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# Closing the low-carbon material loop using a dynamic whole system approach

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ABSTRACT

The transition to low carbon energy and transport systems requires an unprecedented roll-out of new infrastructure technologies, containing significant quantities of critical raw materials. Many of these technologies are based on general purpose technologies, such as permanent magnets and electric motors, that are common across different infrastructure systems. Circular economy initiatives that aim to institute better resource management practices could exploit these technological commonalities through the reuse and remanufacturing of technology components across infrastructure systems. In this paper, we analyze the implementation of such processes in the transition to low carbon electricity generation and transport on the Isle of Wight, UK. We model two scenarios relying on different renewable energy technologies, with the reuse of Lithium-ion batteries from electric vehicles for grid-attached storage. A whole-system analysis that considers both electricity and transport infrastructure demonstrates that the optimal choice of renewable technology can be dependent on opportunities for component reuse and material recycling between the different infrastructure systems. Hydrogen fuel cell based transport makes use of platinum from obsolete catalytic converters whereas lithium-ion batteries can be reused for grid-attached storage when they are no longer useful in vehicles. Trade-offs exist between the efficiency of technology reuse, which eliminates the need for new technologies for grid attached storage completely by 2033, and the higher flexibility afforded by recycling at the material level; reducing primary material demand for Lithium by 51% in 2033 compared to 30% achieved by battery reuse. This analysis demonstrates the value of a methodology that combines detailed representations of technologies and components with a systemic approach that includes multiple, interconnected infrastructure systems.



## 1. Introduction

Limiting climate change to the internationally agreed temperature rise of 2.0 °C on preindustrial levels (United Nations, 2015) will require the almost complete decarbonization of energy and transport infrastructure over the next 35 years (Mulugetta et al., 2014). The scale and rate of this infrastructure transition is unprecedented and, given the high material intensity of infrastructure, it will have a significant impact on the material use of nations (Fishman et al., 2016). Furthermore, the necessity to embed low-carbon technologies into infrastructure involves the use of a wider range of materials than has historically been the case (Greenfield and Graedel, 2013), including rare earth elements (such as neodymium (Du and Graedel, 2011) and dysprosium (Elshkaki and Graedel, 2014) in wind turbines and tellurium and indium in solar panels (Helbig et al., 2016)) as well as cobalt, lithium and platinum group metals. Some of these materials have been labelled as 'critical' due to the resulting high risk of supply disruption (British Geological Survey, 2012), causing concern for US (United States Department of Energy, 2010) and EU (Moss et al., 2011) policy makers, and driving academic research to identify potentially critical materials (see e.g (Erdmann and Graedel, 2011; Roelich et al., 2014).). A recognition of the economic importance of critical materials, and the environmental impacts associated with material consumption (Behrens, 2016) highlights the need for more efficient management of material resources. In the context of the climate change challenge and increasing environmental burden of material extraction and waste production, the concept of a

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**Acronyms**

| | |
|---|---|
| CCS | Carbon capture storage |
| DECC | Department for Energy and Climate Change |
| EV | Electric battery vehicle scenario |
| GPT | General Purpose Technology |
| GDP | Gross Domestic Product |
| HF | Hydrogen fuel cell vehicle scenario |
| ICE | Internal Combustion Engine |
| LCA | Life Cycle Assessment |
| Li-ion | Lithium-ion |
| NdFeB | Neodymium Iron Boron |
| PV | Photovoltaic |
| S&F | Stocks and Flows |

'circular economy' is finding increasing interest across academia (see (Ghisellini et al., 2016) for a recent review) and in policy and industry spheres. At the core of the concept is the idea that the currently dominant linear path of products and materials from production through use to disposal is replaced by a circular path of production, use and recovery. China has held the circular economy as a development goal since 2009 (Mathews and Tan, 2011a), the European Commission published a circular economy action plan in 2015 (European Commission, 2015) and industry interest is reflected in recent reports from major international consultants (e.g. Accenture, 2014; McKinsey & Company, 2015) and the Ellen MacArthur Foundation (2013).

