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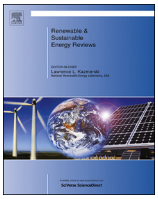

Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables

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ABSTRACT

The German government has set itself the target of reducing the country's GHG emissions by between 80 and 95% by 2050 compared to 1990 levels. Alongside energy efficiency, renewable energy sources are set to play the main role in this transition. However, the large-scale deployment of renewable energies is expected to cause increased demand for critical mineral resources. The aim of this article is therefore to determine whether the transformation of the German energy system by 2050 ("Energiewende") may possibly be restricted by a lack of critical minerals, focusing primarily on the power sector (generating, transporting and storing electricity from renewable sources). For the relevant technologies, we create roadmaps describing a number of conceivable quantitative market developments in Germany. Estimating the current and future specific material demand of the options selected and projecting them along a range of long-term energy scenarios allows us to assess potential medium- or long-term mineral resource restrictions. The main conclusion we draw is that the shift towards an energy system based on renewable sources that is currently being pursued is principally compatible with the geological availability and supply of mineral resources. In fact, we identified certain sub-technologies as being critical with regard to potential supply risks, owing to dependencies on a small number of supplier countries and competing uses. These sub-technologies are certain wind power plants requiring neodymium and dysprosium, thin-film CIGS photovoltaic cells using indium and selenium, and large-scale redox flow batteries using vanadium. However, non-critical alternatives to these technologies do indeed exist. The likelihood of supplies being restricted can be decreased further by cooperating even more closely with companies in the supplier countries and their governments, and by establishing greater resource efficiency and recyclability as key elements of technology development.

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1. Introduction

Major reductions in greenhouse gas (GHG) emissions will be necessary in the coming decades in order for the global community to avoid the most dangerous consequences of human-caused global warming [1]. In Germany, the federal government has set itself the target of reducing the country's GHG emissions by between 80 and 95% by 2050 compared to 1990 levels [2]. To achieve this target, the energy system will inevitably need to be transformed. Alongside energy efficiency, renewable energy sources are set to play the main role in this transition. One example is the power sector, where the government seeks to meet 80% of gross electricity demand from renewables by 2050 [2].

In recent years, there have been intense discussions about the impact of a large-scale transformation of the energy system on resource demand [3–10]. The literature places a strong emphasis on minerals that are thought to be particularly scarce or “critical”, such as rare earth elements (REE). Several studies analysed photovoltaic (PV) technology, and came to the conclusion that the manufacture of some types of PV modules (above all, thin film) would probably be faced with resource constraints if deployed on a large scale [3–5]. Habib and Wenzel [7] evaluated the REE neodymium and dysprosium. The authors found that, while geological reserves were unlikely to be depleted for several centuries, a much higher extraction rate would be required in the future to meet expected demand for wind turbines, electric vehicles and other technologies. Some studies point out that alternative technologies that are reliant on more abundant resources exist for a number of renewable energy technologies that require critical minerals [3,4,8]. A number of studies stress the potential benefits of recycling critical minerals, as recycling can reduce primary resource requirements, at least in the longer term [5,7,9,10]. However, to our knowledge, no studies have systematically quantified and assessed the long-term need for critical minerals required for the deployment of renewable energy sources in an industrial country aiming to decarbonise its energy system.

This article is organised as follows: Section 2 describes the research question and an overview of the methods used. Section 3 identifies and quantifies plausible ranges for the critical mineral needs of the German power sector. This is followed by Section 4, in which the availability of the minerals identified is assessed. Finally, the results are discussed in Section 5, whilst Section 6 concludes the paper.

2. Methodology

Considering the issues that have not yet been addressed in the literature, this article aims to provide a preliminary answer to the following research question: Will the intended transformation of the German power sector (including generation, transport and storage of electricity from renewable sources) be restricted by a lack of critical minerals? We use several methods to answer this research question.

(1). In the first step, we conduct a meta-analysis of 12 existing studies on critical minerals in order to learn which, and how often, elements and minerals have been identified as “critical” in previous studies. We then screen all renewable energy technologies referred to in existing energy scenarios in Germany that are expected to be used in the decades ahead to determine whether they require any of the critical minerals identified. This enables us to narrow down the subsequent technology development and roadmap analysis to a limited number of technologies. Screening, which also includes infrastructure such as electricity storage and grids, is based on our expert knowledge and a literature analysis. We classify the technologies as “relevant”, “potentially relevant” and “non-relevant”. “Relevant” means that a technology requires a mineral that has been rated as critical in more than two studies. “Potentially relevant” means that the technology either contains an element or a mineral that has been rated as critical in one or two studies or that the future development of that technology could necessitate the use of such minerals. In the succeeding steps, only “relevant” and “potentially relevant” technologies are considered further. For the technologies classified as “non-relevant”, we abstained from a detailed analysis.

(2). The technologies classified as being “relevant” are analysed in terms of their potential long-term development based on a combination of our expert knowledge, a literature review and expert interviews. However, the demand for mineral resources in future energy systems depends strongly on the particular technologies that will actually be deployed. For this reason, we initially create roadmaps describing a number of conceivable quantitative market developments in Germany. We then estimate the current and future specific material demands of the technology options selected. In this paper, demand refers to the quantity of the material at the production site (from regional storage), including material losses due to further processing.

(3). For technologies classified as “potentially relevant” we determine the cumulated demand of the elements and minerals identified that is required to realise the most ambitious energy scenarios. If this demand is found to be sufficiently low compared to overall global demand, we downgrade the technology to “non-relevant”, otherwise we upgrade it to “relevant” and proceed as outlined in step 2.

(4). In order to identify future needs for new capacities of “relevant” technologies, we conduct a meta-analysis of nine different long-term energy scenarios created in recent years for the energy supply system in Germany. A range of conceivable future deployment levels until 2050 is derived, differentiating between three pathways: “low”, “medium” and “high”. This enables mineral resource restrictions to be considered depending on different deployment levels of renewable energy technologies.

(5). The market shares of the “relevant” technologies outlined in step 3 are combined with the future need for new plant capacities and their specific material consumption over time (step 2), enabling us to determine the cumulative material demand by 2050.

(6). In the final step, we aim to assess the availability of the critical minerals identified. This assessment is based on the proportion of Germans in the world population, which we assume will remain close to the current level of around 1%. We apply

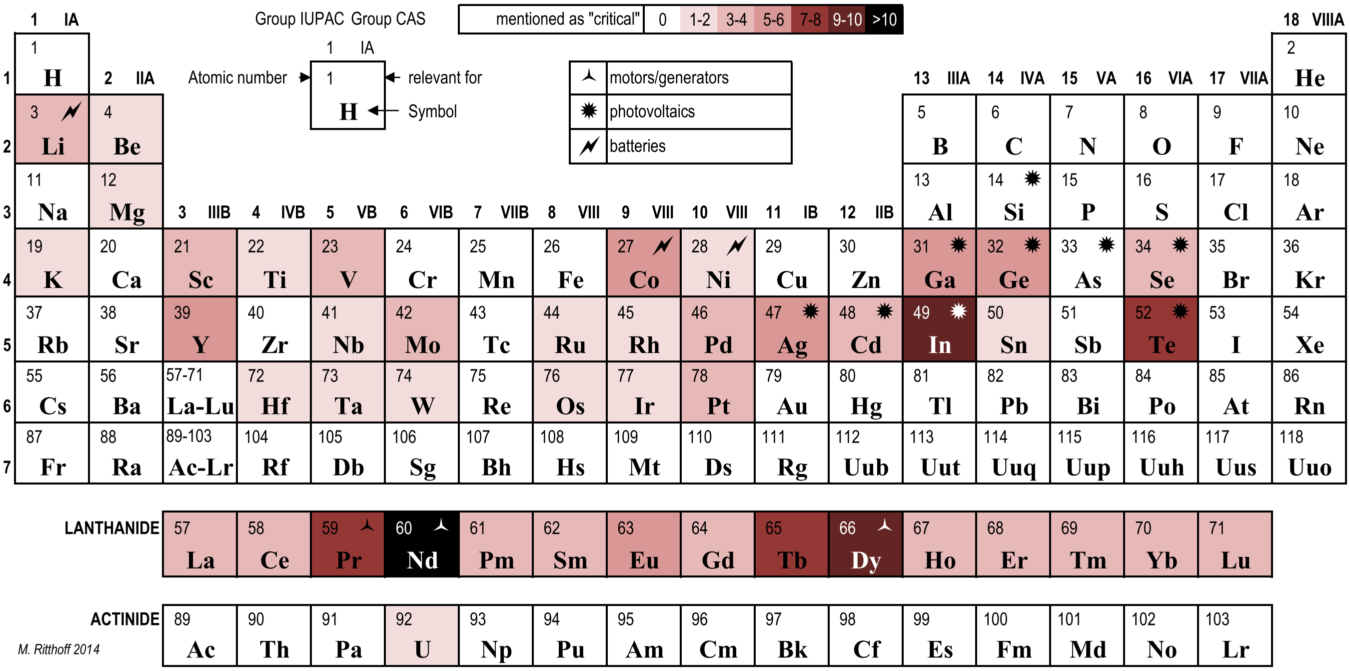

Fig. 1. “Criticality” and usage of elements according to an evaluation of 12 studies.

