Assessing the critical material constraints on low carbon infrastructure transitions

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Abstract. We present an assessment method to analyze whether the disruption in supply of a group of materials endangers the transition to low-carbon infrastructure. We define criticality as the combination of the potential for supply disruption and the exposure of the system of interest to that disruption. Low-carbon energy depends on multiple technologies comprised of a multitude of materials of varying criticality. Our methodology allows us to assess the simultaneous potential for supply disruption of a range of materials. Generating a specific target level of low-carbon energy implies a dynamic roll-out of technology at a specific scale. Our approach is correspondingly dynamic, and monitors the change in criticality during the transition towards a low-carbon energy goal. It is thus not limited to the quantification of criticality of a particular material at a particular point in time. We apply our method to criticality in the proposed UK energy transition as a demonstration, with a focus on neodymium use in electric vehicles. Although we anticipate that the supply disruption of neodymium will decrease, our results show the criticality of low carbon energy generation increases, as a result of increasing exposure to neodymium-reliant technologies. We present a number of potential responses to reduce the criticality through a reduction in supply disruption potential of the exposure of the UK to that disruption.

1 Introduction

Emissions reductions of the scale required to meet the challenging targets set by international and national bodies (HM Government 2008; UNFCCC 2008) will require rapid, systemic change including extensive refurbishment and replacement of infrastructure systems and unprecedented roll out of low carbon technologies. Many technologies required to make this systemic change exist today, but often rely on critical materials and components at risk of supply disruption and which are difficult to substitute (US Department of Energy 2011). It has been recognized that the deployment of low carbon technologies is potentially susceptible to disruption in the supply of critical metals and could thus constrain and derail decarbonisation efforts (Moss et al. 2011). However, the degree of criticality and its potential effect on the roll-out of new low-carbon technology have only been so far described in preliminary, qualitative terms (International Energy Association - Renewable Energy Technology Deployment 2012).

Previous research has identified factors that contribute to material criticality, as well as the groups of materials that might be considered to be critical to specific low carbon technologies (for example (European Commission 2010; T E Graedel et al. 2012; Moss et al. 2011)). The majority consider criticality to be a combination of the potential for disruption of the supply of these materials and the vulnerability of the system of interest to that potential for disruption (which includes an assessment of the exposure to disruption and the ability of the system to respond to exposure. For example, Graedel et al (T E Graedel et al. 2012) consider vulnerability to be a combination of the importance of the material of interest and the ability of the system to respond to disruption. The European Commission (European Commission 2010) uses a more specific conceptualization in its definition of critical materials, which was the contribution of the sector using the material of interest (in terms of Gross Value Added).

Less work has been done to determine the risk of criticality to entire infrastructure systems (and by consequence the economies that rely thereon) posed by these critical materials and components, or to analyse how this vulnerability might change over time. This paper is concerned with the assessment of the risk associated with constraints from critical materials supply that is introduced as a result of the extensive refurbishment and replacement of both current infrastructure systems, and the unprecedented roll out of low carbon energy technologies.

2 Assessing Material Criticality

The scope and purpose of the assessment method used in this paper differs substantially from that of previous assessments, which attempt to quantify the criticality of a material in a particular geographic or business context. Instead, we use a method that assesses whether the disruption in supply of a group of materials could impede strategic infrastructure transitions.

This has three implications for the approach used to assessing material criticality: it requires us to assess the combined potential for constraint posed by a range of material required for low carbon technologies (i.e. many materials for one use rather than one material for many uses); it requires us to assess the change in constraints on a particular goal during the transition towards that goal, rather than the quantification of criticality of a particular material at a particular point in time; and it requires us to recognise that the effects of any disruption are specifically concerned with ability to achieve a particular goal. The methodology is described in full in an associated paper (Roelich et al 2013) but is summarised below.

We use a stocks and flows model to forecast demand for potentially critical materials from a pre-defined scenario of infrastructure roll-out. The assessment of risk of constraints from critical materials determines whether disruptions in the supply of these critical materials could constrain this infrastructure roll-out and whether this constraint could prevent achievement of the overall goal. Our assessment of the risk of material constraints contains two principal indices:

- Supply disruption potential, which quantifies the likelihood that the production of a material, or group of materials, will be disrupted.
- Exposure to disruption, which quantifies the effect of disruption on the goal in question.

