



Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity



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HIGHLIGHTS

- We present a method to analyse material criticality of infrastructure transitions.
- Criticality is defined as the potential for, and exposure to, supply disruption.
- Our method is dynamic reducing the probability of lock-in to at-risk technologies.
- We show that supply disruption potential is reducing but exposure is increasing.

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ABSTRACT

Decarbonisation of existing infrastructure systems requires a dynamic roll-out of technology at an unprecedented scale. The potential disruption in supply of critical materials could endanger such a transition to low-carbon infrastructure and, by extension, compromise energy security more broadly because low carbon technologies are reliant on these materials in a way that fossil-fuelled energy infrastructure is not. Criticality is currently defined as the combination of the potential for supply disruption and the exposure of a system of interest to that disruption. We build on this definition and develop a dynamic approach to quantifying criticality, which monitors the change in criticality during the transition towards a low-carbon infrastructure goal. This allows us to assess the relative risk of different technology pathways to reach a particular goal and reduce the probability of being 'locked in' to currently attractive but potentially future-critical technologies. To demonstrate, we apply our method to criticality of the proposed UK electricity system transition, with a focus on neodymium. We anticipate that the supply disruption potential of neodymium will decrease by almost 30% by 2050; however, our results show the criticality of low carbon electricity production increases ninefold over this period, as a result of increasing exposure to neodymium-reliant technologies.

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1. Introduction

Emissions reductions of the magnitude required to meet the challenging targets set by international and national bodies [1,2] will require rapid and systemic change to physical infrastructure, especially energy systems. This will require a step-change in both the scale and rate of the roll out of low carbon technologies such as wind turbines, solar panels and hybrid and electric vehicles. All these technologies rely on critical materials, such as rare earth

elements, in a way that fossil-fuelled energy infrastructure, based mostly on concrete and steel, does not [3–5]. Currently the European Commission defines critical materials as those at risk of supply disruption and which are difficult to substitute [6]. If supply of these materials is disrupted, there will be a corresponding constraint on the rate at which such technologies can be manufactured and commissioned. This risk is amplified by the scale of the requirements of low carbon infrastructure, which is unprecedented. The risks of material supply disruption relate not only to low carbon goals but also to the security of our energy supply; delay or disruption to the roll-out of low carbon technologies could also endanger energy security by constraining the planned installation of additional electricity generation capacity, or preventing

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the maintenance and upgrade of previously installed systems. Although it has been recognised that the deployment of low carbon technologies is susceptible to disruption in the supply of critical metals [7], the degree of criticality and its potential effect on the roll-out of new low carbon technologies have only been so far described in preliminary and mostly qualitative terms [7,8]. Indeed, the concept of criticality, while immediately of obvious importance, is in fact best understood as a combination of different factors.

Recent studies have attempted to assess the criticality of raw materials in e.g. specific geographic regions [3,6,9,10], sectors [3,8] or companies [10]. The majority of these have developed assessment methods to identify which raw materials could be considered critical within the particular scope of the study. Recent assessments of material criticality have tended to move away from considering criticality to be solely a function of geological depletion (or resource scarcity), as a result of the large uncertainty associated with reserve estimates [6,11]. Instead criticality is usually described in terms of the *potential for supply disruption* of a particular material, and *the impact* of this disruption on the system of interest; an approach that is analogous to risk assessment. These assessments have not yet reached a common definition of criticality, besides these two dimensions, and the conceptualisation of the dimensions themselves varies significantly between assessments [12].

Supply disruption is conceived to result from a range of factors including constraints on expansion of production (such as co-mining), market imbalances or governmental intervention, as well as geological scarcity [12]. Analysis of supply disruption is predominantly static, although some have done static assessments of different time periods [3,10]. The majority of studies consider the concentration of mineral deposits in a small number of countries to be a potential source of disruption. Shorter term studies have used sources of imports as a measure of the current distribution of supply [13], while others have used the distribution of global production as a measure of the short to mid-term supply basis [6,8,10]. Some studies weight country shares of production by political risk [6] or environmental regulation, emphasizing that some countries have an increased potential for disruption as a result of these factors. The supply disruption aspect of assessments often includes additional factors such as substitution or recycling, to represent the ability to alleviate disruption through reduction in demand for primary material. This contradicts the analogy to risk and is one of the principal causes of difference between assessments, since these factors are considered to be a characteristic of impact in other assessments [12].

In most studies, the conceptualisation of *the impact* of supply disruption is tailored to the system of interest and generally represents the extent to which a system is exposed to the potential for supply disruption [3,6,10,14]. For example, the European Commission [6] uses the relative economic contribution of the sector using the material of interest (in terms of Gross Value Added) to represent this exposure. Others include the ability of the system to respond to disruption or its adaptive capacity in the conceptualisation of impact. For example, Graedel et al. [10] use a combination of the importance of the material of interest and the ability of the system to respond to disruption, which is better aligned with the concept of vulnerability [15]. In a material criticality context, such responses include substitutability or recycling of materials to reduce primary demand [16].

