Resource Management for Carbon Management: A Literature Review

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Abstract

Resource use and climate change are closely related, therefore resource management also needs to be discussed in terms of carbon management. The authors conducted a literature review to identify important aspects of resource management from the viewpoint of greenhouse gas (GHG) emission reductions. As for management of carbon- intensive materials such as steel, cement and paper, it would be impossible to reduce GHGs by significant amounts without lowering global levels of material consumption. However this option has not been explored in detail. Identifying reasons for differences in current material consumption in different countries is an important first step for exploring development in Asia that would be less resource-intense. At the same time, measures such as demand management, weight saving, substitution and lifetime extension need to be explored in more detail. As for management of minor metals associated with mitigation technologies, criticality analyses of metals show that rare earth elements are important to the penetration of mitigation technologies. Recycling, substitution and reduction of intensity of use need to be further investigated for these metals.

Key words: criticality analysis, dematerialization, lifetime extension, recycling, reuse, weight saving

1. Linkages between Resource Management and Carbon Management

The growth rate of China's crude steel production in the 1990s and 2000s has been astonishing: production reached 637 Mt in 2010, nearly ten times greater than the 66 Mt of 1990 (World Steel Association, 2012). The Asia and Oceania regions (including China, Japan, India and Korea) accounted for 65% (45%, 8%, 5%, and 4%, respectively) of the global crude steel production of 1,429 Mt in 2010. China is also an important player in cement production: it produced 1.6 Gt in 2009, which was more than half the global cement production of 3.0 Gt (US Geological Survey, 2012). China and India have more than doubled their cement production in the last decade. Looking at paper and paperboard production, China produced 97 Mt in 2010, which was about 24% of the global production of 400 Mt (ForeSTAT, 2012). China and India have increased their production to three times that of twelve years ago. The Asian region accounted for 44% of global production in 2010.

Further increases in resource demand are expected in the coming decades in Asian developing countries, considering their current per capita resource consumption level and their promising economic growth. These increases in resource demand will inevitably affect greenhouse gas (GHG) emissions. In particular, demand for carbon- intensive materials such as steel, cement, paper and plastics are important when considering global GHG emissions.

As climate change has become an important global issue, various new technologies to reduce GHG emissions, such as energy-saving vehicles, fuel cells, photovoltaic cells, and wind power, have been developed and have penetrated. For example, the global photovoltaic power capacity of 40 GW in 2010 was about thirty times larger than that of 1.4 GW in 2000; and the global wind power capacity of 198 GW in 2010 was more than ten times greater than that of 17 GW in 2000 (Renewable Energy Policy Network for the 21st Century, 2011).

These technologies require the use of various minor metals. For instance, electric vehicle technology needs secondary battery technologies, which require metals such as lithium; fuel cell technology needs precious metals such as platinum; photovoltaic cell technologies require metals such as indium and gallium; and permanent magnets need rare earth elements. Large-scale deployments of these technologies will be necessary for significant reduction of GHG emissions in the future. This, however, implies that strong demand for some minor metals will occur. The supply of those metals may be a factor restricting the diffusion of these mitigation technologies.

As described above, resource use and climate change are closely related: resource management also needs to be discussed in terms of carbon management. For this paper, the authors conducted a literature review to identify important aspects of resource management from the viewpoint of GHG emission reductions. In Section 2, we focus on management of carbon intensive materials. Major questions include, what amounts of carbon intensive materials will be required in coming decades, and what the potential will be for reducing GHG emissions through sustainable resource management. In Section 3, we focus on management of minor metals associated with mitigation technologies. Major questions include, what amounts of minor metals will be required for large-scale deployment of mitigation technologies, and what countermeasures will be needed if demand is not met.

2. Management of Carbon Intensive Materials

2.1 Modeling for estimating materials demand and mitigation measures

Estimating materials demand in the future is the first step toward discussing future GHG emissions and resource management. Several approaches have been adopted for this:

1) Extrapolation approach,
2) GDP-oriented approach, and
3) Service-oriented approach.