> this share in a budget approach as originally developed for climate policy to define fair national emission reduction targets. By analogy to the proposal that each nation should have the right to emit a share of GHG from the totally available global emission “budget” that corresponds to its global population share [11], Germany would be allowed – in a rough approximation – to use 1% of the world's reserves. Following such an equity distribution approach is in contrast to an alternative approach of allocating available resources to a country according to its economic power (or GDP). We chose the equity distribution approach to recognise that the need for specific resources does not necessarily correlate with the level of GDP. Furthermore, we also prefer to base our conclusions on pessimistic rather than on optimistic assumptions about the future availability of resources for the German energy transition, assuming hat Germany's allowed resource use would be higher if per capita GDP were chosen, as Germany has and will likely continue to have a per capita GDP which is above the global average.

We perform the analysis in two steps. First, for each identified material we compare the required cumulated quantity calculated above with the current annual global extraction volume. If the demand exceeds 40% one annual global extraction (40% being the assumed budget of 1% allocated for Germany over 40 years, the timeframe of our scenarios), it cannot be covered in compliance with the German budget under the assumption of constant annual extraction rates. In this case, we proceed with the second step described below. If less than 40% of one annual global extraction is needed, we assess by expert judgement whether this share is low enough to allow other technologies (such as electric cars) to meet their demand for the respective material.

For materials that proved to be critical in the first step, we additionally compare the required cumulated quantity with its global reserves. Basically, a high share of the reserves should be allocated to renewable energy technologies, since their massive global deployment can be regarded as highly important for future human welfare, as it is widely seen to be a key element in preventing the most dangerous consequences of global warming [12,13]. However, there is a high degree of uncertainty surrounding the assessment of reserves regarding, for example, production costs, the quality of storage sites, mining productivity or environmental constraints. In the first approximation, we therefore assume that only 10% of the global reserves will be available for renewable energy deployment, which – according to the budget approach – results in 0.1% of the expected global reserves allocated to renewable energy technologies in Germany. In a sensitivity analysis, we also consider an availability of 50% of the global reserves for renewable energies worldwide, corresponding to 0.5% of the global reserves for Germany.

3. Evaluation of critical minerals in renewable energy technologies

3.1. *Screening technologies*

In order to obtain a rough overview of potentially critical minerals, we analysed 12 studies [14–25]. Fig. 1 shows the frequency of studies that classified an element or a mineral as being “critical”. The more intensive the colour, the more studies highlighted the criticality of that mineral. Furthermore, we illustrate the main fields of application (motors/generators, photovoltaics and batteries) for the minerals that are often considered to be critical. For example, neodymium, mainly used for motors and generators, was labelled critical in more than ten studies.

Table 1 illustrates the qualitative expert screening of technologies for renewable electricity production, storage and transmission. The first three columns define the technology groups and their sub-technologies. Column 4 illustrates the main potentially critical element or mineral resource and the field of application. The classification in the last three columns is the result of assessing these resources with their “criticality” as given in Fig. 1. For example, we assess PV thin film technology as “relevant” since the minerals listed were classified as being “critical” in several of the analysed studies. Further technologies that are identified as “relevant” are onshore and offshore wind. These “relevant” technologies are analysed further in Section 3.2.

Table 1
Qualitative expert screening of renewable electricity production, storage and transmission technologies.

Energy source	**Technology**	**Sub-technology**	**Main potentially critical element/ mineral resources and field of application**	**Preliminary classification as a result of combining with Fig. 2**		
				"relevant" → **Section** 3.2	**"potentially-relevant"** → **Section** 3.3	**"non-relevant"**
Electricity generation						
Solar	Solar PV (photovoltaics) roof-top, ground-mounted, building-integrated	Crystalline	Ag (contact layer), but quantitatively not relevant and replaceable			X
		Thin film, CdTe	In, Ga, Se (absorber, buffer layer, TCO substrate), CdS (buffer layer) *****	X		
		Concentrating PV	See crystalline cells			X
		Organic PV	–			X
		Electrochemical PV	SnO_2 (semiconductor of dye-sensitised solar cells)			X
	Concentrating solar power (CSP) **	Parabolic trough, solar tower	Ag (mirrors)		X	
			$NaNO_3+KNO_3$ (thermal storage)		X *	
			Cu (wires)			X
			Cer (mirror production process)			X
			Ni, V (ferrous alloy)		X	
Wind	Wind power station	Onshore, offshore	Nd, Dy, Pr, Tb (permanent magnet)	X		
			Ni, Mo (ferrous alloy)		X	
Water	Hydropower	Run-of-river plant				X
Geothermal		Organic rankine Cycle (ORC)	Ni, V (ferrous alloy)		X	
Biomass ***	Combustion	Steam power plant, combined heat and power, ORC, Stirling				X
	Gasification ****		Ni, V (catalyst)		X	
	Fermentation ****		P (dedicated energy crops)			X
	Esterification ****		P (dedicated energy crops)			X
Electricity storage						
	Pumped hydro		Ni, V (ferrous alloy)		X	
	Compressed air energy storage (CAES)	Diabatic (CAES)				X
		Adiabatic (A-CAES)	Ni, V (ferrous alloy)		X	
	Hydrogen storage	Alkaline electrolysis	Ni (catalyst, electrical distribution)		X	
		H_2 storage				X
		Fuel cell	La, Y, Sc, Ni (SOFC)		X	
	Batteries (stationary)	Lithium-ion	Li		X	
		Redox flow	V (electrolyte)		X	
Electricity transmission						
	High-voltage alternating current (HVAC)	380 kV overhead line	Ni, V (ferrous alloy)		X	
	High-voltage direct current (HVDC)	HVDC overhead line	Ni, V (ferrous alloy)		X	

* Not derived from Fig. 2 but analysed additionally.

** CSP is not suitable for application in Germany, but several energy scenarios assume the import of CSP-based electricity from southern countries.

*** Producing intermediate products such as synthetic gas, biogas, bio-methane, vegetable oil and bio-diesel.

**** Regarding the assessment of dedicated energy crops, it should be pointed out that only mineral resources have been analysed. The availability of biomass itself and the associated problems, especially with regard to competing demand for land and biomass use [95,96], were not included in the scope of this study.

***** In addition, Ge is used in GaAs-Ge cells. These cells are neglected here because they will only be used in special appliances such as in space flights.

Table 2
Development of photovoltaics commissioned in Germany from 2010 to 2012 in per cent, based on [49].

	2010	**2011**	**2012**
Newly commissioned capacity of all plant types	100	100	100
of which crystalline	91	94	97
of which thin film	9	6	3
of which CdTe	61	59	44
of which CIGS	13	22	25
of which a-Si/μ-Si	26	19	31

Technologies classified as *"potentially relevant"* can be grouped into two categories: those that use ferrous alloys (wind power, concentrating solar power (CSP), geothermal power, pumped hydro, biomass gasification, adiabatic-compressed air energy storage (A-CAES) and power transmission lines) and those in which minerals represent the main part of the technology (CSP and storage options). In Section 3.3 we analyse whether we need to downgrade these technologies to "non-relevant" or upgrade them to "relevant".

3.2. Future technological and market developments of "relevant" technologies

3.2.1. Photovoltaics

3.2.1.1. Roadmaps. A status quo analysis of the German PV market serves as a starting point for the roadmapping process. It incorporates the market shares of different installation concepts (roof-top, ground-mounted, building-integrated) which in turn influence the choice of cell types (crystalline, thin film). While both mono- and poly-crystalline cells consist mainly of (non-critical) silicon and therefore merely contain negligible amounts of relevant resources, thin film cells need to be further classified according to their absorber layers and transparent conductive oxides (TCO). In line with the state of the art of thin film technologies [26], a differentiation is made between amorphous

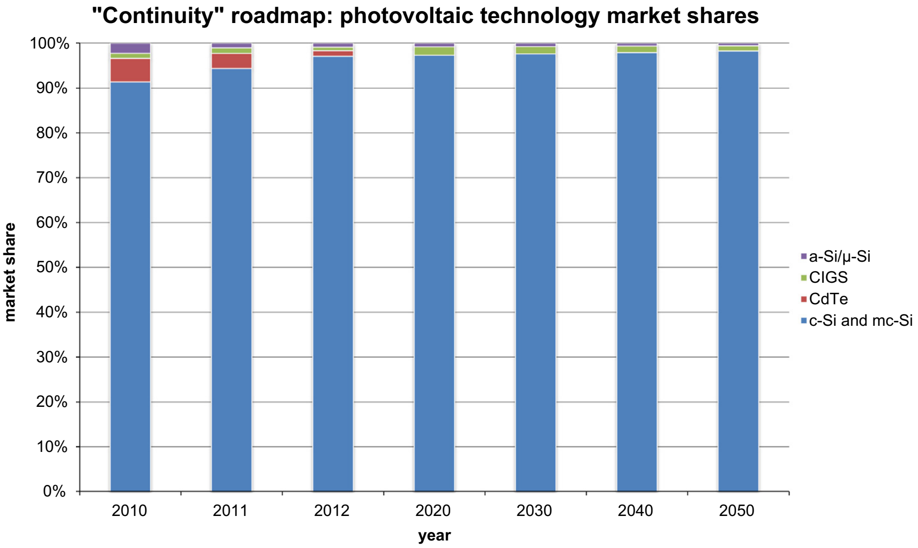

Fig. 2. Assumptions for long-term market share development of photovoltaic cell technologies within the roadmap “continuity” roadmap (past market data based on [49]).