While previous approaches have quantified the criticality of a material in a particular context at a particular point in time, this study differs substantially in scope and purpose. It analyzes whether the disruption in supply of critical materials could impede low carbon infrastructure transitions. Previous methods of criticality analysis have two principal limitations in this context: the

static nature of analysis and the individual analysis of separate parts of a connected system (i.e. a country or a company) rather than systemic analysis of a goal.

Infrastructure transitions happen over a period of decades and decisions taken now will affect technology change up to 40 years hence. It could be expected that both supply disruption potential and exposure of the system will change significantly over this period, since their contributing technical, socioeconomic and environmental factors all vary over time. Therefore, static analysis of criticality at the start of transition will not help to identify the future constraints to which we could be exposed as a result of decisions taken now. Despite this, no previous studies have conducted a fully dynamic criticality analysis, although some have done static assessments of different time periods [3,10], or analysed stock and flows of materials over time [17,18]. Thus, new approaches are required to incorporate the dynamic aspect of criticality [19].

Assessing the material criticality of infrastructure transitions requires systemic analysis of a goal (low carbon transition) which is defined by the function of the system (provision of low carbon electricity). The transition towards low carbon electricity could happen in a range of ways and requires the contribution of economies, companies and technologies. Current approaches, which separately analyse the criticality of an economy, company or technology, underemphasize the systemic nature of criticality. Therefore, new approaches are required to assess exposure of different pathways towards a particular system goal.

We define criticality as the combination of the potential for supply disruption and the exposure of pre-determined pathways (or scenarios) of technology roll out to that disruption, which is consistent with previous assessments. Furthermore, we assess how both dimensions of criticality change over time and present a method which allows us to quantify this definition for the goal of infrastructure transition. In this way criticality helps us to assess whether a disruption in the supply of a particular material could prevent us from achieving the scale and pace of roll out of technologies and materials necessary to decarbonise our infrastructure systems. We do not provide a threshold over which criticality is deemed to be unacceptable; instead we develop a method which enables the comparison of the criticality of different pathways. To this end we normalise our analysis with respect to the values for some well-characterised element (e.g. iron), which allows us to express *relative* criticality.

We start with a description of the assessment methodology in terms of the metrics, the forecasting of future change in these metrics and the combination of individual metrics into indices. The methodology is demonstrated by applying it to the planned deployment of a low carbon technology in the UK. We conclude with a discussion of the application and limitations of this approach to quantifying the risk to low carbon infrastructure transitions, and thus the energy security of a system that relies heavily thereon, posed by critical material supply disruption.

2. Materials and methods

2.1. Criticality assessment

We conceptualise criticality as analogous to risk, which is a well-established and familiar process to policy-makers and commercial organisation. This increases the potential of the approach to engage policy makers and industry [20]. We use risk, as opposed to the concept of vulnerability,¹ to avoid the endogenisation of potential policy responses, such as substitution and recycling. One of

¹ Which includes an assessment of the ability of the system to respond to a particular hazard, or its adaptive capacity [15].

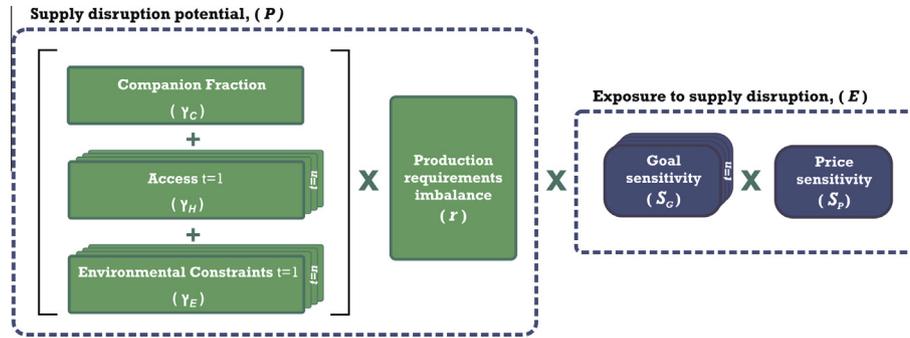


Fig. 1. Indices (P and E) and metrics for assessing the criticality of infrastructure transitions.

the aims of this approach is to enable the identification of potential policy responses to reduce criticality; therefore, we exclude measures such as substitutability and recyclability, which have been used in other assessments [12].

Analogously to risk, criticality is defined as the product of the probability of an event and the severity of harm resulting from that event. We create two principal indices to represent these dimensions of risk:

- Supply disruption potential (P), which quantifies the likelihood that access to a particular material could be restricted.
- Exposure to disruption (E), which quantifies the effect of disruption on the goal in question.

