Doctoral Thesis

Mines of Tomorrow
Evaluating and Classifying Anthropogenic Resources: A New Methodology

submitted in satisfaction of the requirements for the degree of Doctor of Science in Civil Engineering of the Vienna University of Technology, Faculty of Civil Engineering

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Dissertation

Mines of Tomorrow
Eine neue Methodik zur Bewertung und Klassifizierung von Anthropogenen Ressourcen

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Abstract

This PhD thesis is concerned with anthropogenic resources, which are defined here as “stocks and flows of materials created by humans or caused by human activity, which can be potentially drawn upon when needed”. Various recent policy initiatives, promoting the efficient use of resources, indicate an increasing need for a comprehensive picture of totally available and potentially minable raw materials originating from both the lithosphere and the anthroposphere. The overall goal of this thesis is to develop a method for the classification and evaluation of anthropogenic resources, meaning for waste flows and material stocks, in analogy to existing concepts used for geogenic resource deposits. To achieve this goal, three major topics are tackled in this PhD thesis. The first fundamental question to be answered is, whether the “United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009“ (UNFC-2009) can in principle be applied to anthropogenic resources. The second topic deals with the general characteristics of anthropogenic resource deposits, which are to be considered for their classification. In this context, not only the differences of anthropogenic resources compared to geogenic resource deposits are taken into account, but also the differences within the heterogeneous group of anthropogenic resources. The third knowledge area investigates different settings of anthropogenic resource classification, to provide specific methods, indicators and criteria in order to systematically map different types of anthropogenic resource deposits within the three axes / dimensions of UNFC-2009, i.e. “knowledge on composition and extractable material content”, “technical and project feasibility” and “socioeconomic viability”.

This thesis comprises three research papers. The first paper presents an initial evaluation procedure for mining obsolete stocks, more specifically for a case study on landfill mining, to facilitate the integration of anthropogenic resources into UNFC-2009. Building on these results, the main goal for the following two research papers was to develop a general concept that allows for evaluating and classifying various other types of anthropogenic resources, by going beyond landfill mining. While the first paper answers the basic question, whether the framework is generally suitable for anthropogenic deposits (top-down approach), the focus of the second paper was more on the nature of various anthropogenic resource deposits, to see, how they can be fit into a classification system, that has originally been designed for geogenic resources (bottom-up approach). The third paper brings those two perspectives together. In order to account for the heterogeneity of anthropogenic resources, the newly developed method was applied to case studies for landfill mining (obsolete stocks), recycling of obsolete personal computers (waste flows) and recovering materials from in-use wind turbines (in-use stocks).

The major contribution of this PhD thesis is to lay a foundation for a comprehensive knowledge base of various existing potentially minable anthropogenic resources. The integration of geogenic and anthropogenic resources into UNFC-2009 will facilitate complete and comprehensive assessments of raw material supply. Also, criticality considerations can be extended by including anthropogenic material stocks. In addition, waste management as well as product designs can be optimized, based on the classification results, to facilitate future resource recovery. This methodology will assist governments, potential investors and waste management companies in the future to classify anthropogenic resource deposits and prioritize potential extraction projects in a systematic and transparent way.

Keywords: Anthropogenic resources; Resource classification; United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009); Resource policy, Urban Mining, Circular Economy

Zusammenfassung

Das Kernstück dieser Dissertation sind anthropogene Ressourcen, die hier als Lager und Flüsse von Materialien definiert werden, „die von Menschen geschaffen oder durch menschliche Aktivitäten verursacht werden, und auf welche potentiell zugegriffen werden kann wenn nötig". Verschiedene politische Initiativen der jüngsten Vergangenheit zielen auf die effiziente Nutzung von Ressourcen ab. Sie deuten somit auf ein gesteigertes Bedürfnis hin, ein ganzheitliches Bild über die insgesamt verfügbaren und potentiell abbaubare Rohstoffe zu erhalten, welche sowohl in der Lithosphäre als auch in der Anthroposphäre vorhanden sind. Das übergeordnete Ziel dieser Arbeit ist es, eine Methode zur Klassifizierung und Bewertung von anthropogenen Ressourcen, d.h. für Abfallströme und Materiallager, in Analogie zu bestehenden Konzepten für geogenen Lagerstätten zu entwickeln. Drei große Themenbereiche werden in dieser Arbeit behandelt. Die erste grundlegende zu beantwortende Frage lautet, ob das Klassifikationssystem “United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009“ (UNFC-2009), prinzipiell auch auf anthropogene Ressourcen angewendbar ist. Das zweite Themenfeld beschäftigt sich mit den Eigenschaften von anthropogenen Lagerstätten, welche im Rahmen ihrer Klassifizierung berücksichtigt werden müssen. In diesem Zusammenhang werden nicht nur die Unterschiede von anthropogenen Ressourcen im Vergleich zu geogenen Lagerstätten untersucht, sondern auch die Unterschiede innerhalb der sehr heterogenen Gruppe von anthropogenen Ressourcen beleuchtet. Der dritte Themenschwerpunkt konzentriert sich auf verschiedene Settings der Klassifizierung von anthropogenen Ressourcen. Ziel ist es, spezifische Methoden, Kriterien und Indikatoren zu entwickeln, um systematisch verschiedene Arten von anthropogenen Rohstoffvorkommen innerhalb der drei Achsen / Dimensionen von UNFC-2009 zu verorten. Diese umfassen 1) das Wissen über die Zusammensetzung und den gewinnbaren Anteil an Materialien, 2) die technische Machbarkeit und den Projektstatus und 3) die sozio-ökonomische Machbarkeit.

Drei wissenschaftliche Artikel vervollständigen diese Dissertation. Der erste Artikel präsentiert ein erstes Bewertungsverfahren für die Rückgewinnung von Ressourcen aus obsoleten Lagern anhand einer Fallstudie zum Rückbau einer alten Deponie in Belgien. Damit soll die mögliche Integration von anthropogenen Ressourcen in UNFC-2009 ganz grundsätzlich gezeigt werden. Darauf aufbauend war das Hauptziel der beiden folgenden Artikel, ein allgemeines Konzept für die Bewertung und Klassifizierung von verschiedenen weiteren Arten von anthropogenen Ressourcen zu entwickeln. Während der erste Artikel die grundlegende Frage beantwortet, ob UNFC-2009 auch für die Kllassifizierung von anthropogenen Lagerstätten geeignet ist (Top-Down-Ansatz), wurden im zweiten Artikel

verschiedene anthropogenen Rohstoffvorkommen im Detail betrachtet, um sie bestmöglich in ein Klassifikationssystem zu integrieren, welches ursprünglich für geogene Ressourcen geschaffen wurde (Bottom-Up-Ansatz). Der dritte Artikel bringt dann diese beiden Perspektiven zusammen. Um der Heterogenität von anthropogenen Ressourcen Rechnung zu tragen, wurde die neu entwickelte Methodik auf drei Fallstudien angewendet: 1) Rückbau einer Altdeponie (obsolete Lager), 2) Recycling von obsoleten Computern (Abfallströme) und 3) Recycling von Permanentmagneten aus Windturbinen (Lager in Nutzung).

Das Anliegen und der wichtigste Beitrag dieser Arbeit ist es, die Grundlage für eine umfassende Wissensbasis bezüglich verschiedener bestehender und potentiell abbaubarer anthropogener Ressourcenbestände zu schaffen. Die Integration von geogenen und anthropogenen Ressourcen in UNFC-2009 ermöglicht eine ganzheitliche Eischätzung und Bewertung der Rohstoffversorgungssituation. Außerdem können Kritikalitätsüberlegungen auf anthropogene Materialbestände ausgeweitet werden. Darüber hinaus können auf Grundlage der Klassifikationsergebnisse abfallwirtschaftliche Entscheidungen sowie das Design von Produkten hinsichtlich potentieller zukünftiger Ressourcen-Rückgewinnung optimiert werden. Diese Methodik wird politische Entscheidungsträger, potentielle Investoren sowie Abfallwirtschaftsunternehmen in Zukunft dabei unterstützen, anthropogenen Rohstoffvorkommen zu klassifizieren und mögliche Extraktionsprojekte in systematischer und transparenter Weise zu priorisieren.

Schlagwörter: Anthropogene Ressourcen; Ressourcenklassifizierung; United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009“ (UNFC-2009), Ressourcenpolitik, Urban Mining, Kreislaufwirtschaft

List of Appended Papers

I. Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2015. Framework for the evaluation of anthropogenic resources: A landfill mining case study–Resource or reserve? Resources, Conservation and Recycling 96, 19-30.

II. Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2016. Integrating anthropogenic material stocks and flows into a modern resource classification framework: Challenges and potentials. Journal of Cleaner Production 133, 1352-1362.

III. Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2016. Evaluation and classification of different types of anthropogenic resources: The cases of old landfills, obsolete computers and in-use wind turbines. Journal of Cleaner Production.

Contribution to the Papers

All articles have been written by Andrea Winterstetter. Johann Fellner and David Laner have supported the research design and contributed detailed comments to all articles. Helmut Rechberger contributed valuable comments.

Related publications and selected conference contributions

- Fellner, J., Lederer, J., Purgar, A., Winterstetter, A., Rechberger, H., Winter, F., Laner, D., 2015. Evaluation of resource recovery from waste incineration residues–The case of zinc. Waste Management, 37, pp.95-103.

- Winterstetter, A., Laner, D, 2015. Wirtschaftliche Rückgewinnung von Wertstoffen aus Deponien–Untersuchung eines Deponierückbauprojekts in Belgien. Österreichische Wasser-und Abfallwirtschaft, 67(1-2), pp.54-63.

- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2015. Evaluating and classifying landfill mining in analogy to natural deposits; In: Sardinia 2015, 15th International Waste Management and Landfill Symposium, S. Margherita di Pula (Cagliari), Italy.

- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2014. Old landfills: Anthropogenic resources or reserves?; In: SUM2014, 2nd Symposium on Urban Mining, Bergamo, Italy.

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- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2015. United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 - How do anthropogenic resources fit in?; In: Taking Stock of Industrial Ecology - ISIE Conference 2015, Surrey, UK.

- Winterstetter, A., Laner, D., Rechberger, H., Stiftner, R., Weber, L., Fellner, J., 2015. United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 - How do anthropogenic resources fit in?; In: UNECE Resource Classification Week: Expert Group on Resource Classification, Sixth Session, UNECE Geneva, Switzerland.

- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2016. Integrating anthropogenic material stocks and flows into UNFC-2009 – Challenges and potentials; In: UNECE Resource Classification Week: Expert Group on Resource Classification, Seventh Session, UNECE Geneva, Switzerland.

- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2015. Framework for the evaluation of anthropogenic resources: Economic analysis of recovering recyclable materials from old landfills; In: ISWA World Congress 2015, Antwerp, Belgium.

- Winterstetter, A., Laner, D., Rechberger, H., Fellner, J., 2016. Integrating anthropogenic material stocks and flows into modern resource classification frameworks; In: World Resources Forum 2015, Davos, Switzerland.

CONTENTS

1. WHY WE NEED A CLASSIFICATION FRAMEWORK FOR ANTHROPOGENIC RESOURCES: THE BIGGER PICTURE

In this chapter the rationale of this thesis is presented by highlighting the relevance of anthropogenic resources and their classification in the bigger context of resource and waste management. Definitions of key terms as used in this thesis are provided.

Rapidly increasing population and growing wealth have resulted in an excessive demand for energy and resources over the past 25 years, leading to growing waste generation and concerns over future supplies of raw materials (Meadows et al., 1972, Jones et al., 2013). The concentrated exploitation of certain resources, such as rare earth elements, gives countries like China enormous market power, while the risks of supply shortages for economies that heavily depend on raw materials imports are exacerbated (Graedel et al., 2012). With increasing extraction rates and rising prices, ore grades have significantly declined over time (Bridge, 2000). At the same time, accessing and exploiting deposits has become increasingly difficult, risky and potentially polluting for the local environment (Ahnert and Borowski, 2000, Ayres et al., 2013). Also, more and more energy is required for mining activities, leading inevitably to higher emissions of greenhouse gases (UNEP, 2013). Concurrently, the amount of materials and goods in use is steadily growing, moving inexorably towards their final fate as waste flows and obsolete stocks (Rauch and Pacyna, 2009, Pauliuk et al., 2013, Gerst and Graedel, 2008). As a consequence more and more final sinks, such as sanitary landfills, are needed, in order to avoid that wastes are simply dumped into the ocean or disposed of in any other inappropriate way (Kral and Brunner, 2014). Although even a recycling rate of 100 % will by far not suffice to cover steadily increasing demands, recovering and recycling materials from obsolete stocks and flows can ease the pressure on geogenic deposits (UNEP, 2011). The need for final sinks will decrease or at least not proportionally increase along with growing waste quantities. In addition, the secondary production of metals, for instance, is generally less polluting for the immediate environment (Ayres et al., 2013) and considerably less energy intensive than primary production, leading to reduced greenhouse gas emissions (UNEP, 2013).

Being aware of those issues, European institutions as well as national governments have been increasingly promoting improvements in resource efficiency as well as in the utilization of so-called ‘anthropogenic resources’, as the European Raw Materials Initiative (European Commission, 2008), the Circular Economy Package (European Commission, 2014) as well as various other European directives on recycling prove (e.g. Directive (EC), 2003, Directive (EC), 2008). Moreover, the Commission wants to achieve an absolute decoupling of

environmental impacts caused by the use of resources and economic growth by 2030, as announced in the Roadmap to a Resource Efficient Europe (European Commission, 2011). In an international context, one of the outstanding initiatives was the formation of the International Resource Panel in 2007 (UNEP, 2007) as well as the Sustainable Development Goals contained in the UN Resolution A/RES/70/1 of 2015 (UN, 2015). In particular, Goal Number 12 promotes sustainable production and consumption, postulating the efficient use of natural resources together with a substantial reduction of waste generation to be achieved by 2030.

These political initiatives indicate that boundaries between policies related to waste, energy, products and other materials, are progressively blurring. Also, waste vs. non-waste discussions are becoming irrelevant, since practically all materials are part of the same cycle (Sverdrup and Ragnarsdóttir, 2014). As an integral part of resource planning strategies, the efficient use of resources, including urban mining, recycling and re-use, and the management of waste, has gained increasing importance and will continue to do so in the upcoming decades (Simoni et al., 2015). Reflecting and accelerating this trend, anthropogenic resources have also experienced increased scientific attention during the past years. Already in the 1960s the US-Canadian activist and writer Jane Jacobs acknowledged the resource potential of cities and predicted a future transition from geogenic to urban mines (Jacobs, 1970). More recently, various authors, such as Johansson et al. (2013), Simoni et al. (2015), Sverdrup et al. (2015) or Weber (2013), have pleaded for establishing a link between mining geogenic materials and mining anthropogenic resources. Static material flow analyses have been performed to quantify material turnovers and to provide bottom-up estimates of in-use stocks (e.g. Chen and Graedel, 2012, Laner et al., 2015, Rostkowski et al., 2007), while dynamic material flow analyses have been used to determine the overall material stocks in specific use sectors, their development over time and consequent material flows (e.g. Müller et al., 2014, Buchner et al., 2015, Hatayama et al., 2009, Pauliuk et al., 2013, Ciacci et al., 2013). A number of authors (e.g. Kleemann et al., 2014, Hashimoto et al., 2009, Lichtensteiger, 2006) have specifically investigated the resource potential of buildings. Several studies (e.g. Krook et al., 2012, Kapur and Graedel, 2006) conclude that anthropogenic deposits, such as landfills, old buildings and hibernating infrastructure, are comparable in size to the remaining natural stocks of certain metals. Half of the previously extracted primary materials are no longer in use (e.g. Spatari et al., 2005, Müller et al., 2006, UNEP, 2010). Rettenberger (2009) underlines both relevance and size of the resource potential contained in German landfills. Exploring the potential of milling and smelting wastes, Gordon (2002) identifies mill tailings as the single largest source of copper in anthropogenic deposits in the US copper cycle. But not only the size of exploitable

anthropogenic stocks is comparable to virgin material deposits, but also the grade of minerals. Ongondo et al. (2011), for instance, argue that the concentration of gold in old cell phones is two orders of magnitude higher than in natural ores. Being highly relevant for strategic resource planning, several studies (e.g. Fellner et al., 2015, Krook et al., 2011) compare different types of anthropogenic material deposits with the aim to prioritize potential projects to extract a specifically sought resource under certain aspects and constraints, e.g. copper from hibernating infrastructure in different cities. Some of these studies even made concrete attempts to map anthropogenic resources or related recovery projects into existing primary resource classification frameworks (e.g. Lederer et al., 2014, Mueller et al., 2015) .

Despite increasing scientific and political attention, the knowledge on anthropogenic resource deposits is still limited (Simoni et al., 2015). As shown in Winterstetter et al. (2016b), anthropogenic deposits, compared to geogenic resources, are more heterogeneous and subject to various dynamics, due to the human impact on their genesis. They are created and altered by anthropogenic activities via the production, consumption and disposal of materials and goods, and are renewed over drastically shorter time spans than geogenic deposits. Often they must be assessed not only under aspects of resource recovery, but with respect to alternative waste treatment and disposal options. In order to grasp those multiple facets, it is vital to create a methodological framework for the evaluation and classification of anthropogenic resources. The systematic integration of anthropogenic resources into existing primary resource classification systems, such as UNFC-2009, seems like a coherent and consequent step towards a comprehensive picture of totally available and potentially minable raw materials, and will certainly help to close the knowledge gap on anthropogenic deposits. This will also facilitate decision-making concerning primary materials, products, waste materials and their management. Making potential resource extraction projects comparable is relevant for political actors, such as governments and institutions involved with strategic resource planning purposes, as well as for private business stakeholders interested in investing in resource recovery undertakings. Furthermore, waste management operators would benefit from information, on how to optimize waste management, e.g. what wastes would pay to be stored temporarily for valorisation in the future (Simoni et al., 2015, Jones et al., 2013). However, UNFC-2009 just like all the other resource classification codes and standards, serves for classification means only, meaning that it does not provide specific rules or guidelines for assessing a mining project. Therefore, the goal of this thesis is to develop a set of methods for the classification of various kinds of anthropogenic resources including an operative evaluation procedure.

In this thesis “mining” is used as a synonym for extracting / recovering materials from a defined resource deposit. “Deposit” is used as a general umbrella term comprising material stocks and flows, according to one of the term’s dictionary definitions designating “a layer or mass of accumulated matter” (Oxford Dictionaries, 2016b). In geological economics, the difference between “resources” and “reserves” is, that “reserves” are “resources” known to be economically viable for extraction, while “resources” have “reasonable prospects for eventual economic extraction in the foreseeable future” (CRIRSCO, 2013). However, unless explicitly stated, in this study, the term “resources” is understood in a broader sense, namely as “stock or supply of money, materials, staff, and other assets that can be drawn on by a person or organization in order to function effectively” (Oxford Dictionaries, 2016d). Thus, while geogenic resources result from geological processes, “anthropogenic resources” are defined here as ´”stocks and flows of materials created by humans or caused by human activity, which can be potentially drawn upon when needed” (Winterstetter et al., 2016a). Thinking of quantities in “stocks” and “flows” originates from business related disciplines, such as financial accounting (Fisher, 1896). However, these two terms are used in many other contexts as essential elements of system dynamics models. Jay Forrester (1969) originally referred to stocks as "levels", considering them as bodies, which are accumulated over time by inflows and/or depleted by outflows. Stocks typically have a certain value at a specific moment in time, for instance the number of computers in use at a specific moment. A flow (or "rate") changes a stock over time and is usually measured over a certain time period, for example the number of computers becoming obsolete over one year. Consequently, the main difference between anthropogenic stocks and flows in a system is the residence time (Baccini and Brunner, 2012). “Evaluate” is used according to one of the term’s dictionary definitions, namely to “form an idea of the amount, number, or value of” anthropogenic resources (Oxford Dictionaries, 2016c). “Classify“ is used to “arrange (a group of people or things) in classes or categories according to shared qualities or characteristics” (Oxford Dictionaries, 2016a), in this thesis according to the UNFC-2009 criteria and based on the evaluation results.

2. THE OBJECTIVES & STRUCTURE OF THIS THESIS

In this section the objectives of the dissertation as well as its structure and research questions are outlined.

The PhD thesis is part of and funded by the large scale research project "Christian Doppler Laboratory for Anthropogenic Resources" pursuing the goal to develop a methodological framework to identify, characterize and evaluate anthropogenic resources with respect to material quantity, quality, and availability, and under changing boundary conditions (Fellner, 2015).

The overall goal of this thesis is to develop a methodology for the classification and evaluation of anthropogenic resources, i.e. waste flows and material stocks, in analogy to existing concepts used for geogenic resource deposits.

The following research questions are tackled in this thesis:

1. Can the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) in principle be applied to anthropogenic resources? ("See *if* UNFC-2009 is applicable").
2. What *general characteristics of anthropogenic resource* deposits are to be considered for the prospection, exploration and evaluation of anthropogenic resources? To what extent are they different from geogenic deposits? How can various types of anthropogenic resource deposits be described and structured?
3. What methods, indicators and criteria can be applied to systematically evaluate and classify various types of anthropogenic resource deposits under UNFC-2009? ("See *how* UNFC-2009 is applicable to *various different* anthropogenic resources").

