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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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ABSTRACT

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.

Table 1
Recovery options for metals from steel slag based on recent literature.

Treatment approach	Application	Dust	Leachate	Use
Option 1: Crush residue to increase surface area; heat and apply sulphuric acid to release V Aarabi-Karasgani et al. (2010), Xiao et al. (2010), Tavakoli et al. (2014)	Slag; potentially viable for legacy residue, but would have risks to the environment	Process may create dust	Necessary to control the acid as well as capture leachate	Potential capture of V; residue unsuitable for aggregate
Option 2: In situ application of organic matter to hasten leaching of V Karlsson et al. (2011), Mirazimi et al. (2015), Sjoberg and Karlsson (2015)	Slag and legacy residue	Reduced	Rate of leaching of metals is increased, also increasing the V content at a given time. Containment of leachate essential	Potential capture of V; bulk material unsuitable for use as aggregate

Significantly where IS has been successful, residues are diverted from disposal (Jensen et al., 2011). Though such residues are likely to be technically waste in the terms of EU waste regulations (Waste Framework Directive, 2008), uptake as an input by another organisation happens before they pass through a disposal facility. In the case considered in this paper, i.e., of waste that has arisen from previous industrial activity (known as legacy waste; Graedel et al., 2002), residues have been officially disposed before potentially being wanted by someone else. This may further complicate the already recognised multidisciplinary conceptualisations of waste (Gregson and Crang, 2010) as well as the technical and policy implications more typically addressed by IS studies. It also introduces the potential of a further stakeholder, i.e., the entity overseeing the disposal facility.

Clearly, the successful conclusion of a vanadium IS network requires the building of connections between suppliers and end-users, i.e., companies engaged in the production of renewables technologies. Before that situation can be contemplated, though, much more attention needs to be given to the issues around the availability of vanadium.

2.2. Environmental context

Vanadium is a prime example of a metal with demand in the renewables industry which has the potential to be recovered from present and legacy residues from the heavy industries. It is associated with highly alkaline wastes produced by industries such as aluminium extraction from bauxite, steel processing, and coal-fired electricity generation. An estimated 90 billion tonnes of highly alkaline residues are estimated to have accumulated worldwide from previous activity in just these industries, with an estimated two billion tonnes per year being added to stockpiles (Gomes et al., 2016a).

The content of metals such as vanadium in these residues (dependent on the source of iron ore, as well as potential addition of vanadium to influence the type of steel obtained) can be equivalent to the concentrations found in ore-grade deposits (up to 5% vanadium pentoxide (V_2O_5) in steel slag whilst concentrations can be less than 2% in mined ores (Aarabi-Karasgani et al., 2010). Given growing demand for vanadium as outlined above, there has been an explosion of interest in the technical and environmental science literature exploring the potential for extraction (e.g., Barik et al., 2014; Mirazimi et al., 2015; Gladyshev et al., 2015).

Although varied in function (extraction, processing and combustion respectively) and composition, vanadium-bearing residues (from bauxite processes, steel manufacturing and electricity generation) have in common the fact that water in contact with them (i.e., rainwater that has passed through residue piles exposed to the atmosphere, known as leachate), has elevated pH levels (i.e., is alkaline). Certain metals, including vanadium, are known to have increased mobility levels in highly alkaline leachate (Mayes et al., 2008b), which is why these residues constitute environmental hazards. Environmental risks associated with high-alkaline residues range from catastrophic pollution-episodes resulting from the failure of leachate containment measures to chronic exposure, for example, to dust (Gomes et al., 2016a). Vanadium has been associated with toxic effects on wildlife (Liu et al., 2012; Rattner et al., 2006) and chronic exposure, e.g. in the workplace, is a risk to humans (Moskalyk and Alfantazi, 2003), albeit the effects of environmental exposure on human health are uncertain. Highly alkaline slags are therefore a matter of environmental concern in addition to presenting a potential new source of metals.