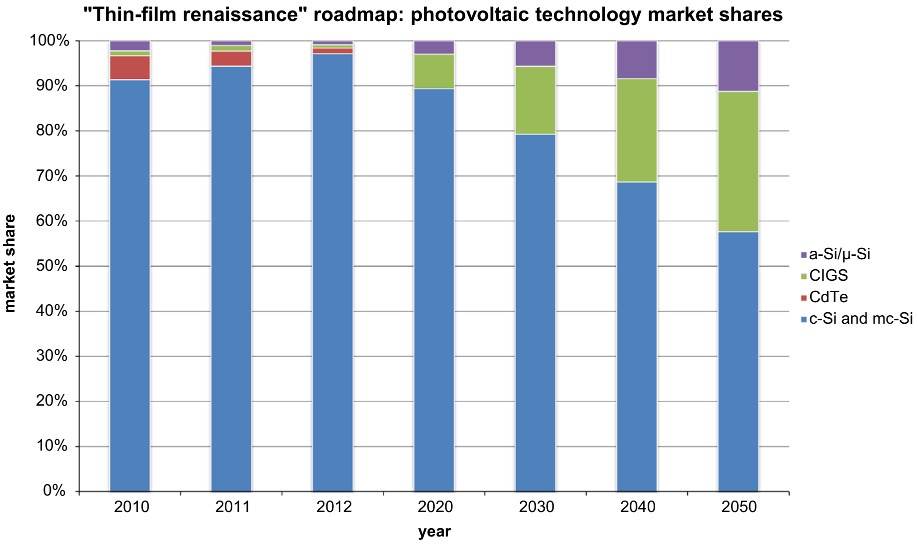

Fig. 3. Assumptions for long-term market share development of photovoltaic cell technologies within the roadmap “thin film renaissance” roadmap (past market data based on [49]).

and micromorphous silicon (a-Si and µ-Si), cadmium-telluride (CdTe) and copper-indium-gallium-diselenide (CIGS) cells. For the period from 2010 to 2012, Table 2 shows the market shares of different cell types in Germany as a percentage of total annual photovoltaics commissioned, taking into account all three installation concepts mentioned above.

It appears that thin film cells, which already had little market significance in 2010, have become less important over time, providing merely 3% of new PV installations in 2012. Within this small segment, the market data indicates a shift of absorber materials from CdTe to CIGS and a-Si/µ-Si. The extrapolation of the current PV market up to 2050 is not based on existing scenarios because existing studies have tended to overestimate the market significance of thin film PV over the past few years or have analysed global developments instead of explicitly referring to the German market [27,28]. Instead, we define a possible bandwidth of the future PV market in Germany by developing our own two roadmaps, “continuity” and “thin film renaissance”.

The *“continuity” roadmap* assumes a continuing market dominance of crystalline PV. It describes a market based mainly on small and medium-sized rooftop plants. In accordance with the current market situation, these plants are assumed to use crystalline PV technology, while thin film modules remain a niche product due to their higher demand for space and higher balance of system costs [29]. The annual market shares of newly commissioned cell types in Germany within the “continuity” roadmap are displayed in Fig. 2.

The *“thin film renaissance” roadmap* assumes a trend towards large rooftop and ground-mounted plants. For these types of PV plants, space restrictions are less important than for smaller rooftop plants. Consequently, market shares of thin film PV modules increase, attaining 42% in 2050. Fig. 3 shows the market shares of cell types within this roadmap. Assumed future developments of the thin film segment are in line with recent market shares (Table 2): an extrapolation of the decreasing importance of CdTe modules leads to a market phase-out of this technology by 2018. Apart from recent market statistics, this development is backed by further indications, including low efficiency [30], public discussions on toxicity issues [31] and the absence of collaborative research projects at the EU level [29]. We further assume that

Table 3
Advancement in absorber thickness and module efficiency of photovoltaic cells

Cell type	Characteristic	Unit	Source	2013		2025		2050	
				This study	Literature	This study	Literature	This study	Literature
CIGS	Thickness	[μm]	[29]	3	2–3	2	n. s.	1	(< 1.0)
	Efficiency	[%]	[29,43]	12	10–12	18	14–20	25	18–25 and more
	Overall technology development		Based on [33]					no CdS, no ITO TCO	
CdTe	Thickness	[μm]	[29]	1.8	1.8	1.0	1.0	1.0	1.0
	Efficiency	[%]	[29-43]	14	9–14	15	12–18	18	16–22
	Overall technology development		Based on [33]					no CdS, no ITO TCO	
a-Si	Overall technology development		Based on [33]			no ITO TCO		no ITO TCO	

n.s. = not specified
CdS = cadmium sulphide buffer layer, ITO TCO = transparent conductive oxide of indium tin oxide

Table 4
Current and future demand for critical raw minerals in photovoltaic cells (kg/MW$_P$)

Cell type	Raw material	2013	Source	2025	2050
CIGS	Indium	55.5	[16],[29]	45.0	3.0 *
	Cadmium	1.3	[33]	1.3	0 ***
	Gallium	7.2	[16],[29] **	3.2	1.2
	Selenium	39.3	[33]	17.4	6.3
CdTe	Tellurium	99.7	[16],[33] **	43.1	35.3
	Cadmium	116.7	[33]	63.8	33.0 ***
	Indium	15.5	[16],[29]	15.5	0 *
a-Si	Indium	4.0	[16]	0 *	0 *

* no ITO TCO
** the mean value of both sources is taken
*** no CdS buffer

market shares of CdTe will be taken over by CIGS (instead of a-Si), which can be regarded as a worst-case estimate regarding critical materials.

3.2.1.2. Current and future material consumption. Potentially critical minerals in thin film technology are indium (In), gallium (Ga), selenium (Se), cadmium (Cd) and tellurium (Te). Table 4 illustrates the specific demand for these minerals for the current (2013) and future situation (2025, 2050). We derive the *current* material demand from a review of life cycle assessment (LCA) and life cycle inventory (LCI) studies [32–39], studies focusing on material constraints and their economic consequences [22,40,41] and studies on current and future raw material consumption [16,29,42]. One specific value is selected for each mineral of each cell type out of the full range of literature values. Criteria for selection are topicality (year of publication and reference year of datasets) and plausibility (data is revisable in terms of basic cell and module information). The (single) data that fits both criteria best is selected for further data processing. If two pieces of data are equally good, the arithmetic mean is calculated. If no data fits at least one criterion, study [16] is selected from the studies under consideration, since in terms of scope and approach this source is similar to the study at hand. Its data is based on manufacturer consultation and preliminary studies.

We select data for layers of TCO separately because the amount of indium in indium tin oxide (ITO) correlates highly to the TCO thickness. We choose a certain specific amount (g/μm) from the existing data and then dimension the layer according to the presumed TCO layer thickness for each cell type. Thus, a possible substitution of ITO TCO by other non-indium TCO reduces the overall demand of indium in cell types.

We calculate the *future* material demand as given in the formula by assuming improvements on both the input side, based on a reduction of the absorber thickness, and the output side, based on an increase in module efficiency. Table 3 depicts the figures estimated for the current (2013) and future situation (2025, 2050). The data selected is based on the technology development outlined in [29,43]. It was not possible to incorporate other parameters such as changes in material composition.

$$FD_i = \frac{\left(\frac{FT_c}{CT_c}\right)}{\left(\frac{FE_c}{CE_c}\right)} CD_i$$

where FD_i: Future demand for material i [kg/MW$_P$]
CD_i: Current demand for material i [kg/MW$_P$]
FT_c: Future absorber thickness of cell type [μm]
CT_c: Current absorber thickness of cell type [μm]
FE_c: Future module efficiency of cell type [%]
CE_c: Current module efficiency of cell type [%]

The absorber thickness for CIGS is assumed to decrease linearly from 3 μm [29]. In the light of recent price declines for crystalline PV cells, we assume that thin layer PV cells will only succeed on the future market in the event of a considerable increase in efficiency, so optimistic module efficiencies are used for both cell types. Further developments concern the use of CdS for buffer layers in CIGS and CdTe cells and ITO for the TCO ("overall technology development" in Table 3). Since a-Si cells without ITO TCOs already exist on the market [33], we assume that ITO TCOs are not obligatory and will no longer be used in the future due to raw material constraints.

3.2.2. Wind power

3.2.2.1. Roadmaps. In line with the methodology applied for PV, the roadmapping process for wind power is based on an analysis of the recent market situation in Germany. The roadmaps take into account the market shares of different types of generator technologies (synchronous or asynchronous), the type of excitation (permanent or by electricity) and the type of gear unit (high speed, middle speed or direct drive) as given in Table 5.

Since the market distribution may differ noticeably between onshore and offshore wind power, both market segments are treated separately. The analysis of the recent *onshore wind power* market is based on data comprising the annual commissioning of wind power capacity by manufacturer and plant type [44] covering the period from 2009 to 2012. Further statistical data from 2007 to 2008 is included in some evaluations below in order to highlight certain market development trends. Fig. 4 depicts the shares of different generator types in annual wind power commissioned between 2007 and 2012, illustrating a remarkable decline in the market share of asynchronous generators from 50% in 2007 to a

Table 5
Current generator types in the German wind power plant mix.