The thesis is structured as follows: Chapter 3 presents the research design and the methods applied in the articles appended, while Chapter 4 demonstrates the papers' results and theoretical contributions. In the following chapters, the question of how anthropogenic resources could be potentially integrated into modern classification systems for geogenic resources is answered. Chapter 5 mainly relies on reviewed literature. Taking the mining sector as a starting point, currently existing resource classification systems and their historical development were reviewed (cf. Chapter 5.1.1). In Chapter 5.1.2 the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) is described in detail, for being the most comprehensive resource classification system, and for representing recent efforts to harmonize national classification codes for diverse commodities. Chapter 5.1.3 provides an insight into the principles and

procedures generally used for the classification of geogenic resources. In Chapter 5.2 previous attempts to classify anthropogenic stock resources are reviewed. Chapter 6 relies on the results of the appended articles with respect to the research questions in order to show the integration of anthropogenic resources into UNFC-2009. After describing the general characteristics of anthropogenic resource deposits, a newly developed operative evaluation procedure is presented, including the indicators used for each of the three UNFC-axes, as well as the criteria applied to distinguish between the different UNFC-categories, to systematically classify different types of anthropogenic resource deposits. Further, classification guidelines, similar to a "cooking recipe", are provided. In Chapter 7, case studies for each of the three identified types of anthropogenic resources (i.e. obsolete stocks, in-use stocks and waste flows) are evaluated and finally classified under UNFC-2009. Chapter 8 compares the results from the case studies as well as factors, influencing the classification results. Finally, the challenges and potentials for the classification of anthropogenic resources under UNFC-2009 are discussed, to guarantee full and systematic integration of anthropogenic resources into UNFC-2009. Chapter 9 concludes the thesis by putting the study in a wider context, and presenting some suggestions for future research.

3. RESEARCH DESIGN & METHODS

In this chapter the research design is presented by describing the development of this thesis and a contextual presentation of each paper, primarily focusing on the methods used.

The title I had originally foreseen for this thesis "Mine of the Future" has been taken and trademarked already by the mining company Rio Tinto for its concept of automatizing mining operations (Rio Tinto, 2011). Being forced to pick another one, I eventually came up with "Mines of Tomorrow", which I felt was even better: The plural hints at the big number of decentralized anthropogenic deposits, compared to the huge, isolated and cumbersome geogenic mines. Moreover, "Tomorrow" feels way closer than "Future", making mining the anthroposphere a more present and therefore more urgent cause. Finally, renouncing to put a question mark, reveals the underlying assumption, that the matter of discussion is not, whether the anthroposphere should be mined or not. The issue at stake is rather, how this can be done in the best way and what factors are considered critical.

3.1 THE RESEARCH PROCESS

The research design to address the question of how to evaluate and classify anthropogenic resources is of rather explorative nature. As mentioned in Chapter 1, a lot of research effort has been made to describe and quantify anthropogenic flows and stock on a macro level.

Several studies investigated the composition, volumes, grade and the economics of potential extraction of materials from a specific deposit. But only few authors compare different types of anthropogenic material deposits with the aim to prioritize - under specific aspects and constraints - potential projects to extract a specifically sought resource. And even fewer studies make concrete attempts to map anthropogenic resources into existing classification frameworks, by evaluating recovery projects according to similar procedures as used in the mining sector (cf. Chapter 5.2). Therefore, although the general direction of this thesis was set by the initial project proposal of the Christian Doppler Laboratory for Anthropogenic Resources as published in Lederer et al. (2014), the idea on the expected outcome has initially been not very clear, “terra incognita” in a way. To understand the step-by-step approach of my research, the articles can be seen as building blocks needed to construct the final framework. The findings of one article serve as the fundament for the next one.

First of all, I started with reviewing existing classification systems to find out, whether they are potentially adaptable to anthropogenic resources. The review showed that there is a number of national reporting codes and classification systems out there, some of which are designed for financial reporting only, while others are used for strategic resource planning or internal company reporting, as described in Chapter 5.1.1. The United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) was identified as the most comprehensive and flexible resource classification system. However, the UNFC-2009 framework serves for classification purposes only without providing standardized procedures or guidelines for the detailed evaluation of a mining project.

To facilitate the integration of anthropogenic resources into UNFC-2009, in Paper I an initial evaluation procedure was developed for mining obsolete stocks, more specifically for a case study on landfill mining. Mining waste deposits, compared to other resource recovery undertakings, exhibits the most similarities with conventional mining projects. Building on the results from Paper I, the main goal for Paper II and Paper III was to develop a general concept allowing for evaluating and classifying various other types of anthropogenic resources. Paper I answers the basic question, whether the framework is generally suitable for anthropogenic deposits (top-down approach). Paper II focuses more on the items to be classified, namely on the characteristics of anthropogenic resources, to see, how they can fit into a classification system, which has originally been designed for geogenic resources (bottom-up approach). Paper III brings those two perspectives together (top-down & bottom-up), by applying the newly developed method to case studies for landfill mining (obsolete stocks), recycling obsolete personal computers (waste flows) and recovering materials from

in-use wind turbines (in-use stocks), accounting for the heterogeneity of anthropogenic resources. An additional case study on landfill mining (Bornem landfill site) embedded within the project RECLAF (Resource Classification Framework for Old Landfills in Flanders), was cooperatively realized by TU Wien and the Public Waste Agency of Flanders (OVAM) (Winterstetter et al., 2016c). So in total four case studies with each two scenarios were evaluated and classified in this thesis.

The endeavour of creating precise specifications and guidelines to fit anthropogenic resources into UNFC-2009 was presented at the sixth and seventh session of the UNECE Expert Group on Resource Classification in Geneva (Winterstetter, 2016, Winterstetter et al., 2015b). While the meeting in 2015 resulted in an official "encouragement" of continuing our research (UNECE, 2015), at this year's (2016) meeting the Expert Group recommended "that, subject to volunteers being identified, a small sub-group be established to explore the potential applicability of UNFC-2009 to anthropogenic resources and to report its findings to the eight session" (UNECE, 2016).

3.2 Methods Used in Appended Articles

PAPER I

The goal of Paper I is to see, whether the primary resource classification framework UNFC-2009 is applicable to a landfill-mining project, in order to categorize the landfilled materials either as anthropogenic 'resources' or 'reserves', and to identify critical factors for the resource classification of the project. Therefore, an operative evaluation procedure has been developed and applied to a case study on enhanced landfill mining (ELFM) at the Remo Milieubeheer landfill site in Houthalen-Helchteren, Belgium. This project was selected as a first case study due to its scale, the open communication strategy and the detailed level of documentation. Moreover, the project's aim was to valorise to the maximum extent possible the various waste streams either as material or as energy (Jones et al., 2012).

Published articles regarding the ELFM project complemented by personal communication with involved researchers and project managers to clarify specific questions served as main sources of data. To keep the research as unbiased and neutral as possible, it was decideded to examine four different scenarios. Moreover, all information received was crosschecked with existing literature data, to avoid falling for too optimistic assumptions with respect to landfill mining. As the focus of the evaluation was set on technological options and economics as well as on the effects of system boundary choices, different alternatives for the combustible waste fraction's thermal treatment (gas-plasma technology vs. incineration) and for specific stakeholder interests (public vs. private perspective) were explored. For each

scenario relevant material and energy flows were quantified in a Material Flow Analysis (MFA), by comparing the landfill's total resource potential to the extractable and potentially usable share of materials.

Subsequently, the economic viability of mining the identified extractable raw materials from the landfill was explored from different stakeholders' perspectives, based on a discounted cash flow (DCF) analysis. Uncertainties originating from model input parameters of the economic analysis were considered in an uncertainty and sensitivity analysis by performing Monte Carlo simulations. Similar to the mining industry, cut-off prices (alternatively also cut-off quantities or costs) were calculated for important economic performance parameters, to determine under which conditions an anthropogenic deposit can be labelled a 'resource' or a 'reserve'. The constantly evolving boundaries between resources and reserves are determined by modifying factors.

In the macro scenario, representing the perspective of a public entity as compared to a private investor, potential greenhouse gas (GHG) emission savings of a landfill mining project compared to a "Do-Nothing" scenario were valued with a hypothetical CO_2 tax to show exemplarily how externalities can be included in the evaluation. To account for GHG emissions the global warming potential (GWP100) was calculated for all relevant project activities and processes, using a life cycle approach. Detailed description of the case study, its respective scenarios and all underlying assumptions for the calculations can be found in the appended Paper I and its Supplementary Information (SI). Finally, the classification of the four scenarios was attempted under UNFC-2009, with a main focus on the E-axis.

PAPER II

To raise the findings from Paper I to a more generic level by going beyond the mining of old landfills, the main goal for Paper II was to develop a general operative procedure, allowing to evaluate and classify various other types of anthropogenic resources under UNFC-2009. Hereby, the focus was on the specific features of anthropogenic resources, to see, how they can fit into a classification system, which has originally been designed for geogenic resources.

First, official documents and reports were reviewed to provide an overview over the historical development and to understand the context and the purpose of existing resource classification systems and reporting codes. Representing recent efforts to harmonize national classification codes for diverse commodities, the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) had been identified as the most suitable framework to host anthropogenic resources and is therefore described

in detail. Continuing the work started in Paper I of defining specific and generally suitable indicators and criteria for categorizing diverse types of anthropogenic resources under UNFC-2009, firstly the differences between anthropogenic and geogenic resources were analysed. To account for the heterogeneous nature of anthropogenic resources, different settings of anthropogenic resource classification were then illustrated based on two cases: Mining an old landfill, representing an anthropogenic obsolete stock, is contrasted in a qualitative discussion to mining E-waste, an example for mining a waste flow. Existing literature on E-waste management and landfill mining was reviewed according to the principle of snowball sampling (Biernacki and Waldorf, 1981). Using highly referred literature, such as Huisman et al. (2008), Ongondo et al. (2011) and Schluep (2009), for waste electrical and electronic equipment (WEEE) and Krook et al. (2012) for landfill mining, additional literature was searched amongst the references.

Before establishing a general evaluation procedure, it was important to understand and systemize factors, which influence the evaluation and classification of different types of anthropogenic material deposits (in the following called 'influencing factors'). By means of causal loop diagrams, the roles and interdependencies of those factors were visualized. After that, the influencing factors were matched to the single stages of resource classification (prospection, exploration and evaluation) and then mapped to the corresponding UNFC axis, i.e. "knowledge on composition and extractable material content"(G-axis), "technical and project feasibility"(F-axis) and "socioeconomic viability"(E-axis). With these preliminary indicators for each stage / axis and with the methods as used in Paper I, a general operative procedure was outlined allowing for the integration of anthropogenic resources into UNFC-2009.

Finally, the potentials and challenges still remaining to be tackled to guarantee full and systematic integration of anthropogenic resources into UNFC-2009 were discussed.

PAPER III

Based on the challenges of applying UNFC-2009 to anthropogenic resources identified in Paper II, the method was further refined in Paper III and applied to case studies for landfill mining (obsolete stocks), recycling obsolete personal computers (waste flows) and recovering materials from in-use wind turbines (in-use stocks). The main goal of this article was to compare and illustrate different settings and characteristics of anthropogenic resource classification on the one hand, and to provide detailed indicators and specific criteria to map different types of anthropogenic resources within the three dimensions of UNFC-2009, on the other hand.

The specific case studies were selected to examine different statuses of availability for mining (in use vs. obsolete) and residence time (stocks vs. flows) and also different conditions for mining and handling (push vs. pull). Old landfills come closest to conventional mines, as they are finite just like geogenic resource deposits. A landfill mining project is usually confined and resources are depleted over time. In this case the landfill mining project is a pull situation, as no remediation is required. Thus, the economic results will decide, whether to mine or not to mine. Waste flows in contrast resemble more to renewable energies, as they are in many cases almost infinitely replenished, unless the corresponding in-use stocks are phased out. The project's system boundaries have to be drawn artificially. The PC-recycling case was chosen as a push situation, to see how resource classification can be done for a flow, which is mainly regulated under waste management aspects.

Another criterion for selecting the case studies was to show different levels of economic viability, anticipating better results for PC recycling than for landfill mining. Also different levels of technological and project maturity were of interests. Therefore the hypothetical recycling of permanent magnets from wind turbines was chosen. Information on the current status and size of in-use stocks is highly relevant with regard to future recoverable waste flows and obsolete stocks. Depending on whether there will be future constraints, such as laws and policies, and how the general framework will look like, mining REE materials or entire magnets from wind turbines can potentially become a push or a pull situation. Further, different influencing factors were given special attention to in each case study. In case of the permanent magnets contained in wind turbines, the focus was on different potential recycling methods. As treating obsolete PCs in the EU is regulated by the WEEE directive, which is implemented in different ways at national levels of the EU member states, the focus was on different settings of the legal, institutional, organizational and societal structure. For mining an old landfill in a pull situation the main focus was on modifying factors, which directly influence the economic results. Also the timing of mining was considered as key economic drivers are expected to change over time.

Projects for recovering materials from an old landfill (obsolete stocks), from obsolete personal computers (waste flows) and in-use wind turbines (in-use stocks) were exemplarily evaluated and classified under UNFC-2009. Based on the literature reviewed for Paper II in combination with interviewing a manager of a Viennese dismantling and recycling centre facility (DRZ, 2016), a hypothetical case for a PC recycling project was designed. For the case study on landfill mining the results from Paper I were used. A master's thesis, analysing the material flows of neodymium in high technology applications for Austria, written at our institute served as a basis for the case on permanent magnets in wind turbines (Gattringer,

2012). In order to design a case study including different scenarios on recycling options for permanent magnets, existing literature was reviewed, again using snowball sampling (Biernacki and Waldorf, 1981), starting with the articles by Binnemans et al. (2013) and Schüler et al. (2011). The literature review was complemented by an interview with an expert on wind turbines (Stiesdal, 2015) to obtain more information on the option of re-using permanent magnets.

Using the methods as described in Paper I, the resource potentials of an old landfill, obsolete PCs and in-use wind turbines were evaluated and compared, by first performing a Material Flow Analysis (MFA) to quantify relevant material and energy flows, potentially to be recovered from the anthropogenic resource deposit. Subsequently, the economic viability of mining the deposit was explored from a public perspective, based on a discounted cash flow (DCF) analysis. A detailed description of all case studies, their respective scenarios and all underlying assumptions can be found in the appended Paper III and its Supplementary Information. As those cases served primarily to demonstrate the applicability of UNFC-2009 to anthropogenic resources, by following the newly developed (Paper I and II) and refined (Paper III) operative evaluation procedure, no uncertainty and sensitivity analysis was performed. As the economic results for mining obsolete PCs and the permanent magnets in wind turbines were positive anyway, it was not necessary to calculate cut-off values for potentially changing key economic parameters. Finally, the three case studies and their respective scenarios were classified under UNFC-2009. The detailed indicators used for each of the three UNFC-axes, as well as the criteria applied to distinguish between the different UNFC-categories can be found in the appended Paper III.

4. ARTICLE SUMMARY

This section shows the results of each article appended to this thesis, summarizing aims, methods, data used and theoretical contribution.

All three appended papers contribute to achieve the overall aim of this thesis to develop a method for the classification and evaluation of anthropogenic resources in analogy to existing concepts used for geogenic resource deposits. The chronological succession of the articles fully reflects the research questions tackled one after another, as shown in Table 1.

Paper I answers the fundamental question, whether the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) can be applied to anthropogenic resources, and roughly how this can be done. Although Paper II still deals with this first research question by describing the historical development of UNFC-2009, it mainly focuses on the general characteristics of various anthropogenic deposits to be considered in the classification process, how anthropogenic resources can be described and structured, and to what extent they differ from geogenic resources. Based on this information, an operative evaluation procedure is outlined. Diving deeper into the matter, Paper III solves the issue of how the heterogeneity of anthropogenic resources can be accounted for in a resource classification process under UNFC-2009. By refining the operative procedure, that has been developed previously, various types of anthropogenic resource deposits are evaluated and classified.
The articles are building on each other, with each one increasing the level of detail regarding methods, indicators and criteria used to systematically integrate anthropogenic resources into UNFC-2009.

Table 1: The main contribution of each article to the research questions (RQ).

	RQ 1	RQ 2	RQ 3
Paper 1	x		
Paper 2		x	
Paper 3			x

The following paragraphs summarize the goals, methods, and theoretical contribution of each of the articles. Paper I, “Framework for the evaluation of anthropogenic resources: A landfill mining case study–Resource or reserve?”, is presented first, then Paper II, “Integrating anthropogenic material stocks and flows into a modern resource classification framework: Challenges and potentials”, and lastly Paper III, “Evaluation and classification of

different types of anthropogenic resources: The cases of old landfills, obsolete computers and in-use wind turbines".

4.1 PAPER I - FRAMEWORK FOR THE EVALUATION OF ANTHROPOGENIC RESOURCES: A LANDFILL MINING CASE STUDY – RESOURCE OR RESERVE?

The aim of this article is to apply the resource classification framework UNFC-2009 to a landfill-mining project to identify the landfilled materials as potential anthropogenic 'resources' (reasonable prospects for eventual economic extraction in the foreseeable future) or 'reserves' (current economic extraction possible), and to reveal critical factors for the classification of the project.

Due to a lack of existing guidelines and standardized methods used in the primary sector, a first operative evaluation procedure is developed for a landfill-mining project. This procedure comprises a Material Flow Analysis (MFA) to quantify the potentially extractable amounts of materials, a Discounted Cash Flow (DCF) analysis including an uncertainty and sensitivity analysis for the economic evaluation and a Life Cycle Assessment (LCA) for the environmental evaluation.

Based on data from a landfill-mining project in Belgium, the focus of the evaluation was set on technological options and economics. Four scenarios have been investigated, representing different alternatives for the combustible waste fraction's thermal treatment (gas-plasma technology vs. incineration) and for specific stakeholder interests (public vs. private perspective).

The Net Present Values (NPV) were found to be negative for all four scenarios, implying that none of the project's variations is currently economically viable. The main drivers of the economic performance are parameters related to the thermal treatment of the combustible waste fraction as well as to the sales of recovered metals. Similar to the mining industry, cut-off prices (alternatively also cut-off quantities or costs) were calculated for important economic performance parameters, to determine under which conditions an anthropogenic deposit has reasonable prospects for future economic extraction, and to decide whether it can be labelled a 'resource' or not. Based on required future price increases for non-ferrous metals or electricity to make the project economically viable, the scenarios resulted in different final resource classifications under UNFC-2009. This study shows exemplarily the inclusion of greenhouse gas (GHG) emissions and longer aftercare obligations in the macro scenario. However, by investigating the global warming potential, the list of non-monetary effects owing to landfill mining, and to be included in a macro evaluation, has been by no means treated exhaustively.

Main difficulties in evaluating costs and benefits of landfill-mining projects arise from the fact that modifying factors affecting the project's socioeconomic viability differ for each site and are often linked to high uncertainties. For example, costs for the potential treatment of the fine fraction are largely depending on its level of contamination and thus on the landfill's specific composition. The classification as 'resource' or 'reserve' (or none of both) depends on a number of factors. Only by extending the system boundaries of the evaluation from a micro to a macro perspective as well as the choice of certain technological options can have a significant impact on the final results.

The theoretical contribution of this paper is, that the applicability of UNFC-2009 to landfill mining has been proven successful by providing a first set of methods, indicators and criteria to map a landfill mining project analogous with the axes and classes of the UNFC-2009 framework. The need to define more specific and generally suitable indicators and criteria for categorizing various types of anthropogenic resources under UNFC-2009 was pointed out.

4.2 PAPER II - INTEGRATING ANTHROPOGENIC MATERIAL STOCKS AND FLOWS INTO A MODERN RESOURCE CLASSIFICATION FRAMEWORK: CHALLENGES AND POTENTIALS

Going beyond the mining of old landfills, the aim of this article was to develop a general operative procedure, allowing for the integration of various other types of anthropogenic resources under UNFC-2009.

By reviewing existing resource classification systems and reporting codes, the choice of UNFC-2009 to apply to anthropogenic resources is justified by hindsight. First, differences between anthropogenic and geogenic resources are analysed, in order to continue the effort started in Paper I to define specific and generally suitable indicators and criteria for mapping diverse types of anthropogenic resources under UNFC-2009. To create a general evaluation procedure, factors, influencing the evaluation and classification of different types of anthropogenic resources, are structured. Two cases illustrate the heterogeneous nature of anthropogenic material deposit and also different settings of anthropogenic resource classification: Mining an old landfill, representing an anthropogenic obsolete stock, is contrasted in a qualitative discussion to E-waste recycling, an example for mining a waste flow. Finally, the potentials and challenges still remaining to be tackled to guarantee full and systematic integration of anthropogenic resources into UNFC-2009 are discussed.

The review shows that UNFC-2009 represents recent and still ongoing efforts to harmonize national classification codes for diverse commodities and addressing different stakeholders, in view of an increasingly globalized mining industry. A decisive advantage of UNFC-2009 over the two-dimensional systems (like most of the codes from the CRIRSCO family), is its

broad scope and the additional third axis, displaying a mining project's "technical feasibility and field project status". The two-dimensional systems only account for the knowledge on composition of a deposit and the economics of a mining project. This might produce a distorted picture, especially where technologies for extraction or processing do not exist yet or are immature and therefore expensive. From a two-dimensional system, one would only get the information, that the project is "uneconomic", while the F-axis under UNFC-2009 offers a more nuanced view by potentially showing the development status of technologies applied in the project, which is particularly relevant for the classification of anthropogenic resources.

Compared to geogenic resources, anthropogenic deposits are created and altered by human activities via the production, consumption and disposal of materials and goods, and are renewed over drastically shorter time spans than geogenic resources. Due to various dynamics, the planning of mining activities is linked to high uncertainties, with respect to the legal and technological framework, as well as to the quality of the materials. Moreover, anthropogenic deposits often must be assessed not only under aspects of resource recovery, but also regarding alternative waste treatment and disposal options, and including non-monetary externalities. Besides classifying obsolete stocks and waste flows, information on the future mining potential of in-use materials can help manufacturers to increase their products' recyclability and so improve future resource availability.

