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Critical materials for infrastructure: local vs global properties

Phil Purnell BEng, PhD
Professor of Materials and Structures and Director, Institute for Resilient Infrastructure (iRI), University of Leeds, Leeds, UK

David Dawson BSc, PhD
Research Fellow, iRI, University of Leeds, Leeds, UK

Katy E. Roelich MSc, CEng, MCIWEM
Senior Research Fellow, iRI/Sustainability Research Institute (SRI), School of Earth and Environment, University of Leeds, Leeds, UK

Julia K. Steinberger BSc, PhD
Lecturer in Ecological Economics, SRI; Institute of Social Ecology, Vienna, Alpen-Adria University, Austria

Jonathan Busch MSci, PhD, ARCS
Research Fellow, SRI, University of Leeds, Leeds, UK

Introducing new technologies into infrastructure (wind turbines, electric vehicles, low-carbon materials and so on) often demands materials that are 'critical'; their supply is likely to be disrupted owing to limited reserves, geopolitical instability, environmental issues and/or increasing demand. Non-critical materials may become critical if introduced into infrastructure, owing to its gigatonne scale. This potentially poses significant risk to the development of low-carbon infrastructure. Analysis of this risk has previously overlooked the relationship between the 'local properties' that determine the selection of a technology and the overall vulnerability of the system, a global property. Treating materials or components as elements having fixed properties overlooks optima within the local–global variable space that could be exploited to minimise vulnerability while maximising performance. In this study, a framework for such analysis is presented along with a preliminary measure of relative materials criticality by way of a case study (a wind turbine generator). Although introduction of critical materials (in this case, rare earth metals) enhances technical performance by up to an order of magnitude, the associated increase in criticality may be two or three orders of magnitude. Analysis at the materials and component levels produces different results; design decisions should be based on analysis at several levels.

Notation

BH_{max}	magnetic energy product
$C_{EC,\,n}$	European Commission Raw Materials Supply Group 'supply risk' for a given element n rebased to $0 \leq C_{EC,\,n} \leq 1$
I_n	UK imports for a given element n
p_n	mass fraction of element n
Q	output for a given technology

1. Introduction

In response to sustained criticism regarding the crumbling condition of UK infrastructure (e.g. CST, 2009; ICE, 2009) the government initiated a series of national infrastructure plans (HM Treasury, 2010, 2011). These propose long-term upgrades amounting to over £250 billion and recognised that this enhanced infrastructure must be designed to enable our transition towards a low-carbon economy in a changing climate. Infrastructure must undergo a technological transformation by: radically increasing the proportion of electricity generation from low-carbon sources, such as wind and nuclear power; introducing electric vehicles and their recharging infrastructure; preparing physical infrastructure for more intense loading from weather conditions; enhancing the capacity and controllability of the electricity network (the 'smart grid'); changing the balance of rail, road and water-borne freight; and exploiting low-carbon bulk materials for large civil engineering artefacts (HM Government, 2009, 2010a).

The scale and pace of the proposed upgrades to infrastructure will certainly place pressure on traditional resources such as metals, aggregates and cement. The demand for novel generation, motive, control and information technologies will introduce materials and components to the infrastructure that were previously not required. Some of these are 'critical' – at risk of supply chain disruption and difficult to substitute (European Commission, 2010). These include various rare earth metals (used in permanent magnets for electric vehicles and wind turbines) and chromium (used in stainless steel components for nuclear power stations or high-resilience reinforced concrete). Others could become critical if introduced into infrastructure owing to the sheer scale of the total output (gigatonnes per year), such as lithium (for electrical storage cells used in vehicles), or magnesium compounds (used in low-carbon cements). Growing domestic requirements will have to compete with external demand from rapidly growing economies, expected to increase by 500–1000% (Graedel and Cao, 2010).

