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China's supply of critical raw materials: Risks for Europe's solar and wind industries?

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A B S T R A C T

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.

Keywords:
Critical raw materials
Renewable energies
European energy security
China
Industrial policy

1. Introduction

In order to significantly decarbonize its energy sector (DG Climate Action 22-07-2016), the European Union (EU) has set a target of increasing the share of energy obtained from renewable sources to 27% by 2030. While European renewable energy firms possess the technological expertise to meet this goal, they are heavily reliant on imports of certain raw materials that enable greater complexity, sophistication and miniaturization; indeed, these raw materials have fueled the rapid boom in technological advancements for renewable energies. Given this strong dependence on a single country—China—for the sourcing thereof, both governments and industry analysts have raised concerns over future pricing and availabilities. Taskforces working for the European Commission have identified such raw materials as "critical", meaning that they are of high economic importance to the EU while entailing high supply risks (EU COM, 2014).

This paper examines raw materials deemed critical to the solar and wind energy sectors. These industries are at risk for supply bottlenecks and price volatility because the anticipated rapid growth in demand is coupled with difficulty in expanding capacity for the extraction of indispensable raw materials, the supply of which is concentrated in just a few countries that, in turn, themselves pose political risks (Moss et al., 2013). Our analysis focuses on five elements: tellurium, gallium and indium (used in making photovoltaics); and two rare earths, neodymium and dysprosium (used in manufacturing wind turbines). These industries stand as examples for other sectors, such as electric vehicles, that also require critical raw materials that might be chokepoints for production.

We analyze the supply risks associated with these five critical materials and assess the strategies undertaken by the European

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Commission and European renewable energy companies to preempt such risks. We argue that a clear differentiation between the sectors and technologies—as well as between the five materials themselves—is necessary to understand current and potential risks for the European wind and solar energy industries. Given the different market developments for these elements, our findings suggest that the solar and wind sectors are affected in different ways.

For European solar firms, several options exist to diversify the materials used in photovoltaics (PV); this fact moderates reliance on China for tellurium, indium and gallium. Because prices are currently low and there are alternative supply sources, European solar firms are, relative to their wind sector counterparts, less concerned about possible bottlenecks of raw materials for their technologies. Moreover, we find that the number of purely European solar companies using these materials is very small; many have either gone bankrupt or been taken over by foreign competitors, such as from China, and the global market is currently dominated by larger Japanese and US firms.

In contrast, the European wind turbine manufacturers, particularly those associated with producing offshore wind turbines, are more concerned about sourcing of the two critical materials used in their technologies: neodymium and dysprosium. The separation and processing of these rare earths are almost completely dominated by China. The future of Europe's rapidly expanding offshore wind energy will depend on the stable supply and pricing of these two materials, which, in turn, depend on Chinese interests and policies towards the raw materials industry.

Our research draws on fourteen semi-structured interviews conducted between January and July 2016 with representatives of European solar and wind companies, research institutes and European government agencies. A list of all interviews is included in Table A1 in the appendix. The analysis is also based on documents by the European Commission, as well as on media reports, information published on companies' websites and academic articles. Reports by the Chinese government and media in Chinese language were an additional source of valuable insights.

The next section examines how critical raw materials are used by European wind and solar manufacturers and discusses projections of future EU demand. The article then analyzes where the EU sources these materials and the extent of its dependence on China. The subsequent section provides an overview of China's recent policies towards the raw materials industry, followed by responses and strategies of the European wind and solar sectors. Our study finds that some materials are more critical than others and that the short-term tactics of some European companies to reduce their risk exposure may hinder their longer-term competitiveness on the global market. The research concludes by discussing several concerns and providing policy recommendations.

2. Demand and supply of critical raw materials in the EU renewable energy technologies

This section discusses the respective solar and wind technologies that depend on critical raw materials, reviews projected demand for these materials and provides an overview of the EU's primary and potential suppliers.