When combined through multiplication, the two indices provide our assessment of the risk, $C(t)$ that material criticality poses to a low carbon electricity system transition:

$$C(t) = P(t) * E(t) \quad (1)$$

Importantly, both indices are produced as a forecasted time-series, which allows us to estimate criticality over time and identify trends of increasing (or decreasing) criticality. Each index is composed of a series of metrics, the trends in which can be tracked individually. This is essential to provide more detailed insights into the drivers of criticality for particular materials or technologies and the associated policy interventions that might reduce criticality. The combination of metrics contributing to indices is summarised in Fig. 1 and the metrics themselves are described below.

Using this method it is possible to analyse the criticality of a range of transition pathways, such as those outlined by DECC in the Carbon Plan [21], to compare the material risks of different pathways to the same goal. This is demonstrated in Section 3 of this article.

2.2. Supply disruption potential, P

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, which could be exacerbated by a range of factors that could constrain future increases in production. Therefore we produce a metric ' r ' which represents the potential scale and frequency of imbalance over the period of analysis and a series of exacerbating factors γ_x . Comprehensive analysis of each exacerbating factor would be complex and require advanced modelling. Therefore, we have selected three factors that are considered to have significant and direct influence on production-requirements imbalance, have widely recognised metrics associated with them, and are readily quantifiable. These three factors are: co-production (γ_c) (many of critical materials are not produced as primary products but as co-products of other

materials); geographic distribution of production (γ_H) (geographic monopolies in production may tempt policymakers to impose supply restrictions for geopolitical purposes); and environmental constraints (γ_E) (the environmental sensitivity of land surrounding mines may give rise to restrictive legislation).

For a given material, we assume that the exacerbating factors tempering the production-requirements imbalance r (namely $\gamma_c, \gamma_H, \gamma_E$) are independent and equally weighted. The sum of the exacerbating factors is multiplied by the production-requirements imbalance to provide an overall assessment of the potential for supply disruption.

In order to compare criticalities of materials we normalise with respect to the values for some well-characterised element (e.g. iron), denoted by the subscript 0. This allows us to express *relative* criticality: we will be able to analyse the magnitude of the increase in criticality (e.g. "moving to the new technology will increase the risk of probability of disruption by a factor of p/p_0 "). Normalising with respect to a reference material, we can write (Eq. (2)):

$$\frac{P(t)}{P_0} = P(t) = \left(\frac{\sum \gamma(t)}{\sum \gamma_0} \cdot \frac{r}{r_0} \right) \quad (2)$$

The production of individual metrics contributing to P is described below.

2.2.1. Production-requirements imbalance, r

Historically, production of materials has increased in response to market signals driven by greater demand. However, a number of emerging technologies, such as wind turbines, electric vehicle and solar photovoltaics that rely on materials identified as potentially critical [3,6,9] are forecast to be rolled out at an unprecedented scale and rate, increasing demand for materials such as neodymium and indium by up to 700% and 800% respectively [6]. Expanding the production of mines can be slow; the lead times involved can be in the order of years or even decades [22]. This limits the ability of production to respond to the projected increase in requirements within the timescales required [9]; normal market signals will not be effective in stimulating new production.

This increase in pressure on production is measured using a ratio of requirements to production over the period under investigation (2012–2050). The European Commission (EC) study on critical raw materials uses a version of this ratio with a static level of production and only taking into account requirements from new technologies [6]. This ratio has been adapted in this study to include a forecast of production and requirements and to include requirements from all uses, not just new technologies. A shortfall between potential production and forecasted requirements implies that there is potential for disruption of supply.

The metric of imbalance r , depends on the expected level of global production $M(t)$ and the expected global requirements $R(t)$ at a point in time. $M(t)$ is forecast by projecting historical trends in

production. $R(t)$ includes future requirements for low carbon technologies as well as future requirements for other uses, which has often been excluded from previous assessments [23–25]. The specific assumptions used for the derivation of $M(t)$ and $R(t)$ for the case study in this article is presented in [Supplementary information](#).

We derive two metrics to quantify the severity of a supply imbalance between $M(t)$ and $R(t)$, and multiply these to provide at total severity estimate r .

- (1) n : Likelihood of supply disruption is the probability that $R(t) > M(t)$ over the period considered i.e.:

$$n = \frac{a_{R>M}}{a} \quad (3)$$

where $a_{R>M}$ is the number of years in which $R > M$ and a is the total number of years of the period under investigation (2012–2050). n therefore varies between 0 (requirements exceeds production in none of the years) to 1 (requirements exceeds production in all of the years).

- (2) σ Scale of potential supply disruption is the average of $(R - M)/(R + M)$ over the time period of analysis, counting only years where there is a deficit (i.e. where $R > M$) and thus effectively assuming a worst case scenario where surpluses cannot be carried forward; σ therefore varies between 0 (production exceeds requirements in all years) to 1 (production is insignificant compared to requirements in all years).