Without consideration of criticality, the roll-out, operation and maintenance of low-carbon infrastructure will become vulnerable to disruption of the supply of these materials and components. While constraints to technological progress imposed by, for example, critical metals have received extensive academic attention (e.g. Kleijn *et al.*, 2011; Moss *et al.*, 2011), few credible scenarios for widespread implementation of low-carbon technology explicitly consider criticality; engineers faced with designing our new infrastructures are bereft of the tools required to model it. Thus, choices are likely to be made that reduce nominal carbon emissions but lock society into technologies that become prohibitively expensive to commission, operate or maintain. This will reduce the sustainability, adaptability and resilience of the infrastructure.

Clearly, society should be able to keep track of important materials and components in infrastructure: the stock already contained therein; how much flows in (as components for new infrastructure or maintenance of old infrastructure); and how much flows out (as waste, recoverable or otherwise). The process can be operated 'bottom up', where information on stocks is analysed and flows inferred from changes in the annual data, or 'top down', where stocks are calculated from differential analysis of inflows and outflows. The traditional tool used for this type of analysis is called 'stocks and flows' (S&F) modelling. This is very useful for analysing the quantities of a single substance moving through a system, particularly national economies (Binder *et al.*, 2006; Spatari *et al.*, 2002). However, it is also necessary to know where the material or component is and when it enters and leaves the system, in order that resources can be targeted and possibly recovered. Accordingly, some studies are now adding information on long-term changes in materials flow (e.g. Brattebø *et al.*, 2009), basing analysis on stock dynamics (e.g. Sonigo, 2011) and/or adding '4D' spatio-temporal data layers (e.g. Tanikawa and Hashimoto, 2009). These studies are focused on national or city scale analyses, rather than analysing infrastructure systems. Müller (2006) studied housing in the Netherlands using a stock dynamics-based approach focused on the services enabled by the materials stocks, rather than stocks themselves; this allows technology-level interventions, such as substitutions, to be analysed.

Recent study (e.g. Busch *et al.*, 2012; Roelich, 2012a) is radically extending S&F modelling, extending the work of Müller, specifically to analyse infrastructure transition in response to resilience or low-carbon agendas. This adds dynamic information on historic and future stocks and flows, the vulnerability of future inflows to criticality, and the properties or quality of the materials and components to inform reuse and recycling. The new model disaggregates the system stock into infrastructure, technology and materials levels; the technology stocks are further sub-divided into multiple (as necessary) structures and components. Currently, the model takes two top-level inputs – technology roll-out scenarios and the materials mix required for each technology – and produces plots of material (or component) requirements against time for each material (or component) of interest. These are then compared with current supply data (e.g. import or consumption figures) to provide insight into likely material supply bottlenecks. Figure 1 shows the projected lithium (Li) required for lithium-ion batteries to fulfil the roll-out of UK passenger vehicles based on politically accepted scenarios. Within a short period, the UK requirement for this single technology becomes a multiple of the current total UK consumption, questioning the sustainability of current scenarios and the future criticality of lithium, which is not presently considered a critical material.

1.1 Criticality

Analysis of criticality is more sophisticated than comparing current and projected supplies. Roelich (2012b) identifies four primary issues that will affect the probability of supply disruption for a given material and/or component.

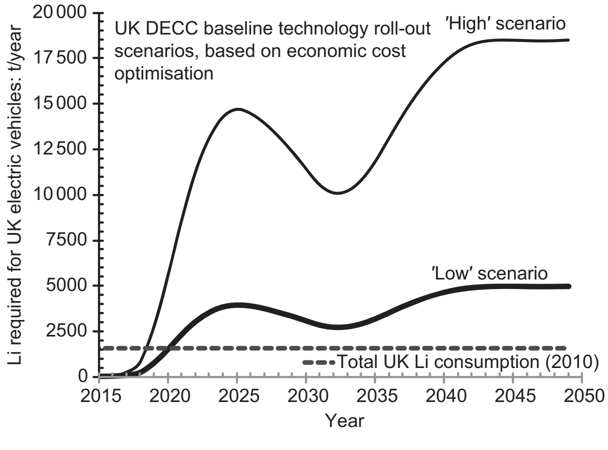


Figure 1. Lithium required for new electric vehicles in the UK calculated according to model of Busch *et al.* (2012) using UK government Department of Energy and Climate Change 'MARKAL' scenarios for technology roll-out (HM Government, 2010b, 2011). Total UK lithium consumption (imports) according to Bide *et al.* (2011)

(*a*) Geological reserves: the balance between consumption, reserves, reserve base and recoverability is complex and driven by economic factors, with long lag times between market stimuli and response, since mining operations are expensive and time consuming to commission. Many critical materials are only produced as co-products of other mining operations, adding further complexity.