2.1. Demand for critical raw materials in European wind and solar sectors

Five raw materials are consistently cited as being at high risk for future supply disruptions in the European wind and solar energy technologies (Institute for Energy and Transport of the European Commission, 2011; Joint Research Center, 2013; Oakdene Hollins and Fraunhofer ISI, 2013). These are tellurium, indium and gallium for the solar industry, and neodymium and dysprosium for the wind industry. The EU's future demand for these materials depends on several factors: which renewable technologies will increase in efficiency, remain successful in the future and expand their EU-wide share (Schriefl and Bruckner, 2016). Thus, there can only be rough estimates for the EU's future demand and associated import dependencies. However, given current trends, political and commercial actors have raised concerns that both the use of renewable energies and Europe's technological competitiveness might be endangered by high prices and supply shortages of raw materials. Numerous factors have led to this emerging anxiety, including growing demand for certain high-tech applications in emerging economies and the domination of the production and supply of critical raw materials by a few companies in a few countries (Glöser et al., 2015; Sievers and Tecero, 2012).

Solar PV manufacturers use tellurium, gallium and indium in the production of thin film solar cells. Two different types of thin film cells use critical raw materials: CdTe (cadmium telluride) and CIGS (copper indium gallium selenide) cells. CdTe cells use tellurium and account for six to seven percent of global solar PV (IN20160203Solar). They are highly controversial because of the toxicity of cadmium, which renders their future in Europe uncertain (Marscheider-Weidemann et al., 2016). CIGS cells use indium and gallium; they currently hold a share of two percent of global solar PV (IN20160203Solar).

The European Commission expects demand for tellurium, gallium and indium to rise in the EU (Joint Research Centre, 2013). Table 1 indicates that the EU's demand for these materials is anticipated to peak around 2020 and then start waning. Demand is rising, as experts believe that the use of thin film cells will expand in the future, but their share of the global PV market is expected neither to exceed ten percent nor to outpace the growth rate of cheaper silicon cells (IN20160202Solar; IN20160203Solar). Experts also stress that the efficiency of thin film cells will increase; thus, in the long term, production of thin film solar cells will require significantly less tellurium, indium and gallium (Marscheider-Weidemann et al., 2016).

Wind turbine manufacturers use neodymium and dysprosium to produce permanent magnets for the generators used in two different types of offshore wind energy: 1, hybrid systems that combine a gearbox with permanent magnets and 2, direct drive technologies that eliminate the gearbox. A key advantage of permanent magnets over alternative technologies is that they reduce turbine size, thereby decreasing overall weight. As permanent magnets can replace mechanical gearboxes or their moving parts, they also allow for greater resilience (IN20160202Wind; SETIS, 2015). This makes permanent magnets crucial for offshore applications, where maintenance is expensive and the size of the turbines is continually increasing.[1]

Table 1
Projected demand of critical raw materials in EU wind and solar energy.Source: Joint Research Centre, 2013, 76

Material	Annual EU Demand *(in tons)*	
	2020	**2030**
Solar		
Tellurium	150	126
Indium	145	121
Gallium	4	3
Wind		
Neodymium-Praseodyium[a]	845	1.222
Dysprosium	58	84

[a] The report treats neodymium and praseodymium together, as they are not always separated out (Joint Research Centre, 2013, 76).

Table 2
Deployment scenario for wind energy development in the EU.Source: Arántegui and González, 2015, 36

	Year	Total (in GW)	Onshore (in GW)	Offshore (in GW)
Cumulative capacity	2014	130	121	9
Installations	2015–20	78	60	18
	2021–30	145	60	85
	2031–50	150	40	110

The EU anticipates demand in the EU for neodymium and dysprosium to rise by 2020 and 2030, respectively (see Table 1). This projected growth in demand is due to significant EU investments in wind energy, especially in offshore wind installations (see Table 2). Currently, offshore wind installations account for only about ten percent of the EU's wind energy (IN20160708Wind). By 2020, offshore wind is expected to increase 15-fold to 44 GW (Joint Research Centre, 2013) and, within ten years, possibly accounting for 30–40% of all wind energy in the EU (IN20160708Wind). Onshore installations currently produce about 90% of the EU's wind energy; however, as indicated in Table 2, growth in this area is expected to be much lower than that of offshore wind.