Within the EU, highly alkaline residues are governed by a suite of regulations relating to environmental protection and remediation, in addition to requirements, incentives and constraints relating to resource recovery. Whilst the locations of residue generation have shifted with trends of global production, site closure does not end liability, and environmental impacts can extend well beyond the duration of industrial activity (Mayes et al., 2008a). Legacy residue, therefore, remains in the landscape and environmental monitoring (e.g., of leachate composition) continues to present a cost for producers to monitor it until the site has stabilised. Thus even when residues have been disposed of, the responsibility and liability of producers are not terminated. They have either a direct responsibility or a duty of care (that is a responsibility to ensure that any company to whom they have passed a residue is meeting its requirements, DEFRA, 2016).

2.3. Vanadium recovery technologies

Recent research has focused on how to extract vanadium from freshly produced slag (see Table 1) and we consider below (Section 4.2) the extent to which these approaches might be applied to legacy slag. A second line of research is to improve the rates of recovery of metals from leachate (Hocheng et al., 2014; Kim et al., 2016). Research into vanadium recovery is poised on the verge of transferring from the laboratory to field scale (Gomes et al., 2016b).

2.3.1. Option 1: crushing and acid-treatment

Crushing of slag and addition of acid is one approach to the treatment of freshly produced slag for vanadium recovery. Numerous studies have explored approaches to acid-leaching of vanadium (see examples in Table 1). The basic (i.e., alkaline) nature of the steel slag means that the application of acid preferentially dissolves the vanadium-bearing mineral phases (typically alkaline calcium oxide and calcium silicates) (Cornelis et al., 2008). Laboratory studies have relied on the crushing and heating of samples to achieve enhanced rates of V recovery (Aarabi-Karasgani et al., 2010; Tavakoli et al., 2014; Xiao et al., 2010). Whilst the process might be controllable for slag as produced (i.e., be carried out indoors where emissions can be contained), using this process for legacy material appears to require either extensive and expensive removal of slag for ex situ treatment, or the need for complex engineering to control an in situ process.

2.3.2. Option 2: organic matter to increase rate of vanadium leaching

The addition of organic matter has been shown to increase the rate of vanadium leaching from crushed steel slag under laboratory conditions. (Karlsson et al., 2011; Sjoberg and Karlsson, 2015). In a related approach, Mirazimi et al. (2015) showed that on a laboratory scale applications of bacteria and fungi could increase the recovery of vanadium from crushed slag. Upscaling this type of approach to field conditions could have the benefit of providing an outlet for organic waste (which is under increasing prioritisation of diversion from landfill). As the vanadium would be collected from leachate, disturbance to slag piles would be much less than under other approaches. The technique could be applied to legacy as well as fresh slag. This approach offers good potential for vanadium recovery, with environmental benefits, and was, therefore, a focus of our discussions with industry and regulators.

In summary, recent literature discussing IS relationships in the context of the circular economy indicates the importance of the policy context, and companies' understanding of it, as critical to the willingness of companies to consider IS as an outlet for their residues. Given the lack of case studies of IS involving legacy waste, it is less certain who the parties to those relationships would be. The importance of the procedures of recovery to be followed is attested to by the environmental sensitivities of the highly alkaline materials and consequent ongoing responsibilities of producers. In this study, we employ the PIE concept to investigate these issues as a concrete example of a metal resource, which might or might not ultimately constitute a reserve.

3. Methodology and methods

This paper draws on a large scale multi-disciplinary study which is investigating scientific issues and developing a technology for the recovery of vanadium from steel slag. The environmental science work package of the project, not presented here, examines the behaviour of leachate in steel slag, investigates alternative approaches to increase the rate of vanadium leaching and the recovery of vanadium from leachate. That natural science approach is attempting to establish an objective understanding of the behaviour of vanadium in specific environmental conditions, which should apply to similar settings elsewhere. However, technical compatibility of an IS solution may not be followed by social applicability across geographic contexts (Deutz and Lyons, 2015). Thus, an understanding of the political economic context of a particular development is essential, both to consider the suitability for application in that context, and to comprehend what elements of the innovation may be contingent on context (Deutz, 2014). Although in this particular paper, we are primarily presenting the social science aspects of the research to date, we refer to insights gained from the environmental science aspects of the study. Hence we conceptualise the issues relating to resource recovery using the in depth analysis of our case, i.e., the potential to recover vanadium from legacy waste associated with a specific (but for confidentiality reasons unspecified) steel works in the north east of England. We start to address the absence in the literature of in-depth case studies relating to IS (Velenturf and Jensen, 2016), which have the potential to increase understanding of what has and has not been effective in contributing to IS occurring in specific circumstances. The object is to indicate what can be important, not to say that this is always the case, but to generate an understanding beyond the observation of patterns (Sayer, 2000).

