only a small part of the host product and it is difficult or inefficient to recycle copper from alloys. For these reasons, Harmsen claims that it is difficult to expect a very high recycling rate (Harmsen, 2011).
- In many applications, copper can be **substituted** for other materials. Examples are plastics in tubing and glass fiber in telecommunication. For the technologies examined in this chapter, aluminium is the most likely candidate for substitution. Aluminium is a good material to use for electricity infrastructure, although the lower density of aluminium would lead to wires with a larger diameter. For electrical motors, the lower density of aluminium could result in

performance loss. It is important to keep in mind that even though aluminium is more abundant than copper, it requires more energy to produce (Harmsen, 2011).

## Conclusion

In spite of the many different applications of copper in a fully sustainable energy system as represented in TER, demand is still low compared with supply in 2011 and reserves and resources. Reducing demand through substitution and increasing supply by recycling further reduce the likelihood of the occurrence of a bottleneck.

## Semiconductors for smart electronics

Semiconductors are important components in electrical and electronic equipment including cell phones, personal computers, automotive electronics, LEDs and solar cells. Accordingly, the production volumes for these components have increased in recent decades and are expected to continue to increase up to 2050.

For power electronics, which have been mentioned in chapter 3, it has been difficult to find information on the materials involved in their production and the development of demand for power electronics in the future. For lack of information, they have been excluded from further analysis.

Semiconductors are an integral part of improving energy efficiency in the built environment as well as in industry and transport. Electronics containing semiconductors are required, for instance, to regulate temperature in buildings and optimise production processes in manufacturing plants. Semiconductors are hence an important aspect in The Energy Report (TER) scenario and it is worthwhile to assess the possibilities for bottlenecks in the supply of semiconductors for the TER scenario.

However, it is difficult to quantify the expected increase in the global demand for semiconductors and, in particular, which share to attribute to developments in the TER scenario versus other demand sectors. In addition, many different types of semiconductors exist, consisting of many different materials, including arsenic, germanium, indium, gallium, rhenium, silicon and tellurium (USGS, 2011 and UNIA, 2011). It is worth noting that the supply of a number of these materials, such as gallium, indium and tellurium, may already be strained by the introduction of other technologies in the TER scenario, such as photovoltaics.

Many materials required for the production of semiconductors can be substituted with other materials, although these are often also scarce. In addition, since these materials are used for other applications, it may be possible to reduce their usage in these other applications to free up materials for the production of semiconductors when supplies become tight.

All these different factors make it a difficult and time-intensive task to quantitatively assess whether any material bottlenecks for semiconductors are likely to occur in the TER scenario. It would require an in depth assessment of all the different materials

## NITROGEN, PHOSPHORUS & POTASSIUM ARE MOST IMPORTANT COMPONENTS OF FERTILISERS

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involved in the production of semiconductors, their production forecasts, competing demand sectors and mitigation measures such as recycling and substitution. While this analysis is outside the scope of this project, additional research in this area would provide worthwhile insights if undertaken.

### Nitrogen, phosphorus and potassium for biofuels

The Energy Report (TER) tries to limit the use of biomass for energy purposes. When other renewable energy sources are not feasible, TER resorts to biomass. For example, biomass is assumed as the fuel source for trucks, planes and ships, for which it is presently difficult to switch from fossil fuels to electric energy sources. Biomass is also used for industrial processes, where very high temperatures are required.

The TER scenario conservatively assumes that it will be necessary to obtain biomass from sustainably grown biofuel crops and from sustainable forest management, even though a portion of biomass demand can be met using waste streams. Care is taken not to threaten food and water supplies and biodiversity and to prevent CO<sub>2</sub> emissions.

The need to grow additional biomass for biofuels, albeit as sustainably as possible, raises the issue of potentially increased demand for artificial fertilisers. The most important components of fertilisers, also mentioned in TER, are nitrogen, phosphorus and potassium. The TER scenario considers a closed loop approach in order to minimise the need for fertiliser. This includes precision farming, minimising losses to the environment and recycling nutrients from residue and waste streams. It is, however, likely that at least some additional demand for fertilisers will be caused by the increased production of crops for biofuels

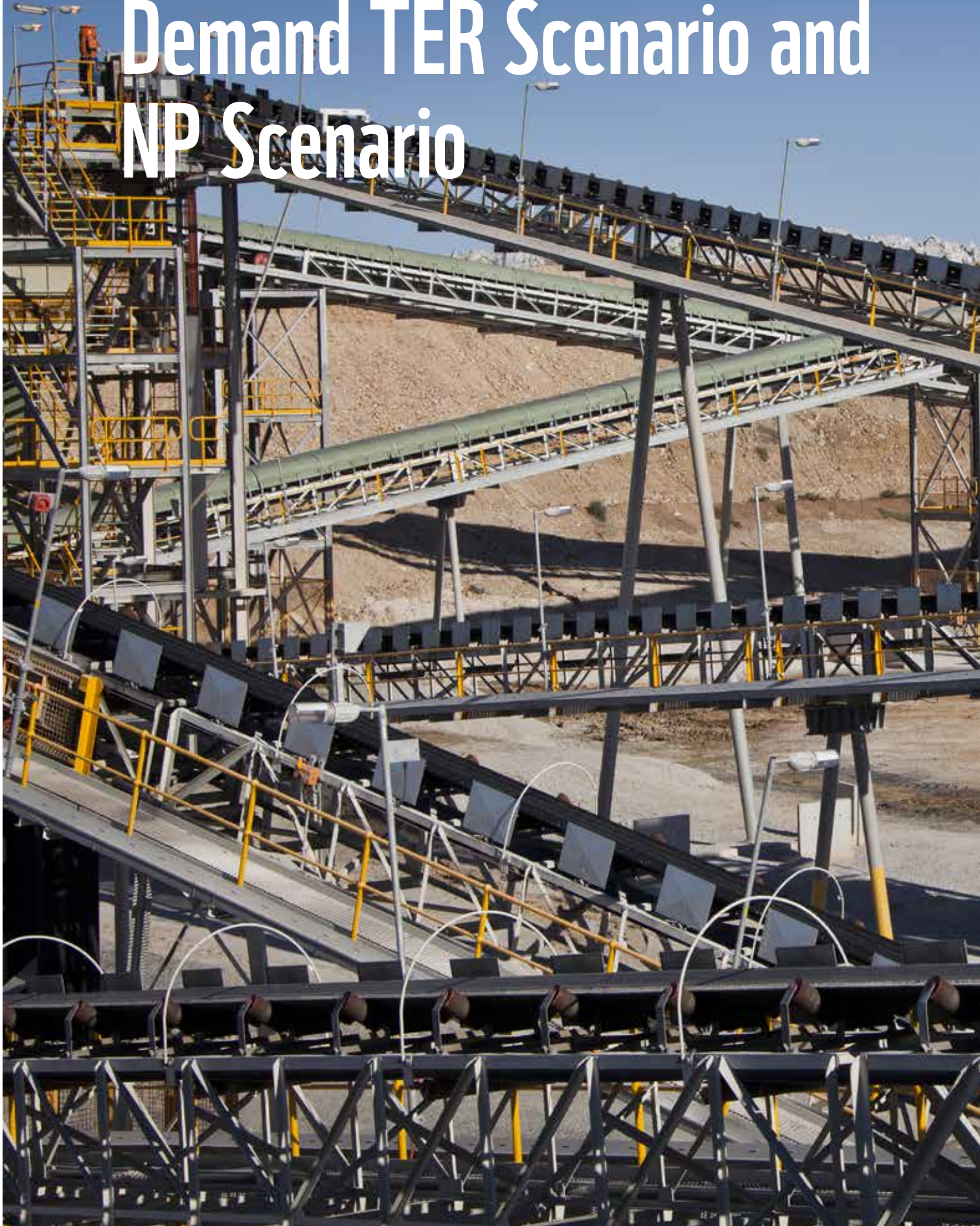
Since atmospheric nitrogen is freely available for nitrogen fixation on a global level, nitrogen is not expected to be a bottleneck for the production of fertilisers. However, phosphorus and potassium have to be mined from phosphate rock and potash.