(*b*) Geopolitics: the supply of many critical materials is concentrated in politically unstable states (e.g. cobalt in the Democratic Republic of Congo); other jurisdictions may restrict supplies of critical materials for political or economic reasons (e.g. China's autumn 2010 restrictions on exports of rare earth metals to Japan).

(*c*) Increasing demand: introducing new materials into a system with the unparalleled scale of infrastructure can place severe pressure on critical materials and push previously abundant materials into scarcity. The pace of development in Asia and Africa, and the global move towards a low-carbon infrastructure, increases competition for resources from overseas. Many critical materials are used in competing high specific value sectors (e.g. information technology).

(*d*) Environmental impact: production of many materials and components, particularly those requiring metallic elements, result in significant discharge of pollutants, require energy from fossil fuels (contributing to depletion and carbon dioxide emissions) and consume water. Declining ore grades and increasingly stringent environmental legislation exacerbate the problem.

Combining these factors into dynamic measures of criticality as a function of materials mix (for a material or component) and vulnerability (of an infrastructure system) will require an understanding of the relationship between

- the design properties of the materials and components that determine their technical performance and hence control decisions regarding their proposed introduction into infrastructure products
- the criticality of components or technologies proposed to be introduced, engendered by their particular materials mix
- the change in the vulnerability of the infrastructure system to disruption by critical material supply induced by the proposed technology change.

This requires a framework for relating local and global properties and the aim of this paper is to propose the basis for such analysis.

1.2 Relationship between local, translation and global properties

Interventions in infrastructure technology, at elemental, material or component scale, are made on the basis that improvements in some combination of technical design criteria (e.g. tensile strength, magnetic energy product, mass; defined here as the local primary properties) will lead to improvements in a particular property of the whole system (e.g. capital expenditure required, running costs, system capacity; defined here as the global primary property).

However, the detailed relationships between local and global properties are often poorly understood. Specifically, the consequences of changing local properties on global properties other than those directly considered in the design (e.g. embodied carbon, or vulnerability to material criticality; defined here as the global secondary properties) are unknown. Global properties will also change according to local properties that are not necessarily central to design; defined here as local secondary properties, which may be strong or weak functions of the local primary properties. To understand these relationships, the translational properties – the subset of local properties, primary and/or secondary, that link local and global properties – must be identified and evaluated.

Consider the hypothetical example of steel bodywork for a vehicle. In order to optimise its fuel consumption, a designer decides to reduce the mass of the bodywork by specifying steel with higher tensile strength, thus requiring less steel for the same performance. This may require a change from mild steel to alloy steel. The designer will know the cost of this more expensive high-performance steel and the budget available, which will further constrain his design. The alloy steel will have a higher processing energy requirement, and thus higher embodied energy and carbon. It will also contain larger quantities of elements with much higher criticality than iron and carbon (e.g. chromium or manganese).

In this case, the local primary properties are tensile strength and the cost of steel. The global primary properties are fuel consumption and the overall cost of the vehicle. The translational properties are the density of the steel (a very weak function of the tensile strength) and the cost of the steel (a stronger function of the tensile strength, and also a local primary property). There is of course a multiplicity of secondary properties, but only those useful for evaluating global properties (i.e. those that can act as translational properties) will be of interest. If the lifetime and embodied carbon of the vehicle are global secondary properties of interest, then the translational properties required would include the corrosion resistance and embodied carbon of the steel, ideally as continuous functions of the tensile strength. (Note that for many systems, issues related to environmental impact such as embodied carbon dioxide (eCO_2) are analysed as secondary global properties). Thus the attributes of primary, secondary and/or translational are not intrinsic to a property, but rather a function of the study of the system at hand.