The visualization based on causal loop diagrams helped to structure factors, which influence the evaluation and classification of anthropogenic resources, according to their role during the individual phases of resource classification, namely prospection, exploration and evaluation. During the pre-prospection phase, the deposit's status of availability for mining, discriminating between "in-use stocks", "obsolete stocks" and "waste flows" as well as the specific handling and mining condition are checked. These preconditions for potential mining activities define the setting for the following classification. During the prospection phase (displayed on the G-axis), mainly information on a specific resource deposit's type, location, volume and composition shall be gained, allowing first estimates on the resource potential. In the exploration phase (reflected on the G- and F-axis), the knowledge on the deposit's resource potential has to deepen. To identify the potentially extractable and usable share of materials as a function of different technology alternatives and project set-up options, system variables receive particular attention. In the evaluation phase, the socioeconomic viability of extracting and utilizing the identified extractable raw materials is explored and displayed on the E-axis. Modifying factors with direct impact on the project's economics are investigated,

such as prices for secondary products, (avoided) costs as well as possibly monetized externalities and indirect financial effects.

The major theoretical contribution of this paper is a general operative procedure for the evaluation and classification of different types of anthropogenic resources, which needs to be refined and illustrated via case studies.

4.3 PAPER III – EVALUATION AND CLASSIFICATION OF DIFFERENT TYPES OF ANTHROPOGENIC RESOURCES: THE CASES OF OLD LANDFILLS, OBSOLETE COMPUTERS AND IN-USE WIND TURBINES

The main goal of this article is to compare and illustrate different settings of anthropogenic resource classification, and to provide detailed indicators and specific criteria to map different types of anthropogenic resources in analogy with the axes and classes of UNFC-2009. Based on the potentials and challenges of applying UNFC-2009 to anthropogenic resources identified in the previous papers, the operative evaluation procedure was further refined.

Using the same methods as in Paper I, based on three hypothetical cases, the resource potentials of an old landfill (obsolete stocks), from obsolete personal computers (waste flows) and in-use wind turbines (in-use stocks) were exemplarily evaluated and compared. The factors, which are influencing the final classification, are similar for the different types of anthropogenic resources, but their individual weight varies in the different scenarios designed for each case study. When treating obsolete PCs in the EU, the focus was on different settings of the legal, institutional, organizational and societal structure, affecting the quantities of extractable and potentially usable materials via collection and source separation rates, but also influencing the modifying factors (e.g. via labour costs). In the landfill mining case study the timing of mining as well as the modifying factors was given particular attention, to see how future developments of key drivers (e.g. metal prices) can change the final result, and to decide, whether there are reasonable prospects for future economic extraction. In case of future potential recycling of permanent magnets contained in wind turbines, currently in use in Austria, the focus was on the choice of recycling technology. After quantifying relevant material (and energy) flows in a Material Flow Analysis (MFA), which can potentially be recovered from the respective anthropogenic deposit, the economic viability of mining the deposit was explored from a public perspective, based on a discounted cash flow (DCF) analysis. Finally, the three case studies and their respective scenarios were classified under UNFC-2009.

The economic results differ in the respective scenarios of each case study, where the timing of mining is varied, different organizational and societal settings are compared and different choices for technological options are made. Recycling the entire in-use stock of permanent magnets from wind turbines in Austria within one year would yield the best economic results compared to mining obsolete PCs and landfill mining. Although currently not available for mining, it is crucial to know the economic performance of hypothetically mining the in-use stock's resource potential under current conditions as detailed as possible, in order to develop suitable recovery strategies for future waste flows and obsolete stocks. In some cases, information on the recyclability of in-use materials might be useful for manufacturers to improve their product design. Moreover, the information on the economic viability of a hypothetical mining project is of high relevance for decision makers, since expected positive economic results might make future laws on recycling obsolete.

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. On the scenario level, the economic result is better for PC recycling in a high-income EU member state than in a low-income EU member state, due to higher collection and source separation rates and in spite of higher labour costs. In case of the permanent magnets from wind turbines the re-use scenario is economically clearly to be preferred over the hydrometallurgical extraction. Based on the three case studies, detailed indicators used for each of the three UNFC-axes, as well as specific criteria applied to distinguish between the different UNFC-categories were developed.

The major theoretical contribution of this paper is that a new operative procedure in line with UNFC-2009 has been developed to coherently evaluate and classify anthropogenic resource deposits under different conditions. This procedure will assist governments, potential investors and waste management companies to classify anthropogenic resource deposits and prioritize potential extraction projects in a systematic and transparent way.

5. FROM CLASSIFYING GEOGENIC RESOURCES TO ANTHROPOGENIC RESOURCES – A LITERATURE REVIEW

This chapter answers the first Research Question, by giving an overview of existing resource classification systems and their development. It also describes the UNFC-2009 framework in detail, and provides information on how geogenic deposits are generally classified. Finally, previous attempts of evaluating anthropogenic stock resources are presented.

5.1 CLASSIFICATION OF GEOGENIC RESOURCES

5.1.1 The Historical Development of Resource Classification Systems

The classification of natural resources looks back on a long history (cf. Figure 1). Starting in the early 18th century in Europe, the perception of temporary scarcity of key raw materials provoked first reflections on a more sustainable use of natural resources. Around 1700, an acute scarcity of wood threatened the livelihood of thousands in Saxony, as the mining industry and smelting of ores had used up entire forests. Rising timber prices resulted in bankruptcy and closure of parts of the mining industry. Influenced by this environment Hans Carl von Carlowitz was the first one to formulate the concept of sustainability in forestry (Von Carlowitz, 1713). Over half a century later, Thomas Robert Malthus focused on the availability of food, forecasting a forced return to subsistence-level conditions, once population growth had outperformed agricultural production, without, however, deriving concrete instructions on how to solve this issue (Malthus, 1798). In the mid-nineteenth century, during the industrial revolution, when the British economy was heavily dependent on coal for energy, Stanley Jevons (1865) warned against dwindling coal deposits and rising coal prices for having the potential to undermine economic activity and to end the British supremacy. In this context Jevons covered various issues fundamental to sustainability, such as limits to growth, resource peaking, taxation of energy resources and renewable energy alternatives.

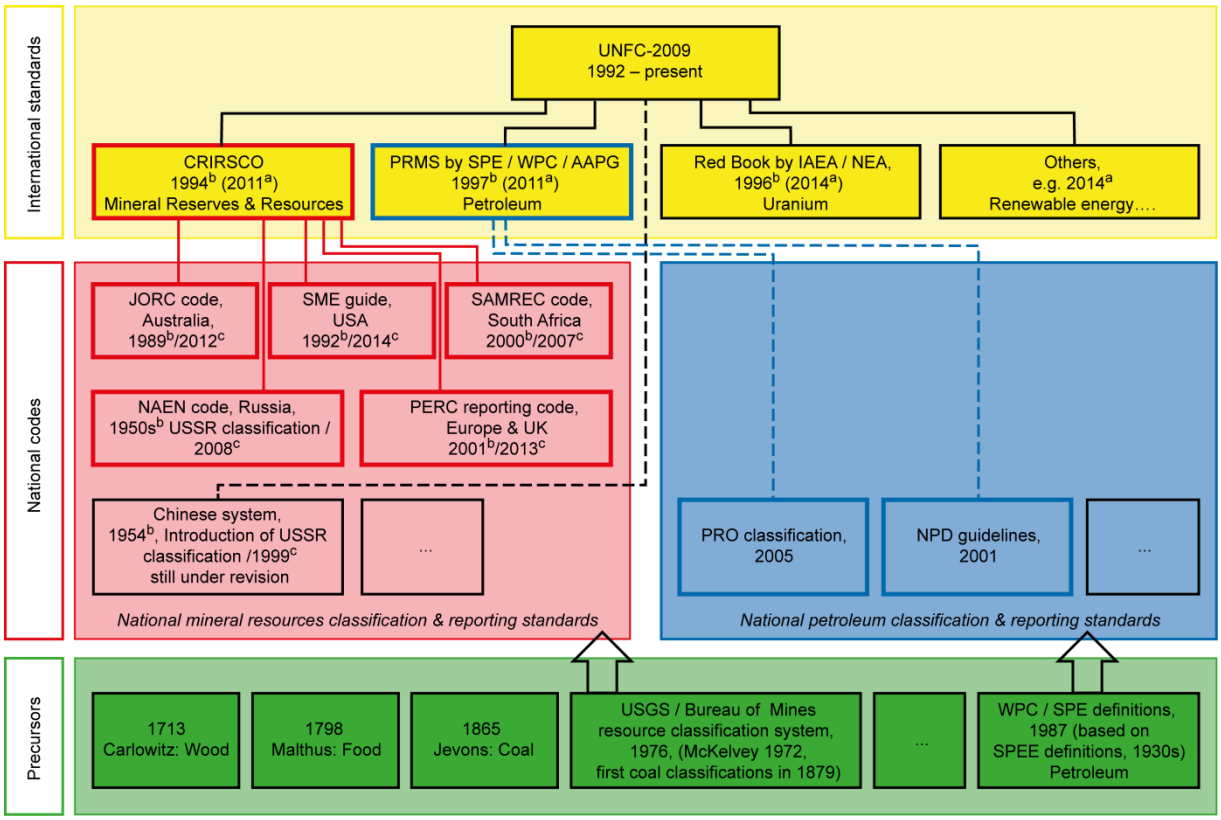

Figure 1: History of resource classification.

Legend:
a … Date of official alignment with UNFC-2009
b … Date of creation
c …Last revised version

AAPG:	American Association of Petroleum Geologists
CIM:	Canadian Institute of Mining, Metallurgy and Petroleum
CRIRSCO:	Committee for Mineral Reserves International Reporting Standards
IAEA / NEA:	International Atomic Energy Agency / Nuclear Energy Agency
JORC:	Joint Ore Reserves Committee
NAEN:	National Association for Subsoil Use Auditing
NPD:	Norwegian Petroleum Directorate
PERC:	Pan-European Reserves and Resources Reporting Committee
PRMS:	Petroleum Resources Management System
PRO:	China Petroleum Reserves Office
SAMREC:	South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves
SPE:	Society of Petroleum Engineers
SPEE:	Society of Petroleum Evaluation Engineers
SME:	Society for Mining, Metallurgy, and Exploration, Inc.
USSR:	Union of Soviet Socialist Republics
USGS:	United States Geological Survey
WPC:	World Petroleum Council

In the United States the U.S. Geological Survey (USGS) (founded in 1879 and originally charged with the classification of public lands) and the U.S. Bureau of Mines (founded in 1920) have conducted modest continuing programs in coal resource estimation, starting already from their early years of existence. Until the 1940s, tonnage estimates of the US coal deposits were derived from estimates calculated by gross statistical methods. They did not discriminate thin from thick coal beds, separate shallow from deeply buried coal, or differentiate the quality of coal based on physical and chemical criteria. After World War II, there was a need for a more detailed coal classification system including the occurrence, distribution, and availability of national coal resources. Therefore programs for assessing the national coal resources on a State-by-State and a bed-by-bed basis were launched (Wood et al., 1983). In 1972, Vincent E. McKelvey, at that time USGS director, adapted and extended an old and long-used way to classify mineral reserves by the U.S. Bureau of Mines, including all of the undiscovered deposits that might be out there (McKelvey, 1972). In 1976 his work was adopted with minor changes for joint use by the U.S. Bureau of Mines and U.S. Geological Survey (Wood et al., 1983).

In the petroleum industry international efforts to standardize the definitions and estimation methods started in the 1930s. Based on work done by the Society of Petroleum Evaluation Engineers (SPEE), the Society of Petroleum Engineers (SPE) released definitions for all Reserves categories in 1987. In the same year, the World Petroleum Council (WPC) published independently definitions that were quite similar. In 1997, the two organizations jointly published a single set of definitions for Reserves for global use (Petroleum Reserves Definitions, 1997). In 2000, the American Association of Petroleum Geologists (AAPG), SPE, and WPC jointly released a classification system for all petroleum resources (PRMS). National codes by NPD-2001 (Norway) or PRO-2005 (China) were developed based on these international guidelines (Corcoran, 2007).

Unlike the top-down development in the petroleum industry, in the mineral resource sector over time various parallel mineral resources classification systems have been developed at national level (Weber, 2013). By now, almost all major mining nations as well as economies that heavily depend on mineral resource imports have developed their own national classification code. However, as the mining industry has become more and more of a global business, starting from the 1990s on, there have been increased efforts to harmonize those codes in order to create transparency and comparability in the reporting of primary raw materials (UNECE, 2010, CRIRSCO, 2013).

The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) was set up by the Council of Mining and Metallurgical Institutes (CMMI) in 1994. After the

CMMI disbanded in 2002, CRIRSCO has become a partner organization of, and is partly funded by the International Council on Mining and Metal (ICM). Agreeing on the definitions of the two major categories, ‘resources’ and ‘reserves’, and their respective sub-categories (measured, indicated, inferred mineral, proved and probable), the CRIRSCO family currently includes the following national codes and standard: JORC (Australasia), NI43-101 & CIM Definition Standards (Canada), SAMREC (South Africa), PERC (Europe), SME (United States), Comisión Minera de Chile (Chile), NAEN (Russia) as well as several other candidate member countries (CRIRSCO, 2013).

5.1.2 Striving for Harmonization: United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009)

In 1992, after the collapse of the Soviet Union the German Government proposed a new classification system to the UNECE Working Party on Coal to compare the vast resources in the previously centrally planned economies to those in the market economies (UNECE, 2013). Therefore the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) has been initiated by the UN Economic Commission for Europe under a global mandate from the UN Economic and Social Council. In order to facilitate comprehensive worldwide application, in 2009 a revised and simpler version of the classification system was prepared, known as UNFC-2009.

UNFC is a generic project and principle based system, in which quantities are classified on the basis of the three fundamental criteria of “socioeconomic viability” (E1 – E3), “field project status and technical feasibility” (F1 – F4), and “geological knowledge” (G1 – G4), with E1F1G1 being the best category. These criteria are each subdivided into categories and sub-categories, which are then combined in the form of classes or sub-classes, creating a three-dimensional system by using a numerical coding scheme (UNECE, 2010) (cf. Figure 2).

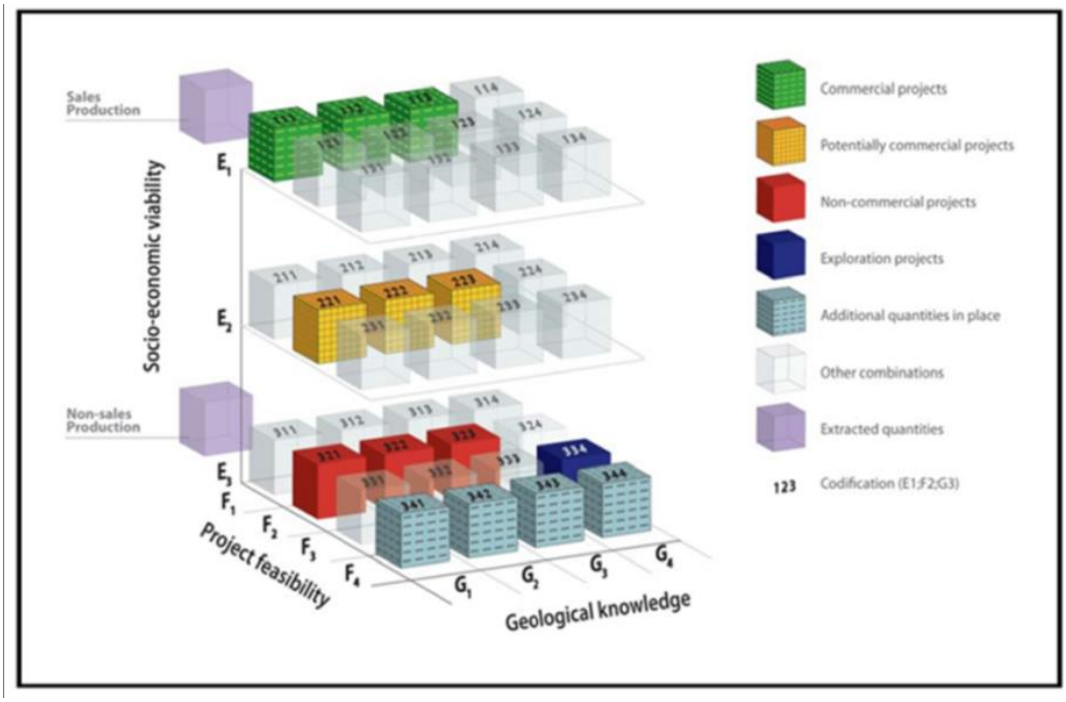

Figure 2: United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009). Reproduced courtesy of the United Nations Economic Commission for Europe.

In 1999 an agreement between UNECE and CMMI CRIRSCO was made in order to harmonize terms that had previously often been used incoherently. The CRIRSCO template provides the commodity-specific specifications for solid minerals under UNFC-2009, defining mineral resources as “concentration of naturally occurring materials in or on the Earth's crust with reasonable prospects for eventual economic extraction, either currently or at some point in the future” (CRIRSCO, 2013). Mineral reserves are defined as resources that are known to be economically feasible for extraction under present conditions. Modifying factors (legal, market, economic, technological etc.) determine the constantly moving boundaries between resources and reserves (CRIRSCO, 2013). As a result of the alignment and mapping work that has been done so far, since 2011, quantities reported under the two-dimensional CRIRSCO template can also be reported under UNFC-2009 with its numerical codes (cf. Figure 3). UNFC-2009 can either be applied directly or used as a harmonizing tool (UNECE, 2010).

The CRIRSCO template was primarily created to ensure consistent standards of public reporting in an international setting, for mining companies, financial institutions, stock exchange regulators and shareholders. It excludes the categories “undiscovered”, “unrecoverable” and “uneconomic”, which may be relevant for other purposes, e.g. information on national resource inventories (CRIRSCO, 2013, Henley, 2011).

Governments, for instance, have to be able to understand and report their full resource base, especially for long-term planning purposes, for instance to plan the search of new mineral deposits and to anticipate mineral supply. UNFC-2009 fulfils both governmental as well as to a certain extent corporate stakeholders' requirements (cf. Figure 3).

<table>
<tr><td></td><td></td><td colspan="5">UNFC -2009</td><td colspan="2">CRIRSCO Template</td></tr>
<tr><td rowspan="11">Total commodity initially in place</td><td rowspan="2">Recovered</td><td rowspan="2">Extracted
(Past Production)</td><td colspan="2">Sales Production</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2" colspan="2">Extracted</td></tr>
<tr><td colspan="2">Non-sales Production</td></tr>
<tr><td></td><td></td><td colspan="2">Class</td><td>E</td><td>F</td><td>G</td><td colspan="2"></td></tr>
<tr><td rowspan="8">Known deposits</td><td rowspan="2">Future recovery by commercial develop-ment projects or mining operations</td><td colspan="2" rowspan="2">Commercial Projects</td><td rowspan="2">1</td><td rowspan="2">1</td><td>1</td><td rowspan="2">Mineral Reserves</td><td>Proved</td></tr>
<tr><td>2</td><td>Probable</td></tr>
<tr><td rowspan="3">Potential future recovery by contingent development projects or mining operations</td><td colspan="2" rowspan="3">Potentially Commercial Projects</td><td rowspan="3">2</td><td rowspan="3">2</td><td>1</td><td rowspan="3">Mineral Resources</td><td>Measured</td></tr>
<tr><td>2</td><td>Indicated</td></tr>
<tr><td>3</td><td>Inferred</td></tr>
<tr><td colspan="2" rowspan="3">Non-Commercial Projects</td><td rowspan="3">3</td><td rowspan="3">2</td><td>1</td><td colspan="2" rowspan="3">Not reported
Discovered not economic</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td colspan="4" rowspan="3">Additional quantities in place associated with known deposits</td><td rowspan="3">3</td><td rowspan="3">4</td><td>1</td><td colspan="2" rowspan="3">Not reported
Discovered unrecoverable</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td rowspan="3">Potential deposits</td><td colspan="2">Potential future recovery by successful exploration activities</td><td colspan="2">Exploration Projects</td><td>3</td><td>3</td><td>4</td><td colspan="2">Exploration Results</td></tr>
<tr><td colspan="4" rowspan="2">Additional quantities in place associated with potential deposits</td><td rowspan="2">3</td><td rowspan="2">4</td><td rowspan="2">4</td><td colspan="2" rowspan="2">Not reported
Undiscovered unrecoverable</td></tr>
<tr></tr>
</table>

Figure 3: Comparison of UNFC-2009 and CRISCO Template: UNFC-2009 provides broader coverage of the full resource base than the CRIRSCO Template by including non-commercial projects and additional quantities in place. Based on UNECE (2013).

UNFC-2009 serves for classification means only, meaning that it does not provide detailed evaluation guidelines for assessing a commodity or a mining project. For instance, it does not prescribe standardized methods and techniques on how to account for modifying factors or on how to report a mine's by-products (Weber, 2013). The actual evaluation for the purpose of public reporting is done at an earlier stage, often by a team of experts around a "competent person". According to the CRIRSCO family codes, those evaluators must possess an appropriate level of expertise and relevant experience in the estimation of quantities associated with the type of deposit under evaluation. Also, they must be a member

of a recognized professional organization with a code of ethics and disciplinary procedures (CRIRSCO, 2013). However, none of the existing codes forbids estimates from the mining companies' own competent persons. Internal evaluation procedures differ from one company to another and rely heavily on the personal experience of the respective competent person, resulting in a substantial lack of transparency and objectivity (e.g. Sinclair and Blackwell, 2002, Falcone et al., 2013).

Although UNFC-2009 had been originally designed to address specific primary mineral resource deposits and fossil fuels, this framework has proven to be quite flexible and to be subject to regular negotiations and re-definitions in response to stakeholder needs and changes in society and technology. As a major mining nation China has been actively participating in designing UNFC from 1999 on (UNECE, 2015). China is about to create a similar national classification system for mineral resources and reserves, requiring all new project classifications to be conform with this new system (UNECE, 2015). The Petroleum Resources Management System (PRMS) was officially aligned with UNFC-2009 in 2011 and the Red Book on Uranium in 2014 (cf. Figure 1). This means that quantities can be estimated either in the "aligned systems or directly under UNFC (UNECE, 2010).