For phosphate rock, world resources exceed 300 billion tonnes (USGS, 2012). Global reserves are estimated to be 71 billion tonnes. With an estimated production of 0.191 billion tonnes in 2011, phosphate reserves and resources are able to meet demand far beyond 2050, even if demand grows significantly.

For potash, world resources and reserves total 250 and 9.5 billion tonnes respectively. With an annual production in 2011 of 37 million tonnes, a large increase in demand should be easily accommodated within existing resources (USGS, 2012).

Since all three key components of artificial fertilisers are readily available and production is spread out over many countries with a broad geological spread, materials required for the production of fertilisers are not expected to become bottlenecks for achieving the TER scenario.

# 5. Comparison Material Demand TER Scenario and NP Scenario







# COMPARISON MATERIAL DEMAND TER SCENARIO AND NP SCENARIO

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As discussed in chapter 4, a fully sustainable energy scenario like The Energy Report (TER) will lead to additional material demand for some materials.

However, a development of society as described in TER also has certain benefits in terms of material use. This chapter will qualitatively assess the key differences in material demand between the TER scenario and a conventional ambitious scenario, the International Energy Agency's (IEA) New Policy Scenario (NPS), the business as usual scenario.

The NPS is the most central scenario for forecasts from the IEA and is commonly used as a basis for energy market studies. Although the NPS only runs until 2035, the comparison has been made based on the information which is available.

## Material requirements to achieve the TER scenario and NPS

Both the TER scenario and NPS require increasing amounts of materials including critical materials. However, due to the different technology types deployed, there are important differences in the types of critical materials required.

The most critical bottlenecks in a transition to the TER scenario are:

- **lithium** and **cobalt** for electric vehicles.

As detailed in Chapter 4, other materials, such as rare earths for wind turbines and copper for wind and solar energy, energy efficient motors and a more elaborate electricity infrastructure, are less likely to be bottlenecks. Indium, gallium and tellurium are not considered an important bottleneck, because their use in photovoltaics can be substituted by using technologies using less critical materials, such as silicon.

Material supply bottlenecks illustrate the importance of an early material strategy. Whether or not a technology is prone to suffer from supply chain bottlenecks should be taken into consideration when making an investment decision or making R&D decisions. In these cases, technologies that rely on abundant materials have an advantage over technologies that rely on critical materials.

A continued reliance on conventional energy sources such as fossil fuels and nuclear energy in the NPS means an increased demand for materials used in the fossil fuels and nuclear industries. For example, the IEA estimates that in 2035 the share of fossil fuels in global primary energy consumption is 75% and the output of nuclear energy rises by 70% over the period to 2035 (IEA, 2011). Although only playing a role at the end of the 2035 period, carbon capture and storage (CCS) is important due to the continued reliance on fossil fuels, and would be expected to play an increasingly important role up to 2050. Examples of critical materials which will experience increased demand can be found in the USGS Mineral Commodity Summaries 2012 (USGS, 2012):

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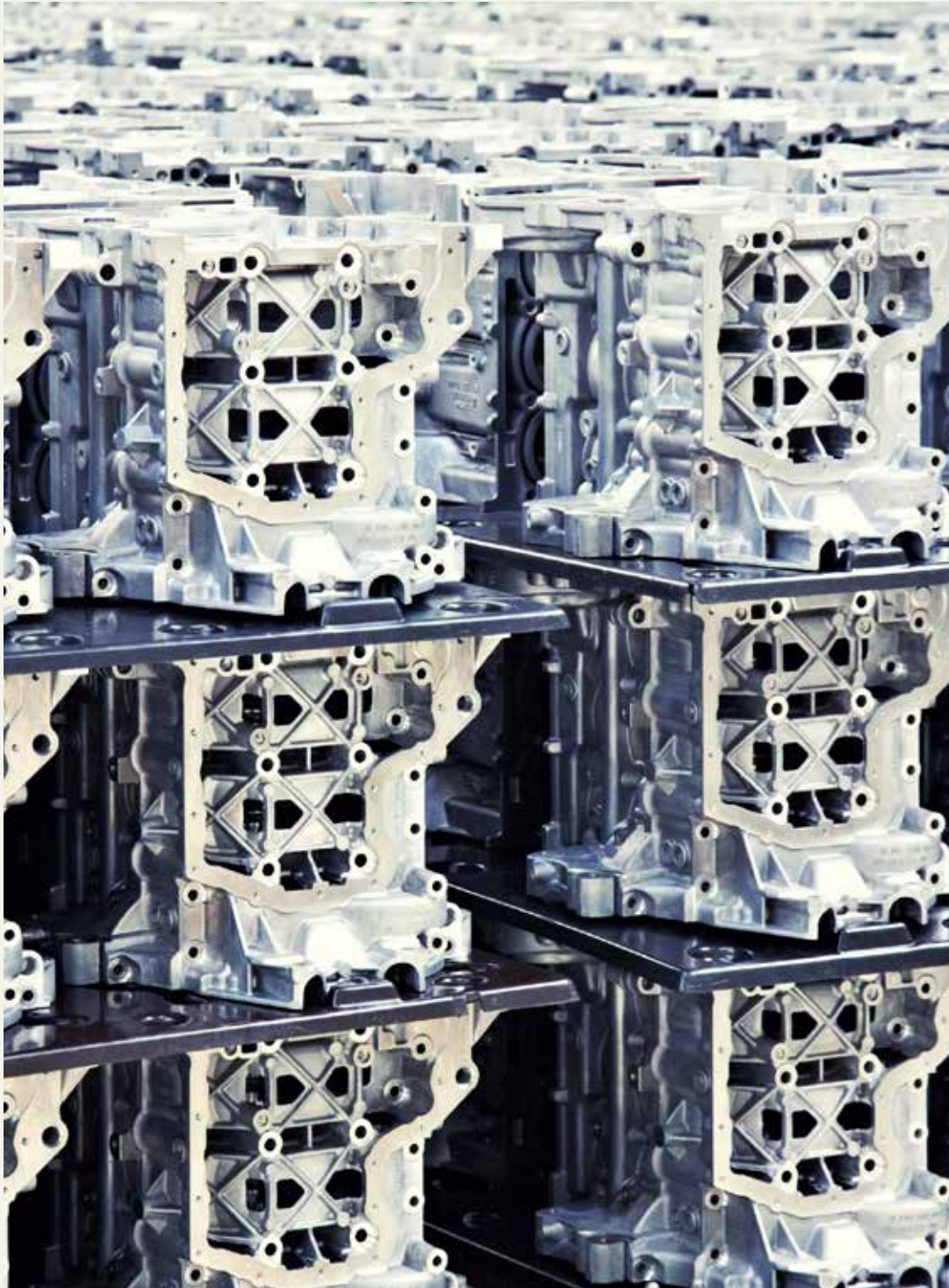


