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Resource recovery and remediation of highly alkaline residues: A political-industrial ecology approach to building a circular economy

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A B S T R A C T

Highly alkaline industrial residues (e.g., steel slag, bauxite processing residue (red mud) and ash from coal combustion) have been identified as stocks of potentially valuable metals. Technological change has created demand for metals, such as vanadium and certain rare earth elements, in electronics associated with renewable energy generation and storage. Current raw material and circular economy policy initiatives in the EU and industrial ecology research all promote resource recovery from residues, with research so far primarily from an environmental science perspective. This paper begins to address the deficit of research into the governance of resource recovery from a novel situation where re-use involves extraction of a component from a bulk residue that itself represents a risk to the environment. Taking a political industrial ecology approach, we briefly present emerging techniques for recovery and consider their regulatory implications in the light of potential environmental impacts. The paper draws on EU and UK regulatory framework for these residues along with semi-structured interviews with industry and regulatory bodies. A complex picture emerges of entwined ownerships and responsibilities for residues, with past practice and policy having a lasting impact on current possibilities for resource recovery.

1. Introduction

This paper examines the issues involved in realising a potential source of a material, vanadium, considered important for the production of innovative renewables technologies, which in turn are seen as pillars of economic development in the European Union (Moss et al., 2011). Policy initiatives in the EU relating to raw material supply draw on circular economy activity including the recovery of materials from industrial residues (EC, 2008, 2014). Given that a potential source of vanadium is the residue of steel production, i.e., a waste, insufficient critical attention has been paid to the contingencies that may be involved in operationalising resource recovery. Besides the technological obstacles, which remain significant (Gomes et al., 2016b), the interests of economic actors need to be examined. Here we analyse environmental, technological and stakeholder considerations using a political-industrial ecology framework to judge the extent to which residue-based sources of vanadium might constitute a reserve, i.e., a resource which is viable for extraction.

Current interest in vanadium as a raw material stems from the expected rise in demand for new electronic technologies, notably related to renewables (Zhang et al., 2014). Long used as a strengthening agent in steel, vanadium is now important for example in energy storage cells. These can offset intermittent renewable electricity sources or function as part of a stand-alone local renewable system (Joerissen et al., 2004). Another potential use is in carbon capture and storage pipelines (Moss et al., 2013). Vanadium is seen as critical to the EU's Strategic Energy Plan (Moss et al., 2011), which seeks not only to secure energy supplies but promote low-carbon energy and support innovation in EU industry (EC, 2016). However, although in global terms a relatively abundant material, vanadium is not produced in the EU (EC, 2014). Production of vanadium is heavily concentrated in China, Russia and South Africa, which led Moss et al. (2013) to categorise it as a medium security risk metal for US and European markets. Notably, the designation of a material's criticality is not without subjectivity (Hobson, 2016). It involves predicting technological change, the uptake of innovations, knowledge of sources (existing) and potentially commercially sensitive information on reserves (available to use) of potentially economically or politically sensitive materials, as well as the political stability of nations with reserves and their willingness to trade (Moss et al., 2011, 2013).

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The need for what are considered secure sources of vanadium and other so-called "hi-tech" metals has resulted in EU raw material policy explicitly considering sourcing them through recycling and recovery from previously discarded waste (EC, 2008; Johansson et al., 2014; Gregson et al., 2015). The recovery of materials from waste is also a component of the circular economy, which seeks to maximise the value obtained from resources by extending lifespan and recovering pre- and post-consumer industrial residues for further productive use (EC, 2015; EEA, 2016). Increasing security of resource supply is just one postulated benefit of a circular economy, others including increasing competitive advantages for companies, creating new jobs, as well as carbon emission and waste reductions (EC, 2015; EEA, 2016).

There has been a surge in research interest around metal recovery from sources such as steel slag (Barik et al., 2014; Mirazimi et al., 2015; Gladyshev et al., 2015). By comparison, little attention has been paid to the non-technical issues relating to resource recovery from industrial residues (Gomes et al., 2016a). There is an implicit assumption that existence within in a political territory (whether a nation state or the EU) equates to availability for the benefit of that economy. Clearly, without technical and scientific research, the potential to extract metals such as vanadium will not be realised. However, whilst necessary, positive outcomes from that line of research may not be sufficient to ensure that metals are available to be used in new technologies. The outcome in terms of access and ability to use vanadium are contingent; the balance of factors either favouring or hindering recovery will be influenced by historically and geographically varying circumstances. The uncertainties and sensitivities around residue-based resources, however, are less well known than those of virgin deposits and have also received less attention than the "economisation" of post-consumer and post-industrial residues via recycling (Gregson et al., 2013).

