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Evaluation and classification of different types of anthropogenic resources: the cases of old landfills, obsolete computers and in-use wind turbines

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ABSTRACT

Various recent policy initiatives indicate an increasing need for a comprehensive overview of potentially extractable anthropogenic resources, in order to compare them with geogenic resources. Therefore, a method has been developed to evaluate and classify anthropogenic resource deposits and to prioritize potential extraction projects in a transparent manner. In this study we present how anthropogenic resources can be systematically integrated into the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009). The main goal is to illustrate different settings of anthropogenic resource classification, and to provide specific criteria to map different types of anthropogenic resources within the three dimensions of UNFC-2009, i.e. "knowledge on composition and extractable material content", "technical and project feasibility" and "socioeconomic viability". Projects for recovering materials from an old landfill, from obsolete PCs (personal computers), and from in-use wind turbines are exemplarily evaluated and classified under UNFC-2009. The economic results depend on the respective scenarios, where the timing of mining is varied, different organizational and societal settings are compared and different choices for technological options are made. While landfill mining under current conditions is not economically viable, the final result might look different in the future with changing key modifying factors, such as increasing secondary raw material prices. Mining materials from obsolete PCs and from permanent magnets in in-use wind turbines would both yield positive economic results for all investigated scenarios.

1. Introduction

Starting in the early 18th century in Europe, first reflections on a more sustainable use of natural resources were primarily motivated by the perception of dwindling key raw material supply, such as wood and coal (Jevons, 1906; Von Carlowitz, 1713). Considered as the precursors to modern resource classification systems, their common feature is managing scarce commodities by inventorying resource deposits and making potential resource extraction projects comparable for involved stakeholders.

Over time, most major mining nations as well as economies strongly dependent on resource imports have developed their own national classification codes in order to systematically inventory their resource deposits. But from the 1990 s on, when the mining industry started to become more and more of a global business, increased efforts have been made to harmonize those codes to create transparency and comparability in reporting primary raw materials. After the Soviet Union's collapse, the German Government proposed a new classification system to the UNECE Working Party on Coal to compare the vast resources in the formerly centrally planned economies to those in the market economies (UNECE, 2013). The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) was thus initiated by the UNECE, and was revised in 2009, today being known as UNFC-2009 (UNECE, 2010). Under this framework mining projects are classified on the basis of three fundamental criteria displayed on three different axes, namely "socioeconomic viability" (E-axis), "field project status and technical feasibility" (F-axis) and

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"knowledge on composition and extractable material content" (G-axis) (cf. SI, Fig. 2).

In the light of European resource policies, such as the 'Raw Materials Initiative' adopted by the European Commission (EC, 2008), there is an increasing need for obtaining a comprehensive overview of different types of potentially extractable anthropogenic resources, and to facilitate comparisons with geogenic resources. Various authors, such as Johansson et al. (2013), Weber (2013) or Wallsten et al. (2013) strongly support establishing a link between mining virgin materials and "mining" (recovering) anthropogenic resources. Several studies (e.g. Kapur and Graedel, 2006; Krook et al., 2012; Rettenberger, 2009) conclude that anthropogenic deposits, such as landfills, old buildings, and hibernating infrastructure, are comparable in size to the remaining natural stock of certain metals. Ongondo et al. (2011) argue that the concentration of gold in old cell phones is two orders of magnitude higher than in natural ores. Furthermore, there have been concrete attempts to map anthropogenic resources into classification codes for geogenic resources, amongst others by Lederer et al. (2014), based on the examples of Phosphorus stocks in Austria, and Fellner et al. (2015) evaluating the resource potential of Zinc from incineration residues. Mueller et al. (2015) show the potential applicability of UNFC-2009 to waste electrical and electronic equipment (WEEE). However, the UNFC-2009 framework serves primarily for classification purposes without providing standardized methods for the detailed evaluation of a mining project. To facilitate the integration of anthropogenic resources into UNFC-2009, Winterstetter et al. (2015) developed a new operative evaluation procedure to classify recovered materials from an old landfill under UNFC-2009. To fit different types of anthropogenic resources into UNFC-2009, a method for general and systematic application was developed, structuring anthropogenic resources according to the deposit's status of availability for mining: "In-use stocks", "obsolete stocks" and "waste flows" (Winterstetter et al., 2016). Combining aspects of waste and resource management is hereby one of the key challenges. In contrast to geogenic resources, social and environmental externalities (e.g. greenhouse gas emission savings) tend to generate additional benefits and should therefore be included in the evaluation (e.g. Ferreira et al., 2014).