The mineral bismuth is used for liquid coolants

- the usage of **bromine** in flue gas scrubbers in power plants
- **barite**, **beryllium** and **cesium** in oil and gas well drilling fluids
- rare earth chlorides for the production of fluid-cracking catalysts in oil refineries
- **barite** for high-density concrete for radiation shielding
- **bismuth** for liquid coolants
- **hafnium** and **indium** for nuclear reactor control rod alloys
- materials required for CCS include chemicals for the capture installations, materials for pipelines and for drilling platforms

Many of the material bottlenecks for the TER scenario are not relevant for the NPS. A reduced capacity of photovoltaics as compared with the TER scenario means a smaller likelihood of an indium, gallium or tellurium bottleneck. Continued reliance on oil as the basis for transportation fuels (since electric vehicles are not considered commercially viable and the potential for substitution of oil in transport is considered limited) mean significantly less electric vehicles as compared to the TER scenario and hence a reduced likelihood of lithium or cobalt (for batteries) becoming a bottleneck.

However, many of the material bottlenecks for the NPS are also not relevant for the TER scenario. Fossil fuels in the energy mix will meet only 5% of total energy supply in 2050, hence fossil fuel scarcities will not arise in the TER scenario. In addition, since TER excludes CCS and nuclear energy by 2050, these bottlenecks will neither be relevant for TER scenario.



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In the TER scenario higher material efficiency, for example in the building of vehicles with lighter steel frames is assumed.

## **The importance of energy efficiency and material efficiency in the TER scenario and NPS**

An important part of the TER scenario is the far reaching development in efficiency, which is expected to occur in all sectors of society, ranging from transportation, to the built environment and to industry. The NPS also states that efficiency measures will affect energy consumption, but at a much smaller scale than in the TER scenario. As a result, both scenarios have very different predictions about energy consumption in the future.

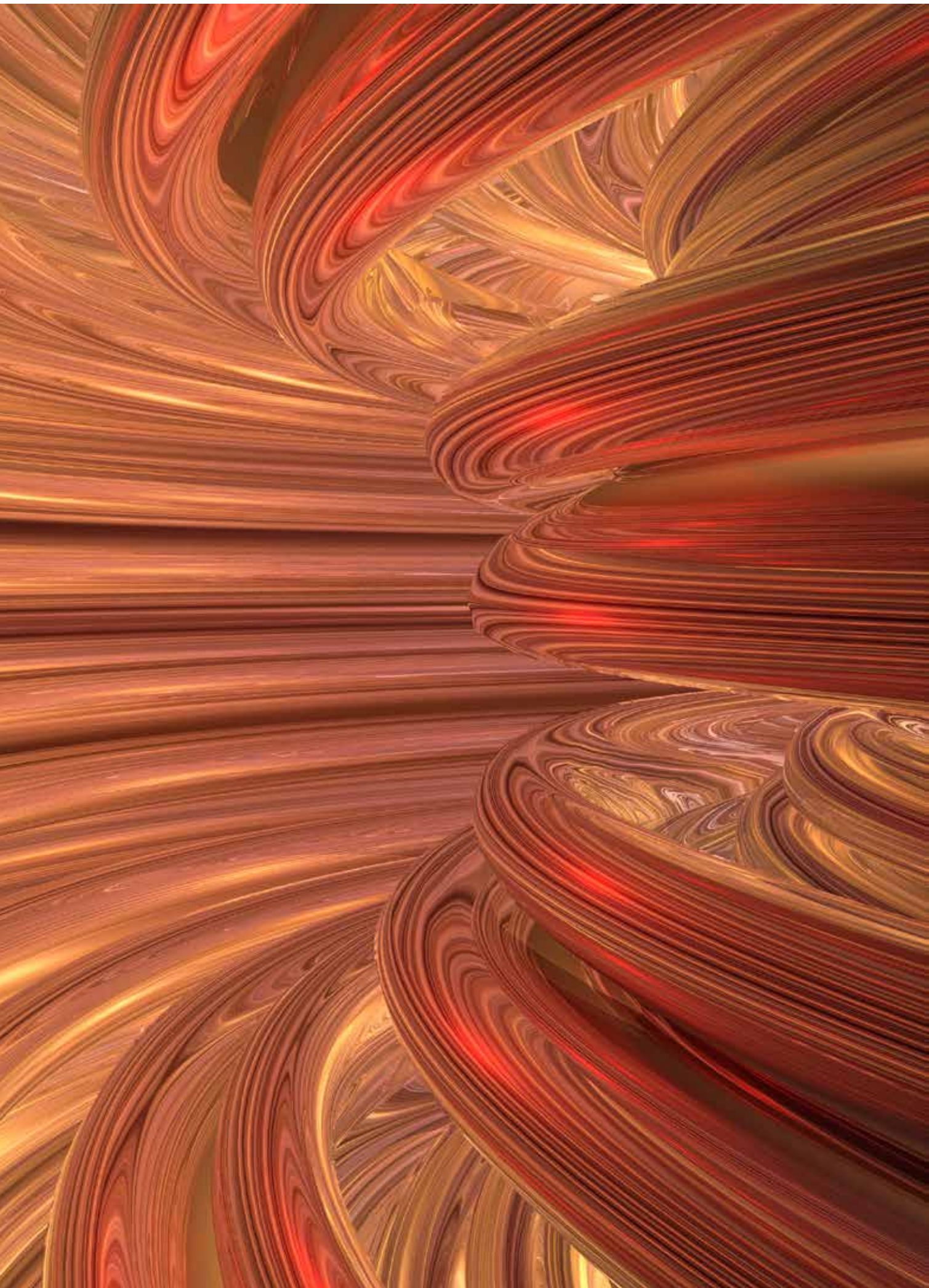
The TER scenario will not only assume a higher energy efficiency, but also a higher material efficiency. An example from TER is building cars with lighter frames, leading to lower steel demand per vehicle. There are many options to reduce demand for primary materials, such as product recycling, material recycling and more efficient product design (Allwood et al., 2011. Worrell et al., 1997).