Acronym	Excitation	Generator type	Drive
AG	Electrically excited (E)	Asynchronous (AG)	Gear, high speed (HS)
SG-E-DD	Electrically excited (E)	Synchronous (SG)	Direct drive (DD)
SG-PM-HS	Permanent magnet (PM)	Synchronous (SG)	Gear, high speed (HS)
SG-PM-MS	Permanent magnet (PM)	Synchronous (SG)	Gear, middle speed (MS)
SG-PM-DD	Permanent magnet (PM)	Synchronous (SG)	Direct drive (DD)

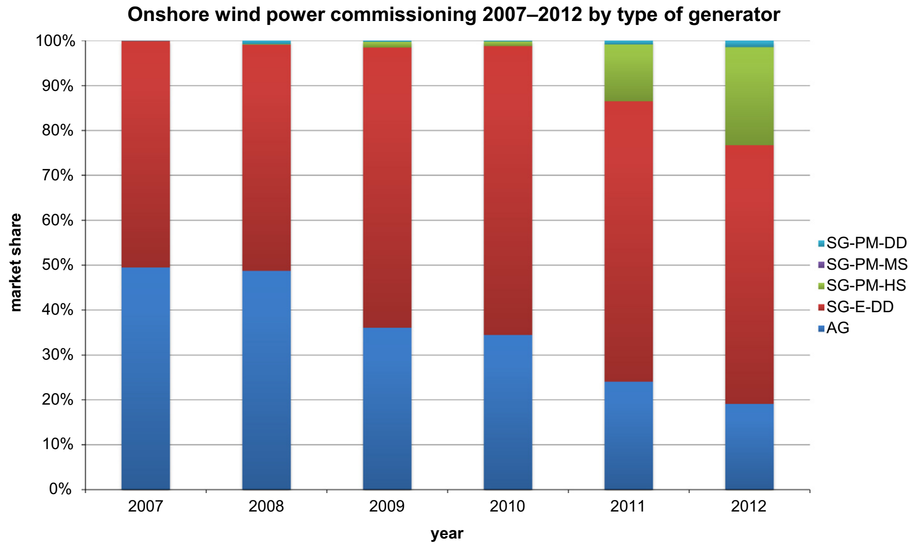

Fig. 4. Development of onshore wind power commissioning in Germany by type of generator from 2007 to 2012 (own calculations based on [44]).

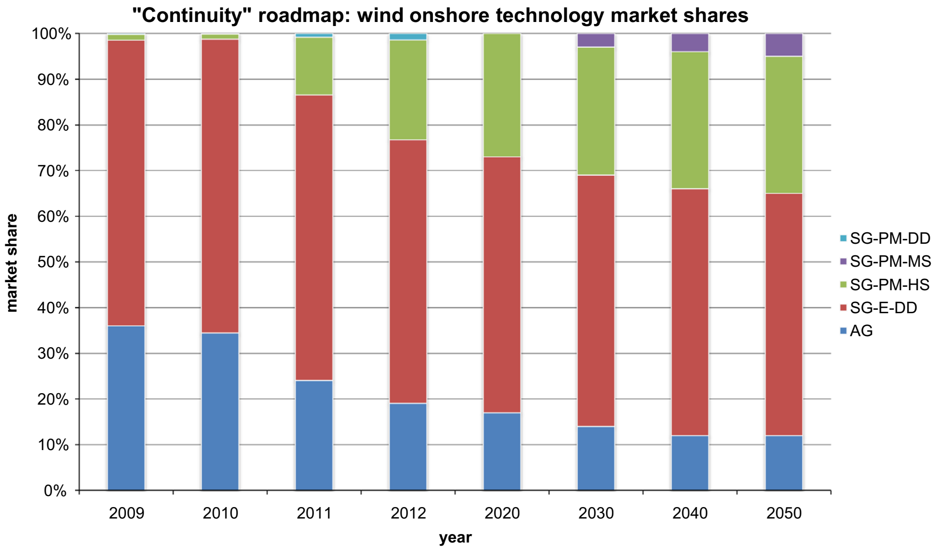

Fig. 5. Assumptions for the long-term market share development of onshore wind power technologies within the roadmap “continuity” roadmap (past market data based on [44]).

mere 19% in 2012. While this decline originally occurred in favour of electrically excited synchronous generators, permanently excited synchronous generators have rapidly been gaining in market significance since 2011, achieving a share of 23% in 2012. These generators use permanent magnets (PM) consisting of neodymium iron boron magnets combined with dysprosium. Their advantage is their expected ability to cope with limiting factors such as the high nacelle weight or high torque, a requirement that is becoming increasingly important as the size of wind generators increases.

As far as *offshore wind power* is concerned, the recently installed capacity in Germany is still low and therefore of minor significance for possible future market developments. From 2010

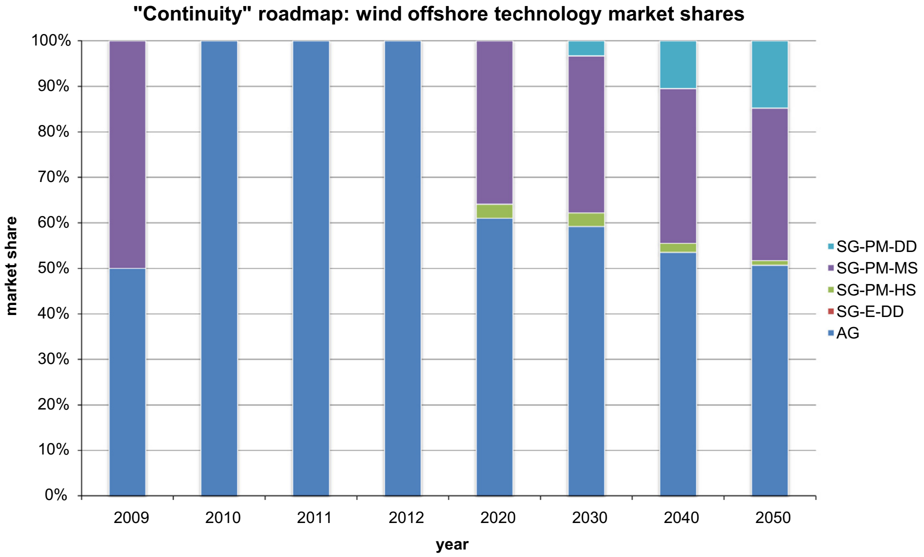

Fig. 6. Assumptions for the long-term market share development of offshore wind power technologies within the roadmap “continuity” roadmap (past market data based on [45-47]).

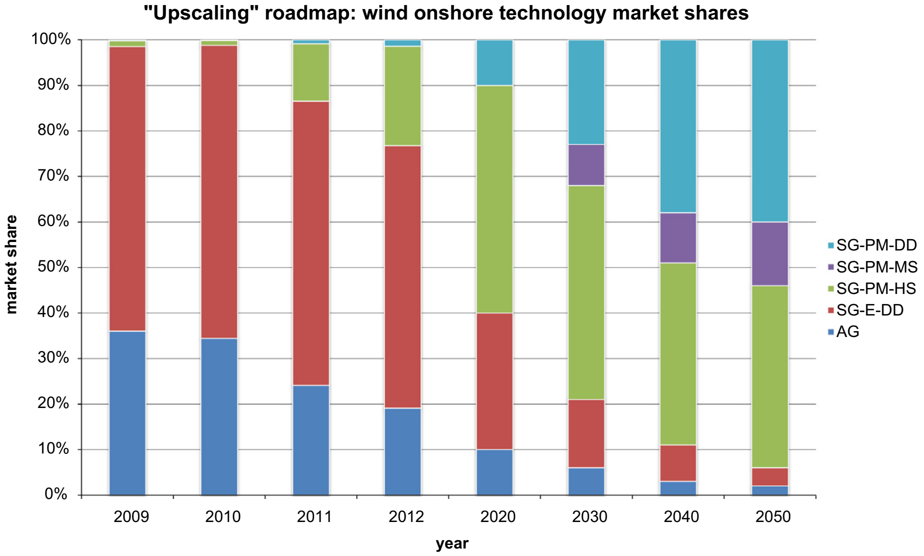

Fig. 7. Assumptions for the long-term market share development of onshore wind power technologies within the roadmap “upscaling” roadmap (past market data based on [44]).

to 2012, all new offshore installations (248 MW) were based on asynchronous generators [45–47].

We define a bandwidth of possible extrapolations of the current German wind power market up to 2050 by developing three roadmaps, “continuity”, “upscaling” and “HTS”. Regarding offshore technologies, we assume identical market shares in all roadmaps up to 2020. These market shares are calculated based on information about the technologies envisaged in planned offshore projects that already possess construction permits as of September 2013 [48]. As a result, the offshore market is expected to consist almost exclusively of AG (61%) and SG-PM-MS (36%) in 2020.

The annual market shares of different generator types within the *“continuity” roadmap* are depicted in Fig. 5 for the onshore and in Fig. 6 for the offshore market. This roadmap assumes a stagnation in the trend towards larger wind generator sizes [47]. As a consequence, currently dominating generator concepts retain most of their market shares, especially SG-E-DD on the onshore and AG on the offshore market. Electrically excited concepts are therefore driven out of the market only slowly by PM generators. Within the field of PM generator concepts, we assume that market-leading technologies of today or the near future (PM-HS onshore and PM-MS offshore) will manage to retain or increase their market significance up to 2050, while other concepts are of minor importance.