2.2. *Supply sources of critical raw materials*

As the section above indicates, the EU will generate substantial demand for tellurium, indium, gallium, dysprosium and neodymium in the coming years, with consumption patterns for the solar and wind sectors diverging as we near 2030. Where the EU sources these materials depends on supply availability and processing capacities. As China is the predominant provider of many raw materials and possesses the only integrated mine-to-magnet value chain in the world (Smith Stegen, 2015a), it tops the list of suppliers. Yet, as the analysis below shows, dependency on China and the existence of alternative supply sources varies between the five critical raw materials used by European wind and solar energy industries.

Of the five materials, tellurium has the most diversified production in terms of quantities (see Table 3). According to the International Copper Study Group, China commands about 20% of global tellurium production. Other producers include Japan and, within Europe, Belgium (IN20160617P-a) and Sweden (U.S. Geological Survey, 2016, 169). The EU's dependence on China for tellurium is therefore less than for the other four materials.

The EU's dependency on China for indium and gallium is much higher. While there is diversified production for indium—in Belgium, Germany, Italy, the Netherlands and the United Kingdom (EC IP/16/2581, 2016)—the quantities are small: the EU relies on China for 58% of its total demand (Eurostat, 2013). Gallium is the least diversified of the three critical materials needed for solar applications. While production facilities for gallium are currently being built in France (IN20160617P-a), the EU meets 69% of its need with supplies from China (Eurostat, 2013).

Compared to European solar firms, the EU's wind industry is much more heavily reliant on China for the rare earths neodymium and dysprosium.[2] Europe does have rare earth deposits, but they all present challenges, such as high radioactivity; thus far, none has been developed (Ebner, 2014). The EU's dependence on China is highest for dysprosium: at the moment, China is the only country with processing facilities for dysprosium (Smith Stegen, 2015a). The EU therefore imports 99% of its dysprosium from China, which makes it fully dependent (Institute for Energy and Transport, 07-04-2016b). Indeed, few alternative sourcing options exist. Although the most promising European dysprosium deposits are in Sweden (Rare Earths Competency Network, 2015, 36); Swedish authorities have rejected mining in the absence of adequate environmental studies (Tasman Metals, 2016).

Table 3
The EU's dependence on Chinese critical raw materials.Sources: Eurostat, 2013; Moss et al., 2013, 560; authors' research

Material	Dependency on China	Percentage sourced from China	Other main possible supply sources
Solar			
Tellurium	Low	20*	Japan, Belgium, Sweden
Indium	Medium	58	Belgium, Germany, Italy, Netherlands, UK
Gallium	Medium	69	France
Wind			
Neodymium	High	90	Australia
Dysprosium	High	99	–

* For tellurium only global production data is available

The neodymium situation is not much better: 90% of that used by EU wind companies is imported from China (IN20160617P-a). After prices for rare earths shot up to their dramatic peaks in 2011, around 200 exploratory projects and start-ups for rare earth extraction emerged around the world. One of the most significant neodymium facilities and an important partner for Germany's Siemens AG was the Mountain Pass mine in California (IN20160622Wind), which also owns rare earth manufacturing facilities in Estonia (Molycorp, 2015). Another important mine is located in Australia (IN20160304Wind) with processing facilities in Malaysia (IN20160617P-a; IN20160622Wind). However, once prices for neodymium fell again and environmental issues caused competition outside of China to stagnate, most of these projects, including the Mountain Pass mine, were shut down (IN20160622Wind). This has led to today's situation, in which China holds a near-monopoly of global neodymium separation and production, despite the relative abundance of other potential sources worldwide (IN20160216P).

In sum, Europe's demand for the critical materials needed in its solar and wind sectors will increase in the coming years. This growth will continue beyond 2020 for the rare earths required for wind energy technologies, particularly for neodymium, but will taper off for the three solar materials. Meanwhile, with the exception of tellurium, China is set to solidify its position as the EU's predominant supplier. Thus, it behooves EU policy and industry analysts to stay on top of developments in China's industrial policies and the implications for—and specific reactions by—EU firms. These are the tasks we tackle in the next sections.