Properties are not restricted to the materials level. At the component or technology level, the relationship between the local and global properties is still of interest. For example, the engine (local) for the vehicle (global) will be chosen on the basis of the relationship between: the global primary properties of speed, acceleration and economy; local primary variables such as power output and torque curves; translational variables would include mass, rotational inertia. Fuel consumption per unit power output would be both a primary and translational property. At the component or technology level, however, property relationships will not generally be continuous functions as at the materials level, but discrete values for each artefact.

It follows that property relationships have to be tracked through the materials, component and technology levels of the system in order that the effect on global variables of interest can be properly determined. Interventions at any level will cascade in both directions; modelling the local–global property relationships could avoid unintended consequences.

1.3 Comparing properties

Most investigators when considering the national stocks and flows of materials with widely varying compositions and properties (such as concrete, steel or plastics) treat these materials as effectively elemental; that is, it is implicitly or explicitly assumed that each has a single set of local properties. Müller (2006) examined the impact of concrete usage in the Netherlands on consumption of mineral resources and production of waste assuming a constant cement content (of 11%) between 1900 and 2100; the effect of the wide variation in the primary local property of concrete (i.e. the compressive strength) was not examined. Pauliuk *et al.* (2012) applied a similar approach to the Chinese steel cycle, explicitly stating that analysis did not differentiate between steel, cast iron and all other iron alloys. These simplifications are necessary in order that initial analysis of complex systems can be made. Including the relationship between local and global properties in the analysis might allow opportunities to improve the impact and performance of the system. Investigators often allude to this, even if not including it in the formal analysis. Pauliuk *et al.* (2012) and Johnson *et al.* (2006) discuss how the ‘quality’ of recycled metal (i.e. its content of tramp elements) could affect the degree to which a closed metal cycle could be achieved for steel and chromium, respectively. Müller (2006) notes that changing the density of the concrete used in the analysis can affect the balance between the output of demolition waste and requirements for new construction. Variation in local properties is sometimes presented as a ‘data sheet’ with ranges of properties (for plastics), rather than as an analysis of the local–translational property relationship, or particular metallic alloys are presented in elemental fashion (Giudice *et al.*, 2005).

Engineering analysis of the relationships between materials properties is carried out using the Ashby plot (Ashby and Johnson, 2002) (see Figure 2). This relates two desirable local indices, either single properties or combinations (e.g. strength-to-weight ratio).

This approach is extremely useful for narrowing down a wide choice to a few likely candidates for a given design, which can then be analysed in more detail. However, a few investigators have used it to evaluate the effect of local property changes – material enhancement and substitutions, or technology choices on global properties (usually an eco-indicator) and thus translational properties included eCO_2, recycled content, or primary energy use.

Rydh and Sun (2005) assigned materials to one of 17 groups according to their typology (ferrous, non-ferrous, composites, wood etc.) and local primary properties (density, elastic modulus and yield strength) to formulate a series of Ashby charts of a composite ‘Eco’99’ index against primary properties. However, only ranges of primary properties and the corresponding eco-indicator were presented, rather than formal functional relationships between the two. Kobayashi (2006) produced ‘factor-X’ charts of environmental factors derived using life cycle assessment (LCA) against product value factors, with the objective of optimising product performance while minimising environmental impact. The relationship between descriptors of the product function and technical parameters of the design – namely, translational as opposed to local variables – is also discussed.

Purnell (2012) analysed the variation on eCO_2 per unit of structural performance for steel, reinforced concrete and

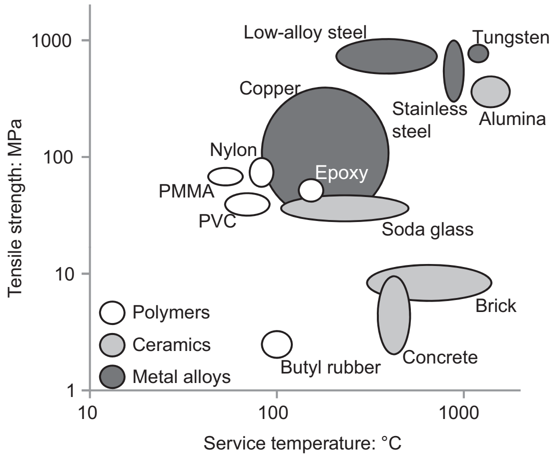


Figure 2. Example of an Ashby diagram (PMMA: polymethyl methacrylate; PVC: polyvinyl chloride)