When combined (i.e. multiplied), the two indices provide an assessment of the risk that material criticality poses to low carbon energy system transition. Importantly, both indices are produced as a forecasted time-series, supporting dynamic analysis of material constraints. When combined, the two indices provide an assessment of the risk that material criticality poses to low carbon transition.
The methodology used to quantify these indices is summarized in Figure 1 and described below.

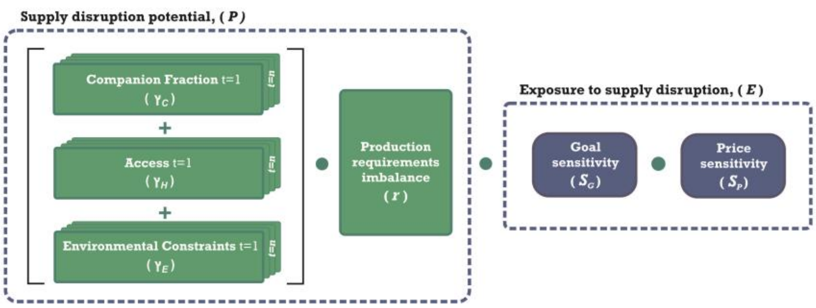

Figure 1: Components of metric for assessing the criticality of infrastructure transitions

2.1 Supply Disruption Potential

The supply disruption potential index represents the likelihood that access to a particular material could be restricted as a result of an imbalance between production and requirements, geo-politics or environmental constraints. This part of the assessment is specific to a particular material but only considers disruption at the point of production.

2.1.1 Production:requirements imbalance

The potential for there to be a future imbalance between the mining production of a particular material and the future requirements for that material from all economic sectors is measured using a ratio of requirements to production over the period under investigation. The EC study uses a version of this ratio with a static level of production and only taking into account requirements from new technologies (European Commission 2010). This ratio has been adapted in this study to include a forecast of production, which has been created by projecting historic trends of production increase and combined with a forecast in requirements from all uses, not just new technologies. An imbalance between potential production and forecasted requirements implies that there is potential for disruption of supply.

There are a number of factors that could exacerbate the requirements:production imbalance by potentially constraining increases in production. Three are considered to be of primary importance in this study: many of these materials are not produced as primary products but as co-products of other materials; the environmental sensitivity of land surrounding mines may give rise to restrictive legislation; and geographic monopolies in production may tempt policymakers to impose supply restrictions for geopolitical purposes. These moderators of production are discussed in turn below.

2.1.2 Companion fraction

A large proportion of materials currently considered critical are not mined in their own right, but rather as a co-product of a primary material, usually a ‘major’ metal with very high demand across a range of economic sectors, such as copper or zinc (Ayres and Peiró 2013). If a critical metal constitutes only a small proportion (in terms of tonnage and/or price) of the output of a mine, it is unlikely that production would increase solely as a result of a rise in demand for this material, since this would result in a surplus (and thus price suppression) of the primary metal, potentially making the mine less economic overall. The companion fraction metric is a combination of the mass fraction of critical materials in the output of mines[1] and the price fraction, which is the percentage contribution of the material to the price of one unit of mine output[2]. It is possible that the companion fraction of critical materials will

[1] This is taken as an average of the output of all mines producing the material of interest and is calculated using data from USGS Mineral Commodity Summaries (US Geological Survey 2010).

[2] This is taken to be the price per unit of material (using 2010 figures taken from USGS Mineral Commodity Summaries (US Geological Survey 2010)) multiplied by the mass of that material, divided by the total monetary output of the mine.

change over time; however, there is insufficient data to forecast how this might develop. Therefore it is assumed that the companion fraction stays the same over the period of analysis.

2.1.3 Access

Mineral deposits, by virtue of the processes by which they are formed, tend to be concentrated in a specific geographic location. This geographic concentration of materials does not directly constrain the acceleration of production; however, the monopoly created by this concentration of production can restrict access to produced materials, further distorting the balance between requirements (outside the country of production) and available production. There is potential for producing countries to pursue industrial and/or geopolitical strategies to reserve resources for their exclusive use though trade restrictions, taxations and investment policies. The Herfindahl-Hirschman Index (HHI) is used to quantify the level of concentration of worldwide production and represents the potential for disruption of material supply for geopolitical reasons (European Commission 2010; T E Graedel et al. 2012). Increases in the HHI indicate a decrease in competition and an increase in market power of the producing country(ies).