In this study's first part, the previously developed method is briefly described (chapter 2.1) and subsequently applied to three case studies (chapter 2.2). Mining, i.e. (extracting and utilizing, materials from three different types of anthropogenic deposits is exemplarily evaluated, namely from 1) an old landfill, 2) obsolete PCs and 3) permanent magnets in wind turbines. By choosing end-of-life PCs as opposed to an old landfill, we explore how mining a waste flow differs from mining an obsolete stock. In case of existing EU policies, such as the WEEE directive, it is important to compare different approaches and degrees of implementation in different European countries, to support decision makers concerning the management of WEEE wastes in a financially and environmentally sound manner (cf. da Cruz et al., 2014). Moreover, it is important to know the in-use potential, which represents the source of future obsolete stocks and waste flows. Thus, the resource potential of permanent magnets in Austrian wind turbines is exemplarily evaluated and classified under UNFC-2009.

Each of the case studies together with the respective scenario variation, as described in chapter 2.3, is eventually evaluated and classified under UNFC-2009 (chapter 3.1–3.3). Based on the three case studies, general influencing factors for mining old landfills, obsolete PCs and permanent magnets in wind turbines are compared. The main goal of the present study is to illustrate different settings of anthropogenic resource classification and to provide specific criteria in order to map different types of anthropogenic resources under UNFC-2009 (chapter 4). Finally, remaining challenges for the integration of anthropogenic resources into UNFC-2009 are discussed, and future research needs are briefly outlined (chapter 5).

2. Materials & methods

To facilitate comparisons between geogenic and anthropogenic resource deposits, anthropogenic resources should be integrated into the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) (cf. SI, Fig. 2). The following sub-chapters describe the conceptual framework, the case studies used, as well as the scenario modeling.

2.1. Conceptual framework

"Anthropogenic resources" are defined in this study as stocks and flows of materials created by humans or caused by human activity, which can be potentially drawn upon when needed. Evaluating anthropogenic resources requires a somewhat different approach compared to geogenic deposits. The human impact on production, consumption and disposal, combined with significantly shorter time spans of renewal were identified as major differences by Winterstetter et al. (2016). To facilitate the classification of mining specific materials from a range of radically different and decentralized man-made sources, which is often linked to big technical and legal uncertainties, influencing factors can be structured according to their role during the individual phases of resource classification. Moreover, each phase can be mapped onto the UNFC-2009 axes (Table 1).

The pre-prospection phase is determined by 1) the deposit's status of availability for mining, discriminating between "in-use stocks" vs. "obsolete stocks" and "waste flows" and 2) by the specific handling and mining condition (cf. Table 1). While the status of availability and the specific handling condition represent the preconditions for potential mining activities by defining the setting for the following classification, system variables determine the amount of technically extractable materials.

There can be two types of conditions: In a push situation, like in the case of e-waste flows, anthropogenic materials have to be treated (this may include material recovery to reduce costs) due to legal requirements, whereas in a pull situation the materials are mined only if the initial socioeconomic evaluation is positive or otherwise left untouched, like in the case of mining a landfill for resource recovery, which comes close to mining geogenic resources. In a push situation optimal solutions within the given legal framework are sought.

System variables play a major role in the prospection and exploration phase (cf. Table 1). During the prospection phase, mainly information on the resource deposit's type, location, volume and composition shall be gained, allowing first estimates on the resource potential. During the exploration phase, knowledge on extractable and potentially usable materials has to be generated and the project status and technical feasibility needs to be checked, which is displayed on the G- and F-axis under UNFC-2009. To account for different (possible) sets of system variables, scenario analysis can be used to investigate different project set-ups and options for extraction and utilization methods and technology with specific recovery efficiencies, under specific legal, institutional, organizational and societal structures. Also the project status is of interest. During the actual socioeconomic evaluation of resource extraction and utilization, the 'modifying factors' are investigated (CRIRSCO, 2013). Modifying factors comprise prices for secondary products, investment and operating costs, costs for external treatment and disposal, avoided costs and monetized external effects (cf. Table 1). They have a direct impact on the project's