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Title: China's Control over Critical Materials: Risks for Europe's Solar and Wind Industries?

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Abstract: This article examines the dependence of the European Union's solar and wind industries on Chinese supply of five critical raw materials: tellurium, gallium, indium, and the rare earths neodymium and dysprosium. Based partly on interviews with experts, this study reviews China's industrial policies that shape the supply of these materials abroad. We also assess the short- and long-term strategies of the European Union and European solar and wind industries to ameliorate potential supply bottlenecks. While these strategies adequately address short-term challenges, we find they pose several long-term risks, such as increasing the dependence on China and hampering European competitiveness in global markets. There is also divergence in the extent to which these two industries are vulnerable to supply bottlenecks and price volatility; because more options are open to them, European solar manufacturers are less exposed to these risks than their counterparts in the offshore wind sector.

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1. Introduction

At the recent climate summit in Paris, the EU agreed to a 40% reduction in greenhouse gas emissions by 2030, with 1990 as the benchmark. In short: the EU has committed itself to becoming the world's climate leader. This task will require a significant decarbonization of the EU's energy sector, and the EU has set a target of increasing its reliance on renewable sources of energy to 27%. To meet these goals, European firms possess the requisite technological know-how, particularly for photovoltaics and wind turbines; however, Europe is missing other capacities necessary for a renewable energy build-out: namely, secure supplies of certain crucial metals.

The rapid technological advancements of recent years—in a wide variety of industries, ranging from medicine, communications, military, entertainment to energy—have been made possible, in large part, because of specialty metals that allow for greater complexity, sophistication and miniaturization. These metals include the rare earth elements (REEs), which comprise the lanthanide series of the periodic table (numbers 57-71) plus two closely-related metals, scandium (number 21) and yttrium (number 39). Because of their "unique magnetic, luminescent, and electrochemical properties", they have become key ingredients of most high technologies (RETA, 2014). Rare earths are also used in several types of permanent magnets, which play an important role in electricity generation—and are thus significant for renewable sources of electricity.

In wind turbines, for example, at least two major benefits can be obtained by using rare earth permanent magnet generators instead of mechanical gearboxes. First, rare earth permanent magnets, by decreasing motor weight and size, reduce costs by requiring less concrete and steel to support the turbine. Second, mechanical gearboxes have more moving parts, which requires more frequent maintenance of turbines and renders them more susceptible to breakdowns. By reducing the number of moving parts, rare earth permanent magnet generators facilitate greater reliability and efficiency (Smith Stegen, 2015).

For European manufacturers—and their customers—to reap the benefits of REEs and other high-tech materials, they will need steady and adequate supplies. However, taskforces working for the European Commission have identified several of these metals as "critical", meaning they are under severe supply pressure (Joint Research Centre, 2011; 2013). For renewable energies, these materials are the light rare earth element (LREE) neodymium, the heavy rare earth element (HREE) dysprosium, and three non-REE metals, gallium, tellurium, and indium.

The source of the supply pressure or, more aptly, supply risk, is that one country—China—dominates the production, processing and value chains. For decades, China was a reliable supplier of most of the world's scarce materials, particularly the rare earth metals and permanent magnets; however, for myriad reasons, including China's own rapidly growing demand, concerns have been raised over future prices and availability. In the early 2010s, China reduced export quotas, which triggered dramatic price increases around the world. These increases were a highly problematic for manufacturers, but a boon for non-Chinese mining companies and for the illegal mining trade inside China.

As new supplies entered global markets—with a significant portion from illegal Chinese producers—prices dropped (Treadgold, 2015). The Chinese government, to keep revenues up, responded by cutting back its official production, which stabilized prices. During this same time frame, China began re-structuring its REE industry: attempting to stamp out illegal producers and consolidating REE-related companies into six conglomerates. The value of the global rare earth industry has been estimated at $1.3 billion, whereas the end-use industries are reportedly worth a thousand-fold more: $4.8 trillion (Seaman, 2010). One of the Chinese government's objectives is to move its industries from the billion-dollar raw materials market to the trillion-dollar market for end-use applications (Smith Stegen, 2015). Seen in this light, China's industrial policies of recent years—both domestic and international—reveal forward-thinking planning and acumen unmatched by any other governments or public bodies.

This article uses primary interview data as well as extensive desk research, including Chinese sources, to explore the recent turbulence in the markets for raw materials and the vulnerability of European manufacturers. Specifically, we seek to understand the impact of recent developments for the EU's renewable energy industries. What are the implications? How have EU companies responded? We begin by examining how critical materials are used by EU manufacturers and projections of future EU demand. Next, we report where the EU sources these materials and the extent of EU dependence on various suppliers, including China. We then delve into China's rare earth industrial policy and China's intentions, followed by the responses and strategies of the European wind and solar sectors. We close by discussing short gaps in EU policy and provide our recommendations.