The *“upscaling” roadmap* assumes an ongoing increase in wind generator sizes, consequently leading to a further market preference for PM generators. The corresponding annual market shares of this roadmap are illustrated in Figs. 7 and 8 for the onhore and offshore markets, respectively. The above-mentioned expectations placed on PM generators lead to a significant market advantage in this roadmap. Compared to the “continuity” roadmap, therefore, PM generators achieve much higher market shares at the expense of electrically excited concepts. Within the PM generator market, rising shares of market-leading technologies (PM-HS onshore and PM-MS offshore) up to 2030 are expected to be followed by an increasing importance of PM-DD that tackle high drive torque

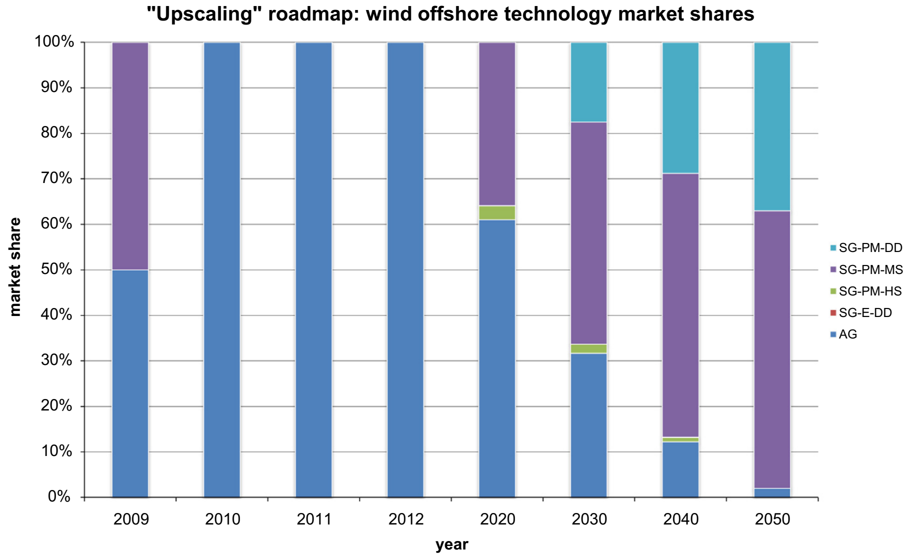

Fig. 8. Assumptions for the long-term market share development of offshore wind power technologies within the roadmap "upscaling" roadmap (past market data based on [45-47]).

Table 6
Current and future demand of critical raw materials in wind turbines (kg/MW$_P$)

Generator type	Mineral	2013	2025	2050
Direct drive (DD)	Neodymium	201.5	162.5	130.0
	Dysprosium	15.0	11.7	11.7
Middle speed (MS)	Neodymium	49.6	40.0	32.0
	Dysprosium	3.7	2.9	2.9
High speed (HS)	Neodymium	24.8	20.0	16.0
	Dysprosium	1.8	1.4	1.4
High temperature superconductor (HTS)	Yttrium	–	0.3	0.3

The values for DD, MS and HS generators are derived from [60]; those for HTS generators are the result of an expert survey.

caused by a further increase in plant size. While maintenance requirements are regarded as a barrier for the access of PM-HS plants to the offshore market, comparatively low future market shares are assigned to onshore PM-MS due to the absence of suppliers offering PM-MS plants on today's onshore market [44].

The third *"HTS" roadmap* takes into account the uncertainty associated with a possible market entry of high temperature superconductor (HTS) generators. HTS technology may facilitate relevant reductions in the generator weight and volume of electrically excited generators [50]. If, hypothetically, these generators were to become technically viable, series-manufactured industry products one day, they could directly compete with SG-PM generators. The "HTS" roadmap is therefore a variant of the "upscaling" roadmap, with the shares of SG-PM-DD generators reduced in favour of HTS generators with direct drive (HTS-DD) (shares of SG-PM-DD and HTS-DD in 2050 onshore: 28% and 12%, offshore: 20% and 17%, respectively).

3.2.2.2. Current and future material consumption. Critical minerals in wind turbines are neodymium (Nd) and dysprosium (Dy) if they contain permanent magnets, and yttrium (Y) in the case of HTS. Table 6 illustrates the specific demand for these minerals for the current (2013) and future situation (2025, 2050).

A literature screening of LCA and LCI of REE magnet-based converters [51–54] revealed that most inventories refer to conventional turbines that do not use REE. For this reason, we derive the *current* material demand by combining the weight of permanent magnets (kg/MW) [16,55–61] with the material composition of REE magnets (kg/kg)[1] [16,57,59–62].

In the literature, the *weight* of permanent magnets is mainly given related to the specific type of generator. Here we assume that it increases linearly with generator performance[2]. The specific magnet weights for generator types vary within the literature. For DD generators, for example, it ranges from 470 to 1000 kg/MW. Owing to this variation, we chose the most current average values [60] and then validated them by expert interview: 650 kg/MW for DD generators, 160 kg/MW for MS and 80 kg/MW for HS generators.

Regarding the *material composition* of REE magnets, the screening of the literature also revealed significant differences. The share of neodymium and dysprosium ranges from 20 to 32% and 2 to 5%, respectively. As with the magnet weights, we chose the final values (31% Nd and 2.3% Dy) from [60], which is also based on a respective literature review.

Taking into consideration *future* improvements in wind generators, we assume that the share of neodymium and dysprosium in REE magnets can be decreased, e.g. by substituting REE at the grain boundaries [55], and that there will be no reductions in the weight of the magnet. The "Materials Roadmap" of the European Commission [63] sets targets for shares of neodymium and dysprosium in REE magnets reaching 20 and 1.8% in 2030, respectively. However, experts interviewed considered the target values for neodymium to be very optimistic. Instead, we make a moderate estimation, assuming a share of 25% in 2025 and 20% in 2050. In order to estimate the yttrium demand in future HTS generators, we conducted an expert survey with nine participants because only a few prototypes such as [64] exist at present.

3.3. Rough analysis of "potentially relevant" technologies

3.3.1. Concentrating solar power

Silver, used for coating solar mirrors, has been identified as a possible critical material in Fig. 1. The use of *solar salt* in

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[1] Since no data is available on the specific production overspill of REE magnets, demand refers to material composition. It is assumed that losses during production are well within the literature range of magnet weights and shares of REE metals.

[2] Further use of this data should be restricted to current turbines with an installed power between 2 and 5 MW, since generator weight increases rather exponentially with high diameters [56].

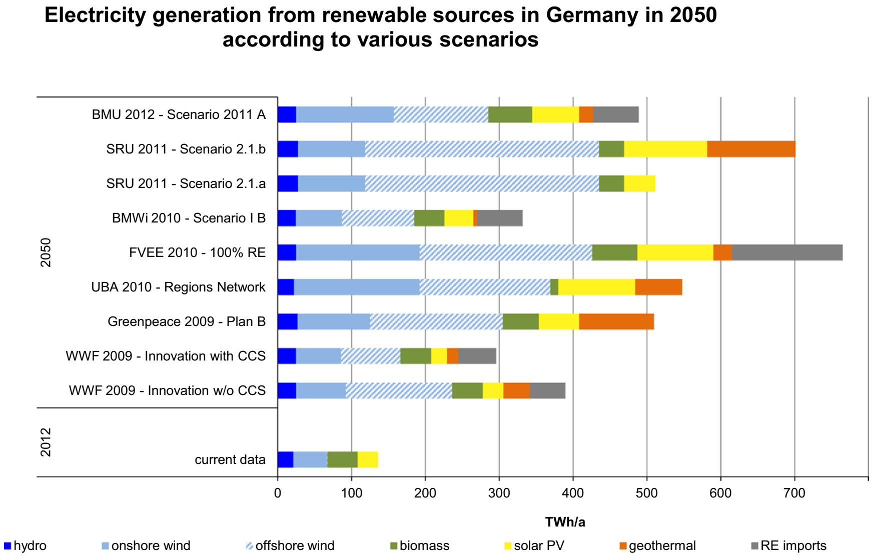

Fig. 9. Electricity generation from renewable sources in Germany in 2050 according to various scenarios.

thermal storage systems is also analysed because it usually contains potassium nitrate (KNO_3), which is also used globally as an artificial fertiliser. Although CSP will not be applied in Germany directly, several energy scenarios (Section 3.4) consider the importation of electricity generated by CSP plants. In order to provide a "worst-case" calculation, the scenario "THG95" [65] is selected because it foresees the most significant net electricity imports in 2050. While in the scenario itself only part of this electricity is assumed to come from CSP plants, we assume that all of the electricity imported stems from CSP, starting in 2030. Assuming thermal storage capacities covering 15 h/day and 6400 annual full load hours, a total CSP capacity of 27.7 GW_{el} and a storage capacity of 1185 GWh_{th} is derived.

In order to estimate *silver* consumption, a mixture of 40% parabolic trough, 40% Fresnel collectors and 20% solar towers [66] is assumed. Having derived average figures for the specific silver consumption of CSP plants without storage from [16,22,67,68] (5.53, 13.88 and 6.25 kg/MW_{el}, respectively) and having considered the solar multiple of 3.5, a total silver consumption of 800 t is calculated. Referring to a deployment phase from 2030 to 2050 yields an average annual consumption of 40 t, which is 0.12% of the global consumption of silver in 2012 (32,604 t, [69]). Considering the budget approach selected (Section 2), this equals 12% of the silver consumption budget allocated to Germany. The result is not considered to be critical, bearing in mind that a worst case was estimated. In fact, future silver demand will decrease due to technical improvements; anodised aluminium could be an alternative to silver, and no recycling of silver was considered.