timber beams and columns (a translational variable implying the global warming potential was the global variable of interest) as a function of size and loading (local primary variables for structural engineering design). The complexity of the relationships uncovered (Figure 3(a)) demonstrated clearly that any materials comparison based on simple consideration of eCO_2 per unit volume or mass is likely to be deeply flawed. Purnell and Black (2012) reported that concrete, which can vary over a wide range of compressive strength (its local primary property) from ~20 to 100 MPa, has a distinct optimum in the strength plotted against eCO_2 curve at around 50–60 MPa (Figure 3(b)). Thus there are considerable opportunities for minimising carbon dioxide emissions afforded by a knowledge of the local–transitional–global property relationship for structural materials.

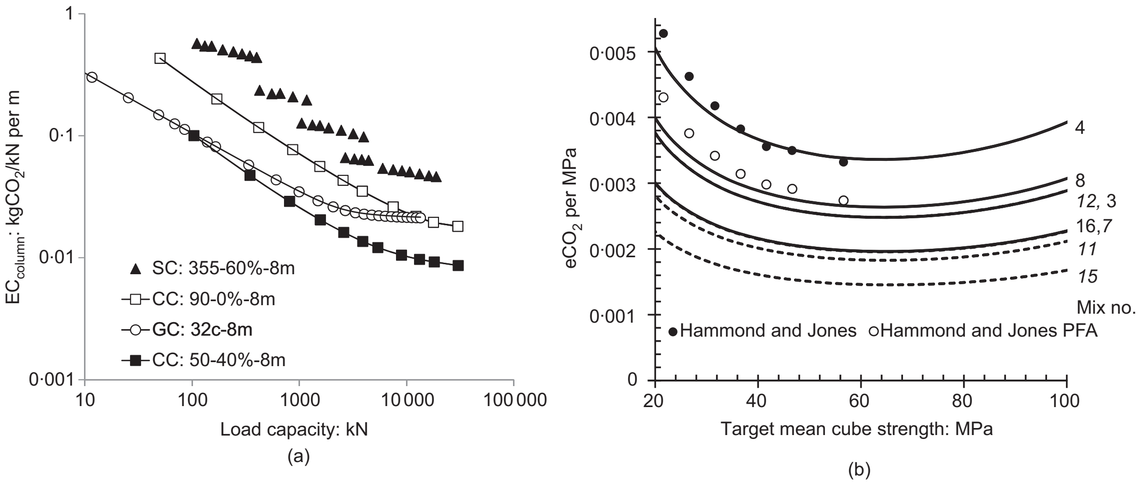
Studies concerned with scarcity, criticality or vulnerability do not typically address the properties issues at all, although they may distinguish between substitutions of elemental choices; for example, the criticality index of Graedel *et al.* (2012) includes both elemental substitution potential and the supply risk of the substitute element. No previous work has analysed how criticality might vary at different levels in the system; for example, materials, component, technology or infrastructure. Thus, in this paper, a preliminary analysis of criticality is presented (as the translational property pertaining to vulnerability to critical supply as the global property) against properties at the material and component level, uncovering complex, non-monotonic relationships.

2. Methodological approach

The concept is explored using two case studies of the same technology – wind turbine generators – at two different system levels. The first, at the material level, examines various permanent magnet technologies to determine the variation of material criticality (the translational property) as a function of a local primary property (the magnetic energy product BH_{max}). The second, at the component level, examines the variation in materials criticality with design options for drivetrain technologies. Material criticality, or the probability of supply chain disruption for that material, is an important consideration in determining system vulnerability (i.e. the global property).