In notation form: for a years;

$$\text{where } M_t > R_t \text{ then } \sigma_t = 0, \quad (4)$$

$$\text{and; where } M_t < R_t; \text{ then } \sigma_t = \frac{R_t - M_t}{R_t + M_t} \quad (5)$$

The severity of disruption is the product of the frequency and scale, therefore; we can write:

$$r = n\sigma = \frac{a_{R>M}}{a} * \frac{\sum \sigma_t}{a} \quad (6)$$

The metric r gives a general indication of the potential scale and frequency of market imbalances over the period.

2.2.2. Companion fraction (γ_C)

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 [26]. 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. This effect is particularly significant where the critical metal price is low and the reduced price for the primary metal cannot be compensated for by the increase in production of the critical metal co-product.

To reflect this constraint we have included a metric γ_C which captures the product-co-product balance. In common with other assessments we include a measure of the proportion of critical material by mass in the output of mines where it is produced. However, we enhance this approach by incorporating the percentage contribution of the material to the price of one unit of mine output; the economic value of output. Thus:

$$\gamma_C = 1 - \left(\frac{C_m + C_p}{2} \right) \quad (7)$$

where C_m is the contribution of critical material to the mass of mine output and C_p is the contribution to the economic value of mine output. We weight the contribution from mass and price equally in the absence of evidence that they are not equally important. The inverse is taken to ensure the scale represents the same as other exacerbating factors i.e. 0 is low and 1 is high. Thus, a value of γ_C approaching 0 would indicate that the material is mined in its own right; a value approaching 1 would indicate that it is almost entirely mined as a co-product of another material.

We calculate the proportion of material considered by mass in the output of mines at which it is produced (the mass fraction C_m):

$$C_m = \frac{m_i}{m_x} \quad (8)$$

where m_i is the mass of material i produced at mine x and m_x is the total mass of material produced at mine x (data from [27]). In the event of insufficient data on mine outputs, the typical mass fraction of the most commonly produced ore grade is used.

To account for the effect of the price of the material considered to increase the likelihood of accelerating production we calculate the percentage contribution of the material to the price of one unit of mine output (the price fraction C_p):

$$C_p = \frac{p_i * m_i}{p} \quad (9)$$

where p_i is price per unit of material (using 2010 figures taken from USGS Mineral Commodity Summaries [28]) and p is total monetary output of the mine.

It is possible that the companion fraction of critical materials will 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.

2.2.3. Access (γ_H)

Mineral deposits, by virtue of the processes by which they are formed, tend to be concentrated in a specific geographic location, which has implications for access to these materials in countries that do not have their own deposits. 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 through trade restrictions, taxations and investment policies. An example of this is the tightening restrictions that China has placed on Rare Earth metal exports [29–31]. The geographic concentration of production at present is not necessarily indicative of concentration in the future. For example, China currently produces over 97% of rare earth elements; however, it only holds 36% of reported reserves [28]. This would imply that geopolitics could potentially become a less significant factor in the potential for supply disruption and that a dynamic measure of access is essential.

The Herfindahl-Hirschman Index (HHI) is used in previous criticality assessment to quantify the level of concentration of worldwide production [6,10]. In this assessment we also use HHI but create a forecast to 2050 to support dynamic analysis. HHI is calculated by squaring the share of production from each country for a given year and summing the result for all producing countries (Eq. (10)):

$$\gamma_{H(t)} = HHI(t) = \sum_{i=1}^n H_{it}^2 \quad (10)$$

where H_{it} is the share of production of country i in year t and n is the number of producing countries.

The HHI falls onto a 0–1 scale where HHI approaching 1 would represent a concentration of supply in a single country approaching a monopoly and HHI approaching 0 would suggest very distributed supply and a competitive supply chain. A low level of competition (or a high γ_H) would increase the supply disruption potential as a result of its magnification of the risk associated with the production-requirements imbalance.

We forecast the distribution of production of each critical material and estimate how γ_H might change over time. The forecast is produced by interpolating between the distribution of current production and the distribution of reserves. This assumes that production distribution at the end of the period (2050) is the same as the estimated reserve distribution in 2012. This is a simplification of the real situation but is used to indicate how γ_H might evolve over time based on current reserves and market responses.

2.2.4. Environmental constraints (γ_E)

The production of metals can have significant environmental impacts as a result of pollutant discharge to air, land and water and waste production [32] and consumption of energy and water, which will increase as ore grades deteriorate [33]. 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 the expansion of existing mining operations or the development of mines by increasing the cost of production.