Approach 1 extrapolates past trends into the future. This approach may be effective in the short term, but there is no clear reason to assume continuation of past trends in the long term. Approach 2 analyzes the correlation between materials demand and GDP and uses this correlation to estimate materials demand under a given GDP scenario. Approach 3 estimates materials demand based on demand for services, *e.g.*, for housing and transportation, in the future. While GDP plays as a proxy of service demand in Approach 2, services in physical terms are defined in Approach 3. This would be the most reasonable way to estimate materials demand because materials demand is more directly correlated to services than GDP. However, a large amount of data is required for this modeling. Demand estimates in the following sections apply to Approaches 2 and 3.

From the resource management point of view, several measures are effective at reducing GHG emissions:

A) Demand management,
B) Weight saving / lower intensity of material use.
C) Substitution of materials,
D) Extension of product lifetimes, and
E) Recycling of byproducts and end-of-life products.

Dynamic material flow modeling is necessary for analyzing the effectiveness of lifetime extension and the future scrap supply for recycling. In some studies, Approach 1 (extrapolation) has been adopted for estimating the future scrap supply, but this is less meaningful, considering the dynamics of the scrap supply from end-of-life durables. In addition, the modeling of other materials' demand and supply is necessary when the recycling of byproducts from other industries is considered. This issue is discussed in more detail in Sections 2.2 and 2.3.

2.2 Steel demand and mitigation measures

The iron and steel sector (coke-making process included) is the largest source of GHG emissions from the industrial sector: its global emissions were 2.6 $GtCO_2$ in 2006 (IEA, 2009a), including indirect emissions from electricity. There are three steelmaking routes: blast furnace (BF)/basic oxygen furnace (BOF), electric arc furnace (EAF), and direct reduced iron (DRI). The EAF route uses only 30% to 40% of the energy of the BF/BOF route, with GHG emission reduction being a function of the source of electricity. Significant energy savings can be achieved by switching from BF/BOF to EAF production (measure E). However, such changes may be limited by factors such as scrap availability and the demand for higher grades of steel.

Table 1 shows that global steel demand can be doubled at most in 2050 from the 2010 level of 1.4 Gt, which will lead to a corresponding increase in GHG emissions from the iron and steel sector. China's steel demand is expected to increase and then decrease after reaching a peak. The demand in 2050 may be slightly increased or decreased from the current level of 0.6 Gt in 2010, depending on the estimate. Hatayama *et al.* (2010) and Pauliuk *et al.* (2012) use per capita stock as a driver of future steel demand and their estimates show lower values than those of the IEA (2009) and Zhou *et al.* (2011).

The range of Pauliuk *et al.*'s estimate is the result of assumptions on the per capita stock level and lifetimes of products. A lower per capita stock (0.8 t/cap) (measures A, B, and/or C), which is the saturation level of France and the UK, would decrease steel demand in China significantly to the lower level of 0.3 Gt in 2050. This means that significant GHG reduction could be achieved if a lower per capita stock is realized. Note that Pauliuk *et al.* (2012) reported that longer lifetimes (measure D) would not affect China's steel demand until 2050. Few quantitative studies have been made regarding the potential reduction of steel demand through lightweight design and high-performance steels such as corrosion-resistant steels and high-strength low-alloy steels (measure B). Carruth *et al.* (2011) examined the opportunity to reduce requirements for steel by lightweight design of structural beams, food cans, car bodies, reinforcing bar, and deep sea oil and gas pipelines. If the proposed savings in their design case studies are possible in all steel products, total steel requirements could be reduced by 25%-30%. This means a potential reduction of corresponding GHG emissions.

As for recycling (measure E), the IEA (2009a) esti-

Table 1 Recent estimates of demand for carbon-intensive materials and their scrap supply in 2050.