## **Conclusion**

The most important developments affecting the differences in material demand between the TER scenario and the NPS are the share of renewable energy and fossil fuels, energy efficiency measures, material efficiency measures and energy consumption. Although some of the material bottlenecks for the TER scenario are larger than those in the NPS, energy efficiency measures, an increase in material efficiency, the absence of nuclear energy and a significantly reduced reliance on fossil fuels will most likely lead to a smaller overall demand in scarce resources than in the NPS.

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## COPPER REQUIREMENTS FOR ELECTRICITY DISTRIBUTION INFRA- STRUCTURE

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Estimates on the copper requirements for a global electricity distribution infrastructure in 2050 have been made by extrapolating the current situation in Germany to the World in 2050. The following assumptions have been made.

In transmission lines, which are overhead lines used for long distances at a high voltage, aluminum is mostly used, due to its lower weight. In local distribution systems, where power is distributed on a low and middle voltage level, copper and aluminum is used. Typical copper cables in low voltage levels have a diameter of 150 mm<sup>2</sup> with 2000 kg copper per km. In middle voltage levels, stronger cables are used, with an estimated 3800 kg copper per km.

The length of the German middle voltage grid is 500,000 km, the low voltage level has 1,100,000 km. With very high penetrations of renewable energy sources, it is likely that a stronger distribution grid is required. It is assumed that an additional 100,000 kilometers is required for the middle voltage level and an additional 200,000 km for the low voltage level. This results in 600,000 km of middle voltage cables and 1,300,000 km of low voltage cables.

We assume that all cables in the distribution systems are based on copper. This means that the German distribution system in 2050 requires 4.88 million tonnes of copper (600,000 km \* 3800 kg/km + 1,300,000 km \* 2000 kg/km). Of this 4.88 million tonnes, about 0.78 million are due to the high penetration of renewable energy sources.

The life time of network elements is assumed to be 40 years. Germany has a peak load of about 80 GW and a yearly gross electricity consumption of 600 TWh. The numbers can then be scaled to a global level according to the TER scenario, assuming that every country has a similar network structure.

Based on a global electricity consumption of 20,000 TWh, global copper demand for infrastructure is 163 million tonnes of copper every 40 years or 4 million tonnes per year. Of these 4 million, 0.6 million are due to a very high penetration rate of renewable energy sources worldwide.

The world copper production in 2011 was 16.1 million tonnes per year, which means that the increase in copper demand attributed to an expansion of the electricity grid for the integration of renewable energy sources is almost 4%. (USGS, 2011)

Source: Bernhard Hasche, Ecofys.

# ASSUMPTIONS MADE FOR THE CALCULATIONS

This chapter provides an overview of the most important assumptions and input parameters for the calculations in this study.

The Energy Report (TER) itself contains many assumptions. Some of the most important ones are mentioned here. For more details, please refer to TER itself, available online at <http://www.ecofys.com/en/publication/11/>

## Assumptions for this study

### Materials included in the analysis

For the initial screening of potential supply chain bottleneck materials, metals, such as copper, platinum and rare earth elements, and industrial minerals such as barite and fluorspar were included.

Biotic resources, such as fish and timber, and fuel resources, such as coal and oil, have been excluded from this analysis. In addition, materials which are very abundant, can easily be synthesised, are easily substituted or are precursors of other materials on the list, have not been included either (see Paragraph 2.1).

**Catalysts, carbon fibre and super alloys:** Materials for catalysts are not considered likely bottlenecks for energy efficiency measures in TER and therefore not included in the analysis. Neither are carbon fibre and super alloys, used for instance in low carbon transport, since most resources for these materials are either readily available or can be substituted for alternative materials and their role in TER is not very large.

**Insulation and heat exchangers:** Insulation is assumed not to require scarce materials. Materials for heat exchangers, used for example for improving energy efficiency in industrial processes (copper, aluminum, selenium, chromium), are also not taken into account.

**Semiconductors:** Materials used for semiconductors, such as arsenic, germanium, indium and gallium, are discussed in the report but no quantitative assessment is made. It is assumed that semiconductor use will only to a very small part be for sustainable energy.

**Other uses of cobalt, lithium, manganese and molybdenum:** Cobalt, manganese and molybdenum, sometimes mentioned as potential bottlenecks for wind energy, were not included in the analysis. Other uses of cobalt and lithium in addition to their use in car batteries, was not taken into account. This was the case for many of the material bottlenecks.

**Power electronics:** Material demand for power electronics has not been taken into account.

**Rare earths in electric vehicles:** Rare earths in electric vehicles are not taken into account

### **Assumptions for the calculations**

The scarcity of a material and its likelihood to become a supply chain bottleneck was assumed to be directly related to the discrepancy between the demand for the material from 2000 to 2050 and the resources and reserves of that material in 2011. When no figures were available for reserves and resources, a comparison was made with production figures.

Although sometimes briefly touched upon in their respective chapters, geopolitical constraints have not been taken into account in the analysis of the potential bottlenecks for the materials. A very high demand that outpaces supply (temporary mismatch of supply and demand) is also not taken into account. Developments in reuse, recycling and substitution of critical metals are mentioned, but not quantified and not included in the calculations.

Where possible, technological learning is taken into account, but future technologies with altogether new material demands have not been taken into account. Shifts to alternative technologies due to market forces were not taken into account in the calculations. Additional strain on material supply due to demand for other technologies have generally not been quantified, with the exception of energy efficient lighting.

Environmental effects of mining operations etc. have played no role in the calculations made in this study.

It has been assumed that the International Energy Agency's (IEA) New Policy Scenario is the Business As Usual (BAU) scenario. Even though the IEA scenario only runs until 2035, it has been considered comparable with the TER scenario.

### **Assumptions in demand calculation for renewable energy technologies**

This chapter contains the assumptions made for each of the bottlenecks that were assessed in this study.

#### **Photovoltaics**

For photovoltaics, only the materials indium, gallium, tellurium and silver have been included in the analysis. In 2050, TER assumes that around 29% of total electricity production is derived from photovoltaic energy. It has been assumed that each of the four different technologies for photovoltaics presented in TER has a 25% market share in 2050. For all four materials, a progress ratio of 85% is assumed.

For indium, the material intensity shrinks from 22 to 3 tonnes per GW from 2000 to 2050. For gallium, it shrinks from 39 to 5 tonnes per GW from 2000 to 2050. For tellurium, it shrinks from 14 to 2 tonnes per GW from 2000 to 2050. For silver, it shrinks from 126 to 15 tonnes per GW from 2000 to 2050. Material intensities were taken from Wild - Scholten (2007) and Fraunhofer (2009).