2. Methodology

Research for this article was conducted by collecting and assessing reports published by the Chinese government and the European Commission. In addition, we conducted four semi-structured interviews with experts from mainly German wind and solar industries and consultancies in January and February 2016 (see list of interviewees in the appendix) and used material from an interview conducted by one of the authors in 2014. We also analyzed media reports, information published on companies' websites and academic articles. The Chinese-language secondary literature was an additional source of helpful insights.

3. Supply shortages for EU renewable energy technologies

Globally, concerns about the security of raw material supplies have been increasing along with fears that the use of new innovative technologies might be endangered by high prices and shortages of raw materials. Numerous factors obtain for this growing anxiety: for example, the increasing demand for certain high-tech applications in emerging economies; and the domination of production and supply of critical metals by a few countries and companies (Glöser et al., 2014, 35-36; Sievers and Tecero, 2012). China, as both a leading manufacturer and consumer of many raw materials, plays a key role. The European Union, research institutes and companies therefore carry out criticality assessments of raw materials, which are intended to help policymakers ensure supply security (Glöser, 2014, 35; SETIS, 2015, 8; Joint Research Centre, 2011; Joint Research Centre 2013; Oakdene Hollins and Fraunhofer ISI, 2013; Schriefl and Bruckner, 2016).

We employ a widely accepted definition of so-called critical raw materials. The Ad-hoc Working Group[1] on defining critical raw materials, chaired by the European Commission, developed the EU materials criticality methodology. It assesses each material individually adopting a top-down approach encompassing all the uses and production of these materials within the EU economy (Oakdene Hollins and Fraunhofer ISI, 2013, 99). In their first 2010 report the Working Group labeled "critical raw materials for the EU" as follows:

> "[a raw material is] 'critical' when the risks of supply shortage and their impacts on the economy are higher compared to most of the other raw materials. Two types of risks are considered: a) the 'supply risk' taking into account the political-economic stability of the producing countries, the level of concentration of production, the potential for substitution and the recycling rate; and b) the 'environmental country risk' assessing the risks that measures might be taken by countries with weak environmental performance in order to protect the environment and, in doing so, endanger the supply of raw materials to the EU" (EU COM, 2010, 5).

The following analysis assesses the state of critical raw materials most relevant to Europe's wind and solar sectors.

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[1] The Ad-hoc Working Group on defining critical raw materials is a sub-group of the Raw Materials Supply Group (EU COM 2010, 5), which includes experts from EU member states and candidate countries, industry, research and civil society among others. It advises the European Commission and oversees the implementation of the Raw Materials Initiative adopted by the Commission in 2008 to ensure "(f)air and sustainable supply of raw materials from global markets", "(s)ustainable supply of raw materials within the EU" and "(r)esource efficiency and supply of 'secondary raw materials' through recycling" (EU COM, 2016a). Defining the critical raw materials for the EU's economy lies in the focus of the Initiative's work (Oakdene Hollins and Fraunhofer ISI, 2013, 1).

3.1 Critical metals for the EU wind and solar industry

A recent major study conducted by the Institute for Energy and Transport of the European Commission's Joint Research Centre considers five materials as high risk for future supply-disruptions in low carbon energy technologies: the two rare earth elements neodymium and dysprosium as well as tellurium, gallium and indium (Joint Research Centre, 2011, 14; Oakdene Hollins and Fraunhofer ISI, 2013, 157). A follow-up report in 2013 confirmed these findings, but shifted indium from the high to the medium-to-high risk category (Joint Research Centre 2013; 152). Because these materials have been consistently cited as potential supply chain bottlenecks, we examine the supply security implications for the European wind and solar industries (Joint Research Centre, 2011, 15; SETIS, 2015, 27).

3.2 Critical Metals in Europe's wind and solar industries

Neodymium and, to a lesser extent, dysprosium, are important components in neodymium iron boron permanent magnets, which are used in gearless direct drive wind generators (Lacal-Arántegui, 2015, 277). Since permanent magnets generators reduce turbine size, decrease overall weight and allow greater resilience, less frequent turbine maintenance is required, which makes such generators particularly attractive for offshore installations (Interview 2; SETIS 2015, 21). The leading European companies using permanent magnets generators include the Spanish manufacturer and supplier Gamesa Electric (Gamesa, 2010), the German turbine manufacturer Siemens Wind Power (Siemens, 2002-2016) and the formerly German company Vensys Energy AG, now a subsidiary of the Chinese State-owned turbine manufacturer Goldwind (Vensys, n.d.).