Recently, efforts have been made to integrate renewable energies into UNFC-2009 in order to compare renewable energy resources with non-renewable resources (Falcone et al., 2013, UNECE, 2014). The UNECE Renewable Resources Working Group, an industry-led initiative had called for the application of UNFC-2009 as a template to develop an industry-wide classification system. In 2013, the UNECE Expert Group on Resource Classification reached consensus on this question and approved one year later the draft document entitled "Specifications for the Application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to Renewable Energy Resources" at its fifth session for issue for public comment (UNECE 2014). Another potential future application of UNFC-2009 concerns the oil extraction industry, seeking to integrate the classification of CO_2 storage capacities under UNFC-2009. This is particularly interesting as in that case not only financial effects of CO_2 storage for enhanced petroleum recovery are considered, but also environmental externalities of not emitting CO_2 into the atmosphere (Ask, 2014). The endeavour of creating precise specifications and guidelines to fit anthropogenic resources into UNFC-2009 has been encouraged at the sixth session of the UNECE Expert Group on Resource Classification (UNECE, 2015, Winterstetter et al., 2015b). At the seventh session the Expert Group recommended "that, […] a small sub-group be established to explore the potential applicability of UNFC-2009 to anthropogenic resources and to report its findings to the eight session" (UNECE, 2016, Winterstetter, 2016).

5.1.3 General Procedure & Information Required for the Classification of Geogenic Resources

Before actual mining activities can start, three important steps of resource classification have to be run through, namely prospection, exploration and valuation. The prospection phase involves locating potential deposits, representing the physical search for minerals. The goal is to provide a basic understanding of an ore deposit's formation and the abundance of minerals, i.e. on grade, size, type of mineral, host rock, continuity of mineralization. To increase the knowledge on the geologic environments of a territory, geologists make use of various direct and indirect methods, in order to find specific deposits, which are associated with the wanted type of minerals, e.g. analysing geological reports, surface maps, aerial photography and satellite images, as well as geophysical measurements and geochemical analysis (Hartman and Mutmansky, 2002).

After a deposit has been located, the exploration phase follows, being a more intensive and detailed form of mineral prospection. The exploration aims at identifying ores for mining, i.e. commercially viable concentrations of minerals. Frequently, similar techniques as used in the previous phase are applied again, but more refined than in prospecting. Additionally, methods like sample drilling and excavation and metallurgical testing help, to deepen the knowledge on the deposit's share of extractable and potentially usable materials, i.e. to identify the deposit's tonnage and grade of minerals, which is considered to be minable (Hartman and Mutmansky, 2002).

Being one out of two basic indicators typically used in resource classification frameworks, the geological knowledge of the ore deposit is expressed as the level of certainty, which also reflects the stage of how far prospection and exploration studies have progressed. For example, the geological knowledge and so the certainty of size and grade of a deposit already exploited is certainly greater than that for a prospected deposit, where only maps and aerial photographs exist.

Based on the data gained in the previous two steps and considering the potential mining technology available, in the evaluation phase an economic feasibility analysis is performed, to determine the present worth of the deposit. Hereby, methods such as analysing the project's Internal Rate of Return and / or the Net Present Value are used. Modifying factors such as legal, environmental, sociopolitical, marketing, transportation and technological factors are considered (Hartman and Mutmansky, 2002). The economic viability of exploitation serves as second indicator to classify a deposit. Being the only three-dimensional system, under UNFC-2009, the project feasibility is displayed on a separate third axis (F-axis), as explained in the previous chapter.

Concluding the evaluation stage allows for a decision, whether the project shall be developed

for exploitation, delayed, studied further or abandoned. In case of a positive decision to continue, a feasibility report has to be prepared, including a list of aspects, which might have an impact on the project's success. The following list of topics has to be covered in public reports according to the Canadian National Instrument 43-101 (Canadian Securities Administrators, 2001) and is recurrent in most national reporting codes of the CRIRSCO family.

Table 2: List of topics to be covered in public reporting according to the Canadian National Instrument 43-101.

CONTENTS OF THE TECHNICAL REPORT
Title Page
Date and Signature Page
Table of Contents
Illustrations
Item 1: Summary Item 2: Introduction Item 3: Reliance on Other Experts Item 4: Property Description and Location Item 5: Accessibility, Climate, Local Resources, Infrastructure and Physiography Item 6: History Item 7: Geological Setting and Mineralization Item 8: Deposit Types Item 9: Exploration Item 10: Drilling Item 11: Sample Preparation, Analyses and Security Item 12: Data Verification Item 13: Mineral Processing and Metallurgical Testing Item 14: Mineral Resource Estimates Item 15: Mineral Reserve Estimates Item 16: Mining Methods Item 17: Recovery Methods Item 18: Project Infrastructure Item 19: Market Studies and Contracts Item 20: Environmental Studies, Permitting and Social or Community Impact Item 21: Capital and Operating Costs Item 22: Economic Analysis Item 23: Adjacent Properties Item 24: Other Relevant Data and Information Item 25: Interpretation and Conclusions Item 26: Recommendations Item 27: References

Candidate mining projects that are expected not to be profitable at the moment of method application may be so at a later moment. New and more recent information can be integrated easily in this reporting form, allowing for an iterative evaluation process, taking changing market / legal / technical situations into account, e.g. wait until technologies become mature or more cost-effective, commodity prices rise, changes in legislation occur etc. (CRIRSCO, 2013).

This checklist serves as a guideline for those preparing reports on mineral exploration results,

resources and reserves to use as a reference, without, however, being prescriptive. According to the CRIRSCO template, transparency, relevance and materiality are overriding principles, which determine, what information should be publicly reported. There are some competence requirements regarding the person in charge of compiling such reports, called "competent person" ("qualified person" in Canada). The CIRSCO Template specifies: "A Public Report must be based on work that is the responsibility of suitably qualified and experienced persons who are subject to an enforceable professional code of ethics and rules of conduct." (CRIRSCO, 2013).

Usually, there is a number of experts from different disciplines involved in the evaluation and reporting process. However, the exact methods and techniques applied during the evaluation process are not prescribed (CRIRSCO, 2013). It is, however, important to report any matters that might materially affect a reader's understanding or interpretation of the results or estimates being reported. This is particularly important where inadequate or uncertain data affect the reliability of, or confidence in, a statement of exploration results or an estimate of mineral resources and/or reserves.

5.2 Previous Research Related to the Classification of Anthropogenic Stock Resources

A number of concrete attempts to evaluate and classify anthropogenic resource deposits has been made in the past. Various authors have studied the recycling of different waste streams (e.g. packaging waste or e-waste) embedded within specific settings, for instance, the impact of Extended Producer Responsibility schemes or people's source separation behaviour on the (socio)economics of recycling, or at least on the resultant collection rates (e.g. Ongondo et al., 2011, Ferreira et al., 2014, da Cruz et al., 2014, Zoeteman et al., 2010, Widmer et al., 2005, Schluep, 2009, Baldé et al., 2015, Huisman et al., 2008). However, none of these studies has attempted to evaluate and classify recovered materials from specific waste streams in a comparative manner, and by applying existing resource classification systems. Therefore, the scope of this section's literature review is narrowed down by predominantly focusing on anthropogenic stock resources.

A number of studies is dedicated to segment and typologize anthropogenic deposits according to common properties, in order to account for their heterogeneous nature. Studies using Material Flow or Substance Flow Analysis to demonstrate the metabolism of materials used in society usually distinguish between 'stocks' and 'flows', such as Lifset et al. (2002), Gordon et al. (2004) or Wang et al. (2007). Stocks are accumulated over time by inflows and/or depleted by outflows, with the residence time being the main difference between

stocks and flows (Baccini and Brunner, 2012). Stocks can be further divided into stocks that are in-use vs. out of use, e.g. connected vs. disconnected cables. UNEP (2010) groups metals stocks according to their location, distinguishing between in-use stocks, stocks in unmined ores, stocks in tailings, stocks in process facilities, government stocks, stocks in manufacturing facilities, stocks in recycling facilities, and landfill stockpiles. Also Johansson et al. (2013) identify six different types of anthropogenic stocks, discriminating between in-use stocks, landfills, tailing ponds, slag heaps, hibernating stocks, and dissipated metal resources. Further criteria used by Johansson et al. (2013) to classify anthropogenic stocks include the current state of utilization (active vs. inactive), their spatial location (urban, rural or fringe), and the degree of human control (controlled vs. uncontrolled). Kapur and Graedel (2006) contrast in their typology of stocks 'employed stocks' (i.e. taken from nature for human use and not yet discarded) with 'expended stocks', i.e. the amount of materials that - after use – "has been discarded or that has been lost from the technosphere by corrosion or wear during use" (Kapur and Graedel, 2006). 'Employed stocks' comprise in-use stocks and hibernating stocks, the latter being the "amount of a resource that has previously been consumed for a technological purpose, is not now being used, and has not yet been discarded" (Kapur and Graedel, 2006). The expended stock includes deposited stock (i.e. landfills, mining containment ponds), and dissipated stock, i.e. "the amount of resources that has been used in the technosphere, but has then been returned to nature in a form that makes recovery difficult or impossible" (Kapur and Graedel, 2006). In terms of metal containing waste flows, they distinguish between seven flow streams, namely municipal solid waste, construction and demolition debris, hazardous waste, industrial waste, end-of-life vehicles, waste from electric and electronic equipment, and sewage and sewage sludge.

Hashimoto et al. (2007) refer to discrepancies between amounts of construction wastes estimated in studies and the statistical quantities reported as 'missing stock' or 'dissipated stock', presuming that considerable amounts of materials do not emerge as wastes.

Further, Graedel (2011) groups anthropogenic metal stocks according to their occurring forms, which differ significantly for different metals and considerably influence their recyclability. For each application the metal is used for, it is assessed, whether the metal is recoverable in pure form (e.g. lead from batteries), multicomponent alloys (difficult to recover), complex assemblages as tantalum capacitors in electronics (difficult to recover), or dissipative forms, e.g. in paint (not recoverable). Concerning the availability for mining Graedel (2011) discriminates between 'abandoned stocks', 'comatose stocks', and 'hibernating stocks'. Abandoned stocks are materials used in a way making it difficult, costly, and sometimes even impossible to recover them (e.g., port revetments, skyscraper pilings).

Recovering materials from comatose stocks is theoretically possible, but very unlikely, as locating and retrieving them is often difficult, and in addition frequently uneconomic. Hibernating stock is defined as “material now asleep”, which means that it is currently not fulfilling any useful function, but might someday wake up, such as old cell phones in a drawer.

Looking at infrastructure systems taken out of use in Sweden, Wallsten et al. (2013b) subdivide hibernating stocks into ‘infrastructure coma’, ‘paralysis’, and ‘dormant cells’. In case of infrastructure coma an infrastructure system is entirely taken out of use due to, for instance, competition from new systems, pressure on prices or decreased demand. Paralysis, i.e. the disconnection of zones of infrastructure, is often related to larger city building projects due to city growth, densification and urban renewal. Dormant cells of infrastructure, i.e. the disconnection of parts of infrastructure, often occur in relation to maintenance and repair. They occur in cases of ordinary breakdowns, failure, bad performance and age, when - instead of repairing - the maintenance contractor replaces a broken part with a new one.

All the above mentioned approaches are useful to understand the nature of anthropogenic resources and their deposits, by categorizing them in a systematic way. However, they do not provide sufficient information on what stocks and flows are worth to be examined in greater detail for potential mining.

There is a number of studies investigating isolated (pilot) projects, to judge, whether materials from a specific anthropogenic deposit can potentially be recovered, without however going beyond the respective single case study. Taking the example of landfill mining, being the most referenced concept for mining anthropogenic stocks, most studies look only at the material composition (e.g. Dickinson, 1995, Kaartinen et al., 2013, Quaghebeur et al., 2012, Hogland et al., 2004), while a detailed socioeconomic analysis of a specific mining project is only included in some of the more recent publications (e.g. Hermann et al., 2016, Breitenstein et al., 2016, Danthurebandara et al., 2015, Frändegård et al., 2015).

Comparative works can be divided in studies that 1) contrast different anthropogenic deposits as sources for a specifically sought material (e.g. Cu recovered from power grid vs. Cu from PC recycling, or Al recovered from two different buildings or from infrastructure in different cities), and studies that 2) compare different settings and conditions, which might impact the final evaluation outcome of mining one specific anthropogenic deposit (e.g. onsite vs. offsite sorting for a landfill mining project). Some studies, following such a comparative

approach, take the evaluation results even one step further, by making concrete attempts to map anthropogenic resources (or related recovery projects) into existing classification frameworks.

Being highly relevant for strategic resource planning, several studies compare different types of anthropogenic material deposits with the aim to prioritize - under specific aspects and constraints - potential projects to extract a specifically sought resource. Krook et al. (2011), for instance, quantified and compared the total in-use and hibernating stock of copper present in the local power grids in two Swedish cities. In Gothenburg, the obsolete share of total copper in the grid amounts to almost 20%, while in Linköping the obsolete share of the total accumulated stock is not higher than 5%. Moreover, two different extraction methods / project set-ups of cable recovery from Linköping's power grid were compared. They conclude that recovery of hibernating cables combined with other maintenance work could be beneficial, whereas separate recovery of obsolete cables is not economically viable under current conditions.

Wallsten et al. (2013a) examined five major types of infrastructure for potential recovery of copper, aluminium and iron, namely the cable and pipes networks for AC and DC power, telecommunication, town gas and district heating in the city of Norrköping, Sweden. Using a GIS-based approach to locate hibernating stocks and MFA to quantify them, the aim was to increase the degree of certainty of knowledge about the potentially recoverable resources, without, however, considering the economics of potential extraction. They found that about 20% of the total stock of aluminium and copper in these systems are in hibernation, and that cables have been disconnected to a larger extent than pipes. Greater stocks of hibernating copper and aluminium can be found in the city's central parts, while iron is rather located in the outer parts.

Lederer et al. (2014) explore the mining potential of different anthropogenic phosphorus (P) stocks in Austria. Based on a very basic economic analysis, they conclude that only 10 % of the total anthropogenic P stock of 1 million tons can be labelled as "subeconomic" according to the classification concept of McKelvey, i.e. is worth to be studied further, whereas the rest is classified as "other occurrences" (low-grade or not extractable). The sources of interest to potentially recover P are municipal sewage sludge landfills, MSW bottom ash landfill and mixed ash landfill. To optimize P recovery in the future they also suggest measures for changing current waste management practice, such as preventing mixing P-rich materials with low-grade materials during landfilling.

Resource classification systems generally include at least the two dimensions of “geological knowledge” and “economic viability” (cf. Chapter 5.1.3). Fellner et al. (2015) investigate the economic viability to recover zinc (Zn) from different solid residues of waste incineration, as well as the degree of knowledge on Zn quantities to be recovered. Based on the McKelvey concept, none of the Zn resources can be economically extracted under current conditions. Filter ashes generated at grate incinerators equipped with wet air pollution control are identified as sources with the highest economic potential.

Mueller et al. (2015) show the potential applicability of the UNFC-2009 classification framework to different types of wastes containing rare earth elements. In accordance with the framework’s G-axis, the confidence level of rare earth elements contained in various anthropogenic deposits in Switzerland is determined. NdFeBe-magnets and fibre optic cables can be labelled as potential deposits for Nd (category G3) and Erbium, respectively (G4). The fluorescent lamps containing Europium are classified as a well-known deposit of category G1 similar to a geogenic deposit.

The second type of comparative studies looks at different conditions and settings, when mining one specific anthropogenic deposit, such as location, extraction technology, stakeholder perspective, supply shortage, and how they impact the final outcome.

Wallsten et al. (2015) use a GIS-based approach to locate and quantify hibernating copper stocks in Linköping’s power grids, followed by an assessment of the economic conditions for their recovery. Besides comparing the two extraction approaches “separate recovery of hibernating cables” vs. “integrated recovery during other maintenance work”, they examine how the economics for cable recovery depend on the stock’s location. The majority of hibernating copper is found in the old, central parts of the city and industrial areas. In terms of economics, integrating cable recovery as an added value to ordinary maintenance operations would make extraction feasible for 2% of the total identified stock.

Prospecting the anthropogenic resources potential present in Vienna's subway network, Lederer et al. (2016) found that 3% of the built-in materials (mainly copper, aluminium, and gravel) will have to be renewed within the next 100 years, and can therefore be seen as potentially extractable resources. The majority of the built-in materials is, however, not extractable (mainly concrete, iron, steel, and bricks), as those materials are part of permanent structures and lines that have been declared as cultural heritage monuments.

Focusing on in-use stocks, Klinglmair and Fellner (2010) investigate the supply management of copper in Austria during World War I, a period with increased demand for copper (for ammunition) and critical shortage. In spite of severe measures, such as confiscation, only 1.7

kilograms of copper per capita could be recovered by the end of the war, corresponding to approximately 10% of the total anthropogenic stock. In a similar study on iron, they found that up to 25% of total demand (which increased by 40 % during the war compared to peace times) was covered by scrap, compared to 15 % in peacetime. This increase was due to newly established authorities and regulations to guarantee sufficient metal supplies to the military and the industry (Klinglmair and Fellner, 2011).

Investigating copper stocks present in subsurface infrastructure, Krook et al. (2015) assess how current conditions influence the economic and environmental benefits of cable recovery from power grids. Evaluating 16 scenarios involving different extraction technologies and techniques, surface materials, urban locations and types of cables, they found that cable extraction is more expensive in city centres with asphalt or cobblestone pavements than in greenbelts. Additionally, cable revenues are not even close to cover extraction costs. Integrating cable recovery as an added value to regular system upgrade projects or by applying non-digging technologies would improve economic performance. They conclude that the arguments for urban mining are currently more of environmental than of financial nature, e.g. for net savings in GHG emissions due to metal recycling.

Breitenstein et al. (2016) compare the economics of six alternative technology combinations and processes, potentially used for one landfill mining project. They range from rather simple approaches, where most of the material is incinerated or landfilled again, to the application of sophisticated technologies, allowing for recovery of various material fractions, such as metals, plastics, glass, recycling sand, and gravel. While none of the scenarios is economic at the moment, they identified land prices and gate fees for incineration as key factors to potentially change in the future and make LFM viable. To incorporate ecological externalities in the evaluation, they plead for governmental subsidies.

The resource classification framework UNFC-2009 has been adapted and applied to two landfill mining projects, respectively by Winterstetter et al. (2015a) and Krüse (2015). For the two landfills investigated, i.e. the Remo landfill in Belgium and the Hechingen landfill in Germany, different technological and project set-up options for the excavated combustible waste fraction were compared (gas-plasma vs. incineration and on-site vs. off-site incineration), to find out, how the project's economic performance is affected. Also different stakeholder perspectives, namely private investor vs. public entity, were compared. All scenarios were finally mapped within the three dimensions of UNFC-2009, i.e. "knowledge on composition and extractable material content", "technical and project feasibility" and "socioeconomic viability".

6. RESULTS: INTEGRATION OF ANTHROPOGENIC RESOURCES INTO UNFC-2009

This chapter answers the Research Questions 2 and 3. After describing general characteristics of anthropogenic resource deposits, this chapter presents an operative evaluation procedure, including indicators, methods and criteria, to systematically classify different types of anthropogenic resource deposits. Finally, the UNFC-2009 categories are adapted to anthropogenic resources and decision guidelines are proposed.

As shown in the previous chapters, the common feature of both early and contemporary resource classification systems is managing raw materials. For this purpose involved stakeholders, such as governments or investors, must be provided with an operative tool to compare and prioritize potential resource extraction projects.

6.1 ANTHROPOGENIC VS. GEOGENIC RESOURCES

Evaluating anthropogenic resources requires a somewhat different approach compared to geogenic deposits (cf. Figure 4).

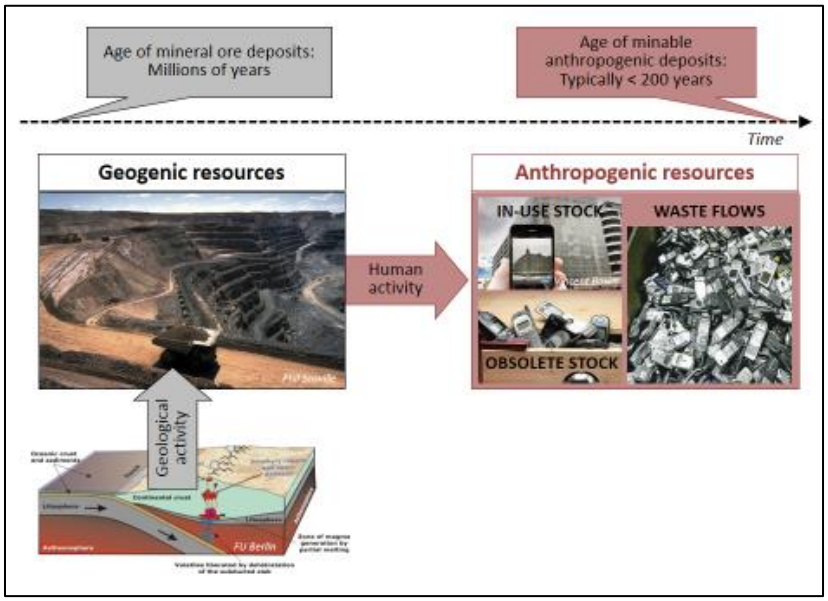

Figure 4: Geogenic vs. anthropogenic material deposits.