		Annual demand (Gt)	Annual scrap supply (Gt)	Scenarios on scrap reuse (Gt)
		Steel		
IEA (2009a)	Global	2.3-2.8	1.2-??	1.2-??
Hatayama *et al*. (2010)	Global	1.8[a]	1.5[ab]	
Hatayama *et al*. (2010)	Asia	1.5[a]	1.2[ab]	
IEA (2009a)	China	0.6-0.7		
Zhou *et al*. (2011)	China	0.8		
Pauliuk *et al*. (2012)	China	0.3-0.5	0.3-0.5[b]	
IEA (2009a)	India	0.3-0.4		
		Cement		
IEA (2009a)	Global	3.7-4.4		
IEA (2009a)	China	0.8-0.9		
Zhou *et al*. (2011)	China	1.1		
Shi *et al*. (2012)	China	0.5-0.9[c]		
IEA (2009a)	India	0.6-0.7		
		Paper and paperboard		
IEA (2009a)	Global	0.69-0.92		0.38-0.56 (55%-61%)
Kayo *et al*. (2012)	Asia	0.42-0.57[d]		0.34-0.46 (81%)[d]
IEA (2009a)	China	0.18-0.25		
Zhou *et al*. (2011)	China	0.12		
Kayo *et al*. (2012)	China	0.26-0.27		0.21-0.22(81%)
IEA (2009a)	India	0.05-0.07		
Kayo *et al*. (2012)	India	0.05-0.14		0.04-0.11(81%)

[a] Steel use for civil engineering, building, and vehicles is considered.
[b] Only end-of-life scrap is considered.
[c] Cement demand for building and transportation infrastructure is considered.
[d] Ten Asian countries are considered: China and Taiwan, India, Indonesia, Japan, Malaysia, Philippines, Singapore, South Korea, Thailand and Vietnam.

mates that the share of steel produced from scrap will increase to 54% in 2050 from 33% in 2006 and shows that recycling will play an important role in GHG reduction, especially in the short term. About 11%-14% of the total abatement of 2.2-2.7 $GtCO_2$ in 2050 can be attributed to increased recycling. Hatayama *et al*. (2010) determined that the potential scrap supply from end-of-life (EOL) products corresponded to 80% of steel demand. Pauliuk *et al*. (2012) estimated almost the same level of EOL product scrap supply with steel demand in China in 2050. Therefore, scrap availability is not a restricting factor for increased recycling in their scenarios. Combining their lower steel demand and higher recycling potential, significant GHG reduction can be expected. As shown above, scrap availability is an important factor when potential usage of EAF is analyzed. Therefore, the assumptions used in estimating the scrap supply should be clarified and discussed in detail. In terms of recycling (measure E), waste plastic can also be used as a substitute for coal in blast furnaces and coke ovens, although its contribution to GHG reduction would be small. When considering this scenario, waste plastic availability needs to be assessed because there will be high competition for waste plastic recycling. The IEA (2009a) reported that the near-decarbonisation of the electricity sector would play a major role in achieving emissions reductions. Therefore, recycling of scrap with clean energy is critical for low-carbon resource management.

2.3 Cement demand and mitigation measures

Cement production processes emit CO_2 from the calcination of limestone. They are also energy-intensive processes. Global emissions from the cement industry were 2.0 $GtCO_2$ in 2006 (IEA, 2009a), including indirect emissions from electricity. The GHG emissions intensity ($kgCO_2$/kgCement) depends on the clinker content of the cement produced, energy efficiency, carbon intensity of the clinker fuel, and carbon intensity of the electricity used. Currently adopted measures to reduce GHG emissions from the resource-management point of view include the replacement of clinker by alternative cementitious materials such as blast furnace slag and fly ash from coal-fired power plants (measure E); and the use of alternative fuels such as waste tyres, plastics, wood and sewage sludge (measure E).

Table 1 shows that the global cement demand in 2050 is expected to increase by about 50% at most from a demand of 3.0 Gt in 2009. While China will increase and then decrease its demand from 1.6 Gt in 2009, India's demand in 2050 will be more than tripled from 0.2 Gt in 2009.

Shi *et al*. (2012) estimated cement demand for several scenarios depending on the lifetimes of building and infrastructure, showing the lowest estimate of cement demand to be 0.5 Gt for longer lifetimes (measure D), compared with 0.9 Gt for shorter lifetimes. Extension of lifetime (measure D) would have a significant impact on cement demand, and thus GHG emissions from cement production.