In order to estimate the consumption of *solar salt*, the mixture used in Andasol power plants (60% $NaNO_3$ and 40% KNO_3) is considered [70]. Future parabolic troughs operating with steam or salt, enabling a 200 K temperature range, are assumed. Regarding a heat capacity of 1.52 kJ/(kg*K), a total salt consumption of 14.03 Mt is calculated, 40% of which is KNO_3. Referring to a deployment phase from 2030 to 2050 yields an average annual consumption of 281 kt of KNO_3, which is 16–18% of the current annual consumption of nitrogen fertiliser and 6% of the current annual consumption of artificial fertilisers in Germany [71,72]. The result is not considered to be critical due to the worst-case estimate and the ongoing development of further storage concepts (phase change, concrete) requiring less or no salt.

3.3.2. *Electricity storage*

For electricity storage, we analyse the options that are suitable for large-scale electricity supply, which is the focus of this article: large-scale stationary batteries, and hydrogen production, storage and re-conversion into electricity.

3.3.2.1. Wind power. From the range of options for stationary batteries, it is usually assumed that *lithium ion batteries* (high energy density but shorter storage periods) and *redox flow batteries* (low energy density but long storage periods) have a high future market potential. For lithium ion batteries, lithium (Li) appears to be the only possibly critical raw material, while non-critical manganese instead of critical cobalt is expected to be used for electrode coatings in the future. The demand for lithium is assumed to be 0.12 kg/kWh [22]. The *vanadium redox battery* is currently the most advanced redox flow battery if long storage periods and large-scale capacities are required. The demand for Vanadium (V), which is assumed to be this battery's only critical material, is derived to be 3.14 kg/kWh, the arithmetic mean of the figures given in [22,73].

3.3.2.2. Hydrogen pathway. Unlike batteries, hydrogen enables electricity to be stored seasonally via electrolysis, which will become increasingly relevant in energy systems based on a high share of renewables. *Alkaline electrolysis* is assumed for the production of hydrogen. Potentially critical minerals are nickel (Ni) and potassium (K). Their demand is assumed to be 2 kg/kW_{el} Ni (derived from [74,75]) and 0.42 kg/kW_{el} K [76]. *Storage* in tanks or caverns is not considered to be critical. Large stationary *solid oxide fuel cells (SOFC)* are assumed for the conversion of hydrogen to electricity. They require 0.057 kg/kW_{el} yttrium anode-side and 2.5 kg/kW_{el} lanthan cathode-side [77].

Due to the amount of potentially critical materials and the high demand for storage capacity envisaged in one of the scenarios analysed (Section 3.4), redox flow batteries and hydrogen storage via SOFC are upgraded to "relevant".

3.3.3. *Ferrous alloys*

Three aspects were taken into account to analyse the technologies classified as "potentially relevant" in Section 3.1 on the basis of their demand for alloyed steel: the specific demand for steel (independent of alloy grade), requirements regarding material properties and capacity expected to be installed in the future. A combination of these three criteria enables us to considerably narrow down the technologies that may actually create a relevant demand for ferrous alloys. Our assessment reveals that the majority of the technologies considered do not create a relevant demand for alloying elements – for different reasons:

- Biogas plants, electricity transmission lines: these technologies rely on non- or low-alloyed steel types [70,78].
- Run-of-river hydropower plants, pumped hydro storage plants, adiabatic compressed air energy storage, concentrating solar power: although these technologies create a demand for alloyed steel that cannot be substituted, the expected capacity development is linked to a low absolute demand for steel compared to annual extraction rates.
- Photovoltaics: The desired lightweight construction can also be achieved by substituting alloyed steels with other materials.

We identified a high specific demand for alloyed steels in combination with relevant expansion potentials for wind power and geothermal plants only. We use an extrapolation of the specific steel demand of *wind power* including all alloy grades to determine the order of magnitude of the cumulative demand. For exemplary wind power plants [79,80] and material losses [81] along a scenario with high shares of renewable electricity [82], this results in a cumulative steel demand in Germany between 25 and 53 Mt by 2050. Compared to the volume of the *annual* German crude steel production in 2012 of 43 Mt/a [83], it is clear that the general demand for steel resources does not represent a limiting factor for the development of wind power.

A comparable calculation for *geothermal power*, assuming specific demands for enhanced geothermal systems [84] along a capacity development described in [85], results in a cumulative demand for 20 Mt by 2050. Hence a similar conclusion as to that for wind power may also be drawn for geothermal power. However, these findings do not necessarily rule out the risk of a relevant demand for various critical alloying elements in the event of a major expansion of geothermal power plants. There are several reasons for assessing geothermal electricity generation as “relevant”, such as the high specific demand for alloying elements in deep geothermal plants [86] or the strong dependence of material requirements on local geological conditions [87,88]. Since the data base is as yet inadequate for forecasting this demand reliably, no final conclusions can be drawn at present for geothermal energy.

3.4. *Choosing a plausible range of long-term technology deployment*

We analysed nine existing *long-term energy scenarios* for Germany from seven different studies [65,82,85,89–92] that fulfil the German government's current long-term renewable energy and GHG emission reduction targets (see supplementary material). These studies differ considerably with regard to the future energy systems they envision. For example, Fig. 9 shows the electricity generation from renewable energy sources in 2050 according to the nine scenarios. It shows that there are considerable differences in the visions of the future German electricity system regarding both the level and composition of electricity generation from renewable sources by the middle of the century. For each technology, we defined “low” and “high” deployment by the scenarios that assume the lowest and highest installed capacity in 2050, respectively. “Medium” deployment is defined by the scenario with the median value for the installed capacity in 2050. By deriving wide ranges of deployment pathways for each technology rather than choosing a single scenario, we acknowledge the significant uncertainties related to the technologies' future level of deployment.

Table 7
Estimated cumulative technology capacity additions of “relevant” technologies in Germany between 2011 and 2050 (GW$_{\mathrm{el}}$)

Deployment pathway **Cumulative plant capacity**	**Low**	**Medium**	**High**	**Very high**
Photovoltaics	67	124	192	363
Onshore wind power	59	79	106	282
Offshore wind power	37	62	113	123
Cumulative hydrogen production capacity				
Electrolysis	–	–	–	88
Fuel cells	–	–	–	7.3
Cumulative electricity storage capacity (GWh$_{\mathrm{el}}$)				
Batteries	–	–	–	52

Another study describing the future German energy system was released [93] after we completed our scenario analysis. Its scenario foresees a higher gross electricity demand in 2050 (around 1000 TWh), partly because, by then, all low-temperature heat is assumed to be supplied by electricity based on renewable sources. Relative to the nine scenarios examined originally, the installed capacities of PV, onshore wind and offshore wind are all higher here in 2050. It was therefore decided to include the technology deployment achieved in this scenario as an additional “very high” 2050 deployment level in our analysis.

For the installed capacity of each technology prior to 2050, we use the data provided within the respective scenario studies. For years for which no data is provided, we interpolate installed capacities linearly. The cumulative capacity installations up to 2050 are derived from the annual installed capacity of a technology by assuming a typical lifetime of 25 years for PV plants and 20 years for wind power plants. Table 7 reflects the considerable differences between the scenarios analysed, with three (offshore wind) to five times (PV and onshore wind) higher cumulative plant capacity added until 2050 in the “very high” deployment pathways compared to the “low” ones.

For *storage technologies* we choose a simplified approach. Ranges are not used because most existing scenarios provide no detailed information about storage capacity requirements. Future deployment is based on the scenario “REMax” [93] as this scenario describes a future German electricity system with very high storage requirements. Furthermore, the study is one of the few available that provides detailed information about the storage technologies deployed (Table 7).

While the REMax scenario assumes that all hydrogen is converted to synthetic methane before being transformed back to electricity, we will assume here – in line with other studies – that some of the hydrogen is used directly in fuel cells. The REMax scenario states that 298 TWh of electricity will be used in 2050 to generate hydrogen. Assuming a conversion efficiency of 75%, 224 TWh of hydrogen may be produced. Assuming further that 42% of the hydrogen available in 2050 will be used in SOFC-based CHP plants (while the rest will be used in conventional gas turbines and the transport sector) that realise 4500 annual full load hours [65] and an electrical efficiency of 35% [94], we derive a need of 7.3 GW$_{\mathrm{el}}$ for fuel cells.

3.5. *Deriving the cumulative demand for critical minerals by 2050*

In order to calculate resource consumption over time, we first subdivide the annual capacity additions into specific technology types, as determined by the market development roadmaps. Next, for each deployment level and each roadmap the capacity of a certain type of technology (e.g. CIGS PV) added in a certain year is multiplied by its specific mineral consumption. Fig. 10 illustrates the results using the example of neodymium. The four bars for

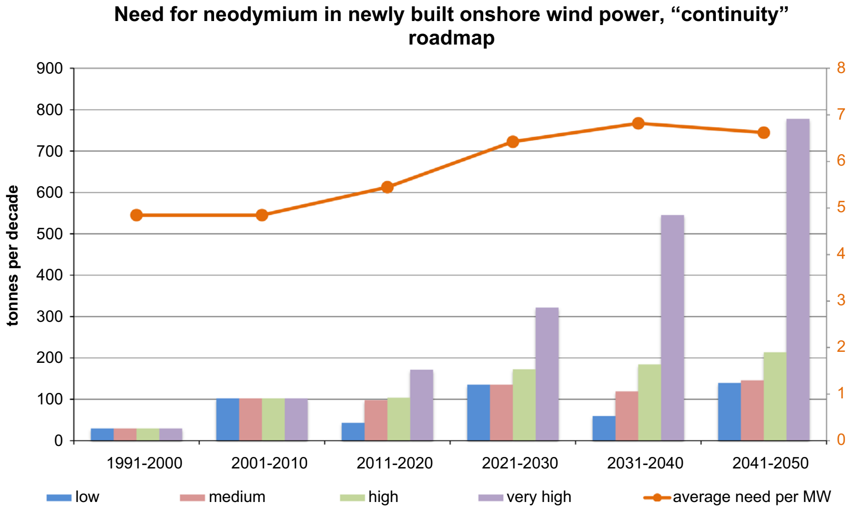

Fig. 10. Need for neodymium of in newly built onshore wind power plants in Germany – specific (line) and absolute (bars) consumption per decade.