Factors, which directly or indirectly influence the classification process, differ or have at least different priorities and implications. There are seven key aspects to be considered when mining anthropogenic material stocks and flows:

1. Human influence on deposit formation: Production, consumption and disposal embedded in a specific system (e.g. laws)
2. Diverse and scattered sources of anthropogenic materials (e.g. E-waste vs. old landfill)

3. Many diverse recoverable secondary products within one anthropogenic mining project (e.g. new land, metals, energy)
4. Time of genesis shorter
5. High uncertainties (legal and technological framework, quality of the materials)
6. Anticipating future obsolete stocks and waste flows by investigating in-use stocks
7. Often positive externalities (e.g. removing source of pollution, greenhouse gas emission savings)

Of utmost importance is the human influence (1) on the creation of anthropogenic deposits, whereas the genesis of geogenic resource deposits and also renewable primary energies entirely depends on natural conditions and processes (cf. Figure 4). The formation of anthropogenic material deposits depends on various aspects related to production, consumption and disposal occurring in a system, which is defined by the cultural, socioeconomic, political and legal context, resulting in very diverse and scattered sources of anthropogenic materials (2). Manufacturers determine the design of products that have to be disposed of later on, e.g. obsolete personal computers. On the one hand they are subject to the influence of consumers and their buying patterns, and on the other hand they are regulated via laws and policies on, for instance, integrated waste management, eco-design or design for recycling (e.g. Oswald, 2013, McCann and Wittmann, 2015). Consumers do not only put pressure on producers through their buying behaviour, but do also play a key role when it comes to waste disposal. For instance, their awareness about source separation of wastes, or their timing of discard decisions potentially increases (or deceases) the quantity, quality and grade of minable materials, which is obviously not possible for a natural ore deposit. In this context also profit-seeking recyclers play a central role, being subject on the one hand to laws and policies and on the other hand to commodity markets. Compared to internationally operating mining companies in the primary sector, these recycling companies are usually much smaller, and lack therefore political power and influence.

It is inherent to human cultures that they are constantly developing. Therefore parameter values and system conditions are not static, but likely to change over time. Old landfills, for instance, are witnesses of changing production, consumption and disposal behaviours as well as changing waste management laws and policies over a certain period of time (Gäth and Nispel, 2012, Bockreis and Knapp, 2011, Hölzle, 2010). Technological changes on both the production and the disposal side are amongst the most powerful forces. On the one hand they influence the demand and prices for certain raw materials (e.g. rare earth elements in renewable energies) and on the other hand they potentially improve technical feasibility of recycling due to decreasing costs.

In the primary sector each mine has commonly only few main products and some by-products, such as selenium in copper mines, which, however, are usually not reported (Winterstetter et al., 2015b). In an anthropogenic mine, there are many diverse fractions to be potentially recovered and sold within one project. Within a landfill mining project, for instance, usually a soil-like fraction is recovered, together with ferrous and non-ferrous metals and a combustible fraction. Also the regained land sale or newly gained landfill capacity together with avoided costs for the landfill's aftercare contributes to the revenues. Revenues for selling all those raw materials and secondary products have to be evaluated as one single project, while markets for each fraction might be very different (3).

While geogenic resources have built up over geologic periods of time, i.e. millions of years, the genesis of anthropogenic stocks occurs over shorter time spans (4) and is subject to various transforming dynamics, such as changing waste legislation, implying high uncertainties (5) for the planning of mining activities. Uncertainties also stem from a potentially changing legal environment or technological developments and sometimes from concerns over qualities of the recovered materials (e.g. fines from landfill mining). While extraction technologies for geogenic resources tend to be well established, the utilization of new technology or existing technology to new materials is associated with high uncertainties for anthropogenic resources (e.g. Bosmans et al., 2012). For some end-of-life materials, such as rare earth elements in permanent magnets, extraction or processing technologies are not available at all or have only been tested at laboratory scale (e.g. Angerer et al., 2009, Schüler et al., 2011).

While mining companies are mainly interested in the commercially recoverable share of the resources, i.e. the reserves, many anthropogenic material deposits are currently likely to be classified as "potentially commercial" ('resource'). The distinction for anthropogenic resources between non-resources and resources is relevant to support decisions on specific treatments or storage for potential future extraction (6), provided that there are reasonable prospects for future economic extraction. Information on the future mining potential of in-use materials can be useful to manufacturers to increase their products' recyclability and thereby improve future resource availability.

Unlike geogenic resources, anthropogenic deposits often must be assessed not only under aspects of resource recovery, but also in view of alternative waste treatment and disposal costs, and including non-monetary externalities (7). Fellner et al. (2015), for instance, highlight, that the economic performance of Zinc recovery from incineration residues is driven by avoided waste treatment and disposal costs, rather than by the revenues from raw material valorisation. Furthermore, in the mining industry non-monetary effects are mainly

considered in order to show potential threats to the economic performance of a project in form of looming additional costs, for instance, due to uncertainties concerning new environmental regulations, regulatory inconsistencies, native land claims and protected areas, infrastructure, socioeconomic agreements, political stability, labour issues and security (McMahon and Cervantes, 2011). For anthropogenic deposits, in contrast, those non-monetary effects tend to generate additional benefits and should therefore be monetized and included in the evaluation, for instance the value of eliminating sources of pollution or saved greenhouse gas emissions (e.g. Hermann et al., 2014; Hogland et al., 2010; Frändegård et al. 2015; Van Passel et al., 2013).

6.2 Operative Evaluation Procedure

The heterogeneous nature of mining specific materials from various different and often decentralized anthropogenic sources requires thorough understanding of the influencing factors. Factors that influence the classification of anthropogenic resources (in the following called ‘influencing factors’) can be divided into A) preconditions, B) system variables and C) modifying factors. They play different roles during the single phases of resource classification, being displayed on the three axes of UNFC-2009 (cf. Table 3).

Table 3: Classification of mining an anthropogenic material deposit under UNFC-2009 (based on Winterstetter et al., 2016b)

Phases & UNFC-2009 axes	**Goal**	**Influencing factors**	**Methods for decision foundation**
1. Pre-Prospection	**Selection of a deposit to be mined**	**A) Preconditions** **a) Availability status** • **In-use stock:** Currently not available for mining, but at some point in the future • **Obsolete stock:** Potentially available for mining, sometimes even required • **Waste flows:** Treatment often required **b) Mining / handling condition** • **Pull:** Deposit can be mined • **Push:** Materials must be extracted from the deposit due to system constraints	Analysis & evaluation of reports / data bases on anthropogenic deposits: Macro Scale MFA, GIS mapping
2. Prospection ***G-Axis***	**Knowledge on the deposit's resource potential**	**B) System Variables*** **a) Type & Location** **b) Volume** **c) Composition**	Detailed investigation of the deposit (e.g. log books, sampling, analysis)
3. Exploration ***G-Axis*** ***F-Axis***	**Knowledge on the deposit's share of extractable & potentially usable materials** **Technical feasibility & Project status: Identify options for technologies & project set-ups**	**d) Legal, institutional, organizational & societal structures** **e) Different options for methods, technologies & project set-ups for extraction & processing with specific efficiencies & maturity** **f) Project status**	Micro scale MFA with specific recovery efficiencies Technology assessment, policy framework analysis, stakeholder analysis
4. Evaluation ***E-Axis***	**Socioeconomic viability of extraction & utilization**	**C) Modifying factors**** **a) Prices for secondary products** **b) Costs** **c) Avoided costs** **d) Indirect financial effects** **e) Monetized external effects**	DCF analysis & cut-off values for key parameters Net Present Values (NPV) a) NPV > 0: Reserve b) NPV < 0: Resource or not?
5. Classification	**Combination of all criteria & classification under UNFC-2009**		

* Determine the physical amount of potentially extractable materials

** Direct impact on the project's economics, but not within the domain of a single stakeholder

In the pre-prospection phase, the deposit's status of availability for mining, discriminating between "in-use stocks", "obsolete stocks" and "waste flows", as well as the specific handling and mining condition (push vs. pull) represent exclusion criteria for potential mining activities. These preconditions define the setting for the following classification (cf. Table 3).

System variables play a major role in the prospection and exploration phase, being displayed on the G- and F-axis respectively under UNFC-2009. They determine the amount of potentially extractable and usable materials and provide the basis for the following evaluation phase (cf. Table 3). To account for different (possible) sets of system variables, scenario analysis can be used, e.g. to investigate different project set-ups. However, throughout a specific evaluation process, the system variables are exogenously given.

During the actual socioeconomic evaluation the 'modifying factors' (CRIRSCO, 2013) are investigated, being reflected on the E-axis under UNFC-2009. They have a direct impact on the project's socioeconomic viability and can hardly be influenced by individual stakeholders, but may change over time (cf. Table 3).

- **Pre-Prospection**

The goal of the pre-prospection phase is to select a specific mining project by screening existing data bases and reports on diverse anthropogenic deposits. To obtain a rough overview of relevant anthropogenic stocks and flows, the method of Material Flow Analysis (MFA) can be used, for instance, to visualize national E-waste flows. MFA is a systematic quantification of the flows and stocks of materials within a defined system (in space and time), connecting the sources, the pathways and the sinks of a material (Brunner and Rechberger, 2004). Also Geographic Information Systems (GIS) mapping can be helpful to localize resource deposits, as used, for instance, by Tanikawa and Hashimoto (2009) or Wallsten et al. (2015).

In this phase the preconditions for mining are investigated, i.e. the deposit's status of availability for mining, and the specific handling and mining condition, defining the setting for the following classification. Anthropogenic resources can be structured according to their status of availability, namely along the lines of obsolete stocks (potentially available for mining) and waste flows (treatment required in most cases). They both originate from in-use stocks of anthropogenic resources, which are currently by definition not available for mining.

Two types of situations, i.e. specific conditions for handling and mining, may arise, namely push vs. pull, each changing the focus and goal of the following phases of exploration, evaluation and final classification (cf. Table 3). In a pull situation, materials are mined only if

the evaluation of the project's socioeconomic viability is positive and otherwise left untouched, similar to mining geogenic resources. Therefore the main focus is on the modifying factors, even though system variables are examined in a first step to determine the amount of extractable materials. In a push situation a "yes-or-no"-mining decision cannot be made, as the anthropogenic materials have to be treated / managed in any case due to legal requirements, like in the case of E-waste flows. This may include mining, i.e. material recovery, in order to reduce the project's costs. It basically means that in the following exploration phase the socioeconomically optimal alternative is sought via scenario analysis within the given legal constraints.

Evaluating the economics of hypothetically mining the current in-use stock can be useful for producers to increase their products' recyclability, to forecast future obsolete stocks and flows and to avoid dissipation and dilution losses (Simoni et al., 2015) and what Tanikawa et al. (2014) call 'lost material stocks' after disasters, such as earthquakes. If laws do not exist yet, like in the case of obsolete wind turbines or solar panels, the evaluation outcome will tell decision makers, whether a legal framework for treatment is necessary (push) or not, in case of positive economics (pull).

- **Prospection**

During the prospection phase (displayed on the G-axis), mainly information on a specific resource deposit's type, location, volume and composition shall be gained, allowing first estimates on the resource potential (cf. Table 3).

- **Exploration**

In the exploration phase (reflected on the G- and F-axis), the knowledge on the deposit's resource potential has to be deepened (cf. Table 3). To identify the potentially extractable and usable share of materials as a function of different technology alternatives and project set-up options, the effect of changing system variables on the final outcome can be investigated. Different sets of system variables are considered via alternative scenarios, e.g. different technology assumptions in terms of material recovery efficiencies.

Based on the respective project's data (e.g. on a landfill's logbook), MFA models of all relevant material flows - and if applicable also energy flows - can be set up for each scenario.

Data on the state-of the art material efficiencies of the relevant processes define that part of the resource potential, which is under current technological conditions extractable and potentially usable. Using MFA further allows to model different project set-ups as well as different options for extraction methods and sorting and processing technologies along with their specific recovery efficiencies.

- **Evaluation**

In the actual evaluation step, the socioeconomic viability of extracting and utilizing the identified extractable raw materials is explored and displayed on the E-axis (cf. Table 3). Within a Discounted Cash Flow (DCF) analysis, the project's Net Present Value (NPV) is computed by subtracting the investment cost from the sum of discounted cash flows over a certain period of time. This method is also widely used for the evaluation for mining projects of geogenic resources (Torries, 1998).

Taking into account the choices (e.g. technological) made in the previous phases along with their implications, the main focus of the evaluation phase is on the modifying factors. Having a direct impact on the project's socioeconomic viability, they can potentially move the classification status of a given material deposit along the E-axis of UNFC-2009 from "non-commercial" to "potentially commercial" (resource) to "commercial" (reserve).

A positive NPV implies that a project is economically viable. Consequently, the evaluated materials can be classified as 'reserve'. If the NPV turns out to be negative, however, one has to judge, whether there are reasonable prospects for economic extraction in the foreseeable future. Whether the deposit can be labelled a 'resource' or not, can be decided by anticipating realistic changes of key parameters, by calculating the so-called "cut-off values", i.e. required changes in prices or costs to reach the break-even point (NPV = 0) (cf. Winterstetter et al., 2015a).

In the mining industry modifying factors "include, but are not restricted to mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors" (CRIRSCO, 2013). Modifying factors comprise costs linked to the use of a specific technology or the choice of a specific mining method (e.g. open pit vs. underground mine), commodity prices or certain laws having an immediate impact on the economics (e.g. laws regarding environmental protection or workers' rights).

This looks similar for anthropogenic resources. Here, modifying factors comprise prices for secondary products (e.g. recovered metals or energy), investment and operating costs, costs for external treatment and disposal of residues, avoided costs (e.g. for a landfill's aftercare) indirect financial effects and monetized external effects. As stated in Chapter 2.3., mining anthropogenic deposits tends to generate additional positive externalities, such as preventing groundwater pollution or saving greenhouse gas emissions. Depending on the evaluator's perspective and interests, non-monetary effects might be considered and monetized, for instance, via a hypothetical carbon tax (Winterstetter et al., 2015a). Also indirect financial effects might be considered, such as the annual land tax a municipality receives in the years after landfill mining after selling the land (Hölzle, 2010).

In pull situations, where a deposit can (but does not have to) be mined, legislation and policy can strongly influence the evaluation outcome, for instance by creating financial government incentives or by imposing costly licensing procedures. In push situations, where material extraction from the deposit takes place in any case, alternative costs for disposal and treatment, which can be avoided due to mining and recovery activities, can have a major impact on the project's economics.

- **Classification under UNFC-2009**

Finally, all of the aforementioned criteria are combined and used as a basis for the classification under UNFC-2009 (cf. Figure 2), as shown in the following section.

6.3 UNFC-2009 Categories Adapted to Anthropogenic Resources

The G-axis (G1 - G4) displays the knowledge on composition and extractable material content of an anthropogenic deposit. The socioeconomic viability of a resource recovery project is reflected on the E-axis (E1 - E3). While obsolete stocks and waste flows can potentially be classified within the entire range of existing UNFC-2009 categories (E1 - E3, F1 - F3, G1 - G4), in-use stocks fall into lower classes on the F-axis, displaying a project's technical feasibility and project status. They are currently not available for mining, but will become waste flows or obsolete stocks in the foreseeable future and are therefore classified as F4 (UNECE, 2013). Table 4 shows the definitions of categories under UNFC-2009 (UNECE, 2013), slightly modified and adapted to anthropogenic resources.

Table 4: Definitions of categories according to UNFC-2009 adapted to anthropogenic resources

	Obsolete Stocks	Waste Flows	In-Use Stocks
E1	Project yields positive NPV		
E2	Project yields negative NPV, but due to future expected changes in key modifying factors (KMF), cut-off values might be reached		
E3	Project yields negative NPV or evaluation is at too early stage to determine economic viability		
F1	Feasibility of extraction by a defined development project or mining operation has been confirmed • Existing legal framework • Existing societal, institutional & organizational structure Mature technologies applied • Project status: Ongoing activities		-
F2	Feasibility of extraction by a defined development project or mining operation is subject to further evaluation, at least one of the F1 criteria is not fulfilled		-
F3	• Feasibility of extraction by a defined development project or mining operation cannot be evaluated due to limited technical data. • Extraction, processing & valorization technologies exist & are planned to be applied, but the project is not sufficiently advanced to determine the quantity & quality of potentially recoverable material, F1 criteria are widely not fulfilled		-
F4	In situ (in-place) quantities that will not be extracted by any currently defined development project or mining operation. • F1 criteria are not fulfilled, also not (yet) existing technologies • F4.1 – F4.3 describe the current state of technological development: ○ F4.1: Technology under development, but no type-specific applications (yet) ○ F4.2: Technology is researched, but pilot studies are not yet available ○ F4.3: Technology for recovery is not currently under research or development		
G1	The stock's / flow's volume, composition & the applied technologies' recovery efficiencies can be estimated with a high level of confidence to assess the share of potentially extractable & usable materials* Alternative: P90 => Low estimate**		
G2	The stock's / flow's volume, composition & the applied technologies' recovery efficiencies can be estimated with a medium level of confidence to assess the share of potentially extractable & usable materials* Alternative: P50 => G1+G2 = Best estimate**		
G3	The stock's / flow's volume, composition & the applied technologies' recovery efficiencies can be estimated with a low level of confidence to assess the share of potentially extractable & usable materials* Alternative: P10 => G1+G2+G3 = High estimate**		
G4	Quantities estimated during the exploration phase, subject to a substantial range of uncertainty & major risk that no mining operation will be implemented to extract these quantities		

* Incremental, ** Cumulative

- **G-Axis**

For the G-Axis, displaying the knowledge on composition and extractable material content of an anthropogenic deposit, the two main indicators are 1) data on volume and composition and 2) on recovery efficiencies of applied technologies and methods for extraction and valorisation. Categories on the G-axis (G1 - G4) may be applied in cumulative form to express low (G1), best (G1+G2) and high estimates (G1+G2+G3), as commonly used for recoverable fluids. Discrete classification (incremental method) is typically used for solid minerals, reflecting the level of geological knowledge and confidence associated with a specific deposit (high, medium, low level of confidence) (UNECE, 2010). For anthropogenic resources, both options might be applicable, but in the following case studies, incremental will be favoured over cumulative classification.

- **F-Axis**

The technical feasibility and project status of a mining project, as shown on the F-Axis, is indicated by 1) the maturity of applied techniques for extraction and valorisation and by 2) the legal, institutional, organizational and societal structures as well as by 3) the specific project status. In a push situation, such as treating obsolete PCs in the European Union, laws define minimum standards for treatment and collection and can be considered as prescribing system variables.

It is evident, that a sharp distinction between the single UNFC-2009 axes, and especially between the G- and the F-axis is not always clear-cut, for instance, the collection system of e-waste has an influence on the waste flow's volume and composition, but also on the project feasibility. Factors, such as the involvement of the informal sector or general source separation behaviour, are strongly dependent on the legal, institutional, organizational and societal structures, in which a project is embedded, being reflected on the F-axis. Therefore, G- and F- categories are often interdependent, particularly for waste flows.

For in-use stocks to be mined in the future, the main question is, whether extraction and valorisation technologies do currently exist or not and how the general framework will look like. It can potentially become a push or a pull situation and is generally scored with F4 to indicate its current unavailability for mining, comparable to in-situ quantities in the mining industry (UNECE, 2013). The sub-categories F4.1 – F4.3 describe the current state of technological development. A clear distinction between the individual categories on the F-axis is often difficult and dependent on the evaluator's subjective assessment, as they cannot or only hardly be quantified.

- **E-Axis**

The socioeconomic viability of a mining project (E-Axis) is expressed by one main indicator, namely by a positive NPV, considering investment and operating costs, costs for external treatment and disposal, prices for secondary products, avoided costs, indirect financial effects and monetized external effects. In case of a negative NPV, it shall be investigated whether there are reasonable prospects to become economically viable in the foreseeable future.

However, the distinction between the categories “expected to become economically viable in the foreseeable future (E2)” and “not expected to become economically viable (E3)” is based on specific assumptions, which can be considered as realistic by some experts, while others might have a completely different view. Each of the four investigated case studies has project specific key modifying factors, which have to be considered for calculating the cut-off values, i.e. how they have to change to reach a neutral NPV.

Moreover, there are also uncertainties originating from the chosen evaluation scenarios and the related assumptions. As under UNFC-2009 only defined projects can be evaluated and classified, arbitrary system boundaries will have to be chosen, e.g. on a spatial and / or temporal level, which is obviously easier for a confined landfill mining project than for a continuous flow of obsolete PCs or the in-use wind turbines. Projects of mining obsolete stocks, such as an old landfill, are comparatively easy to plan ahead. Therefore, depending on the project’s size, project durations can be assumed to be similar to the mining industry. In contrast, waste flows, such as obsolete PCs, underlie more complex dynamics and fluctuations, making it seem unsound to set such projects’ temporal system boundaries at longer than ten years. The same is true for in-use stocks: Since there are typically high uncertainties on the in-use materials’ future availability for mining, on the stock’s size and composition, on the technical feasibility of recovery as well as the future legal framework, the planning horizon of such projects should be kept rather short, unless reliable information and data are available. Hypothetical mining is assumed to occur under current technical and economic conditions, in order to check whether this stock may represent a future resource or not.

To investigate a project’s socioeconomic viability the systematic integration of non-monetary effects will be of high priority, as for many anthropogenic materials extraction is not (yet) economically viable under current conditions. Social and environmental externalities (e.g. eliminating sources of pollution) tend to generate additional benefits and should therefore be monetized and included in the evaluation. Combining aspects of waste and resource management is hereby a key challenge. However, what non-monetary effects to finally

include in the evaluation will depend also on the specific perspective of the stakeholder interested in performing a certain mining project (private vs. public).