Tellurium, gallium and indium, on the other hand, are needed for the production of thin film solar cells. Tellurium is part of cadmium tellurid cells (CdTe-cells), which account for around 70 percent of thin film solar cells (Interview 4). The US company First Solar dominates the thin film and CdTe-cells market with a global market share of 90 percent (Interview 4; Joint Research Centre, 2013, 147). Only a handful of other companies, including the German Calyxo GmbH, also engage in CdTe-cells manufacturing (Interview 4; Calyxo, n.d.). CdTe-cells are highly controversial within the European Union, because of the toxicity of the cadmium (Interview 3; Interview 4). Despite ongoing discussions, CdTe-cells, however, are still excluded from the 2011 Directive of the European Parliament and the Council on the restriction of the use of certain hazardous substances in electrical and electronic and are produced for the European market (Directive 2011/65/EU).

Gallium and indium are part of copper indium gallium selenid solar cells (CIGS-cells) (Schriefl and Bruckner, 2016). Because CIGS-cells do not use cadmium, they are ideal for integration in buildings and thus particularly attractive for the European market (Interview 3). CIGS-cells account for only 2 percent of global market share and are dominated by the Japanese company Solar Frontier. A few European companies, such as MANZ AG, produce CIGS-cells as well. Two former German companies AVANCIS GmbH and Solibro GmbH, who are also producer of CIGS-cells, were acquired by the Chinese manufacturer China National Building Materials Group Corporation (CNBM) and Hanergy Holding Group Ltd. respectively (Interview 4; PV

Magazine, 2014a; PV Magazine, 2014b).

3.3 How much critical metals does the EU need? Future projections 2020-2030

Assessing future demand for critical metals is a tricky business and requires scenario building to project potential usage and consumption (Joint Research Centre, 2013). For example, to assess the rare earth requirements of the offshore wind industry in 2020 and 2030, assumptions have to be made about the overall gigawatts (GWs) that will be produced both onshore and offshore (Joint Research Centre, 2013). However, depending on the future energy mix, demand for critical metal demand could vary. There is, thus, a degree of unavoidable uncertainty in such exercises (Joint Research Centre, 2011, 15).

According to the European Wind Initiative's (EWI) projections, onshore wind is set to become the most competitive energy source by 2020 and offshore wind is expected to follow by 2030. Total wind energy is aimed at supplying 33 percent of Europe's electricity by 2030 and 50 percent by 2050 (Joint Research Centre, 2011, 24). The Joint Research Centre (2013) assumes that offshore wind will increase 15-fold by 2020 (44 GW), whereas onshore wind will increase only 2-fold (169 GW). Similar assumptions are held for 2030 (Joint Research Centre, 2013). As for CdTe- and CIGS-cells, experts predict expansion especially due to growing markets in Asia. Their current market share of 10 percent, however, will remain stable or even decrease, since crystalline cells will continue to dominate the market (Interview 3, Interview 4).

Projections for supply pressure on particular elements critical to renewables vary. Of the critical materials used in solar and wind energy, the Joint Research Centre report sees dysprosium as being the most ‘at risk’. Forecasts expect the EU will require 25 percent of world supply in order to meet its demand for wind turbines as well as for hybrid and electric vehicles (Joint Research Centre, 2013, 11). Moreover, gallium is expected to experience the highest growth rate exceeding 8 percent next to HREEs until 2020 (EU COM, 2014a, 33, 35) which is driven by increasing gallium consumption by Solar PV expansion (Joint Research Centre, 2013, 234). Given the growth numbers for certain technologies, the EU expects that HREEs and indium will experience a small deficit by 2020. Gallium, however, will show a large surplus by 2020 after being in deficit in the middle of the 2010s. LREEs on the other hand, are expected to show large surpluses by 2020 (EU COM, 2014a, 33, 35). Table 1 shows the amount of critical metals that might be needed for the wind and the Solar PV industries in 2020 and 2030.