The geographic concentration of production at present is not necessarily indicative of concentration in the future. For example, China currently produces over 97 per cent of rare earth elements; however, it only holds 36 per cent of reported reserves (US Geological Survey 2010). This would imply that geopolitics could potentially become a less significant factor in the potential for supply disruption. To take this into account, we forecast the distribution of production of each critical material and estimate how the HHI might change over time. The forecast is produced by interpolating between the distribution of current production and the distribution of current reserves. This assumes that production distribution at the end of the period (2050) is the same as the reserve distribution in 2011. This is a simplification of the real situation but is used to indicate how the HHI might evolve over time based on current reserves.

2.1.4 Environmental Constraints

The production of metals can have significant environmental impacts as a result of pollutant discharge to air land and water and waste production (Moriguchi 2010). In addition to these impacts, production processes consume a great deal of energy and water, which will increase and ore grades deteriorate (Norgate 2010). In an attempt to contain these impacts, and as a result of international treaties, environmental regulation is becoming increasingly stringent. This is presenting a barrier to expansion of existing

operations or the development of new reserves by increasing the cost of production.
The Environmental Performance Index is used as a measure of "*the risk that measures might be taken by countries with the intention of protecting the environment and by doing so endangering the supply of raw materials…"* (European Commission 2010). The EPI provides a country level comparison of the extent of environmental policies and indicates the relative effectiveness of countries at managing a range of environmental pressures (Emerson et al. 2012). The majority of critical metals are mined in more than one country, therefore, it is necessary to combine the EPI of individual countries to determine what the European Commission terms the Environmental Country Risk (ECR). The EPI for each country producing the material of interest is weighted using the proportion of production arising in that country and combined to give the total ECR for the material of interest.
The EPI for each country is held static over the period of analysis because there is insufficient historical data on which to base any forecasts about the rate of this improvement. However, the proportions of production is different countries (and therefore the contribution of each EPI to ECR) is likely to change. The split of global production between countries is obtained from the HHI forecasts which assume that the distribution of production in 2050 will match the distribution of reserves in 2011.

2.1.5 Combining indices

Various approaches have been taken to combination of metrics in the literature (Erdmann and Thomas E Graedel 2011). Here, we take a mathematically robust approach to derive a 'first approximation' expression. For a given material, we assume that the exacerbating factors tempering the production:requirement imbalance (namely companion fraction, access and environmental country risk) are independent and thus additive. The sum of these metrics are then multiplied by the production:requirement imbalance to represent their tempering effect. We normalise criticality with respect to a well-characterised element (iron) to allow us to express relative criticality.

2.2 Exposure to supply disruption

The exposure to disruption index has been created to assess the effects of supply chain disruption on the realisation of a particular goal, in this case the transition to a low carbon infrastructure. It includes the sensitivity of the goal to a particular technology with material constraints and the sensitivity of the goal to rises in material prices (which is one of the principal economic effects of perceived scarcity and supply chain disruption).

2.2.1 Goal sensitivity

The overall goal of transition to a low carbon energy system is operationalized as scenarios of technology roll out required to achieve decarbonisation. In this project we use DECC's 2050 pathways, which aim to achieve an 80% reduction in UK carbon emissions by 2050 (DECC 2011). Some of the technologies in these scenarios contain materials at risk of supply disruption, which could in turn disrupt the required roll out of those technologies. The goal sensitivity, or the impact of a supply disruption on the overall goal, is measured in this metric as the proportion of the decarbonisation scenario that relies on the technology or technologies affected by the potential material supply disruption. A high value of goal sensitivity (i.e. approaching unity) would imply that constraining the roll out of the technology of interest could completely derail the goal of low carbon infrastructure. A low value of goal sensitivity (i.e. approaching zero) would mean that the goal was relatively insensitive to the roll out of the technology of interest.

2.2.2 Price sensitivity

As well as having the potential to physically constrain technology roll out; supply disruption could cause an increase in price, which could create further constraints. To capture this effect, the price sensitivity metric quantifies the proportion of the total technology cost contributed by the cost of the material at risk of supply disruption. A high value of price sensitivity (i.e. approaching unity) would imply that the technology cost was very sensitive to fluctuations in material price. A low value of price sensitivity (i.e. approaching zero) would imply that the technology cost was relatively insensitive to price fluctuations and material supply disruption was less likely to constrain the required technology roll out.