Quantifying the extent of environmental constraints on mining or the direct effect of regulation on new mining operations is rather difficult. As an alternative, previous assessments have used the Environmental Performance Index (EPI), 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...” [6]. The EPI and its constituent indicators are described in more detail in the [Supplementary Information, S3](#). Although several of the indicators used for the EPI are directly relevant to mining operations, e.g. Change in Water Quantity and Forest Loss, we do not include it as a direct indicator for environmental regulations that impact mining operations. Rather, it provides a country level comparison of the potential for a country to already have, or institute new environmental regulations that may constrain mining operations [34]. 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) [6], here termed γ_E .

To calculate γ_E for a given year, we divide the EPI for each producing country by 100 to convert to a 0–1 scale, weight the score by the share of production from each country and sum the resulting figures.:

$$\gamma_{E(t)} = ECR(t) = \sum \left(\frac{EPI_i}{100} \right) * \left(\frac{M_{it}}{M_x} \right) \quad (11)$$

where EPI_i is the environmental performance index of country i , M_{it} is the production of a specific material in country i in year t and M_x is total production of that material. A value of γ_E approaching 0 indicates that there is unlikely to be any constraints to the development of new mining operations from environmental regulation.

It is likely that the environmental performance of countries (and hence the EPI) will improve over time, however there is insufficient historical data on which to base any forecasts about the rate of this improvement and this could be balanced (or even outweighed) by the fact that environmental legislation is likely to become more restrictive. Therefore, the EPI for each country is held

static over the period of analysis, using the latest available values from the 2012 report [34]. However, the proportions of production in different countries (and therefore the contribution of each EPI to γ_E) are likely to change. The forecast split of global production between countries is obtained from the HHI forecasts described above.

2.3. Exposure to supply disruption, E

This index represents the effect of supply disruption on the transition to a low carbon infrastructure system. In an overall electricity system in transition towards a low-carbon paradigm, any disruption to the roll-out of the technology on which this transition depends has obvious implications for energy security. Unlike the supply disruption potential, which is a material property, exposure is a property of the technical system and, therefore, must be assessed at the level of the goal we are analysing i.e. decarbonisation of the infrastructure system. Exposure is operationalized as the product of the proportion of the goal affected by any disruption (the goal sensitivity S_G), and the likely effect of increasing price resulting from disruption (the price sensitivity S_P);

$$E(t) = S_{G(t)} * S_P \quad (12)$$

The two metrics contributing to our exposure indicator are described in detail below.

2.3.1. Goal sensitivity S_G

The overall goal of transition to a low carbon infrastructure system is operationalized as pathway or scenarios of technology roll out required to achieve decarbonisation.² The goal sensitivity, or the impact of a supply disruption on the overall goal, is measured in this index as the proportion of the decarbonisation pathway that relies on the technology or technologies affected by the potential material supply disruption. This assessment is based on the contribution of the technology of interest to the low carbon goal (MW of electricity generation capacity, or tonnes of CO₂ reduction) as defined in the relevant pre-defined pathway (in this analysis this is taken to be the Department for Energy and Climate Change’s (DECC) low carbon pathways [21]);

$$S_G = \frac{G_{tech}}{G_{goal}} \quad (13)$$

where S_G is goal sensitivity; G_{tech} is the amount contributed to the low carbon goal (miles, MW, CO₂ reduction etc.) by the technology (defined in relevant scenario); and G_{goal} is the total amount required to achieve goal (defined in relevant pathway).

A high value of S_G (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 S_G (i.e. approaching zero) would mean that the goal was relatively insensitive to the roll out of the technology of interest.

S_G is produced as a time series because the contribution of a particular technology in any year varies according to the pathway.

2.3.2. Price sensitivity S_P

As well as having the potential to physically constrain technology roll out, supply disruption could cause an increase in price, which could have further implications. 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;

² Within the country or region of interest – note that this may differ from the global roll out of low carbon technologies used to determine future global requirements within the production-requirements imbalance metric is the scale of decarbonisation is sub-global.

$$S_p = \frac{V_{mat}}{V_{tech}} \quad (14)$$

where S_p is price sensitivity; V_{mat} is the price of material in technology of interest (i.e. price per tonne multiplied by mass of material in technology); and V_{tech} is the price of technology of interest.

A high value of S_p (i.e. approaching unity) would imply that the technology cost was very sensitive to fluctuations in material price. A low value of S_p (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 as a result of increasing prices. It is recognised that the scale and 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 assumed to be static for now.

3. Results

The criticality assessment method is demonstrated using a case study of neodymium criticality to UK low carbon electricity, with a focus on wind turbines. Rare earth elements, predominantly neodymium, are used in permanent magnets required for gearless, direct drive wind turbines. Wind power has the potential to contribute significantly to the decarbonization of UK electricity generation and is central to many of DECC's 2050 Pathways [21]. An ambitious roll-out programme of wind turbines is required to replace fossil-fuel powered generation, with aforementioned implications for energy security. 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 [3,6,8,18]. We use this case study to determine how this potential supply disruption might affect the deployment of low carbon electricity generation in the UK. We recognise 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 materials and that individual critical elements are essential to the operation of multiple technologies.