The potential level of clinker replacement can be estimated at an accessible level of 30% to an extreme level of 50% (Habert *et al.*, 2010) (measure E). The replacement ratio of 30% in the IEA's global estimate implies the use of about 1.1 to 1.3 Gt of clinker substitutes in 2050 (IEA, 2009a). Scenarios of steel production with BF/BOF and coal-fired power generation need to be discussed at the same time when we consider scenarios of this replacement. The same applies to the use of alternative fuels. Cement plants in some European countries have reached average substitution rates of from 35% to more than 70% of the total energy used, and some individual plants have even achieved 100% substitution using appropriate waste materials (Taylor *et al.*, 2006). However, we need to discuss the availability of alternative fuels when we consider high substitution rates.

From the viewpoint of GHG reduction, replacement of clinker and the use of alternative fuels can make a certain contribution but not significant. Other measures for lowering the level of cement consumption (measures A to D) need to be more fully explored.

2.4 Paper and paperboard

The pulp and paper industry is also an energy intensive sector. Its global emissions were 410 $MtCO_2$ in 2006 (IEA, 2009a), including indirect emissions from electricity. Options to reduce GHG emissions, currently adopted from a resource-management point of view, include the use of black liquor and wastepaper recycling (measure E). Black liquor is the residue from chemical processing to produce wood pulp for papermaking. It contains a significant amount of biomass (dissolved lignin and other materials from the wood) and can be used as a fuel. Recycling of wastepaper has a complex impact on the emissions profile of paper plants, forests and landfills. A number of studies have examined the impacts of recycling on life-cycle GHG emissions (Finnveden & Ekvall, 1998; Villanueva & Wenzel, 2007). In general, the environmental benefits of that as compared to incineration or landfill options have been illustrated.

Table 1 shows that global paper and paperboard demand may double in 2050 from the 2010 level of 0.4 Gt, leading also to a corresponding increase in GHG emissions from the pulp and paper sector. Paper and paperboard consumption and GDP are correlated, and thus GDP, *i.e.*, wealth, can be seen as a key driving force for an increase in paper consumption. Kayo *et al.* (2012)'s estimate for China is similar to the high-demand case of the IEA (2009a). In both estimates, developing countries' consumption will follow developed countries' trajectory. For the IEA's low-demand case, growth in paper and paperboard consumption in developing countries is assumed to rise at a slower rate than under the high-demand case.

The IEA (2009a) expects recovered paper utilization to reach 55% - 61% in 2050, while Kayo *et al.* (2012) assume an upper limit of 81% based on the current recycling rate for Malaysia. As for reduction of paper consumption itself, Counsell and Allwood (2008) examined reuse of paper, *i.e.*, erasing the print on office paper to allow its immediate re-use (measure E (or D)). This is ambitious, but if all existing process improvements are implemented and if a significant amount of demand is met by un-printing and re-use, we can reduce a significant amount of GHG emissions, because a preliminary energy analysis shows that to prepare a sheet of paper for re-use requires around 10% of the energy required for a new sheet (Counsell & Allwood, 2008).

2.5 Summary

The five measures for resource management (A to E) are considered in discussing the GHG emission reduction potential associated with carbon-intensive materials. Recycling (measure E) is an important measure for reducing GHG emissions. It would be impossible, however, to reduce significant amounts of GHGs without lowering the levels of global materials consumption (measures A to D), therefore dematerialized development scenarios are required. So far, these options have not been explored in detail, but some studies have shown a significant potential for reducing materials demand. Identifying reasons for differences in current material consumption in different countries is an important first step in exploring less resource-intensive development in Asia. At the same time, measures A to D described in Section 2.1 need to be explored in more detail.

3. Management of Minor Metals Associated with Mitigation Technologies

3.1 Criticality of minor metals

As stated in Section 1, a variety of minor metals are used in mitigation technologies and those metals' availability in the future may be a factor restricting the penetration of those technologies.

The United States National Research Council (NRC) defined the criticality of minerals as a function of two variables, supply risk (availability) and impact of supply restriction (importance of minerals in use) (USNRC, 2008). Graedel *et al.* (2012) extended this NRC framework by adding a third variable, *i.e.*, environmental implications. In their proposed methodology, supply risk is evaluated on the basis of three components: (1) geological, technological and economic, (2) social and regulatory, and (3) geopolitical. The first component measures the potential availability of a mineral, including both primary and secondary (recycled) sources, while the latter two address the degree to which the availability of that supply might be constrained. The social and regulatory component reflects social attitudes toward and regulations of mining development, while the geopolitical component addresses the political stability of a resource-producing country. Additionally, the impact of supply restriction, which is called vulnerability to supply restriction in the framework of Graedel *et al.* (2012), is evaluated on the basis of components such as importance, substitutability, and the ability to innovate (or susceptibility). The ability to innovate is important because more innovative corporations or countries are likely to be able to adapt more quickly to supply restrictions. Lastly, the environmental implications are evaluated using a life-cycle assessment methodology, *i.e*., the use of energy and water in processing, or emissions to air, water or land are assessed.