2.2.3 Combining exposure metrics

The two indices are multiplied to reflect their cumulative effect on exposure. At this stage they are unweighted, because there is no clear evidence to justify that one factor is more important than the other.

3 Application of methodology – the case of low carbon private vehicles in the UK

The criticality assessment method is demonstrated using a case study of the risk of neodymium criticality to low carbon private vehicles in the UK. We recognize that this is only a first approximation as we need to take into account the fact that almost all significant technologies are exposed to criticality via multiple elements and that multiple technologies contain each element. The method we describe in this article allows us to assess the combined potential for supply disruption of a range of materials required for low carbon energy generation, however only one material and technology are assessed here for simplicity.

Rare earth elements, predominantly neodymium, are used in permanent magnets required for motors in electric, and hybrid electric vehicles. Electric and hybrid electric vehicles are central to many of DECC's 2050 Pathways (DECC 2011). Neodymium is already identified by many recent reports as being at risk of supply disruption as a result of the concentration of its production in China (European Commission 2010; Moss et al. 2011; US Department of Energy 2011). We use this case study to determine how this potential supply disruption might affect the deployment of low carbon personal transport in the UK.

3.1 Neodymium Supply Disruption Potential Case Study: low carbon private vehicles

Permanent magnets used in electric motors contain both neodymium and dysprosium but the quantity of neodymium far outweighs that of dysprosium and the supply disruption potential of both materials is of the same order; so, for simplicity, we show only the supply disruption potential of neodymium.

When we forecast neodymium production and requirements we find that the production: requirements imbalance over the period 2012-2050 is 0.33 compared to 0.0007 for iron, indicating that there is a high potential for supply disruption.

Neodymium is mined as a co-product of other rare earth metals and represents only 15% of rare earth mine output. It also has a relatively low contribution to the economic value of mine output (16%) so could be expected to have limited influence over total mine production when compared to other rare earth elements. This results in a high score for the companion fraction metric (0.85), which indicates that co-mining has a high potential to exacerbate the production:requirements imbalance.

The current production of neodymium is almost a monopoly, with the majority produced in China; therefore HHI is almost unity in 2012 (0.92). However, neodymium reserves are less geographically concentrated that current production would suggest (US Geological Survey 2010). When production distribution is forecast towards reserve distribution (as described above) the HHI reduces to 0.28 by 2050. This reflects the likely future evolution of a far more competitive supply chain, which could mitigate the high disruption potential.

The risk that environmental legislation could constrain the development of new reserves of neodymium, is relatively low in 2012 (0.42) as a result of the dominance of China (which has a low EPI) in its production. However, as we increase the distribution of production, the contribution of countries with a higher level of environmental legislation, such as Australia and the US, increases and *the* ECR increases slightly by 2050 to reflect this increase in constraint from regulation (to 0.47). This increase could exacerbate the production:requirements imbalance by constraining the expansion of production but it is unlikely to be significant given the scale of the increase.

The evolution of Access (HHI) and ECR for neodymium are shown in Figure 2 below. Note that companion fraction and production:requirements imbalance are not currently dynamic so remain at 2012 values.