3.1. Criticality of low carbon electricity

The criticality of two of DECC's 2050 Pathways; Core Pathway and its Renewable Pathway [21]; have been calculated for the period from 2012 to 2050. The data used in support of these calculations are presented in [Supplementary information](#). The results (presented in [Fig. 2](#)) show that criticality in the Core Pathway increases more than threefold over the period from 2012 to 2050, with a step-change occurring in 2030, as shown with reference to 2012 values. This trend is even more dramatic in the Renewables scenario with a ninefold increase.

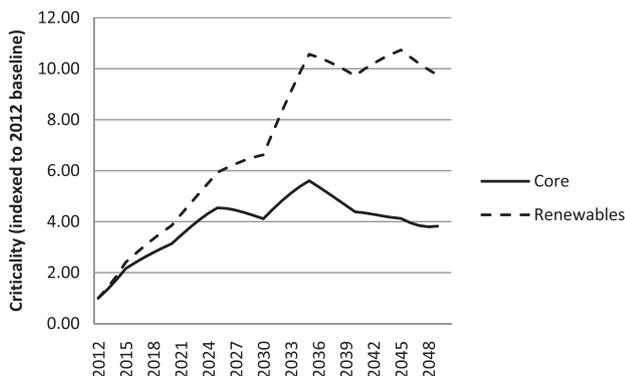


Fig. 2. Criticality of two scenarios of transition to low carbon electricity generation in the UK 2012–2050.

The results of the composite index show a significant increase but provide little insight into how policy makers or commercial organisations might intervene to reduce this criticality. This requires analysis of the metrics contributing to the composite index, which is discussed in the following sections.

4.2. Neodymium supply disruption potential

Despite the significant increase in criticality, the supply disruption potential (P) of neodymium (normalised to iron) decreases over the period of analysis from 10.86 to 7.90, a 27% reduction. This indicates that the overall trend in criticality of UK electricity system decarbonization is driven strongly by the UK's increasing exposure to supply disruption and that intervention would be most effective if focused on reducing this exposure. This is not to say that intervention should not aim to accelerate the reduction in supply disruption potential, therefore we discuss the metrics which constitute this index in more detail below.

3.2.1. Neodymium production-requirements imbalance (r)

When we forecast neodymium production and requirements (using data presented in [Supplementary information](#)) we find that there is an acceleration in projected requirements in 2030 as a result of global demand for low carbon technologies. Production is forecast by projecting the historical exponential growth pattern of neodymium mining; however even exponential growth in production cannot keep up with expansion in the number of technologies using neodymium and the scale of roll out of these technologies (see [Fig. 3](#)). Consequently both the frequency (i.e. 0.92 indicating that requirements are higher than production for almost all of the period) and scale of potential disruption (i.e. 0.36 indicating that requirements are significantly higher than requirements) are high. This results in a production-requirements imbalance (r) over the period 2012–2050 of 0.33 compared to 0.0007 for iron, indicating that there is a high potential for supply disruption.

3.2.2. Exacerbating factors (γ)

Neodymium is mined as a co-product of other rare earth metals and represents only 15% of rare earth mine output ($C_m = 0.15$). It also has a relatively low contribution to the economic value of mine output (16%; $C_p = 0.16$) 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 γ_c (0.85), which indicates that co-mining has a high potential to exacerbate the production-requirements imbalance ([Fig. 4](#)).

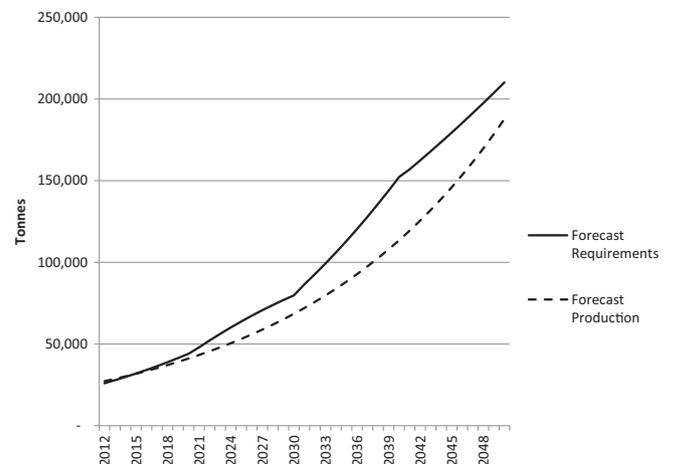


Fig. 3. Forecasts of neodymium production (M) and requirements (R) 2012–2050 (see [Supplementary information](#) for underlying assumptions and data).