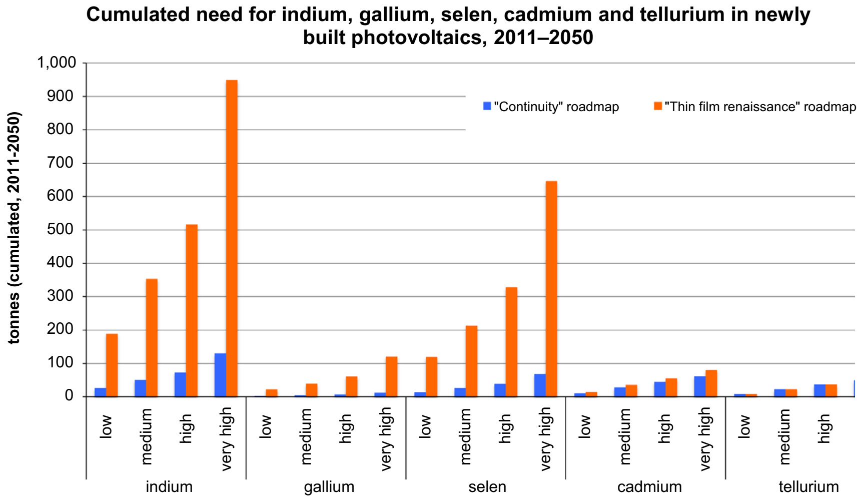

Fig. 11. Estimated cumulative critical mineral demand for photovoltaics deployment in Germany between 2011 and 2050.

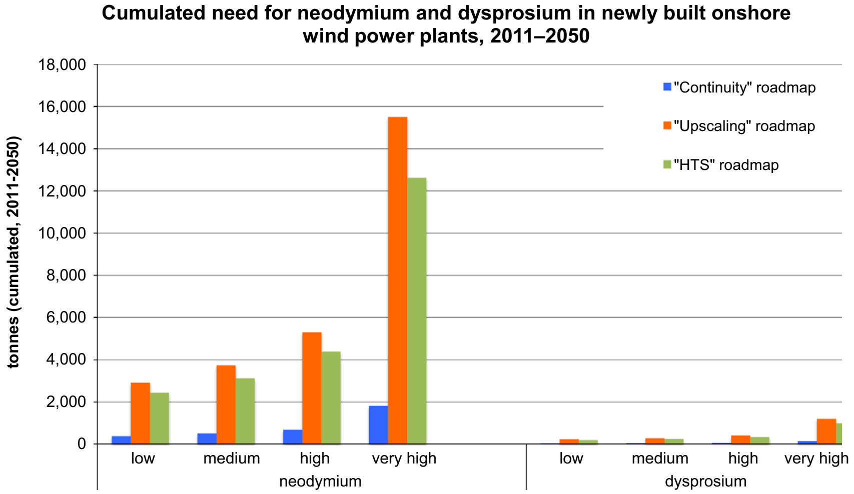

Fig. 12. Estimated cumulative critical mineral demand for onshore wind deployment in Germany between 2011 and 2050.

each decade depict the total need for neodymium of newly built onshore wind power plants in the respective decade and respective deployment pathways. The specific amount of neodymium required for the average newly built plant increases continuously from about 5 to 7 kg/MW from 2001 to 2040 (black line). This is true even though the specific amount for each *individual* type of

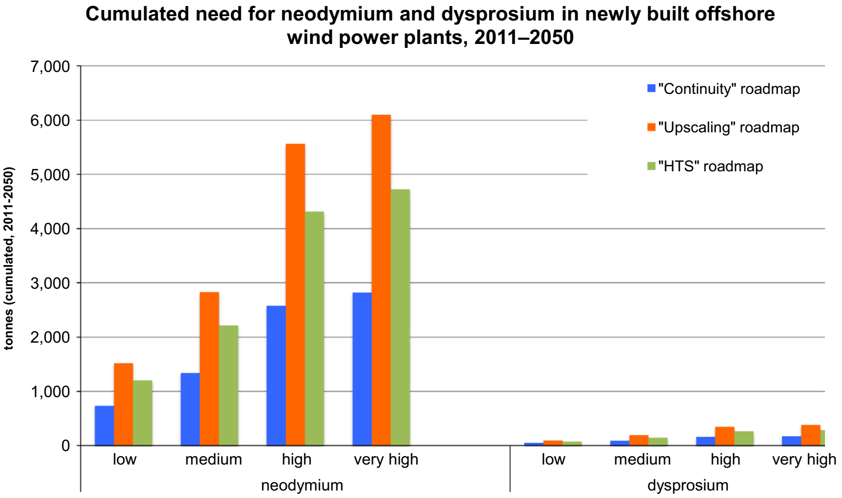

Fig. 13. Estimated cumulative critical mineral demand for offshore wind deployment in Germany between 2011 and 2050.

Table 8
Estimated cumulative critical mineral requirements for battery deployment in Germany between 2011 and 2050

Case	Technology	Capacity	Element	Specific demand	Total demand
		[GWh_{el}]		[kg/kWh]	[t]
(A)	Lithium ion battery	52	Lithium	0.12	6240
(B)	Redox flow battery	52	Vanadium	3.14	162,280
(C)	Lithium ion battery	26	Lithium	0.12	3120
	Redox flow battery	26	Vanadium	3.14	81,640

Table 9
Estimated cumulative critical mineral requirements for hydrogen storage-related technology deployment in Germany between 2011 and 2050

Technology	Capacity	Element	Specific demand	Total demand
	[GW_{el}]		[kg/kW]	[t]
Alkaline electrolysis	88	Nickel	2	176,000
	88	Potassium	0.42	36,900
Solid oxide fuel cell	7.3	Lanthanum	2.5	18,280
	7.3	Yttrium	0.057	416

onshore wind power plant is assumed to decrease over the entire observed period due to efficiency improvements and material substitution (see Table 6). However, the assumed future increase in market share of onshore plants using permanent magnets still leads to an increase in the specific quantity of neodymium in an average newly built plant.

Finally, this annual critical mineral consumption for a certain type of technology is added for all years and types of technologies to obtain the range of estimates of the cumulative critical mineral demand. These ranges are illustrated for PV (Fig. 11), onshore wind (Fig. 12) and offshore wind (Fig. 13) for each combination of deployment level and roadmap. (For the exact figures, see the supplementary material.)

In the case of storage technologies, we assume the same specific mineral requirement over the whole period (Tables 8 and 9). Regarding batteries, three further indicative cases are distinguished: in case (A), the total battery capacity required is made up of lithium ion batteries; in case (B), the total capacity consists of redox flow batteries; in case (C), both types of batteries are assumed to be used to the same extent. Tables 8 and 9 depict the total critical mineral demand derived from the assumptions about capacity and specific demand. In the case of batteries (Table 8), total demand is differentiated by the three cases mentioned above.

4. Assessment of “critical” minerals from a resource perspective

Finally, the cumulated demand for the different materials is considered in relation not only to their current annual global extraction, but also their global reserves. For each material considered in our analysis, Table 10 illustrates the minimum and maximum demand calculated within the renewable energy deployment scenarios by 2050 (columns 2/3). These figures are compared to the annual global production and global reserves of the respective materials (columns 4/5). Columns 6–9 show the relation between these values, and highlight (in bold figures) demands exceeding 40% of one annual global extraction or 0.1% of global reserves, the limits assumed in the budget approach described in Section 2.

Table 10
Demand for critical minerals caused by renewable energy expansion in Germany compared to their annual global extraction and global reserves

Element	**Demand for renewable energy expansion in Germany (2011–2050)** *		**Annual production (2012)** **	**Global reserves** **	**Demand relative to current annual global production,**		**Demand relative to global reserves,**		**Largest mining countries**
	(min [t])	max [t]	[t]	[Mt]	min [%]	max. [%]	min. [%]	max. [%]	
Photovoltaics									
Indium	26	949	670	0.012	3.9	**141.6**	0.2	**8.6**	China
Gallium	2	121	273	1.4	0.7	**44.3**	0.0001	0.009	China, Germany
Selenium	13	647	2000	0.098	0.7	32.4	0.013	**0.660**	Germany, Japan, Belgium
Cadmium	11	80	23,000	0.500	0.05	0.4	0.002	0.016	China, Canada
Tellurium	8	49	80	0.024	10.0	**61.3**	0.033	**0.204**	Japan
Wind power									
Neodymium	1109	21,600	19,000	23	5.8	**113.7**	0.005	0.094	China
Dysprosium	77	1575	420	0320	18.3	**375.0**	0.024	**0.492**	China
Electricity storage									
Lithium	3120	6240	34,000	13	9.2	18.4	0.024	0.048	Australia, Chile
Vanadium	81,640	162,280	63,000	14	**129.6**	**257.6**	**0.583**	**1.159**	China, Russia
Nickel	–	176,000	1,940,000	75	–	9.1	–	**0.235**	Australia, Indonesia, Philippines, Russia
Potassium	–	36,900	28,000,000	7900	–	0.1	–	0.001	Belarus, Canada, Russia
Lanthanum	–	18,280	27,500	25	–	**66.5**	–	0.073	China
Yttrium	–	416	8900	0540	–	4.7	–	0.077	China

Bold figures: Cumulated demand is higher than 40% of one annual global extraction or higher than 0.1% of global reserves.