3. China's raw materials industry: chinese interests and industrial policies

3.1. *Recent government efforts to control China's raw materials*

In recent years, the Chinese government has become more proactive towards managing its raw materials industries. China's

[1] Whereas the size and maintenance of offshore turbines render mechanical gearboxes less attractive than permanent magnet technologies, onshore turbines are well served by gearbox motors, so only about a third employ permanent magnets (IN20160708Wind). Not only are onshore turbines smaller—1.5–3 MW compared to offshore capacities of 3 or even 5–8 MW (IN20160622Wind)—their ease of access makes maintenance less costly. Onshore wind energy therefore does not need to eliminate the mechanical gearbox, and permanent magnets, if used at all, are often combined with a gearbox (IN20160708Wind).

[2] Neodymium is one of the light rare earths, which are more abundant and relatively easier to process than the heavy rare earths, such as dysprosium.

Table 4
Price changes for neodymium and dysprosium.Source: IN20160313WindDoc

	Price changes (USD/kg)		
Wind	**2005**	**2011**	**2014**
Neodymium	11	185	66
Dysprosium	66	2392	341

past implementation of export quotas on neodymium and dysprosium provide a prime example: the price for neodymium increased from 11 USD per kg in 2005–286 USD per kg by 2011. Prices for dysprosium skyrocketed from 66 USD per kg in early 2005–2392 USD per kg by 2011 (IN20160313WindDoc). Prices started declining after 2011; by mid-2014, prices for neodymium had decreased to 66 USD per kg, and dysprosium prices had dropped to 341 USD per kg. As a consequence of its World Trade Organization (WTO) dispute with the EU, Japan and the US, China lifted its export quotas in May 2015 (Association of China Rare Earth Industry, 2015). By the end of 2015, prices were about 10% lower than in mid-2014 (IN20160313WindDoc). Table 4 summarizes the price developments of neodymium and dysprosium between 2005 and 2014.

Although the Chinese government has been blocked from implementing quotas, it continues to introduce other measures to increase state control of critical raw materials and streamline its rare earths industry. The most crucial measures include a massive restructuring of the rare earths industry. In line with the establishment and nurturing of strong national enterprises in other sectors of the Chinese economy (Eaton, 2016), in 2014 the State Council announced plans to merge the major state-owned enterprises active in rare earth extraction and processing (State Council, 2014). Accordingly, the Chinese government has been restructuring its rare earths industry into six state-owned enterprise groups: Northern Rare Earth (Group) High-tech Ltd., China Minmetals Corp., Aluminum Corp. of China (Chinalco), Guangdong Rare Earth Corp., China South Rare Earth Group and Xiamen Tungsten Group (Yu, 2015).

3.2. Chinese interests and industrial policies

Several reasons could account for the Chinese government's drive for greater control. First, the government has been concerned by the severe environmental and health hazards caused by the extraction and processing of rare earth elements. These activities are responsible for environmental pollution resulting from radioactivity and chemical contamination in water and soil, which adversely affect human health and food production (Wübbeke, 2013; Hayes-Labruto et al., 2013). Second, the government is worried about resource depletion, as China will need critical materials for its own renewable energy technologies (Smith Stegen, 2015b). In 2015, China installed 30 GW of new wind turbines, which was nearly double that of 2013 (cnenergy, 2016). Third, since the late 1990s, China's leadership has voiced concern about low prices and slumping revenues for rare earths including neodymium and dysprosium. The inability to set prices for the international trade of rare earths has been regarded as a problem (Wübbeke, 2013). China also attributes low prices to its domestic unofficial mining, which accounts for about 40% of China's total production of rare earths (IN20160216PDoc). The Chinese government has attempted to eliminate illegal extraction, but these efforts are subverted by local governments that have an interest in maintaining their local mining activities (IN20160216P).

The fourth reason the Chinese government would like greater control is to improve its industrial competitiveness. The State Council deems China's research and development on rare earths as lagging behind international standards and high-end-product application technologies as less sophisticated than foreign technologies. This leads to “low-end product overflow while high-end products are in short supply” (State Council, 2012). Permanent magnets produced in China, for example, are reportedly not as good as Japanese magnets (Wübbeke, 2013). R&D and application research has been therefore encouraged, with the goal of building internationally competitive rare earth application enterprises (Xinhua Finance, 2015). Thus, by the end of 2020, China seeks to be a global leader in related technologies (Xinhua, 2016). According to the “Made in China 2025″ strategy, the 13th Five-Year Plan (2016–2020) aims at expanding downstream sectors to make China's rare earths industry successful in high-end applications and high-value-added products (Xiejing, 2016). The formation of six rare earths groups strengthens the central government's control over the production of rare earths and forms a “joint force to face the outside world to change the current rare earths oversupply situation” (Yu, 2015).