6.4 DECISION GUIDELINES

As described in the previous Chapters 6.2 and 6.3, Figures 5 and 6 show the decision path for evaluating and classifying an anthropogenic resources deposit. First, the deposit's status of availability for mining is checked, distinguishing between "in-use stocks", "obsolete stocks" and "waste flows", as well as the specific handling and mining condition (push vs. pull), which often depends on type and location of the deposit. These preconditions for potential mining activities define the setting for the following classification. In a pull situation the decision, whether to mine or not to mine, is based on a positive NPV, depending also on the involved actors' perspective. In a push situation the deposit will be mined, treated or remediated anyway. In that case the socioeconomically optimal alternative within the given constraints has to be determined. Next, information on the deposit's volume and composition shall be gained, in order to deepen the knowledge on the deposit's resource potential. The potentially extractable and usable share of materials is identified as a function of different technology alternatives and project set-up options with their specific recovery efficiencies. In case of waste flows this share also depends on the legal, institutional, organizational and societal structures influencing, for instance, source separation and collection rates. Depending on whether the level of confidence is high, medium, low or whether knowledge on the minable content is practically not existing the deposit is graded with G1 to G4. The feasibility of extraction by a defined development project or mining operation is indicated by an existing and well-enforced legal framework and societal, institutional and organizational structures, by fully mature technologies applied and ongoing activities (F1). One or several of those criteria being unfulfilled results in the lower categories F2 – F4. In-use stocks are by default graded with F4 in order to indicate that they are currently not available for mining. The subclasses F4.1 – F4.3 can be used to express the maturity of technologies.

In a last step, the socioeconomic viability of extracting and utilizing the identified extractable raw materials is evaluated. Modifying factors with direct impact on the project's economics are investigated, i.e. prices for secondary products, investment and operating costs, costs for external treatment and disposal, avoided costs as well as possibly monetized externalities and indirect financial effects. Often they depend on the legal, institutional, organizational and societal structures, in which a project is embedded (e.g. labour costs, source separation behaviour, laws and requirements for alternative disposal options etc.). In pull situations, where a deposit can (but does not have to) be mined, legislation and policy can strongly influence the evaluation outcome, for instance by creating financial government incentives or

by imposing costly licensing procedures. In push situations, where material extraction from the deposit takes place in any case, alternative costs for disposal and treatment (e.g. high landfill gate fees), which can be avoided or at least reduced due to mining and recovery activities, can have a major impact on the project's economics.

The investment and operating costs, and to a certain extent the costs for external treatment and disposal, depend upon the choices made regarding project set-up (e.g. offsite vs. onsite sorting) and the technologies and methods used for material recovery (e.g. manual vs. mechanical PC dismantling).

Positive NPVs result automatically in E1. In case of a negative NPV, cut-of values for key parameters decide, whether there are reasonable prospects for future economic extraction (E2) or not (E3).

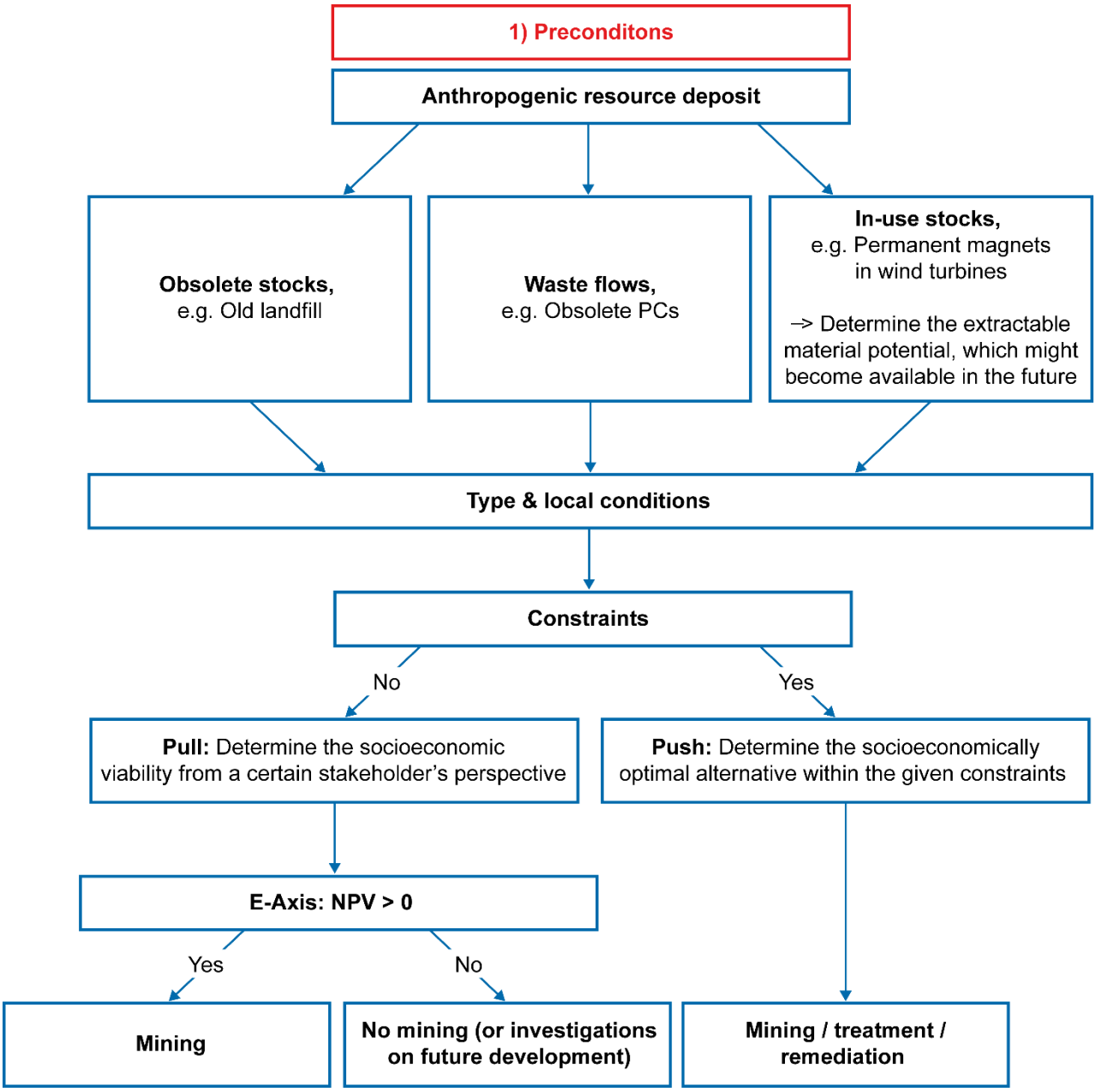

Figure 5: The preconditions define the setting for the following classification.

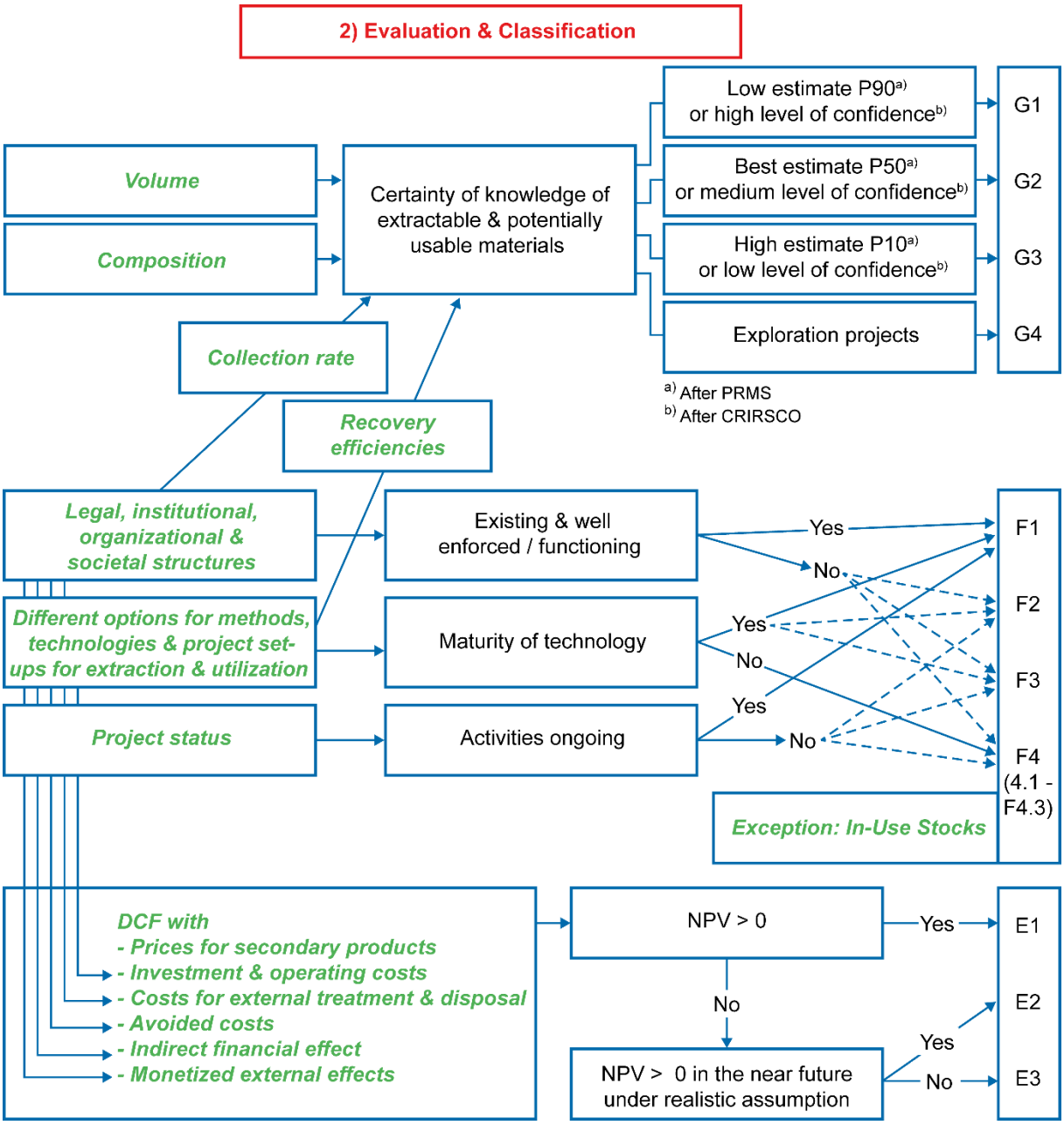

Figure 6: System variables and modifying factors to be considered during the classification process.

7. RESOURCE CLASSIFICATION OF DIFFERENT TYPES OF ANTHROPOGENIC RESOURCES (CASE STUDIES)

This chapter deals with the third Research Question in a more concrete way, by showing, how various types of anthropogenic deposits can be classified under UNFC-2009.

In order to account for their heterogeneous nature, anthropogenic resource deposits can be segmented according to their different statuses of availability for mining (in-use vs. out-of use) and residence time (stocks vs. flows) (cf. Figure 7).

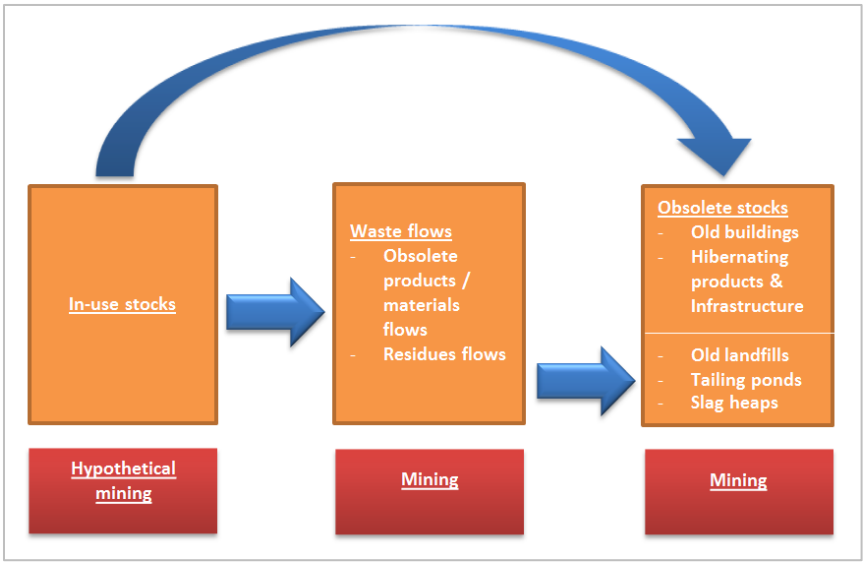

Figure 7: Different types of anthropogenic deposits

The term “obsolete stocks” comprises old buildings, hibernating products and infrastructure, tailing ponds, old landfills and slag heaps, similar to Johansson et al. (2013). However, unlike Johansson et al. (2013), this thesis neglects dissipated stocks, such as lead dissipation from in-use stock or loss after discard (Lohm et al., 1994). The hypothetical in-use mining is listed separately, as in-use stocks represent the source of both waste flows and obsolete stocks. Some goods and materials first turn into waste flows before ending up in obsolete stocks. For instance, products / materials flows might end up in landfills, refinery residues in tailing ponds or smelter residues in slag heaps. Other in-use stocks switch from “in-use” to “obsolete stocks” in direct transition, such as disconnected underground cables being an example for hibernating infrastructure (Krook et al., 2011) or old cellphones in drawers (Ongondo et al., 2015). Old buildings are listed separately. Usually there is a limited time span for recovering resources, before the building is torn down and turns into demolition waste flows, unless it is left abandoned (hibernation). Frequently, materials are recovered from waste flows after demolishing a building (Kleemann et al., 2014).

In addition, the mining of waste flows is included, consisting of a) obsolete products / materials flows (e.g. e-waste, packaging waste) and b) residues flows (e.g. incineration fly ash, slags from smelters).

To illustrate different settings of anthropogenic resource classification, the extraction and utilization of anthropogenic materials from an old landfill (obsolete stock) is contrasted to recovering materials from obsolete personal computers (PCs) (waste flow), and from permanent magnets of wind turbines (in-use stock). These specific case studies were selected to examine different conditions for mining and handling (push vs. pull).

Old landfills come closest to a conventional mine, as they are finite just like geogenic resources and can potentially be recovered as they are out of use. A landfill mining project is usually confined, with resources being depleted over time. In this case the landfill mining project is a pull situation, as remediation is not required. Thus, the economic results will decide, whether to mine or not to mine. However, if the landfill turns out to be an immanent pollution threat to the environment, e.g. to groundwater, the former landfill operator will be obliged to act, which means that the situation in that case is comparable to mining a waste flow, which has to be treated due to legal constraints and where alternative disposal costs play a more prominent role (push situation).

Waste flows, in contrast, resemble more to renewable energies, as they are in many cases infinitely replenished, unless the corresponding in-use stocks and products / materials drastically change or are phased out (Dalrymple et al., 2007). The project's system boundaries have to be drawn artificially. The PC-recycling case was chosen as a push situation, to see how resource classification can be done for a flow, which is mainly regulated under waste management aspects. The management of e-waste flows in the European Union is mainly regulated and driven by laws, in particular by the European WEEE directive 2002/96/EC and 2012/19/EU, determining the annual collection, reuse and recycling targets. The directive, which is implemented in different ways at national levels of the EU member states, also specifies minimum treatment requirements for e-waste providing for the removal of specific components containing hazardous substances. Under the Extended Producer Responsibility (EPR) producers are obliged to finance the take back of WEEE classified in ten categories from consumers and ensure their safe disposal (Zoeteman et al., 2010, Directive (EC), 2003, Directive (EC), 2012). Thus, here the question is not whether to mine / treat or not, but rather on how to fulfil legal requirements in a socioeconomically optimal way.

Information on the current status and size of in-use stocks is highly relevant with regard to future minable waste flows and obsolete stocks. In 2008, rare earth permanent magnets accounted for 21% of total rare earth elements (REE) use in terms of volume and 37% in terms of value (Kingsnorth, 2010), with wind turbines being one of the most important drivers

for the NdFeB permanent magnet demand (Schüler et al., 2011). Depending on whether there will be future constraints, such as laws and policies, and how the general framework will look like, mining REE materials or entire magnets can potentially become a push or a pull situation.

Another criterion for selecting the case studies was to show different levels of economic viability, anticipating better results for PC recycling than for landfill mining. Further, different influencing factors were given special attention to in each case study. In case of the permanent magnets contained in wind turbines, the focus was on technical feasibility and project maturity. As treating obsolete PCs in the EU is regulated by the WEEE directive the focus is on different settings of the legal, institutional, organizational and societal structure. This affects the extractable and potentially usable materials via collection and source separation rates and the involvement of the informal sector. For mining an old landfill in a pull situation the main focus is on modifying factors, which directly impact the economic results. Also the timing of mining is taken into account as key economic drivers are expected to change over time.

7.1 WASTE FLOW: END-OF-LIFE PERSONAL COMPUTERS

Under UNFC-2009 only defined projects can be evaluated and classified (UNECE, 2010). Therefore, for a constantly renewing waste flow, such as obsolete PCs, system boundaries must be arbitrarily chosen. In this case study, two different scenarios of handling obsolete PCs are evaluated for a European city of 1 million inhabitants (cf. Table 5).

Table 5: Mining of materials from end-of-life PCs for two different scenarios: System variables and modifying factors.

Obsolete PCs	**Scenario 1**	**Scenario 2**
Main Goal	Determine the economic performance within a given legal, institutional, organizational & societal structures	
System variables *Availability status* *Type & Location* *Specific mining /handling condition*	• Waste flow • PCs with similar composition & weight • European city with 1 million inhabitants • PCs have to be treated under EU directive (push situation)	
Volume & Composition *Different options for dismantling with specific efficiencies*	WEEE collection in 2012: 9.6 kg(cap/a) (Austria) Separate collection of obsolete PCs: 0.8 kg(cap/a) => 800 t PCs/a Mechanical treatment & further manual dismantling	WEEE collection in 2012: 1.2 kg(cap/a) (Romania) Separate collection of obsolete PCs: 0.1 kg(cap/a) => 100 t PCs/a Manual dismantling
Legal, institutional, organizational & societal structures	High-income EU member state Full compliance with EU laws: High public awareness, good infrastructure	Low-income EU member state Weak compliance with EU laws: Low public awareness, weak infrastructure
Modifying factors *Investment & operating costs*	• Costs for sorting, transport & dismantling (CAPEX & OPEX)	
Prices for secondary products *Costs for external treatment & disposal* *Avoided costs*	• Prices for metals (Fe, Al, Cu), cables, fine fraction, adaptors, (granulated) printed circuits, contacts, brass, processors • Disposal of capacitors • Avoided disposal costs of PCs	• Prices for metals (Fe, Al), printed circuits, (hard) drives, adaptors, contacts, processors

The main focus lies on the WEEE EU directive and its enforcement, as well as on the population's waste collection and source separation behaviour, which affects the waste flow's volume, as well as on the technical options for dismantling obsolete PCs. Scenario 1 reflects the situation of treating obsolete computers in a city of a high-income EU member state,

where the EU directive 2002/96/EC is fully implemented in national law and strictly enforced. The average amount of WEEE collected in 2012 in Austria (taken as pars pro toto high-income EU member state) accounted for 9.6 kg(cap/a) (Eurostat, 2015). In 2012, a share of 8 % out of the total collected WEEE in Austria is assumed to be obsolete PCs, yielding 0.8 kg/(cap/a) separately collected PCs (based on ReUse-Computer e.V., 2013, same share assumed in both cities). Thus, for a city of 1 million inhabitants an annual PC waste flow of 800 t can be calculated. Regarding processing, Scenario 1 represents a hybrid scenario of mechanical processing and manual disassembly (Salhofer and Spitzbart, 2009).

In Scenario 2 obsolete PCs are collected and treated in a city of a low-income EU member state, where the EU directive is implemented, but weakly enforced. In 2012 in Romania (representative low-income EU member state) the average amount of WEEE collected accounted for 1.2 kg/(cap/a) (Eurostat, 2015). Annually, 0.1 kg of waste PCs are separately collected per person. Thus, for a city of 1 million inhabitants the annual PC waste flow amounts to 100 t. In this scenario the obsolete PCs are manually dismantled in a single step, meeting only the basic requirements under the EU directive. Economically interesting materials are recovered, while a considerable share of residues is dumped.

The waste flow in a city of a high-income EU country is assumed to be composed of PCs, which are discarded after an average period of five years. In a city of a low-income EU country, such as Romania, according to Ciocoiu et al. (2010), PCs are used longer than recommended by the manufacturer, which is due to the weaker economic situation. However, neither the composition nor the weight of individual PCs has changed significantly since the 2000s, as shown in the study by Nagai (2011) (cf. Table 6). Discounted costs and revenues are considered for one year with investment costs being depreciated over ten years (cf. case study on landfill mining).

Table 6: Composition of an old desktop PC without monitor dating from 2006, in weight % (based onSalhofer and Spitzbart, 2009).

	Average content (% of total weight) of materials in a PC produced after the year 2000
Iron / Steel	70 %
Aluminum	5 %
Copper	1 %
Printed circuits /Contacts	10 %
Plastics	9 %
Other	5 %

- **Prospection & Exploration**

Table 7 shows the potentially recoverable and usable quantities of materials from obsolete PCs collected in a city of 1 million inhabitants in a high-income EU country with an annual collection rate of 800 tons PCs and advanced mechanical-manual dismantling (Scenario 1), compared to a low-income EU city with an annual collection rate of 100 tons PCs (due to weak enforcement of existing laws) and only one manual dismantling step (Scenario 2).

Table 7: Potentially recoverable and usable material quantities from obsolete PCs in a high-income EU city (Scenario 1) and a low-income EU city (Scenario 2) within one year (own calculations based on Salhofer and Spitzbart (2009)).

Output flows*	Unit	Scenario 1 (800 t PCs collected/ a)	Scenario 2 (100 t PCs collected/ a)
Ferrous metal	[t]	579	59
Non-ferrous metals		25	1.4
Printed circuits		54	7
Hard drives, disk drives, drives, adaptors			22
Adaptors, printed circuits		23	
Cables		27	
Contacts		2.2	0.5
Brass		1.3	
Processors		0.3	0.2
Fine fraction		6	
Capacitors to be disposed of		4	
Other fractions to be disposed of (plastics, residues...)		78	10

*Impurities are included cf. SI, Table 2 and 3.