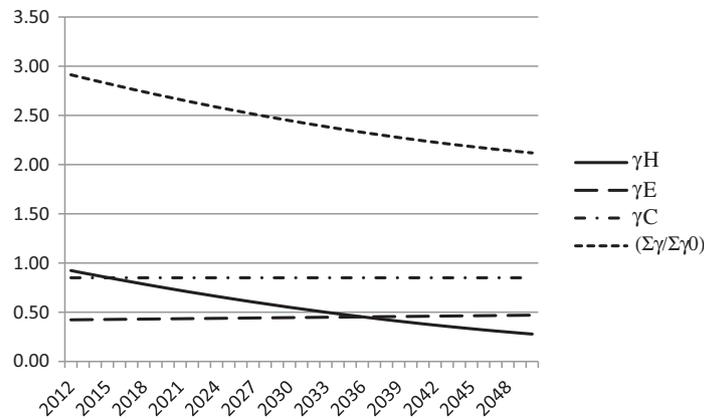


Fig. 4. Time series of factors exacerbating production-requirements balance – individual factors and sum of factors (sum normalised to iron) 2012–2050.

The current production of neodymium is almost a monopoly, with the majority produced in China; therefore γ_H is almost unity in 2012 (0.92). However, neodymium reserves are less geographically concentrated than current production would suggest [28]. When production distribution is forecast towards reserve distribution γ_H reduces to 0.28 by 2050 (Fig. 4). This reflects the likely future evolution of a far more competitive supply chain, which could mitigate the high disruption potential, such as the reopening of historic mines outside of China [35].

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 USA, increases and γ_E increases slightly by 2050 to reflect this increase in constraint from regulation (to 0.47) (Fig. 4).

3.3. Exposure of wind power to neodymium supply disruption

The evolution of exposure of low carbon electricity generation to neodymium supply disruption from 2012 to 2050, is shown in Fig. 5. The trend is the opposite to that of the supply disruption potential, with exposure increasing significantly over the period under investigation, as direct drive wind turbines become more prevalent in the wind power sector. The peaks and troughs in the exposure trend are artefacts of the uneven roll out of wind turbines in the DECC pathways.

The ‘goal’ of low carbon electricity generation, which is exposed to supply disruption, is taken to be the capacity of low carbon electricity generation required each year. This has been derived for

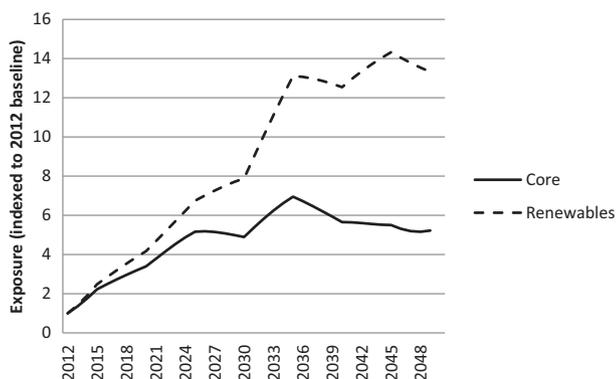


Fig. 5. Exposure of two scenarios of transition to low carbon electricity generation to neodymium supply disruption 2012–2050.

both DECC’s Core Pathway and its Renewable Pathway [21] for the period from 2012 to 2050. The capacity of low carbon electricity provided each year by technologies containing neodymium is calculated using the split of on-shore and offshore turbines (from DECC’s Pathways [21]) and estimates for the proportion of turbines which will be direct drive (taken from [3,36]).

The goal sensitivity S_G increases dramatically over the period under investigation from 0.02 to 0.08 for the Core Scenario and from 0.02 to 0.26 for the Renewables Scenario (i.e. up to 26% of low carbon electricity generation is provided by wind turbines with permanent magnets).

The price sensitivity of the goal S_P is static and was estimated using a 3 MW direct-drive wind turbine, which is representative of the type of turbine that would be deployed in the initial period of the study [37].

4. Discussion

The results of the case study demonstrate the importance of considering the dynamic analysis of the risk of material criticality. In the case of low carbon electricity from wind turbines in the UK, the likely decrease in P for the key critical material is outweighed by the increase in the exposure E of the goal to that material as the electricity system becomes increasingly reliant on wind turbines; thus the overall criticality C increases over the analysis period. The dynamic approach described in this article allows analysis of the nature of the change in criticality over time. The results showed a steep increase in criticality after 2030, when roll out of direct drive turbines 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 systemic nature and goal orientation of this approach allows us to analyse the relative risk to different pathways to achieve the goal of low carbon transition (demonstrated using DECC’s Core and Renewables pathways). This provides more specific and relevant information to support decision making under uncertainty and may prevent reliance on pathways and technologies that could become highly critical in the future (creating ‘lock-in’). The UK aims to replace a significant proportion of current generating capacity with wind turbines, in pursuit of low-carbon goals. Therefore; this analysis could also improve decision making in support of energy security to avoid supply shortfall as a result of restricted roll-out of technology on the scale planned.