## **Energy efficient lighting (LEDs)**

The total floor surface area of buildings in 2050 (square meters) was taken from the TER scenario. The amount of LEDs per square meter was assumed to be 1. The material demand per LED was taken from a Fraunhofer study on resources for future technologies (Fraunhofer, 2007). From this study, the material demand for a high performance WLED (White LED), an efficient LED type, was assumed to be the primary source of energy efficient lighting up to 2050.

## **Wind energy**

In 2050, the TER scenario assumes that 5% of global electricity production comes from off-shore wind turbines. It has been assumed that onshore wind turbines have conventional gearboxes and offshore wind turbines are equipped with direct drive turbines and super-conductive turbines. The share of direct drive turbines in 2050 is assumed to be 90% and the share of super conductive turbines is assumed to be 10%. Estimates on the material intensity of neodymium and yttrium for direct drive and superconducting wind turbines have been taken from Fraunhofer (2009). Just as with solar energy, a progress ratio of 85% is assumed. The material intensity for neodymium is assumed to drop from 676 to 121 tonnes per GW from 2000 to 2050. The material intensity for yttrium is assumed to drop from 46 to 8 tonnes per GW from 2000 to 2050. The reserves of neodymium are assumed to be equal to the reserves of rare earths.

## **Electric vehicles**

The TER scenario assumes a complete shift to plug-in hybrids and/or electric vehicles for light duty vehicles. It is assumed that these vehicles will each have a battery that contains lithium and cobalt. In 2050, the TER scenario contains close to 3.3 billion light-duty vehicles. It is assumed that the batteries for light duty vehicles in the TER scenario will be the same as for plug in hybrid vehicles as presented in DOE (2010). Figures on the amounts of cobalt and lithium in car batteries have been taken from averages in the DOE report (2010) and are 3.2 and 1.9 kg respectively.

Based on information from a BCG study (2010), no technological learning has been taken into account for batteries. The limited lifetime of batteries for electric vehicles has not been taken into account. Other technologies for batteries in electric vehicles have not been taken into account.

## **Copper**

Copper demand for solar (PV and CSP) and wind energy is taken into account, but not for other types of renewable energy technologies, such as wave and tidal energy, bio-energy and geothermal energy, because copper plays a minor role in these technologies or their contribution to the TER scenario is small. Copper used in other technologies, such as electronics is not taken into account.

The copper intensity for both onshore and offshore wind turbines was assumed to be 2000 tonnes per GW. The copper intensity for crystal PV was assumed to shrink from 6,839 tonnes per GW to 801 tonnes per GW from 2000 to 2050 (progress ratio 85%). The copper intensity for thin film PV is assumed to shrink from 5,401 tonnes per GW to 633 tonnes per GW from 2000 to 2050. The copper intensity for CSP is assumed to remain constant over the years at 4,000 tonnes per GW.

For energy efficient motors, it was assumed that electricity consumed by electric motors would grow in accordance with GDP as presented in TER. The electricity consumption in 2050 was used to calculate installed capacity in 2050. It was assumed that copper requirements for current electric motors (class IE2) are 1000 ton per GW installed capacity. It was also assumed that by 2050, all electric motors are of the IE3 class and energy efficient electric motors are of the IE4 class. It was assumed that for each improvement in efficiency class, roughly 1.2 times more copper is required (Ecofys Estimate), 2012). By assuming a lifetime of 20 years for electric motors, the annual copper requirements for energy efficient electrical motors in 2050 have been calculated (IEA, 2011).

Estimates on the copper requirements for a global electricity distribution infrastructure in 2050 have been made by extrapolating the current situation in Germany to the World in 2050. The assumptions made for this estimate can be found in Appendix A: Copper requirements for electricity distribution infrastructure.

### **Semiconductors and power electronics**

Detailed calculations on the materials required for semiconductors and power electronics have not been done in this study.

### **Nitrogen, phosphorus and potassium for biofuels**

In line with the TER scenario, it has been assumed that the use of biomass is limited to energy purposes. It has been assumed that nitrogen is freely available from the atmosphere and is therefore not expected to be a bottleneck. For phosphorus and potassium, it has been assumed that if reserves and resources exceed annual production in 2011 by more than a 100 fold, no resource bottleneck is likely to occur. For both phosphorus and potassium this has been the case.

## COMPARISON OF RESULTS WITH SEI AND STOA STUDY

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The following chapter provides a comparison of the results from this study, the Ecofys study, with the results from two recently published studies on material bottlenecks for renewable energy, one from the Stockholm Environment Institute (SEI) and one from the Science and Technology Options Assessment (STOA) of the European Parliament.

For each of these studies, the differences between their outcomes and the outcomes of the Ecofys study will be explained.

It is important to bear in mind that there are a number of difference in the scopes of the SEI and the STOA study and the Ecofys study, which partly explain the differences in the outcomes from the studies and makes it difficult to compare them on an equal basis. The main differences are the following:

- The time span for the SEI and the STOA studies is 2030/2035, whereas the Ecofys study looks at the TER scenario, which lasts until 2050. This leads to differences in technology deployment, but also influences the material demand of technologies, which is subject to technological development.
- The selection of materials and technologies is different. The Ecofys scenario has considered all technologies for the TER scenario, but selected a limited number of materials for further analysis, whereas the STOA study makes a detailed assessment of materials for photovoltaics (PV) and wind turbines and the SEI study is limited to five materials, but looks at the demand for these materials for several technologies.
- The Ecofys study looks at whether absolute material bottlenecks are likely to occur, whereas the STOA and the SEI study look at relative bottlenecks, caused by regional mismatches between material supply and demand. The STOA and the SEI study takes into account geopolitical constraints whereas the Ecofys study looks at whether enough recoverable material exists on a global scale to enable the transition to the TER scenario, assuming geopolitical barriers can be overcome on the long term by diplomatic means.

The following two chapters provide further details on the differences between the Ecofys report and the SEI and the STOA report, respectively.

## Stockholm Environment Institute (SEI)

The SEI has published a report titled *Metals in a Low-Carbon Economy: Resource Scarcity, Climate Change and Business in a Finite World (2012)* which examines the potential supply chain bottlenecks of five metals used in low-carbon technologies: cobalt, lithium, neodymium, indium and tellurium. The SEI report has been written as part of the partnership programme between the business leaders' initiative 3C (Combat Climate Change) and the SEI.

The SEI report uses scenarios from the International Energy Agency (IEA) *World Energy Outlook 2010* and the World Economic Forum (WEF) *Mining and Minerals Scenarios 2010* to make predictions on the development of supply and demand for these materials in the future. Within the project a scenario calculator has been developed, which was used to estimate the quantity of metals available in three different scenarios for 2008, 2020 and 2035.

The SEI reports the following results:

- Severe risk of medium and long term CSD (cumulative supply deficits) of indium and tellurium;
- Moderate risk of medium term and severe risk of long term CSD of neodymium; and
- Limited risk of long term CSD of cobalt and lithium.

