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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.

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].