A further advantage of the method is its inclusion of demand for critical material from sectors and countries outside the scope of the analysis; to represent the competition with these sectors and countries for material access. The majority of studies of material criticality and low carbon technologies consider only demand for

material from these technologies [8,24,38,39], (with the exception of Alonso et al. [40]), which excludes a significant source of demand. We include demand from these sources in our forecast of global requirements, which affects the production-requirements imbalance and; therefore, the supply disruption potential.

The case study used to demonstrate the methodology was chosen for its relative simplicity but it is possible to extend this application to analysis of multiple materials and technologies or to other societal goals. A further extension could be to undertake additional analysis to explore the effect of substitution (of materials or technologies) or recycling on criticality through exogenous scenarios. This would support analysis of the effectiveness of different interventions to help shape policy approaches to reduce the criticality of particular goals.

We recognise that the use of composite indicator has limitations, particularly in relation to indicator aggregation and combination [6]. A correlation analysis has been undertaken to examine the independence of indicators and the associated assumptions made when combining metrics (results presented in [Supplementary Information](#)). A number of the metrics are shown as having no correlation or total correlation because those metrics are static (r , γ_C and S_P). However, analysis shows a high degree of correlation between some of the metrics used to construct the supply disruption potential index. There is a very high degree of correlation between γ_H and γ_E because γ_E uses the same production distribution data as γ_H , to weight the EPI to produce ECR. When γ_E is forecast, the EPI remains static so the trend is entirely driven by production distribution, which explains the high degree of correlation. This means that the metrics are not entirely independent, which is implied by the additive combination of indicators.

Some metrics which might contribute to our understanding of criticality have been excluded because robust data is not widely available or they are not widely supported as reliable indicators by criticality investigators. For example, some studies have included measures of the stability of government and the potential for instability to constrain production. The Worldwide Governance Indicator (WGI) of 'political stability and absence of violence' has been used in some studies as a proxy for this [6,10]. However, the WGIs are highly criticized [41,42] and there is no reported correlation between political instability and production; therefore, we do not include this measure in our analysis.

The assessment of supply disruption potential only considers disruption at the point of production. We also recognise that the supply chain of critical materials has additional down-stream stages where disruption may occur. This has been explored qualitatively [7] but a quantitative analysis will require significant further data gathering, investigation and analysis.

We have forecast a number of the indicators in order to demonstrate the benefits of a more dynamic analysis of criticality. It has been necessary to make a series of assumptions to support this forecasting that are of course contestable. The methods used to forecast production and requirements rely on the continuation of historic trends to forecast future change. Future production and requirements will in fact be driven and constrained by a multitude of interrelated physical and economic factors, many of which cannot be predicted (e.g. disruptive new technologies, changes in patterns of consumption) [23,25]. A deeper understanding of these relationships and their consequences would require more detailed analysis of agent interactions and decisions [19]. Nonetheless, we consider our forecasts to be appropriate for their intended purpose of providing an indication of the potential for an imbalance between production and requirements in the future.

In common with Graedel et al. [10,43] 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 low carbon infrastructure, rather than defining the point at which criticality becomes unacceptable. This is not to say that it is not possible to define a threshold of this nature rather than 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. Conclusions

In this article we present an assessment method to analyse whether disruption in the supply chain of a critical material could impede strategic infrastructure transitions and thus compromise energy security. We have developed a new approach to enable the dynamic analysis of the risk that disruption in the supply of materials could affect the scale and speed of the roll out of low carbon technologies necessary to achieve the goal of low carbon infrastructure transition. This has required some significant developments from existing methodologies to enable us to: assess the change in constraints during an infrastructure transition; and systematically assess the effects of disruption on a particular goal, rather than individual analysis of separate parts of a connected system. The method we present in this paper does not provide an absolute risk, but a relative risk. However, this still allows us to confidently compare different technology options or roll-out scenarios vis a vis which is likely to be the most heavily exposed to disruption in supply of critical materials.

The importance of dynamic analysis is exemplified in our case study of the criticality of neodymium for low carbon electricity generation. In this case a slight reduction in the supply disruption potential of neodymium over the period of analysis is outweighed by a significant increase in the exposure of the goal of low carbon electricity to this supply disruption as a result of an increasing reliance on direct drive wind turbines. 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.

Abbreviations

C	Criticality
DECC	Department for Energy and Climate Change
E	Exposure
EC	European Commission
ECR	Environmental Country Risk
EPI	Environmental Performance Index
γ_C	Companion fraction
γ_E	Environmental constraints
γ_H	Access
HHI	Herfindahl-Hirschman Index
MW	megawatts
P	Supply disruption potential
r	Production-requirements imbalance
S_G	Goal sensitivity
S_P	Price sensitivity
UK	United Kingdom
V_{mat}	Value of critical material in technology
V_{tech}	Total value of technology
WGI	World Governance Indicator

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2014.01.052>.

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