Critical materials for low-carbon infrastructure: the analysis of local vs global properties

Phil Purnell (iRI, School of Civil Engineering)
Katy Roelich (iRI & SRI, School of Earth & Environment)
Julia Steinberger (SRI)
David Dawson (iRI), Jonathan Busch (SRI)
Changing infrastructure

• 500 projects; £250 billion
• environmental impacts – reducing the carbon intensity

• The nature of our national infrastructure needs to be a primary driver in the move towards a low carbon economy … infrastructure must also be adaptable… to meet changing demand through the adoption of new technologies and materials
Embedding new low CO$_2$ technology introduces critical materials into infrastructure:

- e.g. Nd - motors/generators for wind turbines & electric vehicles
- Not just elements: e.g. aggregates
- Scale of infrastructure means that change in demand can be a step-change: Multiples, not fractions
- Previously abundant materials may become critical

http://www.cathodic.co.uk/information/19/14/Elgard_General_Information.htm
• **Vulnerability**: EU/UK are often 100% importers
• Passive/reactive price & supply volatility: Geopolitical issues

China pledges not to use rare earth minerals as weapon

China has said it will not use exports of so-called rare earth minerals as a diplomatic bargaining tool.

The country produces more than 90% of these valuable commodities, which are used to produce electronic items such as mobile phones.

A row has blown up surrounding their availability, with relations between China and Japan at its centre.

“The US and the EU asked Beijing to clarify its policy on mineral exports after China stopped shipping to Japan.

“The stoppage followed a spat between China and Japan last month over islands whose ownership is disputed.”
• the flow of materials into & out of infrastructure;
• the stocks of materials contained within infrastructure, during operation and demolition;
• the location and properties of these materials and the components they are a part of;
• the criticality of key materials, in terms of substitutability and supply risks;
• the interactions between these factors.
Model Structure

Infrastructure

Abstract stock of the required service level

Technology

Structure: physical stock of infrastructure that directly supplies the service

Components: physical stock of infrastructure parts that indirectly provide the service

Materials

Materials stocks contained in both infrastructure and components
Model Structure: dynamic S&F

Infrastructure

Politically credible roll-out scenarios

Infrastructure stock

\( K^{(i)} (t) \)

Technology

\( I^{(s)} (t) \)

\( K^{(s)} (t) \)

\( O^{(s)} (t) \)

Component stock

\( K^{(c)} (t) \)

\( O^{(c)} (t) \)

Materials

\( I^{(m)} (t) \)

Materials stock

\( K^{(m)} (t) \)

\( O^{(m)} (t) \)
Model Structure: lifetimes

Infrastructure

- Infrastructure stock $K^{(i)} (t)$
- Technology mix
- Structure lifetime $L^{(s)} (t, t_0)$

Technology

- Structure stock $K^{(s)} (t)$
- Component mix
- Component lifetime $L^{(c)} (t, t_0)$

Materials

- Component mix
- Material lifetime $L^{(m)} (t, t_0)$
- Technology mix

- Component stock $K^{(c)} (t)$
- Materials stock $K^{(m)} (t)$
- Material intensity
- $O^{(m)} (t)$

- Infrastructure stock $K^{(i)} (t)$
- Structure stock $K^{(s)} (t)$
- Component stock $K^{(c)} (t)$
- Materials stock $K^{(m)} (t)$

- Technology mix
- Structure lifetime $L^{(s)} (t, t_0)$
- Component lifetime $L^{(c)} (t, t_0)$
- Material lifetime $L^{(m)} (t, t_0)$
UK DECC baseline technology roll-out scenarios, based on economic cost optimisation.