Keeping these various components of supply risks and the impact of supply restriction in mind, we will discuss the management of minor metals associated with important mitigation technologies below.

3.2 Batteries: lithium

Secondary batteries are a key component in electric vehicle (EV) technologies, including plug-in hybrid-electric vehicles (PHEVs) and hybrid-electric vehicles (HEVs). Current generation HEVs use nickel metal hydride (NiMH) batteries, while EVs and PHEVs employ lithium-ion batteries because they require greater storage capacity and higher power ratings than HEVs. The demand for lithium and other materials associated with lithium-ion batteries will likely grow substantially with the large-scale deployment of EVs and PHEVs.

As Table 2 shows, global lithium demand could increase substantially in coming decades in high penetration scenarios of EVs and PHEVs. Since there are sufficient reserves of lithium, the absolute amount of resources will not be a restricting factor. In addition, there are no significant political, regulatory or social factors in the lithium producing countries. However, expansion of the supply may not keep pace with the expected rapid demand growth in coming decades, so there is a supply risk for lithium. Yaksic and Tilton (2009) and Gruber *et al.* (2011) assumed a recycling rate of 80% and 90%, respectively (measure E). If such high recycling rates cannot be achieved, the cumulative lithium demand in high penetration scenarios may reach the amount of identified resource in the lithosphere.

3.3 Fuel cells: platinum

Currently platinum is an indispensable component of catalytic converters for controlling automobile emissions because of its outstanding catalytic properties. It is also expected to play an important role in the envisioned hydrogen economy as catalytic electrodes in hydrogen fuel-cells. With the large-scale deployment of fuel cells, the demand for platinum will likely grow.

As Table 2 shows, global platinum demand could increase significantly in coming decades in scenarios with high penetration of fuel cell vehicles (FCVs). Kondo *et al*. (2006) and Saurat and Bringezu (2009) estimated primary platinum demand, while Sun *et al*. (2011) and Hashimoto *et al*. (2010) estimated platinum demand, including both primary and secondary. Saurat and Bringezu (2009) reported higher cumulative demand until 2050 than Hashimoto *et al*. (2010) because of their much higher FCV penetration scenario (80% and 20% of vehicle sales in 2050, respectively). The higher platinum demand of 44,000 t is 1.5 times larger than the current platinum reserves of 29,000 t estimated by Gordon *et al.* (2006). The platinum supply has been inelastic due to constraints from producers' sociopolitical environment and infrastructure (Sun *et al*., 2011). In addition few substitutes are available. Therefore, if fuel cell technology cannot reduce the platinum loading (measure B) and if efficient recycling systems for platinum (measure E) cannot be established, widespread commercialization of FCVs will not be possible. For example, platinum use intensities of 4.55-39.11 g/FCV are used for estimating demands in 2050 by Saurat and Bringezu (2009) and Hashimoto *et al*. (2010), so lower platinum use intensities must be achieved. The recycling rate assumed in Saurat and Bringezu (2009)'s estimates is 75% for all scenarios, so higher recycling rates need to be achieved as well. Note that Sun *et al*. (2011) estimated a platinum demand of 250 t in 2050 for other products such as catalytic converters for automobile emissions control and jewelry. Their share is small compared with growing demand for FCVs.

3.4 Photovoltaic cells: indium, gallium and tellurium

Various types of photovoltaic (PV) cells have been developed. So far, crystalline silicon-based cells have been the dominant PV technology. Thin film technologies, however, are increasingly prominent among PV technologies. In particular, deployment of copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe) thin films is increasing.