In order to address this political economic context, we undertook an analysis of secondary data sources including a detailed analysis of the relevant legislation impacting upon steel slag. In addition a total of 20 semi-structured interviews were conducted (during 2013 and since October 2015) with a total of 24 individuals comprising industry representatives (e.g., environmental managers and chemists at steel companies; regulators (Environment Agency, EA), policy makers (Department of Environment Food and Rural Affairs: DEFRA; Circular Economy officials in the European Commission), industry associations and consultants. These interviews were transcribed and analysed using NVivo software. The interviews addressed a range of issues including the challenges and opportunities involved in steel slag management, policy influences and relationships with other stakeholders, to obtain their perspective on the potential for recovery of vanadium from steel slag.

The site selected for the study is an approximately 800 hectare integrated steel works in north east England, referred to as the producer, as it is the source of the vanadium-bearing steel slags. The site has a long history of production, recovery and disposal of slag. Iron smelting dates back to the 1860s at the site, where steel production has been ongoing since the 1890s. The attraction of the site was initially the local sources of ironstone and limestone (Jurassic aged Frodingham and Cretaceous Ferriby chalk respectively), and access to water transport for raw and finished materials to international markets. Ownership of the site and the organisation of slag management have both varied over the decades of operation (Table 2). For decades, the iron and steel works have been the major employer in the town and area. The local town has a population of 65,000. Not surprisingly, the site has experienced the vicissitudes of fortune associated with UK heavy industries during the twentieth century. Currently, the site belongs to an independent company and can produce up to 1.5 million tonnes per year of steel, which would produce up to 500,000 tonnes per year of steel slag. Other industries associated with the estuarine location include petrochemicals and one of the UK's busiest port facilities.

4. Examining potential for vanadium recovery at the case study site

4.1. Managing iron and steel-residues at the case study site

The vanadium-bearing steel slag is one of two high-volume residues produced at the case study location. As these are to an extent managed

Table 2
Timelines for the case study site: compiled by authors from interviews, policy documents, permits and company and newspaper websites.

Date	Ownership	Key EU/UK regulations	Slag management
Pre-1967	Private company		Steel slag sent to landfill; iron slag used as road aggregate
1967–88	Nationalised industry	Early waste regulations	Research into slag uses, development of aggregates operation to use steel as well as iron slag
1988–1999	Privatised	UK Landfill Tax; IPPC Directive (1996, 2008)	Focus on core business – partial outsourcing of aggregates business
1999–2007	UK-Dutch company	EU Landfill Directive (1999)	Full outsourcing via 25 year contract
2007–2016	Wholly owned by Indian company	Waste Framework Directive (2008) UK Environmental Permit regime (2010)	Contract continues; more interest in resource recovery, but economic constraints
2016	UK investment firm	Uncertainties of 'Brexit'	High demand for aggregate, but weak demand for steel

together, understanding the current arrangements for the steel slag requires a brief review of the physical characteristics and management of both.

In terms of mass, the two principal residues for the case study company are iron slag from the blast furnace (Blast Furnace Slag, BFS) and slag from the steel conversion stage (BOS slag[3]) (Lobato et al., 2015; Piatak et al., 2015). The latter is the steel slag of primary interest here. The BSF is both physically and chemically stable and can be put to use (e.g., as substitute for virgin aggregates in road construction) without further treatment (Lobato et al., 2015). It has been formally recognised as a by-product residue (EC, 2007; i.e., by definition not a waste, and therefore its handling and storage is not covered by waste management regulations, and the duty of care does not apply). The production of steel slag is an inevitable part of the process of converting molten iron to steel; it achieves the removal of catalysts which are needed for the steel making process, but unwanted in the final product. Approximately 85–165 kg of steel slag is produced per tonne of molten steel (Remus et al., 2013), requiring a multi-stage process before end use is possible. Initially, the slag goes through a de-metallisation process, which recovers iron to put back into production. A further process of physical and chemical stabilisation is accomplished by simply leaving the slag exposed to the atmosphere over a period of approximately six months. Critically, the six-month weathering period is viewed (EA Bespoke Permit, 2014) as a waste management process, and steel slag is therefore seen as a waste residue. It ceases to be to waste only if and when it is sold on to an end-user following the weathering process. The definition of steel slag as waste, though, is based on an assumption of a certain end use, which requires an extended treatment process. The definition may be quite inappropriate for different usages, such as the separation of vanadium or other high-value components, but presently the weathering process is written into the site environmental permit as a requirement for the steel slag.