* According to deployment pathways considered in Section 3

** Source: [98] (global indium reserves from [99])

For *photovoltaics*, the demand for indium required for the deployment of *thin film CIGS* cells considerably exceeds the assumed limit of 40% of one *annual extraction* in the “thin film renaissance” roadmap in all cases, except for the low deployment case. The demand for gallium is 44% of one annual extraction in the “very high case”, and 8–22% otherwise. The latter figure means that 20–56% of the German budget of extracted resources would have to be allocated to renewable energy technologies[3]. The demand for selenium is 10–32% of one annual extraction, corresponding to 25–80% of the German budget needed for renewable energy technologies. Due to the high share of resources taken up by renewable energy technologies, the criticality assessment is extended to global reserves below. The “continuity” roadmap results in much lower demands for indium, gallium and selenium (3.9%, 0.7% and 0.7% of one annual extraction for the “low” deployment case and 19%, 4.5% and 35% for the “very high” deployment case, respectively).

Regarding the *global reserves*, the demand for indium and selenium in the “thin film renaissance” roadmap considerably exceeds the assumed limit of 0.1% of the global reserves in all cases. Assuming that, as a sensitivity analysis, 50% instead of 10% of the global reserves were available for the global deployment of renewables, the resulting limit of 0.5% for Germany would also be exceeded in most cases. This means that the demand does not appear to be secured in the long term. In particular, the overall demand for indium depends on a single supplier country (China) and is expected to increase due to different competing uses, including the production of liquid crystal displays (LCD). It also appears uncertain whether the need for selenium can be met from conventional sources, particularly because selenium is only obtained as a by-product and the significant competing demand from decolouring in glass production is difficult to substitute. Hence a major expansion of CIGS technology must be considered to be critical. In contrast, the estimated demand for gallium in this study and from other applications (603 t up to 2030) [22] can easily be met by mined bauxite.

For *thin film CdTe* cells, we assume a phase-out in Germany by 2020. From the standpoint of resource availability, the quantities of cadmium and tellurium required up to 2020 are regarded as unproblematic.

In the case of *wind power*, the cumulated dysprosium demand considerably exceeds the assumed limit of 40% of one *annual extraction* in nearly all cases, that of neodymium in half of the cases. In the other cases, more than 20% of one *annual extraction* is needed, which means that more than 50% of the German budget has to be allocated to renewable energy technologies. Since dysprosium and neodymium will also be required in competing technologies like electric mobility, the global reserves also have to be considered.

Regarding the *global reserves*, the availability of REE varies, depending on the specific element. In general, heavy REE (for example, dysprosium) are less common than light REE (for example, neodymium), which is also expressed by the relation of demand to global reserves. While the demand for neodymium is less than 0.1% of reserves in each case, the demand for dysprosium exceeds this limit in the “upscaling” and “HTS” scenarios, with 0.1–0.5% of reserves. However, a detailed analysis of deposits currently in use and deposits whose future utilisation is under discussion reveals that their dysprosium content is large compared to existing reserves. If only geological availability is taken into consideration, therefore, all pathways considered could be implemented. However, REE are not “rare” in the strict sense; in fact, their deposits

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[3] 40% of one annual global extraction corresponds to the assumed annual budget for Germany (1% of the annual global, see Section 2), considered over 40 years. Allowing this amount to be used for renewable energy deployment only means that the whole German resources budget would be allocated to renewable energy technologies. Accordingly, 30%, 20% and 10% of one annual global extraction mean that 75%, 50% and 25% of the German budget are allocated to renewable energy technologies, respectively.

are scattered unevenly across the world, resulting in an excessive dependence on a few supplier states with a concomitant effect on security of supply. For instance, China is the world's only noteworthy producer of dysprosium at present. It is currently unclear whether other countries may be able to establish production in the long run and under which conditions (for example, production costs, quality of storage sites, environmental legislation) this mineral would be extracted. Therefore, in spite of a high level of availability, an adequate supply of the quantities required cannot necessarily be guaranteed for Germany.

For *electricity storage*, the raw material demand estimated for vanadium-based redox flow batteries in the system analysed with a "very high" level of expansion of wind power and photovoltaics considerably exceeds both the assumed limit of 40% of one *annual extraction* and the limits of 0.1% and 0.5% of the global reserves. Therefore, it must be considered as being critical. In particular, there is considerable competing demand for vanadium, as it is an important alloying element for steel. In contrast, the estimated lithium demand is relatively low and does not seem to be critical. However, a very rapidly growing demand for lithium through applications such as electrical vehicles may nonetheless create future shortages in lithium availability. In terms of long-term storage (alkaline electrolysis and hydrogen storage with reconversion in SOFC), the demand for all of the elements investigated is expected to be non-critical.

5. Discussion

Our findings indicate that the geological availability of minerals does not generally limit the production and storage of *electricity* from renewable sources in Germany. Our analysis indicates that hydropower, wind turbines without REE magnets, silicon-based crystalline PV and concentrating solar power plants can be considered to be non-critical generation technologies with regard to critical minerals. Non-critical infrastructure technologies are electricity grids, specific types of electricity storage devices, alkaline electrolysis and solid oxide fuel cells. The supply of minerals in the use of biomass and biofuels was not classified as being critical either. However, we disregarded the availability of biomass itself and the associated challenges, especially with regard to competing demand for land and biomass use [95,96]. These issues need to be included in any future comprehensive resource assessment of the German energy transformation. With regard to geothermal electricity, no conclusions can be drawn at present due to the inadequate data base. A similar analysis revealed that the production of *heat* and *fuels* from solar energy, geothermal energy and biomass can also be classified as non-critical.

Possible criticalities are most probably related to certain subtechnologies of wind power, PV and battery storage only, which were identified as being critical with regard to possible constraints in the supply of minerals. However, non-critical alternatives to these technologies generally exist. Regarding *wind power*, the given constraints constitute the need to further develop established or novel technologies that do not involve the use of REE. The use of neodymium and dysprosium is non-essential for onshore facilities, since problems such as very heavy nacelles and expensive maintenance work for turbines mainly affect offshore facilities. Non-critical, electrically excited generators could still be used onshore, particularly in the 1–3 MW class. For offshore facilities, HTS generators could possibly be used in the long run.

In the case of *photovoltaics*, some types of *thin film technologies* generate concerns regarding security of supply: the demand for indium and selenium in CIGS cells does not appear to be secured in the long term. Reasons for this are competing demand from other technologies, a high dependence on single supplier countries (indium) and the extraction of selenium merely as a by-product. If it is thought that thin film technology will be relevant in the future, further research should be conducted on cells containing no or little indium or selenium.

Considering large-scale *electricity storage options*, raw material supply for vanadium-based redox flow batteries must be regarded as being critical in the context analysed. Alternative options are lithium ion batteries (which are considered to be less critical from the perspective of resource availability) or physical storage facilities (pumped storage plants, compressed air reservoirs).

Supply restrictions could be decreased further by establishing recycling systems wherever possible [7,9]. In the case of *photovoltaics*, the relatively high concentrations of the critical elements gallium, indium and selenium used in thin film technology will in principle facilitate the development and establishment of recycling systems. At the same time, the industry should be encouraged to design recyclable photovoltaic systems. In order to further reduce material consumption in general, photovoltaic systems should increasingly be integrated in other applications (for example, façades, roofs, semi-transparent coverings, glazing or shading devices). As long as REE magnets are used in *wind generators*, they should ideally be designed to be recyclable. Due to the bonding of many elements, they are currently difficult to recycle. Looking to the future, the development of a recycling system ought to be tested so that at least recycled neodymium and dysprosium could be resorted to in 20–30 years' time for replacement purposes.

The results of our study confirm previous findings [3–10], putting them in a broader perspective. Embedding the technology and resource development in a set of long-term energy scenarios enabled the transformation of an energy system for a whole country to be assessed. Furthermore, the roadmapping process was based on actual market data for onshore wind and photovoltaics, helping to create plausible ranges for the future mix of the sub-technologies considered. Finally, to our knowledge, this is the first time that a budget approach developed originally for climate policy [11] has been applied for the purpose of assessing resources. Although this approach is based only on rough assumptions, it may nevertheless act as a starting point for developing a detailed methodological framework for criticality assessments.

6. Conclusion

Our main conclusion is that the envisaged transformation of the German energy system will principally be compatible with the supply of mineral resources. However, potential supply risks owing to dependencies on a few supplier countries and competing use should be borne in mind. For this reason, in addition to achieving closer cooperation with companies and governments of supplier countries, increasing resource efficiency and recyclability should be the key elements of technology development to secure Germany's raw material supply. Furthermore, technology policy should focus on types of renewable energy (sub-)technologies that require no or comparatively little critical minerals. It should be noted that our findings are subject to a number of highly uncertain assumptions and data concerning the resource situation. It is recommended to extend the analysis presented here to additional sectors and products for which minerals are required. Moreover, a long-term integrated assessment of the use of the full range of resources (not only "critical" ones) could help to develop schemes for generally minimising the use of resources during the German energy transformation.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2015.04.070.

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