While quotas and restrictions for neodymium and dysprosium have been eliminated, China maintains export restrictions on other materials, including indium. China regards indium along with gallium and tellurium as strategic metals that are important for its expanding thin film solar industry (China Chamber of Commerce for Import and Export of Machinery and Electronic Products, 2015). The Chinese Ministry of Commerce argues that “export duties and quotas are based on the need to protect the resources and the environment (…) and comprehensive measures to strengthen the protection of the ecological environment” (EurActive 19-07-2016). In contrast, between 2009 and 2011, China more than quadrupled its gallium production and now accounts for nearly 70% of global gallium production (EU COM, 2015a). It is expected that China's own use of gallium will grow every year by 20–30% due to increasing use of CIGS cells, LED lighting applications and medical equipment (Asian Metal, 2016; China Chamber of Commerce for Import and Export of Machinery and Electronic Products, 2015). However, at the moment, there is overcapacity in gallium (IN20160617P-a).

4. Strategies to decrease dependence on Chinese critical raw materials

The Chinese government's recent attempts to assert greater control over its materials industries—export quotas, industry restructuring and steering production levels of specific materials—have raised concerns among some members of the European renewable energy community that higher prices may eventually ensue (IN20160630P; IN20160622Wind; IN20160617P-a). The European Commission and renewable energy firms have therefore developed short- and long-term strategies to cope with future uncertainties with regards to critical raw material supply and dependence on China. As we will discuss in this section, because of its greater vulnerability, such strategies are more prevalent in the wind sector.

4.1. Actions taken by the European Union

At the political level, possibly the most visible action by the EU has been to charge China with trade violations through the WTO. In 2012, the EU, together with Japan and the US, filed a WTO case against China's quotas on rare earths. Two years later, the WTO ruled that the quotas were “designed to achieve industrial policy goals rather than conservation” and thus violated international law (WTO, 2014). The message for China was that the EU would fight against trade restrictions (IN20160216P; IN20160627P). Indeed, in July 2016, the EU, together with the US, launched another case against China for limiting supplies of eleven raw materials, including indium. The European Commission expects that the supply of indium will increase once China removes its export restrictions (EC IP/16/2581, 2016). As the WTO examples indicate, the EU regards cooperation with other countries as a useful intervention tool when China imposes trade restrictions beyond the 84 products on which it is allowed to levy export duties. The European Commission also regards dialogue within international forums, such as the G20 or the OECD, as another promising way to ensure that its own interests vis-à-vis China are heard (IN20160627P).

An additional strategy employed by the EU is the promotion of research, both within the EU and with international partners. One example is the research consortium "Replacement and Original Magnet Engineering Options" (ROMEO), which consists of fifteen non-Chinese research centers and manufacturers, with advisors from Japan and the US, and which aims to develop rare-earth-free magnets (Argus White Paper, 2015; ROMEO, n.d.). Other EU-funded projects with similar objectives include the *Suprapower project, INNWIND.EU* and *EcoSwing Horizon 2020* (Arántegui and Gonzáles, 2015).

Beyond filing WTO cases and initiating international cooperation and research, the European Commission's strategies for coping with Chinese dominance also include bilateral negotiations as a way of averting export duties (IN20160627P). The EU maintains dialogue with China, such as within the framework of the EU-China Summit and the EU-China High Level Economic and Trade Dialogue, where it discusses issues in the bilateral trade relationship with China (DG Trade, 2016).

4.2. Actions taken by European solar companies

Compared to their wind sector counterparts, European solar companies have been less concerned about possible supply risks. The difference is attributable to the relative abundance of the three materials critical for the solar sector, as well as changes in ownership. Yet despite their low level of concern, European solar companies nevertheless emphasize the importance of decreasing dependence on China and have developed a range of short- and long-term strategies to that end.