Although the two slags are different in physical-chemical properties and legal definition (BOS being a waste and BSF a by-product), their management has been closely tied together. In 1999 an on-site road aggregate company received a 25-year contract to take both residues, with responsibility to meet regulatory safeguards and financial incentives to seek end-users. Under these arrangements, the producer also stood to benefit if any steel slag was re-used following weathering. This appears an archetypal example of an industrial symbiosis relationship (e.g., Chertow, 2007). The producer effectively outsources its liabilities for managing the residues, whilst the aggregates company receives a raw material (BSF) which can directly substitute for alternatives. It also takes on liability for a waste, but post-weathering there is a known market for steel slag, which can supplement the supply of BSF at times of high demand for aggregates.[4] The superior properties of the iron slag compared to steel slag as an aggregate mean that the former is the first choice for that purpose. However, whilst this symbiosis is working effectively regarding bulk use of slags, so far attention to the steel slag has been limited to preparing it for the same use for which the iron slag is well suited. The producer, moreover, is currently obliged to pass on the vanadium-bearing slag, which is presently locked into a bulk-usage.

Under previous (and potentially future) arrangements, however, the producer had direct control over its residue disposal operations. Slag management at the site has fluctuated in response to economic conditions and changes in site ownership (Table 2). Prior to the 1960s little effort was made to utilise steel slag; it was stored in landfills onsite. The nationalisation of the contracting UK steel industry in the 1960s brought an interest in trying to recover value from slag and with it the inception of the current steel slag weathering regime and a search for potential markets. Privatisation in 1988 brought a different approach to managing financial risks, with a focus on the core business rather than interest in potential value from residue. The practice of BOS weathering continued, but the handling of the residue was externalised. At first, the producer retained ownership of a significant proportion of the slag handling company. This relationship subsequently changed with the next change in ownership of the producer, which after 1999 was part of an international company. At that point, there was separation between the producer and slag processor. The 25 year contract referred to above was instituted to increase incentives to sell processed steel slag.

The change in management in 1999 coincided not only with a change in site ownership but also the advent of the EU Landfill Directive. The latter brought enhanced requirements for landfill management and monitoring. These activities brought costs in addition to those associated with the UK Landfill Tax (albeit beginning at modest levels in 1996), and applicable even if the waste were disposed of in the company's own onsite landfill. Divesting from the aggregate company effectively outsourced these concerns for the producer. However, they have not discharged all liability for environmental protection associated with the slag. Apart from the duty of care for management of one of their residues, as site owners, the producer retains a responsibility for the overall environmental performance of the site, including the monitoring of leachate runoff quality and quantity. A Landfill Directive-compliant landfill coexists onsite with pre-regulation deposits, which are still producing leachate, and for which the producer would retain liability even if production ceases. Furthermore, the slag currently produced is placed on top of older residue for weathering, which makes the environmental impact of the slag and legacy residue very difficult to separate. Any change in the handling of the steel slag that might impact on its environmental impact, therefore, remains of interest to both companies, irrespective of whether either or both might benefit from such a change.

Therefore, a complicated scenario has emerged at the case study site in terms of the ownership of the materials, and liability for environmental protection. The slag producer is not the owner of current and recently produced steel slag, though retains an environmental liability for the slag, which cannot easily be disentangled from the environmental risks associated with older legacy slag.

[3] Also known Linz-Donawitz (LD) slag.