This chapter explains the differences in these results compared with the Ecofys study on material bottlenecks for the TER scenario.

### Key differences

#### Differences in time span

As mentioned in the introduction, the calculations in the Ecofys study were made for 2050, whereas the calculations in the SEI study were made for 2035

#### Differences in scope

The SEI study has been limited to the following five materials: cobalt, lithium, neodymium, indium and tellurium. The Ecofys study has considered the material demand of all energy technologies as presented in the TER scenario and selected a limited number from a long list based on literature reviews and expert opinions. The difference in the amount of materials selected for further analysis, however does not explain the differences in outcome.

#### Differences in material demand and supply modelling

The SEI study has been comprehensive and included scenario development, stakeholder workshops and business and academic interviews. The scenario used by the SEI takes into account social, technological, economic, environmental and geo-political drivers that influence the metals and minerals markets. This includes



technology development, growth in mining, efficiency of use, innovation, metal uptake and recycling.

This allows for a more accurate calculation on the match of supply and demand, but also introduces more assumptions and uncertainties. In addition, the goal of the Ecofys study is to assess whether the absolute availability of materials is a problem for reaching the TER scenario for 2050, i.e. is it theoretically possible, assuming enough effort is aimed at reducing geopolitical, technological or economic constraints. For this reason these factors, including short and medium term supply constraints such as trade barriers and the start-up time of mining operations are not taken into account in the Ecofys study. This makes the results of both studies difficult to compare and might partly explain the different outcomes of the studies.

### Differences in technology deployment scenarios: thin film PV and wind turbines

The SEI study is based on three IEA scenarios, of which IEA 450 Scenario is most similar to the TER scenario. However, between these two scenarios, there are large differences in the implementation of renewable energy technologies and hence material demand over time. The scenarios also differ in assumptions on the percentage of PV containing indium and tellurium and on wind turbines containing neodymium.

The following table shows the global installed capacity for PV containing indium and tellurium and wind turbines containing neodymium in 2035 in the SEI study and for 2035 and 2050 in the Ecofys study. For the SEI values the 450 Economy Scenario was used and the upper limit was taken for the comparison, being both 20% for neodymium containing wind turbines and thin film photovoltaics containing indium and tellurium.

*Table 4*

Global Installed Capacity	SEI (450 Economy, upper limit)	Ecofys
PV containing indium and tellurium 2035 (GW)	150	729
Wind turbines containing neodymium 2035 (GW)	285	154
PV containing indium and tellurium 2050 (GW)		2,877
Wind turbines containing neodymium 2050 (GW)		478

As can be seen in this table, the deployment scenarios between the SEI and Ecofys study are quite different, although in the long run deployment in the TER is higher than for the SEI in 2035. This makes it unlikely that bottlenecks in the SEI study are caused by a higher deployment scenario.

### Differences in technology deployment scenarios: electric vehicles

For electric vehicles the deployment scenarios from the TER and the IEA 450 Economy differ greatly. The 450 economy scenario assumes a total of 93.5 million electric, hybrid and plug in electric vehicles by 2035. The TER scenario assumes

3.3 billion electric, hybrid and plug in electric vehicles in 2050. This explains why cobalt and lithium are considered limited bottlenecks in the SEI study but likely bottlenecks in the Ecofys study.

### Differences in material intensity of technologies PV and wind turbines

The following table contains the material intensity for indium and tellurium for PV and neodymium for wind turbines in the SEI and in the Ecofys study.

*Table 5*

Material intensity	SEI (kg/MW)	Ecofys (kg/MW) in 2009	Ecofys (kg/MW) in 2050
Indium for PV	110 – 2.5	12.5	3
Tellurium for PV	142 – 22	7.75	2
Neodymium for wind turbines	185 - 122	400	121

As can be seen in the table, the material intensity for the SEI study differs greatly, depending on whether a high efficiency or a low efficiency has been assumed.<sup>1</sup> In general, however, assumptions made by Ecofys for the material intensity of indium and tellurium for PV are lower than those made in the SEI study. This explains at least partly why indium and tellurium are considered bottlenecks in the SEI study but not in the Ecofys study. The differences for Neodymium are less pronounced and are not likely to account for much of a difference in the outcomes between the two studies.

### Differences in material intensity of technologies electric vehicles

In the Ecofys study, it is assumed that material demand for batteries for electric, hybrid and plug in electric vehicles is the same, namely 3.2 kg of lithium and 1.9 kg of cobalt. The use of neodymium in these vehicles is considered in the SEI study but not in the Ecofys study. In the SEI study a wide range is used for material demand for batteries, which are generally a bit higher than the assumptions made in the Ecofys study, as can be seen in the table below.

*Table 6*

	Electric vehicle	Hybrid electric vehicle	Plug in hybrid EV
Neodymium (kg)	0.5 - 0.25		
Cobalt (kg)	9.25 - 0	0.5 - 0.25	3.8 - 0
Lithium (kg)	12.5 - 3.25	0	5 - 1.5

The amount of cobalt and lithium required for electric vehicles is most likely not responsible for the fact that cobalt and lithium are considered a critical bottleneck

<sup>1</sup> Sources cited in the SEI study are USDOE (2010); Candelise et al. (2011); Speirs et al. (2011)

in the Ecofys study but not in the SEI study. The fact that the SEI study also takes the use of neodymium into account for electric vehicles, whereas the Ecofys study does not, however, could explain the difference in outcome between the two studies regarding whether or not neodymium is a bottleneck.

## Conclusions

The difference in the outcome between the SEI study and the Ecofys study is caused by the following factors:

- Since the Ecofys report looks at absolute bottlenecks (is enough material available to meet supply in the future), the SEI scenario looks for bottlenecks by identifying a (temporal) mismatch between supply and demand. For this, they take into consideration for example geopolitical and economic constraints. Since the definition of a bottleneck is different in both reports, the results, i.e. whether or not a material will be considered a bottleneck is different in both reports as well.
- A much larger deployment of electric vehicles in the TER Scenario than in the SEI Scenario is the reason why cobalt and lithium are considered potential bottlenecks in the Ecofys report, but not in the SEI report.
- A higher material intensity for indium and tellurium in photovoltaics in the SEI report compared to the Ecofys report is the reason by tellurium and indium are considered potential bottlenecks in the SEI report but not in the Ecofys report. This might be caused by a lack of technological learning in the SEI report. And in the end, in the Ecofys report, it is taken into account that a global sustainable energy supply can be realized without PV technologies relying on tellurium and indium.
- For neodymium, the SEI assumes a larger share of windmills containing neodymium in 2035. In addition, the SEI assumes that electrical vehicles will also include neodymium. This increased demand for neodymium might be why it is considered a bottleneck in the SEI scenario but not in the Ecofys scenario. At least for wind energy, neodymium use can be avoided by sticking to the conventional technology

## Science and Technology Options Assessment (STOA)

The Science and Technology Options Assessment (STOA) panel, which is a committee from the European Parliament, has published a report on “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 STOA uses scenarios from the European Photovoltaics Industry Association (EPIA) (2011) and the European Commission (2011) to calculate the metal demand for photovoltaics and wind turbines.