Over the past decade, the size of the European solar industry has sharply declined, and only a few purely European companies are still active in the thin film market. Many European companies have gone out of business or have been taken over by foreign competitors, such as from China. Larger Japanese and US firms currently dominate the global market. The US company First Solar and the Japanese firm Solar Frontier in particular count among the leading manufacturers of CdTe and CIGS cells (IN20160203Solar). Of the remaining European companies, German firms such as Calyxo and ANTEC Solar produce CdTe cells (using tellurium), and MANZ (IN20160203Solar) produces CIGS cells (using indium and gallium). Two other originally German companies, Avancis and Solibro, still produce CIGS cells but have since been acquired by two Chinese companies, the China National Building Materials Group Corporation and Hanergy Holding Group, respectively (IN20160202Solar; Avancis, 2014; china-investiert.de).

Solar and raw materials experts currently expect no future supply bottlenecks for tellurium, indium and gallium (IN20160203Solar; IN20160202Solar; IN20160226Solar; IN20160617P-a). However, as discussed in Section 2, there are differences across the three materials in terms of demand growth and supply sources. Tellurium is regarded as the material of least risk due to its diversified production, followed by indium and gallium, the latter being the material with the fewest alternative supply sources outside China (IN20160617P-a).

Solar cell manufacturers have developed both short- and long-term strategies to address potential supply risks. In the short run, many firms have improved their access to Chinese raw material supplies by building up a local presence or establishing subsidiaries in China, and European companies acquired by Chinese owners are now essentially domestic entities with direct inroads to supply. These different arrangements increase the dependence of the European solar industry on China, so company representatives have begun arguing for additional EU protections against cheap Chinese products (IN20160226Solar). Furthermore, in the short term it will be important for firms to spot developments in the raw materials markets early on. Market observation and analysis of China's industrial policies are particularly important for indium and gallium, as the bulk thereof is still sourced from China (IN20160617P-a). Although prices for these elements are currently low (IN20160202Solar), fluctuations can be caused by the expansion of other technologies, such as LED lighting and displays, that also use gallium and indium, as well as by changes in Chinese industrial policies (Marscheider-Weidemann et al., 2016, 125).

For the long term, recycling has been touted as a way to alleviate material shortages. At the moment, recycling seems more promising for indium and gallium than for tellurium. Indium, for example, can be retrieved from CIGS post-industrial scrap. It is expected that the amount of indium recycled from post-consumer volumes will increase as products start entering the waste stream. Similarly, gallium is already being reclaimed in Belgium from pre-consumer CIGS waste, but post-consumer recycling has not yet taken off, since products have only recently come onto the market (EU COM, 2015b, 82–5).

Another very important long-term strategy to ensure stable supply is the development of alternative sources. Solar manufacturers are looking into thin film solar PV production in Malaysia, for instance, since over the past few years the Malaysian government has successfully attracted foreign investment through financial incentives such as tax abatements (IN20160202Solar). For the production of tellurium, there are also a few options for increasing the supply, including the potential to increase production in Belgium (IN29160607P-a).

4.3. Actions taken by European wind turbine manufacturers

In contrast to the solar sector, the European wind industry is more alarmed about future supply and prices of critical raw materials for their permanent magnet technologies. The European wind industry is larger than the European solar industry and includes a number of globally significant wind turbine manufacturers, such as Germany's Siemens AG and Denmark's Vestas Wind Systems. While prices for neodymium and dysprosium have fallen from the 2011 peak —hence lowering corporate and government concern about high prices for these materials—price hikes of 3–5 times the current rates are not unthinkable in the future (20160622Wind). Such market developments would have swift profit implications for Europe's wind turbine manufacturers. To improve their resource supply security and decrease their dependence on Chinese imports, European firms have adopted strategies for both the short and the long run, the most important of which include altering their sourcing approaches and re-engineering technologies to reduce or avoid the use of these materials.

For the short term, European wind companies have developed joint ventures with Chinese firms and signed long-term trade contracts with Chinese suppliers. Siemens, for example, is buying its permanent magnets directly from China instead of importing neodymium and dysprosium separately. In this way, Siemens has managed to achieve some insulation from China's previous export quotas on neodymium and dysprosium (Bloomberg, 2010). For their new imports of permanent magnets from China, Siemens also switched to multi-year contracts that ensure both stable supply and constant pricing (IN20160622Wind). However, the new tactic of directly importing permanent magnets does not help decrease dependency on China in the long term (IN20160216P).