[4] At the time of interviews (2016) there was a high demand for aggregate and the current supply of weathered slag was being used. Though helped by the Aggregates Levy (tax on virgin aggregates introduced in 2002), this situation is exceptional over the 100year plus history of steel production.

4.2. Assessing the viability of vanadium recovery options

The analysis above indicates that both the producer and processor of the steel slag have an interest in its further use and effective environmental management. That situation arises in part from regulations designed for waste management (as well as the economic changes and related changes in ownership and attitudes to residues). However, consideration is also needed for the major regulation designed to prevent environmental harm from large-scale production facilities (i.e., The Integrated Pollution Prevention and Control (IPPC) Directive). The latter covers recovery operations as much as it does those relating to production.

4.2.1. Overview of the IPPC Directive

Large industrial facilities of the kind studied here are closely regulated in the EU by myriad policies governing emissions to air/water/land throughout the production process, resource recovery, storage, and disposal activities. The IPPC Directive is the primary regulatory control of industrial facilities, with requirements including monitoring, reporting and inspection requirements across the various stages of activity. As its name suggests, the regulation is designed to limit all forms of pollution (air, water, land) with due care to avoid simply transferring pollution from one medium to another. The major components of the regulation are the requirements for facilities to have permits specifying emissions limit values (reflecting their own operation, and surrounding conditions and the capabilities of existing technology), institution of a specified monitoring regime, and requiring the use of the Best Available Techniques (BAT) (Daddi et al., 2014; Yilmaz et al., 2015; Testa et al., 2014).

The BAT are recommended approaches (including both physical technology and its operation) designed to eliminate, or at least minimise pollution emissions. Allowing for technological change, the techniques are subject to review and not specified in the Directive itself. Rather, there are extensive BAT Reference documents for each covered industry (Remus et al., 2013). The overall impact of this framework has been debated (e.g., the need for BAT to take into account life cycle effects: Yilmaz et al., 2015); and because of allowance for national discretion has not necessarily achieved the desired equality of requirements across the EU (Daddi et al., 2014). Nonetheless, the Directive and BAT requirements distilled through the national permitting process tightly proscribe the activities of an industrial installation including the handling of residues. The recognised BAT for residues all revolves around safe handling, storage and preparation for bulk re-use.

4.2.2. Assessing resource recovery proposals in the light of environmental regulations

Option 1 (Crushing and acid-treatment; Table 1) could, subject to availability of space, be applied to slag under controlled conditions either adjacent to the de-metallisation process or at the site where presently crushing occurs prior to emplacement for weathering. Further research would be required to determine the optimum grain size required for field-scale application of this process (laboratory particle size approximately 0.1 mm (Tavakoli et al., 2014); compared to current maximum 20 mm: EA Bespoke Permit, 2014). This could involve a significant change from current practice. The finer particle size would produce risk enhancing dust production, possibly stretching current dust control techniques. The process then would involve the application of acid, and possibly heating, necessitating quite different technologies, introducing hazardous material, increasing energy consumption, and the requirement of different operational skills. The current permit is very specific about what is allowed to be done and by what means. Even if BAT were established and followed for the new techniques, they would not be covered by current permits. Disturbing the existing weathering slag, let alone the older legacy material, would further exacerbate dust generation as well as leachate generation (this just as a result of the disturbance, not the intentional enhancement of vanadium leaching).

Apart from being entirely outside present regulatory specifications, these environmental effects could also put pressure on the producer through relationships with neighbouring communities. Given how significant the site is as a local employer, industry interviewees reported that the community has been tolerant of the site. If the number of jobs continues to decline, however, that connection between producer and community may be weakened. Currently, the producer takes responsibility for the monitoring of leachate from both the weathering and legacy residue; increasing the rate of run-off of leachate, and/or the concentration of potentially harmful substances, would increase the effort required by the producer, when the financial benefit of vanadium recovery would presently accrue to the company managing the weathering process. This would also be an issue for Option 2.

Option 2 (Organic matter to increase rate of V leaching, Table 1), conversely, appears to offer an advantage, in that the application of organic residue to the weathering slag or legacy material would help to contain dust at the same time as speeding the release of vanadium. Experimental work using organic matter has been done at laboratory scale and did involve crushing material. However, one of the aims of this project was to upscale the organic residue approach to vanadium recovery in a way that would avoid disturbance of the piles. This proposal, though, has met with resistance from industry.