The results of their research states that the following eight materials might “seriously impact” the deployment of large scale photovoltaics and wind turbines: gallium, indium, selenium, tellurium, dysprosium, neodymium, praseodymium and terbium. This appears to differ from the results in the Ecofys study. In the following chapter, the reason for these differences will be explained. Since the STOA study only looks at material constraints for photovoltaics and wind turbines, only the differences in assumptions and calculations for PV and wind turbines will be explained in this chapter.

## Key Differences

### Differences in time span

The time span of the scenarios in the STOA study and of the TER scenario, used in the Ecofys study, is different. The STOA scenarios run up to 2030, whereas the TER scenario lasts until 2050. In addition, the STOA study looks at short and medium term bottlenecks, whereas the Ecofys study looks at long term bottlenecks for renewable energy technologies in TER.

The difference of 20 years between the two studies and the shift of focus on the long term for the TER scenario is an important reason for why STOA signals 8 bottlenecks for PV and wind turbines whereas these are not considered significant in the Ecofys study.

### Differences in scope

This Ecofys study has looked at a very wide range of technologies as presented in the TER scenario. The STOA has limited its focus on photovoltaics (PV) and wind turbines. Due to the large number of technologies in TER, Ecofys has selected only a limited number of materials for further analysis for PV and wind turbines, based on literature reviews and experience with the TER scenario. The selected materials for PV are silver, gallium, indium and tellurium and for wind turbines neodymium and yttrium. This selection is not all inclusive and ignores several of the materials that the STOA has taken into account. A comparison between these materials is therefore not possible.

In addition, as is the case with the SEI study, the STOA study looks at short and medium term bottlenecks and also takes into account the usage of scarce materials for other applications than PV and wind turbines. The Ecofys study, however, looks at long term ‘absolute’ bottlenecks which occur when there is simply not enough of the material present on earth to satisfy demand. This is likely factor in explaining why the STOA study considers certain elements supply chain bottlenecks whereas the Ecofys study does not.

### Differences in material supply modelling

Since the STOA study and the Ecofys study use many similar sources for the global production of materials, namely the USGS (2012) and the DOE (2010), these figures are quite comparable as can be seen in the table below. Differences are caused by

using figures from different years, but do not affect the outcomes of the study much. The production figures used by STOA and Ecofys can be found in the following table:

*Table 7*

Material	STOA production figures (tonnes)	Ecofys production figures (tonnes)
Gallium	106	216
Indium	574	640
Selenium	3,500	2,000
Tellurium	500	At least 115
Dysprosium	1,337	1,377
Neodymium	21,307	21,307
Praseodymium	6,292	6,292
Terbium	252	252
Silver	22,200	23,800

### Differences in technology deployment scenarios

There are a couple of differences between the deployment scenarios used in the STOA study in the Ecofys study. The following table shows the deployment scenarios for PV and wind turbines from the STOA study and the TER scenario:

*Table 8*

Global Installed Capacity	STOA	Of which thin film/ permanent magnet turbines (maximum)	Ecofys
PV 2030 (GW)	184 – 1036 - 1330	439	503
Wind turbines 2030 (GW)	595 – 1733 - 2241	560	101
PV thin film 2050 (GW)	-		2,877
Wind turbines containing rare earths 2050 (GW)	-		531

The modelling scenario for wind turbines as used by the STOA assumes 25% of wind turbines will be permanent-magnets containing rare earth elements. In the TER scenario, it is assumed that only 10% of offshore wind turbines in 2050 contain permanent magnets containing rare earths. This results in a large difference of deployed wind turbines containing rare earths, even though the longer timespan in the TER scenario compensates for this difference (560 GW from STOA in 2030 compared with 531 GW from Ecofys in 2050). This factor is therefore not likely to have caused a difference between the outcomes of the two studies.

The amount of thin film in 2030 in the STOA scenario is quite similar to the amount of thin film in 2030 in the Ecofys study. For 2050, however, which is the year that calculations are based on in the Ecofys study, the amount of thin film is a lot larger than in the 2030 STOA scenario (2,877 vs. 439). This difference therefore does not explain the difference in outcome of the two studies, since the deployment is larger in the Ecofys study, which should make a bottleneck more likely instead of less likely.

### Differences in material intensity of technologies

For the material intensities used in the STOA and the Ecofys study, different sources are used and the figures are quite different. In addition, from the STOA publication, it does not become clear that a progress ratio has been taken into account. For the TER scenario, this has been the case, resulting in a significant drop in the material density up to 2050, as can be seen in the table below.

Table 9

Material intensity	STOA (kg/MW)	Ecofys (kg/MW) in 2009	Ecofys (kg/MW) in 2050
Gallium	6.17	22	5
Indium	5.32 – 7.95 – 83.79	12.5	3
Tellurium	90.38	7.75	2
Silver	5.17	72	15
Neodymium	19.6 – 171.5	400	121
Yttrium	-	27	8

Although the drop in material intensity in the Ecofys study might look like much, bear in mind that this encompasses a time span of more than 4 decades. The difference in material intensities, especially for indium and tellurium, accounts for a large share of the difference between the Ecofys study and the STOA study.

### Assumptions on substitution

The STOA claims that “material substitution possibilities are very limited and that technology substitution options are moderately available” (Executive Summary p.2). In the TER scenario, however, at least four different PV technologies are mentioned and the majority of wind turbines still consist of conventional gearboxes without the use of rare earths. This difference in assumptions can explain why the STOA study considers some materials bottlenecks whereas the Ecofys study does not.

### Conclusion

The differences between the STOA study and the Ecofys study are caused by the following factors:

- The difference in scope of the two studies: The Ecofys study looks at 2050 and considers a material a bottleneck when there simply isn't enough material on earth to satisfy future demand. The STOA study, on the other hand, looks at 2030 and considers a material a bottleneck when there is a temporary mismatch

in supply and demand, which can be caused by for example trade restrictions, natural disasters or economic constraints. This means that the definition of a bottleneck is different in both studies and therefore also in the outcome.

- The fact that the STOA study also takes the material demand for other purposes into account when looking for a mismatch between supply and demand can explain why some materials are considered bottlenecks in the STOA report but not in the Ecofys report. Looking at the long term and assessing absolute bottlenecks, the usage of materials for other purposes is not relevant in the Ecofys study.
- Differences in the material intensities for thin film PV are an important factor in the different outcomes of the study.
- The STOA study claims that very limited substitution is possible for PV and windmills, whereas the Ecofys report considers at least four different types of PV technologies and three different types of wind turbines (conventional, direct drive and superconductive). This means that for the materials involved in these technologies, bottlenecks are more likely to occur in the STOA report than in the Ecofys report.