An important long-term strategy for European turbine manufacturers is the development of alternative technologies that use less neodymium and dysprosium or that replace permanent magnets altogether with other technologies. Avoidance of permanent magnets is of particular relevance for onshore wind turbine manufacturers, because onshore wind turbines can dispense with permanent magnets (IN20160622P). Some onshore wind companies, such as the German turbine manufacturer Nordex, have already opted to substitute permanent magnets with other technologies (IN20162601Wind). The German firm Enercon has also started using a multi-polar synchronous annular generator in their gearless direct-drive generators (ENERCON, n.d-a; ENERCON n.d-b), which makes it (currently) the only company to build sophisticated, direct-drive turbines without permanent magnets. While Enercon's technology is successful for onshore turbines, its heavier weight makes it unsuitable for offshore installations (IN20160708Wind).

Although promising, most replacements for permanent magnets are less efficient and perform less well—which raises costs for manufacturers. There are also concerns among industry experts that some European producers may be resorting to second-best technologies as a way to circumvent supply risks (IN20160622-Wind). While these substitution strategies may solve long-term supply problems, using second-best technologies could hinder global competiveness. Leading European wind manufacturers can only compete against Chinese firms like Goldwind by offering technologically *more sophisticated* and *more reliable* turbines; this long-term advantage stands to be lost to short-term tactics (IN20160708Wind).

Manufacturers of offshore wind turbines simply cannot do without permanent magnets in their generators; instead, they can only reduce the amounts of neodymium and dysprosium required. Vestas, for instance, has already redesigned their direct-drive generators to use one-tenth less neodymium and dysprosium (Bloomberg, 2010). There is further potential to reduce the use of dysprosium in permanent magnets, and experts anticipate that, within a few years, permanent magnets for wind turbines may no longer contain any significant amounts of the element (IN20160216P; IN20160304Wind; IN20160622Wind). However, as neodymium is a crucial component of permanent magnets, and the amounts used in a permanent magnet are much larger than that of dysprosium (IN20160622P), it is much more difficult to reduce demand here.[3] Given this limited potential for savings, and given China's continued monopoly over supplies (IN20160216P), neodymium is the material of highest concern to European wind turbine manufacturers (IN20160630P).

In the long term, recycling neodymium and dysprosium might be another way to lower supply dependence on China. However, recycling research has hitherto produced few breakthroughs, as reclamation of neodymium and dysprosium is extremely complex. Recycling from small devices, such as mobile phones, has so far yielded relatively small quantities. Recycling from larger applications, such as wind turbines or electrical vehicles, might be more fruitful, but most of these will not become waste products for many years, and even in this category there are vast yield differences: “A Toyota Prius uses 2.2 pounds of neodymium… and a new-generation windmill requires 1500 pounds of neodymium” (US EPA, 2012, 5-2; see also Smith Stegen, 2015a, 4–7).

In sum, supply risks do exist for the European wind turbine industry but affect the manufacturers of offshore and onshore wind turbines differently. Onshore wind turbines can potentially employ technologies that forego permanent magnets without major disadvantages, while manufacturers of offshore wind turbines, by contrast, cannot. Instead, they must work on technologies that use less neodymium and dysprosium. It will be particularly challenging to reduce consumption of neodymium.

5. Conclusion and policy implications

By assessing the current challenges posed by import reliance on critical raw materials for European solar and wind companies, this study highlights the need to differentiate between market developments and policies surrounding the five critical raw materials. The findings show that the European solar and wind energy industries are exposed to different demand and supply risks. In the solar sector, demand for the three critical materials tellurium, indium and gallium is expected to rise moderately by 2020 and likely to decline by 2030, by which time experts expect that thin film cells will be produced more efficiently. The supply situation for the three materials is relatively stable because alternative sources exist in European countries and Japan. And, relative to gallium and indium, dependence on China for supplies of tellurium is relatively low.