- **Evaluation**

Discounting the project's cash flows over one year with a discount rate of 3 %, both scenarios treating obsolete PCs yield positive net present values, with Scenario 1 resulting in 96,000 € and Scenario 2 in 36,000 € (cf. Figure 8).

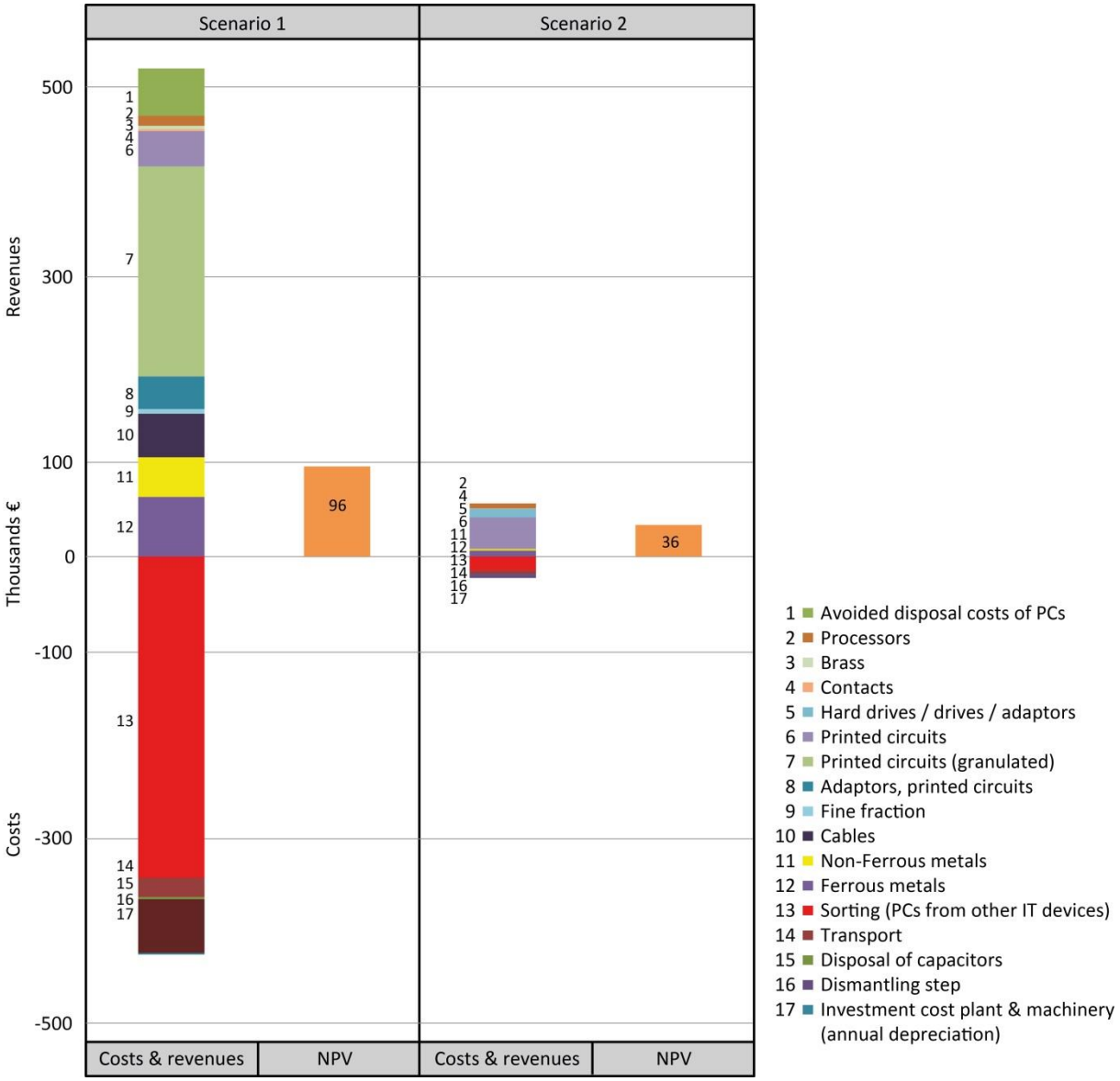

Figure 8: Costs and revenues for Scenario 1 and Scenario 2, i.e. for 800 t and 100 t collected PCs to be treated annually, discounted over 1 year with a discount rate of 3 %

This corresponds to 120 € NPV per ton of collected PCs for Scenario 1 and 360 € NPV per ton of collected PCs for Scenario 2, which is due to the higher costs in Scenario 1, namely 530 € compared to 230 € per ton of collected PCs in Scenario 2. Discounted revenues in contrast are not that different, namely 650 € (Scenario 1) and 585 € per ton of collected PCs (Scenario 2).

For both scenarios the main drivers on the revenue side are recovered printed circuits (50 % in Scenario 1, and 60 % in Scenario 2). In Scenario 1 (high-income EU city) costs for sorting PCs from other IT devices is the biggest share of total costs (81 %) due to assumed labour costs of 17 € per hour, while in Scenario 2 (low.income EU city) labour costs of 6 € per hour

are assumed, amounting to 66 % of total costs. Compared to Scenario 2, a higher number of fractions for potential sale is generated in Scenario 1, due to several dismantling steps, resulting in slightly higher revenues, while requiring a higher number of working hours (7.4 hours vs. 6 hours). On the revenues side of Scenario 2 no avoided disposal costs are assumed (representing 10 % in Scenario 1). The alternative would be dumping, as in this case also other European laws, such as the landfill directive, are assumed to be weakly enforced.

- **Classification**

In terms of "knowledge on the obsolete PCs waste flow's composition and its extractable material content", Scenario 1 is graded with G1, as the flow's volume and composition of obsolete PCs can be estimated with a high level of confidence and the applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the extractable raw material potential. Scenario 2 obtains G2, as the flow's volume and composition can be estimated only with a medium level of confidence due to the informal collection and recycling activities, implying high uncertainties about the collection rate.

Regarding "field project status and technical feasibility" (F-axis), well-known techniques for dismantling and treatment are applied in both scenarios. In Scenario 1 the institutional and organizational infrastructure for collecting WEEE and financing take back systems via EPR schemes in line with the EU WEEE directive is already established. While Scenario 1 is therefore graded with F1, Scenario 2 is classified as potentially feasible (F2). Despite existing EU and national laws, their enforcement is weak. The WEEE collection infrastructure is poor and people and local governments have not yet realized the importance of source separation and recycling electrical and electronic equipment. Also, potentially existing laws on the disposal of (hazardous) wastes are poorly enforced, and due to the informal recycling activities there are high uncertainties on PC collection.

In terms of economic viability, both scenarios are graded with E1 due to positive NPVs. Thus, the overall classification for Scenario 1 is E1F1G1 and E1F2G2 for Scenario2.

7.2 In-Use Stock: NdFeB Permanent Magnets in Wind Turbines

In this case study two different options for a future utilization of end-of-life permanent magnets in wind turbines, which are currently in use, are investigated, namely the re-use of permanent magnets (Scenario 1) and the recovery of Neodymium (Nd), Ferrum (Fe), Boron (B), Dysprosium (Dy) and Praseodymium (Pr) via hydrometallurgical methods (Scenario 2).

A report by Gattringer (2012) provides detailed information and data regarding the in-use stock of recoverable materials in wind turbines in Austria. Based on an installed capacity of

214 MW in 2011, Gattringer (2012) assumed increasing new annual installations, resulting in 277 MW installed wind power at the end of 2014 in form of wind turbines containing NdFeB permanent magnets. Calculating with 0.6 kg NdFeB per installed kW (Hatch, 2008, Wuppertal Institut, 2014) the overall resource potential of in-use wind turbines in Austria in 2014 amounts to 166 t NdFeB materials. Magnet scrap consists typically of 24 % of Nd (Prakash et al., 2014), representing twice the concentration of natural ore deposits (Bleiwas and Gambogi, 2013). The Dy share amounts to approximately 4 %, Pr up to 5 % and Fe varies between 62 and 69 %, while the B content is usually around 1 % (Prakash et al., 2014).

Regarding the project's technical feasibility, two sets of system variables are evaluated in two different scenarios (cf. Table 6).

Table 8: Potential future mining of materials from permanent magnets in wind turbines for two different scenarios: System variables and modifying factors

NdFeB permanent magnets in wind turbines	**Scenario 1**	**Scenario 2**
Main Goal	Determine the extractable material potential, which might become available in the future	
System variables *Availability status* *Type & Location* *Specific mining / handling condition* *Volume & Composition*	• In-use stock • NdFeB permanent magnets in wind turbines in Austria • Hypothetically mined within one year under current conditions (push or pull situation, depending on whether there will be future constraints, such as laws and policies) • Estimates based on data on production and installation of wind turbines and their capacity in Austria	
Different recycling options with specific efficiencies	• Re-use of permanent magnets	• Hydrometallurgical method (Lyman and Palmer, 1992) to extract Nd,Fe,B, Dy & Pr
Legal, institutional, organizational & societal structures	• No legal framework existing. It is very likely that a wind park operator replaces the permanent magnet in case of a defect.	
Modifying factors *Investment & operating costs* *Prices for secondary products*	• Costs of separating magnets out of wind turbines & demagnetization • Price of used permanent magnets	• Costs of separating magnets out of wind turbines & demagnetization • REE extraction from magnet (CAPEX & OPEX of separation plant) • Prices of REE and metals

In Scenario 1, NdFeB permanent magnets are re-used in their current form and shape. Separating the permanent magnets from the wind turbines' nacelles as well as demagnetizing and then re-magnetizing them represent hereby the key steps (Binnemans et al., 2013).

In Scenario 2, a hydrometallurgical method was selected to separate rare earth elements (REE) from the magnet scrap. When mining REE from primary ores this is the most common chemical extraction method to first produce concentrates, which are then leached with

aqueous nitric, sulphuric or hydrochloric acids. Given the variety of different hydrometallurgical methods, for this case study the aqueous process developed by Lyman and Palmer (1992) was chosen. After leaching and entirely dissolving the magnetic scrap in an aqueous H_2SO_4 solution, a salt of an alkali element or ammonium is added to the solution of dissolved rare earth elements, iron and boron in order to selectively precipitate and finally separate an insoluble double sulphate salt of the rare earth element and the alkali element or ammonium from the solution (Lyman and Palmer, 1992).

As under UNFC-2009 only defined projects can be classified (UNECE, 2010), system boundaries must be chosen in order to evaluate in-use stocks that are currently not available for mining. Similar to mining materials from obsolete PCs this can be done on a geographical and temporal level. Due to high uncertainties and for simplicity reasons, NdFeB permanent magnets from wind turbines in Austria are assumed to be mined under current conditions within one year.

For the hypothetical recovery of materials from in-use wind turbines in Austria, treatment costs (OPEX) are based on the market prices of acids, which are required to extract REE from permanent magnets as tested in own laboratory scale experiences. Further, it is assumed that the REE separation plant is newly built, even though treating the relatively small amounts of materials from future obsolete Austrian wind turbines would not justify the construction of a new plant. Estimated investment costs are downscaled from facilities used for the separation of REE from primary ores (Sykes, 2013). Investment costs of the mobile unit are depreciated over ten years (cf. case study on landfill mining). Costs of separating permanent magnets from wind turbines and demagnetizing them are almost negligible (Stiesdal, 2015).

- **Prospection & Exploration**

Table 9 shows the potentially recoverable and usable quantities of materials from NdFeB permanent magnets in wind turbines, which are currently in use, for the total installed capacity of 277 MW in 2014 in Austria. In Scenario 1, the magnets are directly re-used, while in Scenario 2 Nd, Fe, B, Dy and Pr are extracted via hydrometallurgical methods.

Table 9: Potentially recoverable and usable quantities of materials from wind turbines in Austria (own calculations).

	Unit	Scenario 1 (re-use)	Scenario 2 (hydrometallurgy)
Nd	[t]		39
Fe			98
B			1.6
Dy			6.5
Pr			3.2
Used NeFeB permanent magnets		166	

- **Evaluation**

166 t of materials are assumed to be extracted and treated from future obsolete wind turbines in Austria. Discounting the project's cash flows over one year with a discount rate of 3 %, both scenarios clearly yield positive NPVs, with Scenario 1 (re-use) resulting in 6.2 million €, and Scenario 2 (hydrometallurgy) in 5.3 million € (cf. Figure 9).

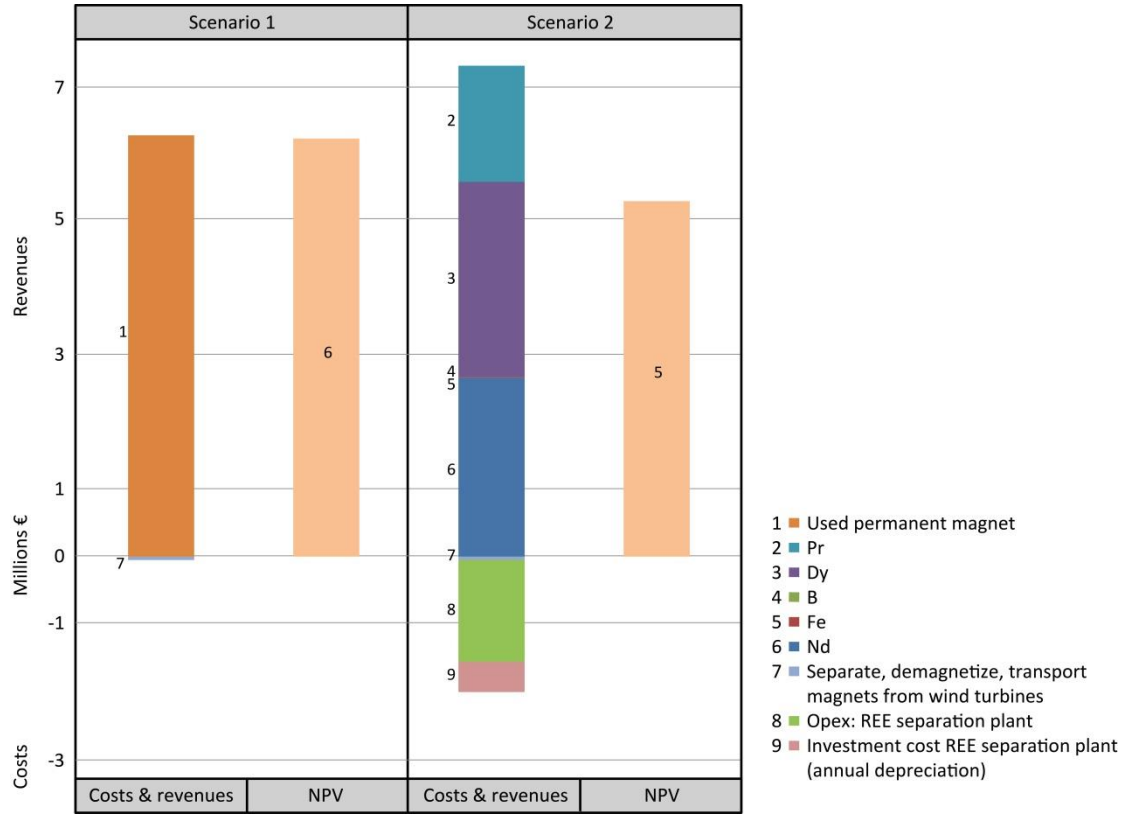

Figure 9: Costs and revenues for Scenario 1 (re-use) and Scenario 2 (hydrometallurgy) for 166 t of materials to be extracted and treated all in one year, discounted over 1 year with a discount rate of 3 %.

This corresponds to about 37,500 € per ton of magnetic scrap in Scenario 1, and 31,800 € per ton in Scenario 2.

Economic drivers on the revenue side of the re-use Scenario 1 are obviously the prices of permanent magnets (40 €/kg, Stiesdal (2014)), and in Scenario 2 the prices of Nd, Pr and Dy, for which average prices between 2008 and 2015 were assumed. Nd represents 36 %, Pr 24 % and Dy 40 % of total revenues.

The costs for separating permanent magnets from wind turbines as well as for their subsequent re-magnetization could almost be neglected (Stiesdal, 2015), representing 2% of the overall cost in Scenario 2. In Scenario 2, the assumed investment costs of the REE separation plant (22 % of total cost) and its operating costs (75 % of total cost) are linked to uncertainties. It seems, however, highly plausible that treatment costs are lower than the extraction of REE from primary ores due to higher concentrations of REE in magnets (24 % Nd compared to 12 % in primary ores (Bleiwas and Gambogi, 2013)), which are additionally less compound and therefore easier soluble. Thus, lower amounts of acids and energy are needed, resulting in lower operating costs compared to primary REE extraction.

- **Classification**

In terms of “knowledge on the in-use wind turbines’ / permanent magnets’ composition and the extractable material content”, both scenarios are graded with G1, as the stock’s size and composition can be estimated with a high level of confidence, based on detailed prospection and exploration studies on the in-use stock. However, there are some uncertainties on the recovery efficiencies in Scenario 2.

Regarding technical and project feasibility, re-using the magnets in their current form (Scenario 1) would be the most evident approach for large and easily accessible magnets used in wind turbines and large electric motors and generators in hybrid and electric vehicles, according to Binnemans et al. (2013) and Stiesdal (2015). Siemens initiated a research project on the re-use of NdFeB magnets from hybrid cars and e-vehicles (Binnemans et al., 2013). Therefore the re-use of permanent magnets from wind turbines obtains F4.1 as the technology is currently “under active development, following successful pilot studies on other deposits, but has yet to be demonstrated to be technically feasible for the style and nature of the deposit in which that commodity or product type is located” (UNECE, 2013). The REE extraction via hydrometallurgical methods (Scenario 2) is graded with F4.2 as the technology necessary to recover some or all of these quantities is currently being researched (e.g. Ellis et al., 1994, Itakura et al., 2006, Itoh et al., 2009), but no successful pilot studies have yet been completed” (UNECE, 2013) or at least there are no published data.

In terms of economic viability both scenarios are graded with E1 due to positive NPVs. Thus, the overall classification for Scenario 1 (re-use) is E1F4.1G1, and for Scenario 2 (hydrometallurgy) E1F4.2G2.

7.3 OBSOLETE STOCK: LANDFILL MINING

Compared to other resource recovery undertakings, mining resources from obsolete stocks exhibits the most similarities with conventional primary resource mining projects. The alternative of mining a landfill is usually regulated aftercare, implying that the closed landfill is left untouched and landfill facilities are maintained, emissions treated, and monitoring is carried on for many decades in case of municipal solid waste (MSW) landfills (Laner et al., 2012b). In the following sub-chapters, two landfill mining case studies are evaluated and classified: For the first case study an evaluation of landfilled materials is performed for the Enhanced Landfill Mining (ELFM) project in Belgium, as presented in Winterstetter et al. (2015a). The main aim of this study was to demonstrate the applicability of UNFC-2009 to

anthropogenic resources, by developing a first basic approach to evaluate landfill mining from a resource classification perspective.

The second case study (Bornem landfill site) is embedded within the project RECLAF (Resource Classification Framework for Old Landfills in Flanders), cooperatively realized by TU Wien and the Public Waste Agency of Flanders (OVAM) (Winterstetter et al., 2016c). The project's goal is to systematically provide information for the future management of 2,000 historic landfills in Flanders, e.g. whether the sites are to be mined or not and under which conditions.

7.3.1 Enhanced Landfill Mining Project: Remo Milieubeheer Landfill

For the Enhanced Landfill Mining (ELFM) project situated at the Remo Milieubeheer landfill site in Belgium, the landfilled materials were evaluated with special focus on the economics (pull situation). From the 1970s until 2003, more than 16 million metric tons of wastes were landfilled on 1.3 square kilometres. It contains a roughly equal share of municipal and industrial solid waste (cf. Table 10) and is engineered in compliance with Belgian legislation and the EU Landfill Directive.

Table 10: Average composition of the landfill (Spooren et al., 2012) presented in mean values and absolute standard deviations. Wt % = Dry weight percentage. Uncertainty ranges are based on own assumptions (cf. Winterstetter et al. 2015a).

	Municipal Solid Waste (Mean value ± std. dev. abs., wt-%)	**Industrial Waste** (Mean value ± std. dev. abs., wt-%)
Plastics	20 ± 8	5 ± 5
Textiles	7 ± 6	2 ± 1
Paper / Cardboard	8 ± 6	2 ± 1
Wood	7 ± 2	7 ± 2
Glass / Ceramics	1 ± 1	1 ± 1
Metals (Cu, Al, Fe)	3 ± 1	3 ± 3
Minerals / Stones	10 ± 4	10 ± 10
Fines <10 mm	40 ± 7	62 ± 7
Unknown	4 ± 4	8 ± 6

The landfilled waste is planned to be almost entirely excavated over a period of 20 years, with operations starting in 2017 (Jones et al., 2013). The present study makes some assumptions that differ from the ELFM consortium's plans: Metals (ferrous and non-ferrous) as well as the stone fraction will be sold after recovery, while paper, plastics, wood and textiles will be entirely converted into Refuse Derived Fuel (RDF) and exported to an offsite incineration plant for electricity generation. At the end of excavation activities the regained land will be sold. A considerable share of materials, mainly from the fine fraction, has to be re-landfilled due to high contamination levels. To carry out a landfill mining project, it is highly

important to know all involved stakeholders, such as the landfill's former operator and its current owner (private investors vs. public authority) (e.g. Diener et al., 2015, Hermann et al., 2014). In this case the evaluation is performed from a public entity's macro view, meaning that the potential greenhouse gas emission saving potential compared to a "Do-Nothing" scenario is monetized via a hypothetical CO_2-tax at 10 € / t CO_2 eq., exemplarily for a non-monetary long term effect. This corresponds to the average price of carbon emission futures between 2010 – 2015 (Investing.com, 2016). In addition, a rather low discount rate of 3 % is applied and aftercare obligations in the "Do-Nothing" scenario are assumed to be 70 years (minimum requirement under the landfill directive is 30 years), which implies that both avoided emissions and avoided aftercare costs are higher due to landfill mining and can be considered as revenues (Winterstetter et al., 2015a). Discounted costs and revenues are considered for 20 years with investment costs being depreciated over ten years (own assumption). Table 11 shows system variables and modifying factors considered in the case study.