Table 2 shows recent estimates of global indium, gallium and tellurium demand in coming decades. There are big differences among the three estimates even though they are not directly comparable because of different timeframes. Reasons include the following. Firstly, the US Department of Energy (USDOE, 2010)'s estimate includes demand for other uses, while Zuser and Rechberger (2011) and Hashimoto *et al*. (2010)'s estimates target photovoltaic cells only. Secondly, their estimates are based on penetration scenarios in the World Energy Outlook 2009 (IEA, 2009b), Renewable Energy Scenario to 2040 (EREC, 2004) and Energy Technology Perspective 2010 (IEA, 2010), respectively. The second scenario is more ambitious than the other two. Thirdly, they use different assumptions of market share and intensity of metal use. They assume that the market share of CIGS PV will be 10-50%, 25%, and 20-40%, respectively. The USDOE (2010) and Zuser and Rechberger (2011) also assume that the market share of CdTe PV will be 10-50% and 25%, respectively. Further, the USDOE and Hashimoto *et al*. (2010) use metal intensities of 16.5-110 kg-Indium/MW, 4-20 kg-Gallium/MW and 16.3 kg-Indium/MW, 6.7 kg-Gallium/MW, respectively. Zuser and Rechberger (2011) also consider yield in production processes. Consequently, Zuser and Rechberger's high estimates are the largest, and Hashimoto *et al.*'s high estimates are smaller than the USDOE's.

As for indium, demand for it in the UEDOE's sce-

Table 2 Recent estimates of demand for minor metals associated with mitigation technologies.

			Annual demand		Cumulative demand
Batteries					
USDOE (2010)	Global	Lithium	0.02 Mt (2010)	0.03-0.16 Mt (2025)	
Hashimoto *et al*. (2010)	Global	Lithium		0.21-0.33 Mt[a] (2050)	2.5-4.1 Mt[a] (2010-2050)
Yaksic & Tilton (2009)	Global	Lithium			17.5 Mt[b] (2008-2100)
Gruber *et al*. (2011)	Global	Lithium			20-32 Mt, 11-20 Mt[b] (2010-2100)
Fuel cells					
Kondo *et al*. (2006)	Global	Platinum		368-468 t[b] (2030)	
Sun *et al*. (2011)	Global	Platinum	250 t (2010)	500-700 t (2050)	
Hashimoto *et al*. (2010)	Global	Platinum		150-1,290 t[c] (2050)	1,300-10,800 t[c] (2010-2050)
Saurat & Bringezu (2009)	Global	Platinum			1,000-44,000 t[bc] (2010-2050)
Photovoltaic cells					
USDOE (2010)	Global	Indium	1,300 t (2010)	2,100-3,800 t (2025)	
Zuser & Rechberger (2011)	Global	Indium			11,000-44,000 t[d] (2010-2040)
Hashimoto *et al*. (2010)	Global	Indium		460-1,128 t[d] (2050)	10,000-24,000 t[d] (2010-2050)
USDOE (2010)	Global	Gallium	200 t (2010)	300-600 t (2025)	
Zuser & Rechberger (2011)	Global	Gallium			5,000-19,000 t[d] (2010-2040)
Hashimoto *et al*. (2010)	Global	Gallium		99-197 t[d] (2050)	2,000-4,000 t[d] (2010-2050)
USDOE (2010)	Global	Tellurium	500 t (2010)	700-2,800 t (2025)	
Zuser & Rechberger (2011)	Global	Tellurium			52,000-245,000[d] t (2010-2050)
Permanent magnets					
USDOE (2010)	Global	Neodymium	18 kt (2010)	27-61 kt (2025)	
Hashimoto *et al*. (2010)	Global	Neodymium		41-48 kt[e] (2050)	0.56-0.66 Mt[e] (2010-2050)
USDOE (2010)	Global	Dysprosium	1 kt (2010)	1.5-6.2 kt (2025)	
Hashimoto *et al*. (2010)	Global	Dysprosium		8-16 kt[e] (2050)	0.11-0.21 Mt[e] (2010-2050)

[a] Lithium demand other than for batteries of EVs, PHEVs and HEVs is not considered.
[b] Recycling is considered, and demand for primary metal is estimated.
[c] Platinum demand other than for fuel cell vehicles is not considered.
[d] Demand for indium, gallium and tellurium, other than for photovoltaic cells, is not considered.
[e] Demand for neodymium and dysprosium, other than for permanent magnets for wind turbines and electric vehicles, is not considered.