A specific complication from Option 2 comes from the use of organic matter as a catalyst for enhanced vanadium production. The process implies the combining of two different residue streams: organic matter (e.g., from local authority collected waste) and steel slag. To implement the synergistic possibilities of combining two residue streams to generate a substance of value (i.e., in this case, vanadium) requires the overcoming of substantial regulatory hurdles. The permitting of waste facilities, or facilities receiving waste, is done on the basis of specific waste codes from the European Waste Catalogue (EWC): EWC "categorises all waste codes, and any potential waste from all sorts of production methods, and in an authorisation you will have a list of acceptable waste codes that you can take into your process, if you will, be that landfill, be that recovery operations, etc.," (EA Interviewee).

Thus to use Option 2, the company would need to be licenced specifically to take organic matter as a waste stream. In addition, in the view of the EA, the organic matter-slag mixture would comprise a new substance whose properties and environmental risks are unknown. The Waste Framework Directive argues stridently against mixing, both to avoid the mistreatment or dilution of hazardous waste and to promote recovery from municipal waste streams. Possibly the idea that separation produces safe and better results for resource recovery may have coloured views on mixing more generally. In any case, the response to the combining of organic waste and slag has resulted in this approach to vanadium recovery having to be reconsidered.

4.3. Regulations and innovation

Besides the specific issues relating to the proposed vanadium recovery technologies discussed above, issues came to light relating to the potential for innovative recovery techniques in general. A further significant issue at present is the nature of the environmental permits that govern all the activities undertaken by the producers and processors of steel slag. In the UK, the IPPC and Waste Framework (and numerous other) Directives are implemented at firm level via their Environmental Permit. These bespoke permits comprise a document that sets out precisely the requirements and actions of the operator, as well as specifying the types of waste to be handled, the processes, quantities, and the monitoring arrangements, etc. The current permit just for slag treatment and storage is 18 pages (EA Bespoke Permit, 2014), with the current draft permit for the production site running to over 70 pages. Testing and research into new approaches to residue management would break pre-existing permitting conditions and therefore involve a process of negotiation with regulatory authorities. Companies saw this as a disincentive to innovate. Carrying out revisions is not lightly undertaken and, reasonably so, firms are highly wary of being seen to deviate from the terms and conditions. Industry representatives point to varying experiences with EA inspectors, who have varying levels of experience/expertise. It is not their role, however, to give advice on alternative resource recovery approaches, or technologies. Industry and EA interviews suggest there is a separation of function between (allegedly) a decreasing number of technical specialists and policy-enforcement people, such as the IPPC permit inspectors. The latter are well-versed in regulations, but in some cases less so regarding their industrial and environmental implications. Decisions on adopting a novel technology, or allowing a mixture of materials, would be made at a higher level. EA decisions are based on evidence, but evidence can be difficult to collect ahead of permission to go ahead with at least small-scale experimentation.

Companies are keenly aware of their regulatory obligations. Under the Waste Framework Directive, these include a duty of care for residues even once passed on to the next handler/processor, until final disposal or official designation of end-of-waste. Applying their own precautionary approach, this can dis-incentivise innovation: “We try and avoid, you know give a wide berth to anything that's going to give some reputational issues down the line. Even if that costs money and it probably means that we don't pursue all possible reuse options we could do because we don't have confidence that it won't come back on us.” (Steel industry B). The Environmental Liability Directive (2004) (UK Environmental Damage Regulations, 2015) makes it clear that if the Permitting conditions are not met, and damage occurs, companies will be held financially liable. This is particularly worrying in the uncertain circumstances of stockpiled slag that may have been accumulating over a process of decades, prior to present-day management standards, and may continue to be a liability into the future, potentially far beyond the continuation of production.