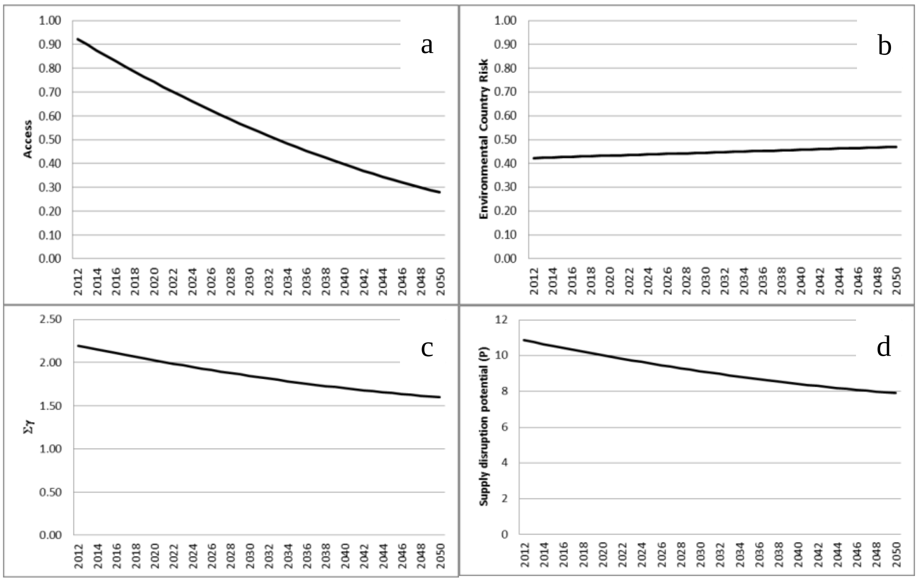

Figure 2: Neodymium Supply Disruption potential 2012-2050 (a) Access (b) Environmental Country Risk (c) combined indices and (d) supply disruption potential.

When combined, the metrics show that the supply disruption potential of neodymium is reducing over the period of analysis from 10.86 to 7.90, a 27% reduction.

3.2 Exposure of low carbon private vehicles to neodymium supply disruption

The ‘goal’ of low carbon private vehicles, which is exposed to supply disruption is taken to be the total number of cars added to stock each year (which is the total number required each year less the number scrapped in that year). This has been derived for both DECC’s Core Pathway and its

Renewable Pathway (DECC 2011) for the period from 2012 to 2050. The number of electric and hybrid electric vehicles (which contain neodymium) is also taken from the DECC scenarios.

The price sensitivity of the goal was estimated using a typical electric vehicle, which is representative of the type of vehicle that would be deployed in the initial period of the study. It is recognised that the design of technologies will change over time, affecting the price sensitivity. However, this change cannot be quantified to any degree of certainty at this time, therefore, this metric is not forecast. Using data in table 1, price sensitivity is calculated to be 8.83×10^{-4}.

Table 1: Cost data used to calculate price sensitivity

	Cost	**Source**
Cost of material	£25.78	0.62kg/vehicle (U.S Department of Energy 2010) high estimate. £41.48/kg (US Geological Survey 2010)(converted from USD using 0.66£/USD)
Cost of technology	£28,490	www.whatcar.com mid range model Nissan Leaf

When combined with goal sensitivity, this gives us the exposure of private vehicles to neodymium supply disruption from 2012 to 2050, shown in Figure 3. The trend is the opposite to that of the supply disruption potential, with exposure increasing dramatically over the period under investigation, electric and hybrid electric come to dominate the private vehicle sector. The significant trough between 2030 and 2040 in the exposure trend is an artefact of the assumptions relating to the scrapping and replacement of vehicles made in the DECC scenarios. The calculations in this paper use additions to stock to calculate exposure. This means that when a vehicle comes to the end of its life it must be replaced if the desired stock is to remain the same. Between 2030 and 2040 the number of electric vehicles added is low, as a result of a long vehicle lifetime and a low increase in stock requirements. In contract, during this period, the majority of internal combustion engine (ICE) cars must be replaced in order to keep stock levels constant (because the stock present has come to the end of its life). Therefore, the ratio of vehicle containing PMGs (electric and hybrid) to those without (ICE) is artificially low, resulting in a reduced index of exposure.