Table 1: Projected demand of critical metals in EU Wind and Solar Energy

Elements	**Annual EU Demand (tonnes)**		**Annual EU Demand / World Supply (in %)**	
	2020	2030	2020	2030

Wind				
Neodymium-Praseodyium[2]	845	1.222	1.3	1.2
Dysprosium	58	84	2.3	2.2
Solar				
Tellurium	150	126	12	6.9
Indium	145	121	7.6	4.9
Gallium	4	3	0.8	0.5

Source: Data extracted from Joint Research Centre, 2013

4. From Which Countries does the EU source its critical metals?

4.1 China's dominance in critical metals and permanent magnets

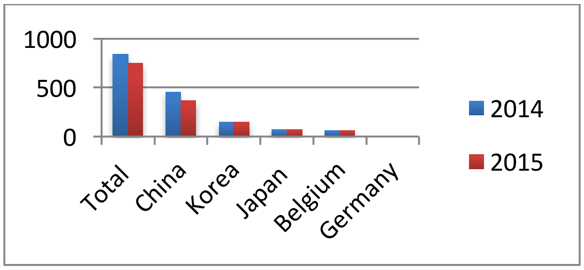
The European Commission attributes the high supply risks for gallium, indium and REEs to the high share of Chinese production in the world market (EU COM, 2010, 7). The US Geological Survey (USGS) estimates global REE reserves to encompass 130 million t in 2015 (USGS, 2016). With 55 million t, China accounts for more than one third of global REE reserves. It is followed by Brazil (22 million t), Australia (3,2 million t), India (3,1 million t) and the United States (1,8 million t) (USGS, 2016, 135). Out of a total of 124,000 t of global REE production, China produced 105,000 t in 2015 (USGS, 2016, 135). It also accounted for 99 percent of global HREE and 87 percent of LREE production between 2010 and 2012 (COM (2014) 297 final). Also, it manufactured 70-85 percent of permanent magnets, followed by Japan (17 – 25 percent) and Europe (3-5 percent) (Lacal-Arántegui 2015: 279; Benecki, 2013; Dent, 2014).

[2] The report treats neodymium and praseodymium together, since they are not always separated from each other (Joint Research Centre, 2013, 76).

Further, China's overall production of gallium has more than quadrupled between 2009 and 2011 and accounts for nearly 70 percent of global gallium production (EU COM, 2015b). Meanwhile, it is expected that China's own use of gallium will grow every year to 20-30 percent due to increasing use of CIGS-cells, and to its use in lighting applications and medical equipment (AM, n.d.; CCCMB, 2015). While the supply risk for gallium is lower than for HREE and LREE, with more than two-thirds of global supply originating from one country, it is still considerable (Joint Research Centre, 2013, 234, 231).

Indium has been considered as being critical by some solar companies in the past years (Interview 3; Interview 4). However, market conditions for solar cell technologies depending on indium are less tight today. In 2015, China returned to being a net exporter of indium. This has been a result of less domestic demand, higher international prices and an elimination of the domestic export tariff on indium (USGS, 2016, 81). In the first half of 2015, indium production in China declined by 15 percent to 30 percent compared to the same period of the previous year as a result of decreasing prices (USGS, 2016, 80). Similar observations can be made for tellurium; According to data from the International Copper Study Group, production of tellurium is even more diversified, including China, Japan (each 20 percent) and European countries (30 percent) (EU COM 2015c). In 2014, prices for tellurium fell significantly as well (USGS, 2016, 169).

Figure 1: World refinery production of Indium in 2014 and 2015 (in tonnes)



Source: Data from USGS, 2016, 81

4.2 The EU's dependence on China's critical metals

China is the main supplier for the EU's dysprosium, neodymium, gallium and indium needs. Given 2012 data published by the most recent report of the Ad-hoc Working Group, the EU imported 41 percent of its total REEs from China, 35 percent from Russia and 17 percent from the US. As for HREEs, China is the only supplier. The EU also imported 43 percent of its indium from China (including Hong Kong) and 47 percent of its gallium from China (including Hong Kong) (COM (2014) 297 final). Table 2 summarizes China's production and export of critical metals into the EU in relation to other producing and exporting countries.

Table 2: Producer countries and sources of import for critical materials

Raw material	**Main producer (2010-2012)**	**in %**	**Main sources of imports into the EU (mainly 2012[3])**	**in %**	**Worldwide use in RE technologies**	**in %**
Gallium	China*	69	USA	49	Solar PV	17
	Germany*	10	China	39		
	Kazakhstan*	6	Hong Kong	8		
Tellurium**	China	20			Solar PV	40
	Japan	20				
	EU	30				
Indium	China	58	China	24	Solar PV	8
	Japan	10	Hong Kong	19		
	Korea	10	Canada	13		
	Canada	10	Japan	11		
HREE	China	99	China***	41	Dy: permanent magnets	100
	Australia	1		35		
LREE	China	87	Russia***			76
	USA	7		17		
	Australia	3	USA***		Nd: permanent magnets	

*Refined production
** Data from EU COM , 2015c.
*** All REE.
Source: Data from COM (2014) 297 final; Joint Research Centre 2013: pp. 198-207; USGS, 2016, 186.