In this paper, we present a case study of vanadium recovery. As we will outline below, research into technology for recovery is being actively pursued, and although significant hurdles remain, there are promising lines of enquiry. Residue management and resource recovery are both tightly regulated with a view to protecting the environment from significant risks associated with steel slag and other comparable materials. We draw primarily on stakeholder interviews and extensive documentary analysis as well as published material on the resource recovery technologies and environmental considerations.

The structure of the paper is as follows. In the following sections, we outline the concept of PIE and its relationship with the present research; we review the literature on industrial symbiosis and the environmental and technology contexts of vanadium recovery. The next section addresses methodologies and methods used in our research. We then present a case study examining the potential for stakeholders to make vanadium from steel residues available for other uses. Finally, we conclude that stakeholder interests, regulatory and technological issues are tightly interwoven with respect to the potential for vanadium recovery from steel slag. Whilst appearing to constrain possibilities, this interrelationship may also hold the key to future exploitation of vanadium in slag.

2. Political-industrial ecology and resource recovery

This paper draws on the concept of "political-industrial ecology" (PIE), which Newell and Cousins (2015) proposed to add new dimensions to multi-disciplinary study of resource use in urban spaces. Their concept combines industrial ecology's quantitative resource flow analysis (e.g., material flow analysis applied to urban systems by Baccini, 1996), urban ecology's appreciation of the biophysical dimensions of urban spaces (e.g., Grimm et al., 2000), and political ecology's analysis of power relationships. The latter for example particularly examines issues of equity and social justice relating to environmental issues (e.g., Heynen et al., 2006). Cousins and Newell (2015) provide an example of an application of their concept. They carried out a spatially specific life cycle assessment of water flows and accompanying infrastructure alongside a qualitative analysis of contemporary and historic interests that have helped to literally and figuratively shape the water supply system in Los Angeles. The combined approach provides a resource analysis informed by a political understanding (infrastructure is influenced by and influences power relationships), a spatially specific understanding of environmental impact (which can identify where to focus amelioration efforts) and a political economic analysis of an environment-related issue that is informed by environmental science.

For this study, PIE similarly provides a framework for analysis of a problem that is likewise inherently multi-disciplinary (with environmental, technological and political economic considerations). Furthermore, the field of industrial ecology, on which PIE draws, has well established interests in resource recovery (e.g., Graedel et al., 2002) and other activities relevant to a circular economy. Industrial ecology is an academic and business approach to resource-use optimisation favouring a system (not company) scale approach, taking lessons from natural ecosystems (White, 1994; Ayres and Ayres, 2002). A broad field, in addition to the quantitative material flow analysis and life cycle analysis techniques used by Cousins and Newell (2015), industrial ecology also considers organisational and policy issues relating to resource efficiencies, variously adopting systems engineering, network analysis and other social science approaches (Deutz and Ioppolo, 2015). Within industrial ecology, the social science field most relevant to the present study is industrial symbiosis (IS). The following subsections first relate research to the present study, before presenting an overview of the environmental and technological issues relating to vanadium recovery.

2.1. Industrial symbiosis

Industrial symbiosis involves taking a residue[2] (whether material, energy, water) from one entity for use as an input to another symbiosis (Chertow, 2000). IS has been practiced and studied in a range of geographic and policy contexts (e.g., Bain et al., 2010; Behera et al., 2012; Boons et al., 2015). Research indicates the considerable challenges involved in building symbiotic resource relationships between companies. Outside of East Asian countries, such as China and South Korea where IS arrangements have been heavily encouraged by national policy and regulation (Yu et al., 2015), the inter-organisational relationships associated with IS have proven difficult to establish (Velenturf, 2016; Yap and Devlin, 2016). The policy context is critical. Policy uncertainties and a perceived lack of reward for innovation and risk-taking leave organisations unwilling to make financial or time investments in IS-relationships, even if the potential benefits are understood (Notarnicola et al., 2016; Wilts et al., 2016; Hirschnitz-Garbers et al., 2016).

Even where there are explicit policy goals to increase resource recovery (e.g., arising from the EU Waste Framework Directive), institutional barriers remain to achieve that in practice (Watkins et al., 2013). For example, work examining resource recovery from the process industries in Finland and Sweden (see Salmi et al., 2012; Watkins et al., 2013; Pajunen et al., 2013) has examined the challenges facing the exploitation of steel industry residues. Companies face challenging procedures to permit recovery activities, especially where international resource flows would be involved. Pajunen et al. (2013) contend that waste regulations are designed to promote environmental protection rather than resource recovery. The provisions emphasise precaution rather than encouraging innovations to increase recovery. Complying with a risk-averse regulatory system, a rigid environmental permitting regime and an unstable policy environment are seen by firms as disincentives to innovation (Wichman et al., 2016; Hirschnitz-Garbers et al., 2016; Wilts et al., 2016).

[2] We use the term residue to avoid policy contingent expressions such as waste or by-product (Deutz, 2014), except where those terms are specifically correct.