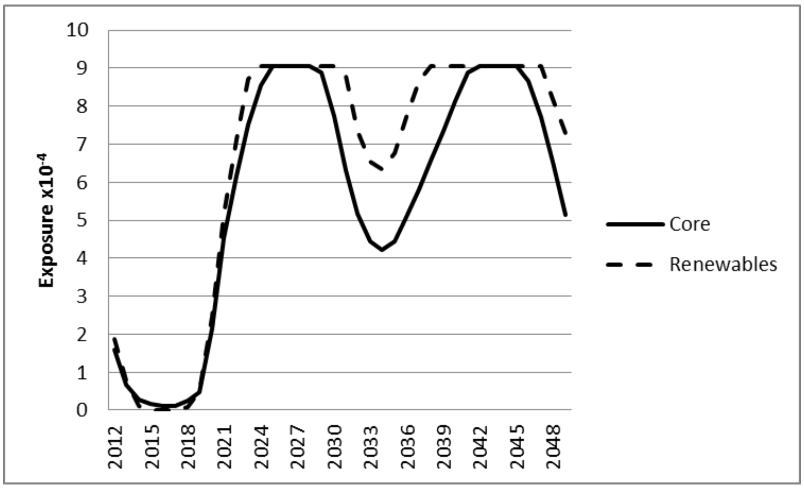

Figure 3: Low carbon private vehicle exposure to neodymium supply disruption

3.3 Criticality of low carbon private vehicles in the UK

The decreasing potential for supply disruption of neodymium mitigates the risk of criticality of low carbon private vehicles, to some extent, but when the indicators of supply disruption potential and exposure are combined, they show an increasing trend for criticality as a result of the increasing reliance on electric and hybrid electric vehicles. Criticality increases to a maximum of 8.5×10^{-3}, an increase of nearly 330%. This trend is similarly dramatic in the renewables scenario. However, toward the latter half of the study the criticality is mitigated by the decreasing supply disruption potential resulting from the anticipated broader distribution of neodymium production.

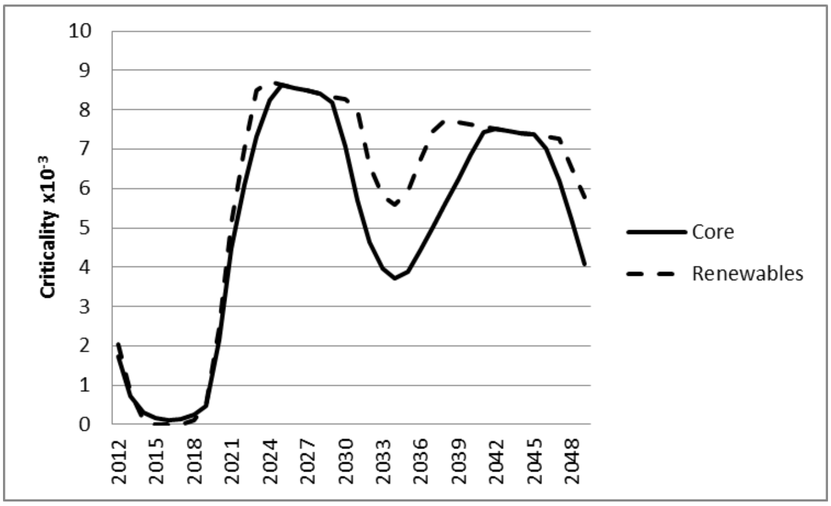

Figure 4: Criticality of low carbon private vehicles in the UK

4 The challenges presented by criticality

The results of the case study demonstrate the importance of considering both the potential for disruption of a particular material and the exposure of the system to that material when assessing the risk of material criticality. In the case of low carbon energy generation, the likely decrease in supply disruption potential for the key critical material slightly mitigates the increase in the exposure of the goal to that material as the UK becomes almost entirely dependent on electric vehicles. However, the dynamic aspect of criticality appears to be dominated by our exposure to disruption, and decreasing technology diversity, indicating that our response to criticality should focus here.

The case study also shows the importance of considering the nature of the change in criticality over time – the results showed a steep increase in criticality after between 2020 to 2025, when roll out of electric and hybrid vehicles is projected to increase dramatically. It will be more difficult to devise industrial policy responses to such steep changes than to static high levels of criticality.

The implication of this steep increase is that the supply chain supporting low carbon vehicles will be unable to respond to the increasing demand for new vehicles and we will not see the reductions in ICE required to meet carbon emission reduction targets. Another significant implication is the effect that this supply disruption could have on the UK economy; we have a burgeoning electric vehicle manufacturing industry in the UK, which could be severely constrained by supply disruptions and the potential associated shift back to ICE vehicles.

We have not included any discussion of a threshold of criticality because our indicators are intended to be used to compare the relative criticality of different pathways to a decarbonized energy system, rather than defining the point at which the risk of criticality becomes unacceptable. This is not to say that it is not possible to define a threshold of this nature rather that it is not the intention of this article; criticality thresholds will need to be informed by a combination of political and economic factors as well as a technical analysis of criticality.

5 Potential responses to criticality

The methodology described above aims to not only quantify the criticality of infrastructure transitions but also to support analysis of how this criticality could be reduced. The methodology is purposefully transparent to support analysis of the causes of criticality and to allow responses to be targeted at the most important causes. We discuss below the potential responses to criticality of low carbon private vehicles in the UK, grouped by the index to which they would contribute.