While this makes the European industry highly dependent on Chinese critical metals, Europe is not the main consumer of Chinese exports (SETIS, 2015, 11): the EU ranks only third after Japan and the US in terms of Chinese REE exports (NDRC, 2013; NDRC 2014). Figures show that EU

[3] The Communication from the European Commission to the European Parliament (COM 2014/297 final) shows data on critical metals imports into the EU from 2012 mainly including also other time frames that are not specifically referred to.

member states imported more REEs in 2013 compared to the previous year. However, growing exports to Japan and particularly to the US have led to a decline of the EU's importance as a market for Chinese REEs. The EU's supply of critical metals will therefore not only depend on Chinese domestic policies. The EU's supply might also be affected by technological development and policies in other countries, mainly Japan and the US. Particularly Germany (10 percent), Italy (4,8 percent), Denmark (4,6 percent) and the Netherlands (3,5 percent), who were among the top ten countries for Chinese permanent magnets export in 2013 (NDRC, 2014, 5-6) might be affected by international technological innovation.

Table 3: Chinese total exports of RE oxides, REE salts and REE by country/region

	2012		**2013**	
	in t	*in %*	*in t*	*in %*
Japan	6607	41	7781	34
USA	3461	21	8058	35
EU	3978	25	4458	20
Total	**14.046**	**87**	**20.297**	**89**

Source: NDRC, 2013; NDRC, 2014

5. China's REE industry

5.1 China's intentions

The Chinese government has justified export restrictions by pointing to the environmental and health hazards of the extraction and processing of rare earth elements. These activities are the source of severe environmental pollution resulting from radioactivity and chemical contamination in water and soil, which adversely affect human health and food production (Wübbeke, 2013, 391; Hayes-Labruto et al., 2013, 60). Possibly more important, the restructuring process of the Chinese REE industry followed upon concerns about low prices and slumping revenues, issues voiced by the Chinese leadership since the late 1990s. The inability to set prices for international trade of REE has been regarded as a problem, particularly since market prices were regarded as too low (Wübbeke, 2013, 391-2). In a 2012 White Paper the State Council argued that prices for REE did not reflect their real value. Also, China was seen to be lagging behind in terms of high-end product application technologies compared to the international level (State Council, 2012), while smelting and separation, on the other hand, is well developed (Xinhua Finance, 2015a). Permanent magnets produced in China, for example, did not reach the same quality as Japanese magnets (Wübbeke, 2013, 293). The 12th Five Year plan emphasizes the need to increase technological levels in REE downstream industries including permanent magnets to further the development of an innovative and sustainable economy (Wübbeke, 2013, 392-3 392). R&D and application research is therefore encouraged with the goal of building internationally competitive rare earth application enterprises (Xinhua Finance, 2015a). By the end of 2020, China thus aims to be a global leader in rare earth related technologies (Xinhua, 2016). The upcoming Five-Year Plan (2016-2020) for China's REE industry will address both resource protection and expansion of downstream sectors to render its REE industry successful in high-end applications and high value-added products (Xinhua Finance, 2015b).

5.2 Extraction and export of REE and REE products

Chinese export quotas on REE, which were lifted in May 2015 (ACREI, 2015), were part of a broader restructuring process of the Chinese REE industry. This process had begun already in the 1970s. First attempts to streamline China's highly fragmented REE industry were less successful, but more profound changes started with the introduction of the "Rare Earth Industry Development Plan" (2009-2015) and the "Several Opinions of the State Council on Promoting the Sustained and Healthy Development of the Rare Earth Industry". The Chinese government aimed at enhancing its control over the industry, which was plagued by inefficiencies as well as by illegal mining and processing activities causing low prices (Wübbeke, 2013, 386-7, 389). Significant amounts of illegally exploited rare earth oxides were smuggled out of the country. It is assumed that illegal exports of REE oxides reached 40,000 t in 2014. This is an increase compared to 20,000-30,000 t of illegally mined REE between 2006 and 2008 and 3,000 t in 2011, standing in sharp contrast to the official 2014 export volume of 28,000 t in 2014 (Stanway, 2015; Wübbeke, 2013, 389).