2.1 Relative materials criticality

In this study, a relative material criticality (RMC) is derived based on the elemental materials mix for the magnets (since the materials used in the gearboxes and ancillaries – steel, polymers and so on – are generally of negligible criticality) based on the 'supply risk' advanced by the European Commission Raw Materials Supply Group (European Commission, 2010). This varies from 0 to 5 and combines 'assessment of the political-economic stability of the producing countries, the level of concentration of production, the potential to substitute and the recycling rate'. It has been rebased in this study to vary as $0 \leq C_{EC,\,n} \leq 1$ and assumed to approximate the probability of a disruption to supply for a given element over a standard time frame (note that since relative criticality is being presented here, the actual time frame is not important). Since each



(a)

(b)

Figure 3. Embodied carbon dioxide per unit of structural performance: (a) long structural columns (CC (open symbols): high-strength reinforced concrete made with ordinary (CEM1) cement, (filled symbols): 50 MPa reinforced concrete with 40% of the CEM1 replaced by pulverised fuel ash (PFA); EC: embodied carbon dioxide; GC: glulam timber beams; SC: steel universal column section). For more details see Purnell (2012); (b) unreinforced concrete (solid lines represent CEM1 mixes, dashed lines represent CEM1-PFA mixes; points are data from the Institution of Civil Engineers database (Hammond and Jones, 2008)). For more details see Purnell and Black (2012)

magnet technology employs a mix of elements, RMC also takes into account the proportion by mass of each element p_n in a given magnet (either in terms of relative concentrations at the materials level, or tonnes per generator at the component level). However, to reflect the fact that the availability of various elements differs enormously – obtaining an extra tonne of neodymium (Nd) is significantly more difficult than obtaining a similar increment of iron (Fe) – for example, these proportions are divided by a number reflecting the relative availability of each element; in this case, UK import data (Bide *et al.*, 2011) have been used for each element, I_n. The partial contribution from each element is then added to derive an overall figure. Finally, for the component case, the difference in the outputs of the various technologies Q (in MWh/year) is taken into account in order that the functional unit remains correct. Mathematically, this is represented (for a set of different elements n) by

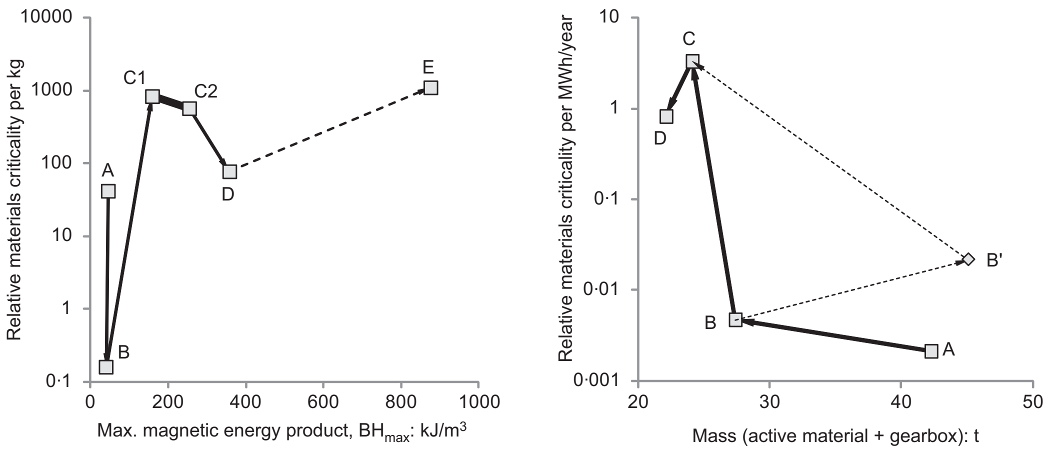
$$1. \quad \mathrm{RMC} = \frac{1}{Q}\sum_n \frac{C_{\mathrm{EC},n}\, p_n}{I_n}$$

For a material-level analysis, $Q = 1$ and the units of RMC are tonnes^{-1}. For a component-level analysis, the summation is dimensionless and the units of RMC are determined by the nature of Q.

2.2 Local properties

At the materials level, the local primary property is $\mathrm{BH}_{\max}$ since this is the single property that most closely determines the utility of a given permanent magnet composition (Coey, 2012). Values of $\mathrm{BH}_{\max}$ and the corresponding permanent magnet compositions were taken from studies by Coey (2012) and Gutfleisch *et al.* (2011). The magnet technologies considered are detailed in the caption to Figure 4(a). Note that only permanent magnet technologies are considered as $\mathrm{BH}_{\max}$ is undefined for electromagnets.