However, it is precisely this ongoing environmental liability that may provide an incentive for the recovery of elements such as vanadium. Given that companies have a responsibility for remediation of closed sites, a technological option to remove environmental risk elements such as vanadium may be an attractive proposition irrespective of the existence of end-users for such elements (Gomes et al., 2016b). Income from the sale of recovered metals may be a bonus, rather than the prime motivation for their recovery. Motivation does not necessarily matter from a CE perspective, providing that the substances do become available. However, interesting questions arise as to ownership of the recovered vanadium, as the slag belongs to the aggregate company, but the vanadium-enriched leachate is the responsibility of the producer.

5. Conclusions

This paper has taken a political-industrial ecology approach to assessing the potential to “economise” steel slag as a source of vanadium. Our analysis of a case study steel production site examined changing practices in slag management in the context of changes to environmental regulations and changes in site and slag management responding to economic trends. Industrial symbiosis considerations, environmental and technological issues were shown to be closely intertwined. Given that the residue of interest, a legacy waste, has already entered into waste management practices and in this case has been passed to another company, the situation is more complex than a more typical case of IS. Environmental issues, and especially, their regulation, are vital to understanding the positioning of economic actors in this case.

The costs associated with managing environmental risks involved with highly alkaline residues provide producers with some incentive to consider alternatives to adding to slag heaps or even to investigate the potential to seek financial gain from legacy residues. But the prospect of financial gain, or reduced cost, from recovery, appears too distant at present to overcome the concerns of the potential for either environmental harm or of violating environmental permit terms and conditions. Thus although current ideas relating to the development of a circular economy promote the recovery of value from residue, present regulatory frameworks have not been designed primarily with that in mind (Watkins et al., 2013; Crang et al., 2013). The emphasis in regulations on recovery has increased over the time since the first Waste Framework Directive in 1975 (e.g., Haigh, 2015), but the stipulations for firms to recover value tend to be more nebulous than those governing pollution prevention. For example, producers are required to consider the waste hierarchy in dealing with residues but face potential prosecution if found guilty of environmental damage through negligence.

Stakeholders are rightly concerned about their current environmental obligations, which in this case study included the liabilities arising from past action, notwithstanding, that there may not have been any infringement of a rule existing at any given time. Since the 1980s, there has been an accumulation of regulations that all attempt to close off, or at least restrict, potential routes to environmental harm. They are backed by the potential for financial and/or reputational damage and the industry representatives to whom we have spoken are keenly aware of the need (both environmentally and legally) to comply. However, legacy residues predating such regulations remain much in evidence. It is not just that the landscape may be blighted by piles of unwanted industrial residues, but these piles may still have the potential to contribute to pollution. This renders companies and regulators wary of action that may unduly disturb the legacy piles, even if action has the potential to recover something of value. It is a complicating factor that the weathering slag and legacy residue have different owners with overlapping environmental obligations.

This study contributes to ongoing technological research by providing insight into the views of economic actors and at least perceived constraints. It also provides a guide to policy makers of issues likely to be increasingly relevant as progressively less (politically and technologically) accessible resources need to be called into economic activity. Steel slag may be a particularly complex residue for metal recovery given that it already has bulk after-uses. Further research needs to address the circumstances around recovery of vanadium from other highly alkaline residues. In addition, this study has examined a case based in the UK. The interrelationships of stakeholder attitudes with environmental and regulatory frameworks, and the shaping effects of economic trends need to be considered in different geographic contexts, both within and beyond the EU. With the potential for vanadium recovery cautiously indicated here, it would also be timely to consider the views and preferences of potential vanadium end-users.

We have emphasised stakeholders’ responses to particular proposals for resource recovery, and how these are closely related to both the environmental impacts and the regulatory context. In so doing we have indicated that industrial and post-industrial locations are subject to the processes of socio-natural relations (cf., Newell and Cousins, 2015), as new potentials for the recovery of materials from residue give rise to debate over definitions of waste/not waste, the roles and responsibilities of stakeholders and the possibility for reshaping material flows. In particular, legacy residue is not just old material but embodies complicated relationships to past as well as present regulation and the practices and understanding of changing stakeholders over time. Given growing demands for certain metals and rare earth elements and concerns over security of supply, such sources are likely to become of greater interest to policy makers in the future. However, we would argue that extraction from current and legacy wastes involves a complex set of relationships that need to be much better understood if such wastes are to constitute part of the process of safeguarding resource supply in the context of a circular economy.

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