"High" scenario

"Low" scenario

Total UK Li Consumption (2010)
Intervention: technology

• Intervention – new technology development – at multiple levels

• New development = new properties
  • Faster, stronger, corrosion resistant, higher output…

• New materials mix = new criticality/vulnerability

• Research question: is there a criticality price to pay for enhanced technical performance?
  • What is the relationship between local design properties and the global property of system vulnerability to critical material supply? (Efficiency – fragility trade-off)
Factors of Criticality

- Geological scarcity
- Geopolitics
- Environmental Impact
- Demand from other sources/sectors
- Substitutability
- Recyclability
- Importance to economy/low carbon strategy

No agreed quantitative metric for criticality: qualitative assessments
Technology development

![Diagram showing technology development process]

- **Material criticality/vulnerability**
- **Criticality** vs. **Local property**
- **Local property**
- **Design evolution (time)**

**Negative system change**

**Positive system change**

- **Tech. 1**
- **Tech. 2**
- **Tech. 3**
- **Tech. 4**
- **Tech. 5**

**Typical design trajectory**
(e.g. material substitution)
Relative material criticality

- EC Raw Materials Supply Group index (expressed as probability i.e. 0→1) $C_{EC, n}$
- Mass fraction of each material $p_n$
- UK imports for each material $I_n$
- At technology level, normalised to ‘output’ $Q$ to retain functional unit

$$RMC = \frac{1}{Q} \sum_{1}^{n} \frac{C_{EC,n} \cdot p_n}{I_n}$$
• Generator A: Total mass 100 t (70 t Fe, 20 t B, 10 t Nd), output 200 MW

• $C_{EC, Fe} = 0.06; C_{EC, B} = 0.12; C_{EC, Nd} = 0.98$

• $I_{Fe} = 700,000 \ t; I_{B} = 900 \ t; I_{Nd} = 20 \ t$

\[
RMC_A = \left[ \frac{0.06 \times 70t}{700,000t} + \frac{0.12 \times 20t}{900t} + \frac{0.98 \times 10t}{20t} \right] \frac{\text{MW}}{200 \ \text{MW}}
\]

• $= 0.0025 \ \text{MW}^{-1}$

• *RMC tends to be dominated by most critical material and/or import data in many cases – needs refining.*
Case study 1: wind turbine design

- Two levels
  - 1a: Materials – magnet development
  - 1b: Technology – nacelle mass
- How does criticality change as technology develops?

1a: Magnetic materials

Graph showing the relative materials criticality in (per kg) against the maximum magnetic energy product $BH_{\text{max}}$ in kJ m$^{-3}$.

- **Sr-Fe**
- **Al-Ni-Co**

The graph displays Sr-Fe at a higher criticality compared to Al-Ni-Co.
1a: Magnetic materials

Relative materials criticality (per kg)

Max. magnetic energy product $BH_{\text{max}}$ / kJ m$^{-3}$

- Sm-Co
- Sr-Fe
- Al-Ni-Co
1a: Magnetic materials

The graph illustrates the relative materials criticality (per kg) as a function of the maximum magnetic energy product $BH_{\text{max}}$ in kJ m$^{-3}$. The materials plotted include Sr-Fe, Al-Ni-Co, Sm-Co, Nd-Fe-B, and superconducting materials. Each point represents the criticality of a specific material, with the x-axis showing $BH_{\text{max}}$ and the y-axis showing the relative criticality.

- **Sr-Fe**
- **Al-Ni-Co**
- **Sm-Co**
- **Nd-Fe-B**
- **Superconducting**
1b: Turbine generator design

![Graph showing relative materials criticality vs. mass for different turbine generator designs.]

- Direct PM
- 1-stage PM
- 3-stage EM
- 1-stage EM

Relative materials criticality (per MWh/yr)
Mass (Active material + Gearbox) / Tonnes
1b: Turbine generator design

- **Direct PM**
- **1-stage PM**
- **3-stage EM**
- **1-stage EM**
- **Direct EM**

**Relative materials criticality (per MWh/yr)**

**Mass (Active material + Gearbox) / Tonnes**

- 0.001
- 0.01
- 0.1
- 1
- 10

- 20
- 30
- 40
- 50
Case study 2: steel properties

- Steel strength is increasing: light-weighting agenda
- Corrosion resistance of increasing importance
- Extra alloying elements = extra criticality

Billingham et al 2003, Review of the performance of high strength steels used offshore” (HSE)
2: Steel properties

![Graph showing relative materials criticality vs. yield strength for different types of steel: Mild steel, Stainless steel, HS alloy steel.](image-url)
• Technological responses to climate change are vulnerable to critical materials supply;
• An enhanced stocks & flows methodology can be used to analyse this;
• Preparing criticality-property charts can help assess the change in relative vulnerability induced by a material and/or technology change;
• A more robust metric for criticality is required.