With the decrease of export quotas in 2011, international concern over supply security grew rapidly (Reuters, 2015b). Exports of REE declined from a peak of 57,400 t in 2007 to 15,660 t in 2011 and were supposed to remain below 35,000 t until 2015. (Wübbeke, 2013, 386). After reaching a price peak in 2011 of 100 times the prices of 2002-3, prices for REE stabilized at 2-3 times quotas before the price SETIS, 2015, 21). In certain cases this led, for example, to increasing prices for permanent magnets wind generators up to 50,000 Euros (Interview 2). Wind turbine manufacturers feared less possible supply shortages; rather they were alarmed by the unpredictability of price hikes and the lack of transparency in the Chinese decision making process. Continued high prices would have rendered permanent magnets technologies too expensive and therefore unattractive (Interview 2). On the other hand, export of REE products increased. The exports of permanent magnets nearly doubled between 2006 and 2010 out of which the USA (13 percent), South Korea (9 percent) and Germany (8 percent) were the main importing countries (Wübbeke 2013: 386). Examples of the development of Chinese exports by product between 2012 and 2013 are highlighted in table 4.

Table 4: Chinese export by product 2012-2013

2012	**Export** (in t)	**Change compared to previous year** (in %)
Rapidly-solidified permanent magnets	5433	-55
Neodymium iron boron poweder	1840	+44
Permanent Magnets	16348	+0.1
2013		
Rapidly-solidified permanent magnets	1334	-76
Neodymium iron boron powder	3277	+78
Permanent Magnets	18826	+15

Source: Data from NDRC, 2013; NDRC, 2014

Chinese export quotas were accompanied by mining quotas for REEs. In 2012, the Ministry of Land and Resources decreased the number of mining rights from 113 to 67, introduced taxes for resource extraction and production quotas for rare earth ore (Wübbeke, 2013, 388). While mining quotas for LREE decreased between 2013 and 2015, they remained constant for Medium Rare Earth and HREE ore (MHREE), a category specific to the Chinese industry that includes dysprosium[4] (see table 5). Following the "National Mineral Resources Plan" (2008-2015) the

[4] Chinese sources sometimes differentiate REE between light, medium and heavy rare earths. Materials are divided between heavy and light REE when the category concerns minerals' characteristics. However, when it is referred to

total amount of extraction was to be kept between 130,000 and 150,000 t until 2015 (Wübbeke, 2013, 386). In 2014, China raised the extraction upper limit so that output increased to 95,000 t (14.5 percent) (PR Newswire, 2015).

Table 5: Mining Quotas (in t)

	2013	**2014**	**2015**
Rare earth oxide (MHREE+LREE)	93,800	105,000	105,000
MHREE ore	17,900	17,900	17,900
LREE ore	75,900	87,100	87,100

Source: Data from Ministry of Land and Resources, 2013, 2014, 2015

5.3 Recent restructuring of China's REE industry – tax law, licenses, national champions

China's lifting of export quotas in May 2015 (ACREI, 2015; Ministry of Finance and Commerce, 2015) did not lead to relaxing exports of REE elements. Rather, the Chinese government introduced new measures that aim at the further streamlining of the REE industry and increased state control of critical metals. The most crucial measures include a new resource tax law, the introduction of export licenses and the establishment of a team of national champions, consisting of six state-owned enterprise groups, an initiative announced in 2014.

In line with the establishment and nurturing of strong national enterprises in other sectors of the Chinese economy (Eaton 2016), the State Council announced its plan to merge major state-owned enterprises active in REE extraction and processing (State Council, 2014). This policy

different ways of extraction and separation, the category MREE is introduced. Neodymium counts in both categories for LREE. Dysprosium, however, is according to its chemical characteristics a HREE but falls into the category of MREE according to ways how it is extracted and separated (Baike n.d.).

aims at strengthening the central government's control over REE production and marketing via the construction of a "joint force to face the outside world to change the current rare earth oversupply situation" (Yu, 2015). The China Treasury subsidizes this restructuring process and built up of national conglomerates by providing them with special funds (Argus White Paper, 2015).

Accordingly, the Chinese government has been restructuring China's rare earth industry into six state-owned enterprise groups since mid-2015: Northern Rare Earth (Group) High-tech Ltd. in Inner Mongolia, China Minmetals Corp. in Hunan, Aluminium Corp. of China (Chinalco), Guangdong Rare Earth Corp., China South Rare Earth Group (Guangzhou Rare Earth Group) and Xiamen Tungsten Group (Yu, 2015). The central government uses an annual evaluation system to control its state-owned enterprises' activities. This system incentivizes most state-owned enterprise managers as well as Party or government officials to meet annually set targets and guidelines. Meeting these targets provides managers opportunities to advance up the career ladder or even be promoted within the government. On the other hand, if managers fail to meet their targets they can be denied year-end bonuses. The central government uses these incentive structures as a tool to steer policy implementation by state-owned enterprises and local authorities and thereby tries to keep a tight grip on the Chinese economy (Kostka and Hobbs, 2012; Harrison and Kostka, 2014). The built up of REE groups clearly indicates the central government's attempt to fully control its REE industry.