For the component-level analysis, the choice of local primary variable is more difficult. Wind turbine generators are to some degree optimised for minimum weight, to reduce the static and dynamic loads on the towers and foundations. The main contributions to overall generator weight come from the mass of the active material (i.e. that contributing to the generation of magnetic field; iron and copper for the electromagnet technologies, and iron, copper and neodymium–iron–boron (Nd–Fe–B) magnet for the permanent magnet technologies) and the mass of the gearbox. Changing drivetrain technology (from three-stage gearbox, to single-stage gearbox, to direct drive; see caption, Figure 4(b)) may decrease gearbox weight at the expense of active material weight and vice versa; thus the local primary property used here is active material mass plus gearbox mass. The necessary technical information for gearbox design and associated materials mixes was obtained from Li *et al.* (2009), Orbital2 (2012) and Polinder *et al.* (2006). Note that this component-level analysis includes both permanent magnet and electromagnet technologies. The permanent magnet composition is assumed in this analysis to be $Nd_2Fe_{14}B$.



(a)

(b)

Figure 4. Relative materials criticality (on a logarithmic scale) plotted against local properties. (a) Materials-level analysis of permanent magnet technologies (A: strontio-ferrite; B: AlNiCo; C1: SmCo5; C2: Sm2Co17; D: Nd–Fe–B; E: superconducting Y–Ba–CuO). (b) Technology-level analysis of wind generator technologies (A: three-stage geared electromagnet (DFIG); B: single-stage geared electromagnet (GDFIG); B′: direct-drive electromagnet (DDSM); C: direct-drive permanent magnet (DDPM); D: single-stage geared permanent magnet (GPM). For acronym details, see Polinder *et al.* (2006))

3. Results

3.1 Permanent magnet technology: material-level analysis

Figure 4(a) shows the material-level analysis of permanent magnet technologies, illustrating the technological improvement in BH_{max} of permanent magnets over the twentieth century moving rightwards from A to E. In assessing the RMC of the evolution, the preliminary results show a significant range of supply risk in orders of magnitude and, coupled with improvements in energy product, this offers an interesting narrative.

The strontio-ferrite magnet (A) has the lowest BH_{max} (45 kJ/m^3) in this analysis, owing to much of the volume being occupied by large O^{2-} anions, which carry no magnetic moment (Coey, 2012). The next generation of 'Alnico' magnets (B, introduced ~1940) gave broadly similar levels of magnetic performance but reduced criticality by ~100, as a result of replacing a reliance on strontium with the less critical cobalt. However, the introduction of first-generation samarium–cobalt magnets (C1, ~1980) reverses this; introducing a reliance on the rare earth metal samarium increases BH_{max} by a factor of four (to 160 kJ/m^3) but intensifies the relative criticality by more than 1000.

Next-generation samarium–cobalt (Sm–Co) magnets (C2) show a more favourable design transition; a reduction in criticality (owing to reduced samarium content) is observed with an increase in BH_{max} (to 250 kJ/m^3 as a result of improved processing). The most recent technology advancement is the introduction of neodymium–iron–boron permanent magnets (*D*, ~1990), which have dominated the market over the past 10 years (Gutfleisch *et al.*, 2011). Performance is again enhanced (by ~40%) and despite the introduction of an alternative rare earth metal that attracts headlines – neodymium – into the materials mix, criticality is reduced, since $C_{EC,\ Nd} = C_{EC,\ Sm}$ (European Commission, 2010) and proportionally less neodymium is required for D than samarium is required for C1, C2.

The energy product of neodymium–iron–boron comes within 10% of the theoretical limit for traditional permanent magnet technology and advancements are slowing (Coey, 2012; Gutlfleisch *et al.*, 2011). The final stage of analysis presents a move to high-power superconducting permanent magnets (e.g. $YBa_2Cu_3O_x$), for which BH_{max} is estimated to be ~850–900 kJ/m^3 (American Magnetics, 2012). Although this can produce a ~130% improvement in BH_{max}, the cost is a significant increase in relative criticality.