nario of 50% market share of CIGS and indium use of 16.5 kg/MW accounts for only 11% of the total demand of 2,400 t in 2025. Other uses will be dominant if indium intensity can be reduced. Therefore, reducing the intensity of indium use in CIGS (to 16.5kg-Indium/MW from 110) (measure B) would provide a significant reduction of overall demand. This conclusion is also derived from two other estimates. On the supply side, China is now the dominant producer, but mines in other countries could expand their capacity. Increasing recovery from tailings (measure E) could also expand production dramatically in the medium term (USDOE, 2010). However, there are no significant options for additional production in the short term (USDOE, 2010).

As for gallium, demand for other uses dominates in the USDOE's scenario of 50% market share of CIGS and gallium use intensity of 4 kg/MW. High penetration of CIGS PV without reduction in intensity of gallium use (measure B) would require a significant increase in the global supply. Gallium resources are distributed worldwide, so there would be no shortage of raw ore (USDOE, 2010). However, expansion of the supply may not keep pace with the expected rapid demand growth in coming decades.

As for tellurium, the USDOE (2010) concludes that if anticipated new supplies become available and the material intensity (measure B) is reduced, it appears that supply will be sufficient to meet projected demand until 2025.

3.5 Permanent magnets: neodymium and dysprosium

Permanent magnets are a key component of lightweight and high-power motors and generators. Permanent magnet motors are used in EVs, HEVs and PHEVs, and permanent magnet generators are used in wind turbines. Rare earth elements such as neodymium and dysprosium increase the function of these magnets.

Table 2 shows two estimates of global neodymium and dysprosium demand in coming decades. As for Neodymium, about half of the USDOE (2010)'s high estimate of 61 kt in 2025 is for permanent magnets, of which wind turbines account for one-sixth. As for dysprosium, about a quarter of the USDOE (2010)'s high estimate of 6.2 kt in 2025 is for permanent magnets, of which wind turbines account for about one-fifth. On the other hand, the share of wind turbines in Hashimoto *et al*. (2010)'s estimates is only a few percent. This is because they adopt different metal use intensities for wind turbines: the USDOE assumes 124-186 kg-Nd/MW and 22-33 kg-Dy/MW, while Hashimoto *et al*. (2010) assume 27 kg-Nd/MW and 4.8 kg-Dy/MW. They also use different market shares of wind power using permanent magnets: the USDOE assumes a 25% and 75% market share for onshore and offshore wind turbines, respectively, while Hashimoto *et al*. (2010) assumes 100%. In both estimates, however, demand for electric vehicles is dominant.

Neodymium and dysprosium are predominantly produced in China, which has instituted significant export quotas and tariffs on all rare earth elements based on resource conservation and environmental regulatory concerns. High dependence on China's exports would lead to a critical shortage of rare earth elements. Research is needed to reduce the intensity of neodymium and dysprosium use in magnets (measure B) or to develop substitutes (measure C). Recycling (measure E) is also an important option.

3.6 Summary

The USDOE (2010) carried out criticality analyses based on NRC methodology (see Section 3.1) and concluded that rare earth elements including neodymium and dysprosium will be critical in the medium term. Hashimoto *et al*. (2010) also conducted criticality analyses applying simplified NRC methodology, in which the CO_2 reduction potential of each technology was used as an indicator of impact of supply restriction, and concluded that metals used for EVs and PHEVs (*i.e*., lithium, neodymium and dysprosium) are of critical importance. According to these analyses, rare earth elements are important to the penetration of mitigation technologies and this result is consistent with the discussion above. Note that platinum could also be critical based on the discussion in Section 3.3; however, the total CO_2 reduction potential of fuel cell technology is smaller than those of other technologies (Hashimoto *et al*., 2010). In that sense, platinum can be treated as less critical, although it could also be critical if fuel cell technology were to penetrate drastically.

The same set of five measures for resource management (A to E) applies to these metals. Reduction of intensity of use, recycling and substitution need to be further investigated for these metals. Recently development of magnets not using neodymium or dysprosium (measure C) has begun.

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