The largest REE producer amongst Chinese newly established state-owned enterprise groups is the Northern Rare Earth Group in Inner Mongolia (Shen, 2015; Xinhua Finance, 2015c). By the end of 2015 it has integrated rare earth mining, smelting, separation and utilization enterprises in Inner Mongolia and Gansu province (Xinhua Finance, 2015d; Yu, 2015). In April 2015 the group announced that it would invest 100 million RMB in the establishment of a REE R&D center in Baotou. A further 50 million RMB will come from the Inner Mongolia Department of Science and Technology and the Baotou municipal government (China Daily, 2015). Xiamen Tungsten and Chinalco are the other two companies that have formed state-owned enterprise groups by the end of December 2015 (Xinhua Finance, 2015d). The total restructuring process is aimed at being completed by mid-2016 (Xinhua, 2016).

In 2015, China also introduced export licenses and a new rare earth tax law. Accordingly, companies are required to obtain export licenses from Ministry of Finance and Commerce. Issuing a license depends on the respective case. Through the limitation of export locations, China seeks to better control smuggling activities (Argus White Paper, 2015). The new rare earth resource tax law was introduced by Ministry of Finance and Commerce in April 2015. Taxes depend on region and rare earth element (Yu, 2015). The resource tax rate for HREE lies at 27 percent while the tax for LREE in Sichuan, Shandong and Inner Mongolia varies between 7.5 and 11.5 percent (State Administration of Taxation, 2015). The aim is to allow the "tariffs to reflect business growth as it is impacted by market demand" (Yu, 2015).

As a result, it can be expected that prices for LREE - possibly including neodymium - prone to oversupply will remain relatively stable or even decrease, whereas prices for HREE of limited supply but high demand, particularly dysprosium, are at risk to increase (Argus White Paper, 2015). Indeed, Chinese exports of LREE especially from Inner Mongolia have increased tremendously during the last months resulting in a price decline. For example, the US company Molycorp Inc. [5], which owned the largest REE deposit outside of China, filed bankruptcy in 2015 as a result of decreasing prices (BloombergBusiness, 2015; Reuters, 2016).

6. Attempts to decrease dependence on Chinese critical metals

There have been different efforts by governments and businesses to reduce China's control over REEs. Most notable is an international effort to innovate technology away from reliance on rare earth inputs. Faced with rising costs for Chinese dysprosium and neodymium resulting from export restrictions and China's policy of encouraging the relocation of permanent magnets manufacturers to China (ROMEO, n.d.), fifteen non-Chinese research centers and manufacturers, with advisors from Japan and the US, established a consortium under the name "Replacement and Original Magnet Engineering Options" with the aim of developing a totally rare-earth-free magnet and of reducing magnet manufacturers' dependence on Chinese raw materials (Argus White Paper, 2015; ROMEO, n.d.). Possible options to reduce dependence on Chinese supply include substitution of critical elements with alternative materials, re-opening mines in South Africa and the US, exploration of new mines, seabed mining, recycling and supply chain development. However, these strategies will need time to be developed and, for various reasons, do not promise a significant diversification of supply in the near future (Smith Stegen, 2015, 4-7). In the coming years, then, the EU renewable energy sector will continue to heavily rely on

[5] Molycorp extracted LREE, including neodymium, from the Mountain Pass Mine in California (BloombergBusiness, 2015; Reuters, 2016). Bidders for Molycorp were an Australian and a Chinese company (Reuters, 2016).

China's supply of REEs, particularly HREEs. This dependency on China's REEs poses significant supply chain risks for companies in the short and long term, particularly for European wind sectors.

6.1 The European wind sector

Companies in European wind sector have developed short-term and long-term strategies to address the issue of REE supply security. For instance, an executive from Siemens reported that the German company was already buying its permanent magnets directly from China instead of importing neodymium and dysprosium separately. Siemens thereby managed to achieve some insulation from China's REE export quotas (Bloomberg, 2010). Denmark's Vestas — the world's largest turbine manufacturer — was also concerned about the company's dependence on REEs for direct drive generators. By redesigning their direct drive generators, Vestas significantly reduced the amount of REEs in their direct drive turbines, using only a tenth of REE necessary for permanent magnets (Bloomberg, 2010). Other companies even opted for replacing permanent magnets with other technologies. For instance, in order to avoid reliance on neodymium, Germany's Enercon GmbH started using multi-polar synchronous annular generator in their gearless direct drive generators instead of permanent magnets (ENERCON, n.d.a; ENERCON n.d.b). The German turbine manufacturer Nordex also began producing its wind generators without permanent magnets (Interview 1).