## General Conclusion

Both the SEI study and the STOA study claim different bottlenecks are likely to occur in the future compared with the Ecofys study. These different outcomes are mainly due to the different scope and timespan of the studies and differences in material densities for the renewable energy technologies. Other important factors are whether or not substitution is possible and whether material demand for other technologies is considered relevant for bottlenecks to occur.

Especially, it should once more be stressed that certain bottlenecks flagged in the SEI and STOA studies can be overcome by choosing the right technology, i.e. silicon based solar cells and conventional wind turbines.

In spite of the different results with regards for potential future material bottlenecks, the recommendations from both studies are considered equally valid for the analysis made in the Ecofys study. No matter which assumptions and which scenarios are considered, the need for a comprehensive, transparent and long term material strategy is evident, as is the need for additional cooperation between governments and additional research efforts for mitigation options such as recycling and substitution.

# RESULTS OF THE CALCULATIONS

## APPENDIX D

**Table 10** Figures for the material demand calculations for photovoltaics and wind energy, including the installed capacity, material intensity, progress ratio and the resulting maximum annual material demand and the cumulative annual material demand until 2050.

Technology	Materials	Cumulative capacity (EJ)	Maximum installed capacity (GW)	Maximum capacity increase per year (GW)	Material intensity 2009 (tonnes/GW)	Progress ratio	Maximum annual material demand (Mtonnes)	Cumulative annual material demand until 2050 (Mtonnes)
Photovoltaics	Silver	37	7193	494	126	0.85	8,100	140,000
	Gallium	37	7193	494	22	0.85	2,500	42,000
	Indium	37	7193	494	12.5	0.85	1,400	24,000
	Tellurium	37	7193	494	7.75	0.85	870	15,000
Wind	Neodymium	6.7	478	25	400	0.85	3,100	74,000
	Yttrium	0.7	53	3	27	0.85	23	560

**Table 11** Figures for the material contents per battery for electric vehicles, the maximum amount of vehicles and the maximum annual increase in vehicles.

Material contents per battery (kg)	Maximum amount of vehicles (million)	Maximum annual increase in vehicles (million)
3.2	3,400,000	470,000
1.9	3,400,000	470,000



**Table 12** Figures for the material demand calculations for lithium and cobalt in batteries for electric vehicles, including production, reserves and resources, the maximum annual material demand and the cumulative annual material demand until 2050.

Technology	Materials	Production 2011 (Mtonnes)	Reserves 2011 (Mtonnes)	Resources 2011 (Mtonnes)	Maximum annual material demand (Mtonnes)	Cumulative annual material demand until 2050 (tonnes)
Electric vehicles	Lithium	0.034	13.000	30.000	0.300	11.000
	Cobalt	0.098	7.500	15.000	0.180	6.300

**Table 13** Figures used for calculating the material demand for energy efficient lighting, including the maximum of built passive area, the maximum increase in built passive area and the amount of LEDs per square meter.

Maximum amount built passive area (million m <sup>2</sup> )	Maximum annual increase in built passive area (million m <sup>2</sup> )	Amount of LEDs per square meter
460,000	16,000	1

**Table 14** Figures used for calculating the copper demand of solar and wind energy, including cumulative capacity, maximum installed capacity, maximum capacity increase per year, material intensity, progress ratio and the resulting materials required for maximum capacity increase and materials required for total capacity in 2050.

Technology	Cumulative capacity (EJ)	Maximum installed capacity (GW)	Maximum capacity increase per year (GW)	Material intensity 2009 (tonnes/GW)	Progress ratio	Materials required for maximum capacity increase in one year (Mtonnes)	Materials required for total capacity 2050 (Mtonnes)
Crystal photovoltaics	22	4,300	300	3,900	85	0.26	4.4
Thin film photovoltaics	15	2,900	200	3,100	85	0.14	2.3
Concentrating solar power	22	3,000	160	4,000	100	0.65	12.0
Onshore wind turbines	25	2,800	95	2,000	100	0.19	5.6
Offshore wind turbines	7	530	28	2,000	100	0.06	1.1

**Table 15** Figures used for the comparison of indium and gallium demand for energy efficient lighting with production, reserves and resources for indium and gallium in 2011. Also includes maximum annual material demand and cumulative annual material demand until 2050.

Technology	Materials	Production 2011 (tonnes)	Reserves 2011 (tonnes)	Resources 2011 (tonnes)	Demand per LED (mg/LED)	Maximum annual material demand (tonnes)	Cumulative annual material demand until 2050 (tonnes)
Energy efficient lighting	Indium	640	NA	NA	0	3	78
	Gallium	220	NA	1,000,000	1	9	240

**Table 16** Results of the calculations for the maximum annual and cumulative copper demand for additional electricity infrastructure, solar and wind energy and energy efficient electrical motors.

Sectors of copper demand	Materials required for maximum capacity increase in one year (Mtonnes)	Materials required for total capacity 2050 (Mtonnes)
Additional electricity infrastructure	0.6	24.0
Renewable energy (photovoltaics, CSP, on- and offshore wind)	1.0	25.0
Energy efficient electrical motors	0.02	0.4

## WWF

WWF is one of the world's largest and most experienced independent conservation organisations, with over 5 million supporters and a global network active in more than 100 countries. WWF's mission is stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, by conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

The Global Climate & Energy Initiative (GCEI) is WWF's global programme addressing climate change and a move to 100% renewable energy through engagement with business, promoting renewable and sustainable energy, scaling green finance and working nationally and internationally on low carbon frameworks. The team is based over three hubs – Mexico, South Africa and Belgium.

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## Ecofys

Established in 1984 with the mission of achieving “sustainable energy for everyone”, Ecofys has become the leading expert in renewable energy, energy & carbon efficiency, energy systems & markets as well as energy & climate policy. The unique synergy between those areas of expertise is the key to its success. Ecofys creates smart, effective, practical and sustainable solutions for and with public and corporate clients all over the world. With offices in Belgium, the Netherlands, Germany, the United Kingdom, China and the US, Ecofys employs over 250 experts dedicated to solving energy and climate challenges.

[www.ecofys.com](http://www.ecofys.com)

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# CRITICAL MATERIALS

100%  
RECYCLED



## TELLURIUM, INDIUM AND GALLIUM

These are three critical materials of greatest importance for thin film photovoltaics.

## COPPER

Copper is a main component of electricity distribution networks. Copper is used in renewable energy technologies such as wind and solar energy but also in transformers and motors. It is not critical for one particular technology but for the system as a whole.



## COBALT AND LITHIUM

Demand for lithium, a major component in batteries for electric vehicles, is expected to increase rapidly and is widely regarded as a key bottleneck for the large scale introduction of electric vehicles. Cobalt is another important component of lithium ion batteries; it is also used for making super alloys and in wind turbines.

## RARE EARTHS

Rare earths are used for magnets in wind turbines and demand compared to supply, reserves and resources are such that no bottlenecks are expected.



### Why we are here

To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

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