Compared to their solar-industry counterparts, the EU wind industry is significantly more vulnerable to supply bottlenecks and price volatility. Demand for neodymium and dysprosium is projected to grow rapidly in the next 15 years; demand for neodymium, in particular, is expected to boom since it is used not only in permanent magnets but also in electric vehicles. The supply situation is especially precarious for European wind turbine manufacturers, as the EU imports 90% of its neodymium and 99% of its dysprosium from China. The lack of alternative sources, the currently low price levels and environmental concerns about extraction render the buildup of supply chains outside of China an extremely difficult and protracted undertaking; indeed, for dysprosium there are no real alternative production sources on the horizon. There are, however, options for producing dysprosium-free permanent magnets. Finally, manufacturers of onshore wind turbines have fewer supply concerns than those of offshore turbines because they can use technologies that forego permanent magnets without major disadvantages.

Given China's role as a key supplier for the five critical materials, this paper also analyzed Chinese domestic interests and policies. Recent restructuring of the Chinese critical materials industry aim to raise prices for materials, to increase China's market share for their applications and to support domestic R&D initiatives and technological upgrading. Since 2015, the central government in Beijing has rolled out additional industrial policies, including a new tax on resources and the introduction of export licenses. As these policies take effect, the Chinese state will tighten its control over the supply of critical metals, and prices are likely to increase for consumers in the EU.

The European Union and European renewable energy firms have moved to reduce their exposure to the risks associated with dependence on Chinese supplies of critical metals; tactical measures include signing long-term supply contracts with Chinese firms, shifting production to China, building joint ventures with Chinese companies and using second-best technologies that minimize reliance on these critical materials. While these responses are important first steps in addressing supply bottlenecks,

[3] The amount of neodymium in a permanent magnet in a wind turbine (together with praseodymium) is about 20–30%. By contrast, the amount of dysprosium is significantly smaller, between 0.5% and 5%. While a permanent magnet for onshore turbines weighs between 100 and 150 kg, direct-drive systems for offshore wind energy use permanent magnets that weigh between 2 and 4 t. This means that, for example, a permanent magnet for a direct-drive system needs about 1700 kg of neodymium (IN20160622Wind).

Table A1
List of Interviews.

	Abbreviation	Date	Representative of
1	IN20160128Wind	28-01-2016	Wind company not using permanent magnets
2	IN20160201Wind	01-02-2016	Consultancy for wind farms (I)
3	IN20160202Solar	02-02-2016	Solar company acquired by Chinese company
4	IN20160203Solar	03-02-2016	Solar company acquired by Chinese company
5	IN20160216P	16-02-2016	Sub-ministerial geoscientific authority
	IN20160216PDoc	16-02-2016	Document received from a sub-ministerial geoscientific authority
6	IN20160226Solar	26-02-2016	Solar company not using critical raw materials
7	IN20160304Wind	04-03-2016	Wind company using permanent magnets
	IN20160313WindDoc	13-03-2016	Document received from a wind firm
8	IN20160617P-a	17-06-2016	Sub-ministerial geoscientific authority
9	IN20160617P-b	17-06-2016	European Commission
10	IN20160622Wind	22-06-2016	Wind company using permanent magnets
11	IN20160627P	27-06-2016	European Commission
12	IN20160630P	30-06-2016	European Commission
13	IN20160708Wind	08-07-2016	Consultancy for wind farms (II)
14	IN20160722Wind	22-07-2016	Offshore wind company using permanent magnets

most actually increase dependence on China in the long term. In the wind sector, in particular, use of lesser technologies could place European companies at a competitive disadvantage to Chinese firms on the global market. For the longer term, the most promising strategies involve pursuing the diversification of suppliers and supply chains, as well as reducing the use of critical materials in renewable technologies.

These findings come with numerous policy implications for both the EU and its wind and solar industries. They underscore the need for European businesses to assess their supply risks clearly and to devise best-practice risk management plans for both short and long terms. For the EU, it will be important to closely follow China's industrial policies in order to detect, early on, any policy changes that may affect the supply of critical raw materials down the line. They also point to a number of areas where investment in further research is warranted: in particular, to overcome barriers to recycling and to find alternative components for permanent magnets. R&D activities in the field of clean processing and the separation of critical raw materials could also be expanded to address environmental concerns. Possible cooperation with China in this area could be explored. Alternate supply sources—both within the EU and outside it—could also be considered. Here, the EU could intensify its joint research efforts with countries that have similar interests, such as Japan.

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Appendix A

See Table A1.

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