At the same time, wind generators using permanent magnets account for only a small proportion of total installed wind energy. Therefore, only a part of the European wind industry is highly dependent on permanent magnets. Tailor-made permanent magnets, which are necessary for wind generators, are highly expensive. Alstom Wind, for example, receives permanent magnets from General Electric, which acquired the component supplier Converteam (Interview 2). Only a few companies, such as Siemens or Vensys, produce permanent magnets themselves. Due to cost advantages, classical technologies will therefore continue to exist in parallel (Interview 2).

6.2 The European Solar Sector

Findings suggest that companies in the European solar sector have been less concerned about possible supply risks of critical metals compared to wind companies. Companies producing CIGS-cells have in the past been concerned about the supply of indium, which is as rare as tellurium. However, due to decreasing prices for indium in the last years, experts are positive about future supply security (Interview 3, Interview 4). Experts in the solar sector also predict that in the near future gallium will not experience bottlenecks, which is reflected by decreasing gallium prices (Interview 3, Interview 4). In addition, European companies producing CIGS-cells have started to enter the Chinese market allowing them to minimize supply risks of critical metals. In recent years, those solar companies that were acquired by Chinese enterprises have enjoyed easier access to critical metals (Interview 3). Other solar companies have established subsidiaries in China which made it possible to secure access of critical metals in the short-term (Interview 3).

CdTe-cells, on the other hand, are produced by very few companies only (First Solar, Calyxo). The US company First Solar produces in Malaysia to take advantage of the preferential policies of the Malaysian government. For its production, First Solar receives most of the tellurium for its CdTe-cells from mines in Mexico (Interview 3, Interview 4). Data therefore suggest that tellurium appears less relevant for the European solar industry.

7. Conclusion and policy implications

We find that there are considerable supply shortages of some critical metals for European renewable energy technologies. In particular, a stable supply of the five critical metals (neodymium, dysprosium, gallium, tellurium and indium) is especially important for wind and solar technologies in Europe. The production of gearless direct drive wind generators used in both onshore and offshore wind generations and the production of thin film solar cells require a stable and affordable supply these five critical metals.

In the EU, the demand for these critical metals is rising. It is projected that by 2030, the demand for neodymium, dysprosium, gallium, tellurium and indium will grow rapidly. Most of these critical metals are predominantly sourced from China. Based on interviews and document analysis, our study shows that recent changes in China’s industrial policies will affect the supply of these four critical metals for the European Union. Recent restructuring of the Chinese critical metals industry aim to raise prices for key materials, increase China’s share of the applications markets, and support domestic R&D initiatives and technological upgrading (Wübbeke, 2013; Smith Stegen, 2015). Since 2015, additional industrial policy measures have been employed to speed up the restructuring process, including a new resource tax law, the introduction of export licenses and support for six state-owned enterprise groups. As these policies take effect, the

Chinese state will tighten its control over the supply of these critical metals and prices are likely to increase for consumers in the EU.

Yet, the companies in the European wind and solar sectors have been pro-active in addressing these growing supply risks. Through various means, they are moving to reduce their dependence on Chinese supplies of critical metals. In the short term, the most promising strategies employed include moving production to China and deepening cooperation with Chinese metal mining companies (e.g., through establishment of joint ventures or takeover of Chinese firms). In the longer term, pursuing diversification of suppliers and supply chains as well as reducing use of critical materials in renewable technologies are the most promising strategies.

The findings of our research underscore the need for more research into critical metals as well as the deepening of international research cooperation. For example, targeted studies should be undertaken to assess how governments in Europe can best address possible supply risks of critical metals. In addition, European businesses in the wind and solar sector also need to assess their supply risks and devise risk management plans for the short term and long term. As our research showed, recent changes in China's industrial policies will particularly affect the supply of critical metals for the European Union. Therefore, a better understanding of the Chinese intentions and policies towards critical metals will be helpful.

Annex: Interviews 2016

Interviews	Position	Date
Interview 1	Employee at a European Wind Company	28-01-2016
Interview 2	Employee at a European Wind Consultancy Firm	01-02-2016
Interview 3	Employee at a Chinese Solar Company	02-02-2016
Interview 4	Employee at a European Solar Company	03-02-2016

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