Whilst these reports and policy initiatives draw on national scale assessments of sustainable material use, their focus is on promoting innovation on the micro level of individual products, processes and firm business models (Su et al., 2013), and the meso level of connecting firms to productively use each other's waste products in eco-industrial parks (Mathews and Tan, 2011b). The link between micro and meso level initiatives and the need to scale material use to remain within planetary boundaries (Steffen et al., 2015) is, however, left vague or unaddressed. More systemic approaches to instituting a transition to a circular economy can draw on several decades of academic work in industrial ecology, ecological economics and related disciplines. These have addressed topics including the physical basis of the economy (see (Fischer-Kowalski and Huttler, 1999) for a review of research between 1970 and 1998 and (Pauliuk and Hertwich, 2015) for a recent discussion) and its sustainable scale (Weizsäcker et al. (1997) and Schmidt-Bleek (2008) have argued for a factor four and factor ten reduction in material intensity), industrial production and consumption patterns and practices that minimize environmental impacts (e.g. cradle-to-cradle design (Braungart et al., 2007; McDonough and Braungart, 2002) and the performance economy (Stahel, 2006)), and the dynamics of material accumulation and waste generation in infrastructure (Pauliuk et al., 2012b) and the built environment (Müller, 2006).

Industry and policy approaches draw most directly on eco-efficiency (Ehrenfeld, 2005) with a focus on maximizing the efficiency of value creation from resources through innovations in product design, reuse and remanufacturing, and materials recycling (see e.g (Accenture, 2014)). This is also reflected in circularity indicators, e.g. (Ellen MacArthur Foundation and Granta Design, 2015), which are primarily based on material flow accounting, lifecycle analysis and supply chain risk analysis. Academic studies mainly focus on interventions to products and processes to enhance circularity; such as enhancing the recovery of resources from post-consumer waste (Singh and Ordoñez, 2015), finding uses for specific waste streams such as sewage sludge ash (Smol et al., 2015), or designs that promote product life extension (Bakker et al., 2014). Whilst this approach, and the methods it employs, give valuable insights into strategies for enhancing the circular flow of material resources in products, and reducing environmental impacts, its application to the resource basis of large-scale infrastructure such as energy and transport systems is not straightforward. Infrastructure, unlike consumer goods, is long-lived and highly interdependent. Materials are embedded in use for periods of decades, or even centuries, only then becoming available for recovery and reuse. Furthermore, the deployment of infrastructure, particularly in energy systems, is subject to long term planning that must take its interaction with other systems into account.

As the concept of the circular economy has taken hold in policy and industry discourses, the concept of *socio-economic metabolism* has emerged as a research paradigm in sustainable development (Pauliuk and Hertwich, 2015). Socio-economic metabolism can be defined as "the set of all anthropogenic flows, stocks, and transformations of physical resources and their respective dynamics assembled in a systems context" (Pauliuk and Müller, 2014). In contrast to the circular economy perspective, socio-economic metabolism is explicitly concerned with the total scale of physical resources in the economy and their dynamics. In the context of transitions to low carbon infrastructure systems, this is important because it recognizes the absolute scale of material resource requirements, and also the importance of the long lifetimes of in-use stocks that are a significant determinant of the future requirements of primary resources and availability of secondary resources (Voet et al., 2002). Previous work has shown that recycling and reuse can significantly reduce reliance on critical materials in the long term, but there is the potential for a fundamental conflict between the adoption of new infrastructure technologies with novel material makeup and a circular economy with closed material flow loops (Busch et al., 2014).

As complementary approaches, the circular economy and socio-economic metabolism represent a respectively micro and macro focused analysis of sustainable resource management. Circular economy perspectives provide an analysis of technological and process details lacking in socio-economic metabolism, whereas socio-economic metabolism addresses the scale and temporal dynamics of resource flows in an entire economy or industrial sector. Emblematic of the gap between circular economy and socio-economic metabolism perspectives is the issue of 'general purpose technologies' (GPTs), and the potential they hold for systemic efficiencies in material use. GPTs are widely discussed in the innovation systems literature (Lipsey et al., 2006) in reference to significant technological inventions that have a broad range of applicability and whose invention and widespread adoption are related to significant economic and social transformations (techno-economic paradigm shifts) (Perez, 2009). Often quoted examples of GPTs include steam power, electricity and information and communication technologies. Renewable energy technologies have now been proposed as new GPTs and the basis for a new techno-economic paradigm (Mathews, 2013).

Renewable energy infrastructure relies on a number of technological components that could be described as GPTs. Permanent magnets, which contain neodymium and dysprosium, are widely used in electric motors and generators in electric vehicles and wind turbines as well as a variety of non-energy applications. Li-ion rechargeable batteries, which contain lithium and cobalt, are used in electric vehicles and grid attached storage as well as mobile phones and laptop computers. The breadth of use of these technologies across the supply and demand side of energy systems exacerbates the criticality of the materials they contain, but could