3.2 Generator technology: component-level analysis

Figure 4(b) presents the preliminary result of the component-level analysis of five 3 MW wind generator technologies as modelled by Polinder *et al.* (2006). As before, technology options moving leftward A through to D are in chronological order of introduction. All five technologies produced very similar annual energy yields *Q* of 7·69 GWh (A) to 7·89 GWh (C).

The transition from A to B involves a shift from a three-stage (A) to a single-stage gearbox (B), reducing gearbox mass from 37 to 16 t but increasing total active material mass (to compensate for the lower angular velocity of the rotor) from 5·2 to 11·4 t. The small increase in criticality is associated with the extra copper and iron required by the enlarged magnet. The transition from B to C involves both a transition from a single-stage gearbox to 'direct drive' – that is, elimination of the gearbox – and the introduction of a permanent magnet more efficiently to generate and maintain the high magnetic fields necessary to compensate for the further reduced rotor speed. Note that the relatively small improvement in the local primary property (the gearbox is eliminated but the total mass of active material is 24 t, including 1·7 t of permanent magnet) increases criticality by a factor of ~1000 owing to the introduction of neodymium. Further development (D) involves re-introducing a single-stage gearbox to increase the rotor speed, allowing a reduction in the quantity of active material (to 6 t, including 0·4 t of permanent magnet) and concomitant reduction in criticality, at the cost of a 16 t gearbox.

An alternative development path at B involves a direct-drive electromagnet generator (B′); however, the increase in active material mass (from 11 to 45 t) involves an increase in both criticality and total mass (as the gearbox mass saving is only 16 t).

5. Discussion

At the material level (Figure 4(a)), the introduction of neodymium into the system (D) appears to be justified, as it both increases performance and decreases criticality over the previous technology. Substitution with a previous generation, reduced criticality permanent magnet technology – Alnico (B) – would involve a 10-fold performance penalty. However, a decision as to whether this would be balanced by the concomitant reduction in criticality (× 400) would be based on factors outside this analysis, namely the relative value of criticality against performance. At the component level, introducing the neodymium-based permanent magnet technologies has a much less dramatic effect on performance (in terms of generator weight) but a similar effect on criticality. Thus the value of the introduction of neodymium is less clear-cut, especially as other factors will contribute to the decision regarding generator technologies (e.g. that simplifying or removing the gearbox reduces maintenance costs and the frequency of generator failures). Substitution of a previous generation technology in order to reduce criticality would be a far more likely design decision resulting from the component-level analysis than it would from the material-level analysis, suggesting that a multi-level analysis is required in order to produce a coherent design strategy concerning criticality reduction.

The derivation of RMC as presented here is necessarily a first approximation and should attract further scrutiny. It is unlikely that the value of C_{EC} maps directly onto a probability of supply disruption, and alternative criticality indices need to be examined in a similar framework. The variation of RMC over several orders of magnitude is largely driven by the normalisation against I_n. This tends to swamp the effect of $C_{\mathrm{EC},\,n}$. The implicit assumption is that if element X is imported at a rate one-10th that of element Y, then X is 10 times more difficult to obtain. A more sophisticated relationship between I_n and the probability of supply disruption could be derived from, for example, price elasticity data.

6. Conclusion

A framework has been presented for analysis of the effect of material and component substitution on vulnerability to critical material supply as a function of local properties and applied to a case study of wind-turbine generation. Preliminary analysis suggests that even where the introduction of critical materials (in this case, rare earth metals) enhances technical performance by up to an order of magnitude, the associated increase in criticality may be two or three orders of magnitude. Analyses at the materials and component levels produce rather different results, suggesting that design decisions should be based on analysis at several levels. The relative materials criticality values derived here should be treated as preliminary, because the relationships between the component parameters and the probability of supply disruption are not known with confidence. Nonetheless, this analysis serves to highlight the importance of analysing the introduction of critical materials into infrastructure and introduces a methodology for further development.

Acknowledgements

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