5.1 Supply disruption potential

The principal points of intervention to reduce the supply disruption potential of neodymium are to reduce the production:requirements imbalance and to encourage the diversification of the production of neodymium. The UK has greater potential to address the former through its contribution to reducing the global requirements for neodymium. It has three approaches to doing this: reducing total consumption of neodymium through consuming less to deliver the same output, using less resource per unit of consumption and recovering secondary neodymium to displace requirements for primary material. The former response would also reduce the UKs exposure to supply disruption potential so would have a greater cumulative effect on criticality.
Within the context of this case study, there is little potential to reduce the quantity of neodymium within each vehicle, without substantial technology change. The magnetic strength of the most recent generation of neodymium magnets is believed to be close to fundamental and technical limits of this material (Kara et al. 2010).
Increasing recovery of neodymium also prevent challenges; despite a significant amount of research into recycling technologies there is no commercially developed processes due to drawbacks on yields and cost (Kara et al. 2010). There is an increasing focus on collection and separation of end-of-life vehicles and electronics, as a result of recent EU legislation (Official Journal of the European Communities 2000; Official Journal of the European Communities 2012), however, there are currently no treatment facilities in the UK. There is potential that facilities could be developed, which would not only reduce supply disruption potential but could also retain neodymium in the UK, contributing to both security and the economy.

5.1.1 Exposure

In addition to reducing exposure through reducing the total number of vehicles required to deliver the same service to the UK economy, diversifying the technology contributing to low carbon vehicles could further reduce our goal exposure. Electric motors which require permanent magnets are favoured in the UK, therefore; technology diversity would require a move away from electric vehicles to hydrogen or other fuel cell vehicles. This would have significant implications of the UK;

- It would increase uncertainty over the required capacity of the electric vehicle charging infrastructure, which goes hand in hand with dominance of this technology. This could serve to increase the unit cost of this infrastructure and to delay its roll out, which is already constraining electric vehicle uptake; and
- It could reduce the contribution of the burgeoning electric vehicle manufacturing sector to the UK economy.

Price sensitivity could be reduced by either reducing the amount of material used per unit (as discussed above) or by substituting neodymium for another, cheaper material. The only appropriate replacements for neodymium are dysprosium or praseodymium, both of which are more expensive than neodymium (Kara et al. 2010). Samarium-cobalt magnets have similar performance at high temperatures to neodymium but have only half the magnetic strength, making them less suitable for use in electric vehicle motors. Substitution at a material level is unlikely to be appropriate for permanent magnets.

6 Conclusions

The approach to analysis of risks of constraints from critical materials developed in this article, integrated with the stocks and flows modelling, represents initial steps towards developing a systematic framework for analysing the future material constraints on infrastructure transitions. It is hoped that such a framework will ultimately become a key ecological economics tool, implemented in infrastructure planning processes.

This article presents an assessment method to analyze whether disruption in the supply chain of a group of materials could impede strategic infrastructure transitions. We conceptualize this as criticality, which is a combination of the potential for supply disruption and the exposure of the system of interest to disruption that enables us to; consider the potential for disruption of multiple materials; assess the effects of disruption on the installation of physical infrastructure; and assess the change in constraints on a particular goal during the transition towards that goal, rather than the quantification of criticality of a particular material at a particular point in time.

We found that it is important to consider both aspects of criticality; the potential for supply disruption and the exposure of the goal to that disruption. This is exemplified in our case study of the criticality of neodymium for low carbon private vehicles where the likely decrease in supply disruption potential for the key critical material slightly mitigates the increase in the exposure of the goal to that material as the UK becomes almost entirely dependent on electric vehicles. However, the dynamic aspect of criticality appears to be dominated by our exposure to disruption, and decreasing technology diversity, indicating that our response to criticality should focus here.

It is not just the overall trend that is of concern in this case study, but the steep increases in criticality over short periods of time. These step changes in criticality are more challenging for industry and policy makers to respond to than static, high levels of criticality. This shows the value of a more dynamic, infrastructure-focused analysis of criticality, which can potentially be useful in providing policy makers with information to reduce the probability of 'locking-in' to currently attractive but potentially future-critical technologies.

7 Acknowledgements

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