Table 11: Mining of materials from the ELFM landfill: System variables and modifying factors

	Enhanced Landfill Mining Project
Main Goal	Determine the socioeconomic viability from a public entity's perspective
System variables	
Availability status	• Obsolete stock
Type & Location	• MSW / IW landfill in Belgium
Specific mining condition	• Mined for resource recovery (pull situation)
Volume & Composition	• Data from the sample excavations & the landfill's logbook
Project set-up for thermal treatment	• Offsite incineration of the combustible waste fraction
Legal, institutional, organizational & societal structures	• No legal framework existing, but established institutional structure with a number of committed partners, positive public perception
Project Status	• Project is still in the feasibility stage with mainly design & planning activities, operations only on a pilot scale
Modifying factors	
Investment & operating costs	• Costs for licenses & permits • Costs for excavation & storage • Costs for separation & drying (CAPEX & OPEX)*
Prices for secondary products	• Prices for secondary products: Fe-metals, NF-metals (Cu, Al), stones, regained land
Costs for external treatment & disposal	• Costs for transport, baling & gate fees for energy recovery
Avoided costs	• Avoided costs for final landfill cover & after care for 70 years
Monetized external effects	• Hypothetical CO_2 tax

*OPEX: Operating expenses (ongoing costs a company pays to run its basic business)
CAPEX: Capital expenditures (used by a company to acquire or upgrade physical assets such as property, industrial buildings or equipment)

- **Prospection & Exploration**

Table 12 shows a range of scenario estimates regarding the landfill's potentially recoverable and usable fractions. In line with the Petroleum Resources Management System (PRMS) specifications for petroleum under UNFC-2009 the G-categories can be used to cumulatively express low, best and high estimates of potentially recoverable and usable quantities of materials and energy. The best estimate (G1+G2) is P50 from a cumulative probability distribution.

Table 12: Potentially recoverable and usable quantities from an old landfill (total), expressed in a cumulative way

	Unit	G1 Low estimate	G1+G2 Best estimate	G1+G2+G3 High estimate
Regained salable land	[m²]	490,000	520,000	550,000
Off-Site incineration: RDF to external incinerator	[kt]	2,600	3,400	4,200
Salable net electricity (produced in a plant with 30 % efficiency)	[GWh]	3,600	4,700	5,800
Stones / minerals	[kt]	1,000	1,700	2,400
Non-ferrous metals (Al, Cu)		28	54	79
Ferrous metals		320	550	810
Amount of materials to be re-landfilled (fines, sorting residues, incineration ash)		11,200	9,600	8,000

- **Evaluation**

Discounting the project's cash flows over 20 years with a discount rate of 3 %, the landfill mining project yields a negative NPV of -277 million € (-17 €/t excavated material) (cf. Figure 10), implying that under current conditions the project is not economically viable, and the landfill cannot be classified as reserve (cf. Winterstetter et al., 2015a).

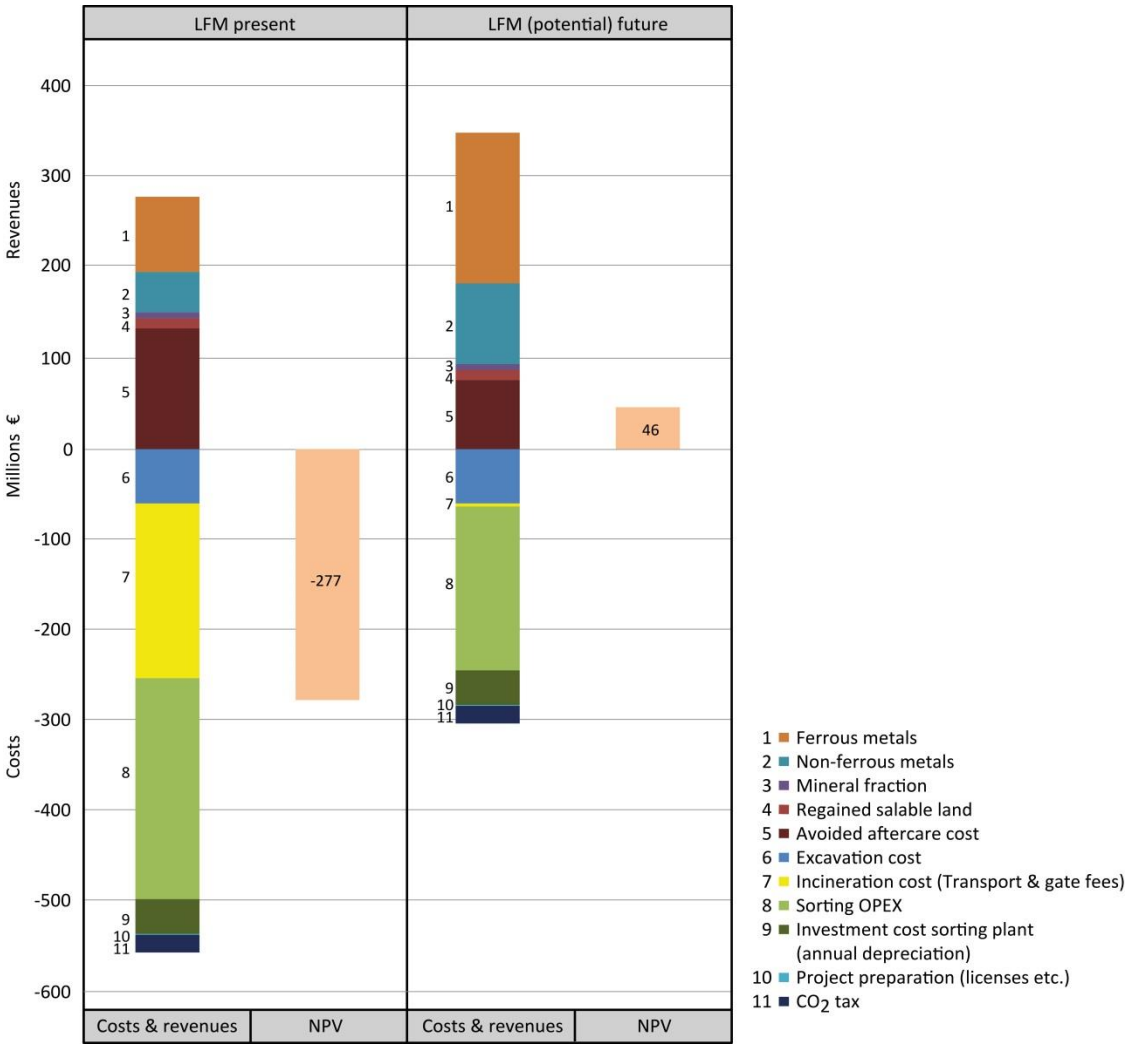

Figure 10: Costs and revenues of a landfill-mining project, discounted over 20 years with a discount rate of 3 % (comparison between present and potential future conditions)

On the cost side, incineration costs, comprising transport and gate fees (35 %) as well as operational expenses for the sorting plant (44%) represent the major shares of total costs. The greenhouse gas emission saving potential compared to a “Do-Nothing” scenario turned out to be negative and therefore appears on the cost side.

On revenue side, avoided after care costs for 50 years after closure (48%) and ferrous metals, including the metals from RDF preparation and the fine fraction, (30 %) and non-ferrous metals (16%) are the biggest parts.

To determine under which conditions landfill mining can be labelled “potentially commercial” or “non-commercial”, cut-off values are calculated under consideration of potential future changes of a set of key modifying factors. Nispel (2012), for instance, assumed that within 20 years ferrous and non-ferrous metal prices will double and operators of incineration plants will pay, due to overcapacities, at least 10 € per ton of RDF made from the landfill’s

combustible materials. Additionally, he forecasts operating costs of sorting plants to decrease by 20 %, due to the use of more energy efficient technologies. Moreover, avoided aftercare costs for 30 years instead of 50 years after closure were assumed, as the landfill-mining project will be postponed by 20 years into the future and aftercare costs have to be paid in the meantime. Given all these hypothetical assumptions, the landfill-mining project would yield a positive NPV of in average 46 million € (2.9 €/t) (cf. Figure 10). In fact, keeping doubling metal prices and 20 % lower sorting costs, a landfill miner could still pay a cut-off price of 5.7 €/t (instead of currently 65 €/t) for the incineration of RDF to reach at least the break-even point (with NPV = 0).

- **Classification**

In terms of "knowledge on the landfill´s composition and its extractable material content", the project is graded with G2[1], as the quantities contained in the landfill can be estimated with a medium level of confidence based on data from both the sample excavations and the landfill's logbook data. In addition, the applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the landfill's extractable raw material potential.

The F-axis indicates a project's "field project status and technical feasibility". Even though only well-known technologies are applied and the institutional structure is already established, meaning that the current landfill owner is seriously planning the project with a number of committed partners, the LFM project is still in the feasibility stage with mainly design and planning activities and operations on a pilot scale. Generally, a legal framework for landfill mining has not been developed so far and thus various individual licenses are needed to advance the project. Therefore, the project is classified as "potentially feasible" (F2).

While the landfill-mining project does not achieve positive results under present economic conditions, reaching cut-off values in the foreseeable future seems, however, possible. Therefore it is classified as "potentially commercial" (E2). Combining those three criteria, the landfill-mining project is categorized as E2F2G2 ("resource").

7.3.2 Historic Landfills in Flanders: Bornem Landfill

The Flaminco model (Flanders Landfill Mining, Challenges and Opportunities) was created as a decision support tool by OVAM, in order to prioritize the landfills from the ELFM-database for potential mining, according to a) their contamination risks and b) their respective resource potential. The model is based on a multi-criteria analysis using different criteria and specific weighing factors (Behets et al., 2013, Wille, 2016).

[1] Incremental (not cumulative) classification, as usually used for classifying solid minerals

The selected former landfill under investigation site is located in Bornem, a municipality in the Belgian province of Antwerp. The nearest residential area is the community of Temse with 30,000 inhabitants, which is located on the other side of the Schelde river, about 600 m away from the former landfill site. The adjoining areas are largely undeveloped and are primarily used as forest and meadow. The landfill received over 390,000 metric tons of mainly municipal solid waste (MSW) between 1947 and the late 1970s, when it was closed. The former operator was under contract with the municipalities Bornem and Puurs. Today it covers an area of 50,000 square meters (Van Vijle and Van Vooren, 2010).

It is partially covered with a clay cover from the dike reinforcement work carried out between 1978 and 1980. The bottom layer consists of sand and bulk material. Water catchment areas and protection zones are not in the landfill's immediate vicinity. However, according to the vulnerability map of the county Antwerp the surrounding groundwater is classified as "very vulnerable" (Ca1 index). The nearest groundwater well is located at a distance of approximately 400 m across the Schelde river. Therefore, no influence on groundwater extraction is expected.

For this landfill site test excavations, trial sortings and waste characterizations of a batch of 500 tons have been performed in order to generate and deepen the knowledge on the landfill body's quantitative and qualitative composition as well as on the best suited sorting option (OVAM, 2015). For the evaluation the landfill is assumed to be excavated within one year, with operations starting in 2017. The evaluation is performed from a public entity's macro perspective, considering direct monetary effects (i.e. costs for excavating, transporting, processing materials and the disposal of residues, revenues for selling secondary products and avoided aftercare costs) as well as some selected non-monetary (avoided GHG emissions) or indirect financial effects (newly gained land tax). The fine fraction is sold as construction material after extraction, while plastics and wood fractions are entirely turned into Solid Recovered Fuel (SRF) and used in an off-site cement kiln in Antwerp (gate fee 50 €/t). A certain amount of excavated materials has to be re-landfilled off-site (gate fee 65 €/t). At the end of excavation activities the regained cleaned-up land will be sold at a price of 150 €/m^2. Potential greenhouse gas emission (GHG) savings of a landfill mining project compared to a "Do-Nothing" scenario are included via a hypothetical CO_2 tax at 10 €/t CO_2 eq. This corresponds to the average price of carbon emission futures between 2010 – 2015 (Investing.com, 2016). Additionally, the prevented pollution of soil, ground and surface water due to landfill mining is counted in by avoided aftercare costs. Moreover, after selling the cleaned-up regained land, revenues from annual land tax are incorporated as indirect financial long-term effects for municipalities. In addition, a rather low discount rate of 3 % is

applied and aftercare obligations in the “Do-Nothing” scenario are assumed to be 70 years (minimum requirement under the landfill directive is 30 years), which implies that both avoided emissions and avoided aftercare costs are higher due to landfill mining and can be considered as revenues (Winterstetter et al., 2015a). All costs and revenues are discounted over 1 year. Table 13 shows all relevant information regarding the landfill mining project.

Table 13: Mining of materials from the Bornem landfill: System variables and modifying factors

	Bornem Landfill Mining Project
Main Goal	Determine the socioeconomic viability from a public entity's perspective
System variables	
Availability status	• Obsolete stock
Type & Location	• MSW landfill (some IW) in Flanders
Period of landfilling	• ca. 1947 - 1977
Distance from LF to stationary sorting plant (km)	25
Distance from stationary sorting plant to cement kiln (km)	25
Distance from stationary sorting plant to disposal (km)	50
Proximity to other landfills (km)	25
Land use: Location in relation to actual /potential residential, industrial, agricultural, recreational & ecological valuable area	• Nearest residential area: Community of Temse, located across the Schelde river, about 600 m away from the site. • Adjoining areas largely undeveloped, used primarily as forest and meadow (nature /recreational area)
Vulnerability of the soil & groundwater	• Landfill is partially covered with a clay cover from the dike reinforcement work. • Bottom layer consists of sand and bulk material, but there is no bottom liner, leachate infiltrates into the subsurface. • Water catchment areas and protection zones are not in the landfill's immediate vicinity. • According to the vulnerability map of the county Antwerp the surrounding groundwater is classified as "very vulnerable" (Ca1 index).
Location in relation to surface water, water wells & flooding area	• Nearest groundwater well is located at approximately 400 m across the Schelde river. No influence on groundwater extraction is expected.
Specific mining condition	• No urgent need for remediation, mainly mined for land / resource recovery (pull situation)
Volume *Wet / dry weight (t)* *Height (m)* *Area (m^2)* *Density (t/m^3)*	390,000 / 273,000 6 50,000 1.3
	• Data from old reports, sample excavations & trial

Composition	sorting (combustible fraction, fines, plastics & organics, wood, others)
Legal, institutional, organizational & societal structures	• No legal LFM framework existing, but established institutional structure with a number of committed partners, positive public perception
Project Status	• Project is still in the pre-feasibility stage with mainly design & planning activities, operations only on a pilot scale
Project set-up for	
Planned project period	• 1 year (start 2017)
Considered aftercare period	• 70 years*
Interest rate (real)	• 3 %
Sorting Options	• Stationary off-site sorting
Thermal treatment	• Off-site co-combustion of the combustible waste fraction in a cement kiln
Options fine treatment	• Advanced (to obtain soil-like quality)
Re-landfilling	• Off-site
Modifying factors	
Prices for secondary products	• Regained cleaned-up land, soil / construction material
Costs	• Costs for excavation & pre-treatment • Costs for sorting & separation • Costs for fine treatment • Costs for disposal of SRF at cement kiln • Costs for disposal of residues • Transportation costs
Avoided costs	• Avoided costs for aftercare, considered for 70 years • Expected newly gained land tax, considered for 70 years
Indirect financial effects	
Monetized external effects	• Avoided GHG emissions via hypothetical CO_2 –tax, considered for 70 years

Table 13 (continued)

*In practice the landfill is not managed, hence no aftercare measures are taken. However, in order to evaluate the "environmental damage" caused by the landfill, a hypothetical aftercare period of 70 years (including the collection and treatment of leachate and landfill gas) has been assumed.

- **Prospection & Exploration**

Table 14 presents the potentially recoverable and saleable quantities of secondary products as well as the amount of materials, which will have to be re-landfilled again at a fee.

Table 14: Total potentially recoverable and usable quantities from the Bornem landfill

	Unit	
Regained saleable land	[m²]	50,000
Solid Recovered Fuel (SRF)	[t]	129,200
Soil / construction material		207,400
Amount of materials to be re-landfilled (sorting residues)		34,600

- **Evaluation**

Total discounted cost amount to -28 million € (-73 €/t). The overall evaluation yields a negative NPV of in total -17 million €, which equals to -44 € per ton of excavated waste. This implies that the project is currently not economically viable, and can therefore certainly not be classified as 'reserve' (cf. Table 15).

Table 15: Total discounted cost and NPV (total and per 1 ton of excavated waste). Cash flows are discounted over 1 year with a discount rate of 3 %

Total discounted cost (million €)	- 28
Total NPV (million €)	- 17
NPV in € /t of total excavated waste	- 44

Main drivers of the economic performance on cost side are clearly the relatively high sorting costs, owing to the complex sorting procedure selected (OVAM, 2015) (45 %). Gate fees for co-combustion in a cement kiln (50 €/t SRF) amount to 22 %, representing the second biggest share of total costs. Compared to other landfill mining projects, total revenues are lower, since the share of metals present in the landfill is a) relatively small and b) not being recovered. Avoided after care costs for 70 years and selling regained land amounts each to approximately 40 % of the total revenues. The land tax gained by the municipality for a period of 70 years plays a minor role (10 %). The greenhouse gas emission saving potential compared to a "Do-Nothing" scenario turned out to be negative and therefore appears on the

cost side. Based on required future changes in key modifying factors to make the project economically viable, it could be decided, whether the landfill can be labelled at least as 'resource' or not. The calculated cut-off land price to reach the break-even point is 502 €/ m^2 (instead of currently 150 €/ m^2) (cf. Figure 11).

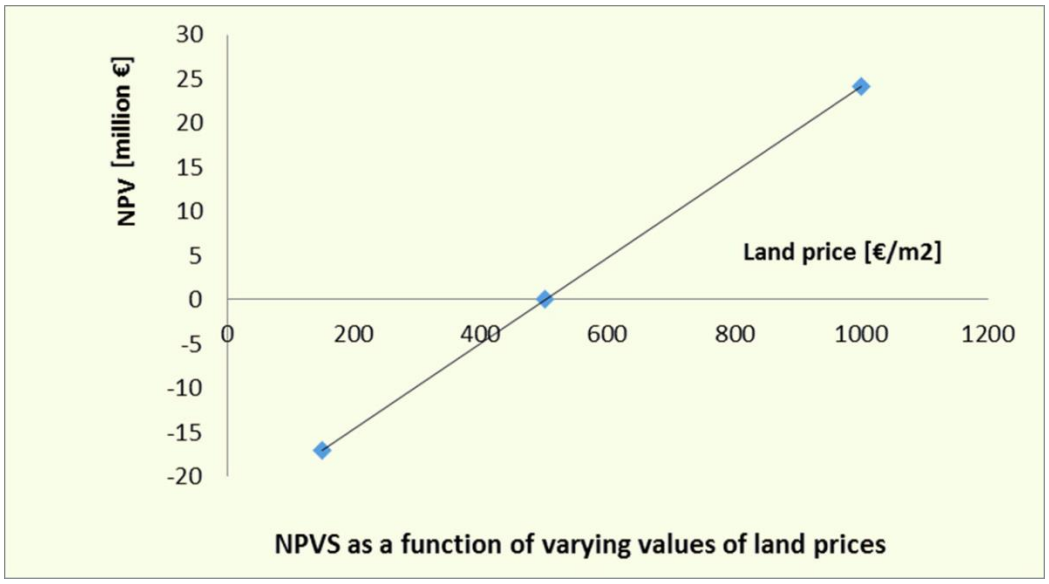

Figure 11: NPVs are shown as a function of varying values of land prices. Cut-off land price is reached at 502 €/ m2 (instead of currently 150 €/ m^2).

A combination of increasing land prices up to 350 €/m^2 and parallel decreasing sorting costs to 15 €/t (from currently 35 €/t), can in the authors' opinions realistically be reached. Consequently, the landfill has reasonable prospects for economic extraction in the near future and is classified as 'resource'.

- **Classification**

In terms of "knowledge on the landfill´s composition and its extractable material content", the Bornem landfill mining project is graded with G2, as the quantities contained in the landfill can be estimated with a medium level of confidence based on data from both the sample excavations and the landfill's logbook data. In addition, the applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the landfill's extractable raw material potential.

For the F-Axis, displaying the project's "field project status and technical feasibility", the landfill mining project is graded with F3. Even though only well-known technologies are applied and the institutional structure is already established with OVAM as committed partner, there are no activities on-going other than test-excavations. The LFM project is still in the pre-feasibility stage with mainly planning activities and operations on a very small

[2] Incremental (not cumulative) classification, as usually used for classifying solid minerals

scale. In addition, a legal framework for landfill mining has not been developed so far and so various individual licenses are needed to advance the project. Therefore, the project obtains F3, and is in total classified as E3F3G2 under present conditions.

While the Bornem project does not achieve positive results under present economic conditions, reaching cut-off values in the foreseeable future seems, however, possible. Therefore it is classified as “potentially commercial” (E2). Combining those three criteria, the landfill-mining project is categorized as E2F3G2 (“resource”).

8. DISCUSSION: COMPARISON OF CASE STUDIES' RESULTS & APPLICABILITY OF UNFC-2009 TO ANTHROPOGENIC RESOURCES

This chapter first compares the results from the case studies as well as factors, influencing the classification results. Finally, the challenges and potentials for the classification of anthropogenic resources under UNFC-2009 are discussed.

The following three subchapters discuss the classification of anthropogenic resource deposits first from the perspective of the items to be classified, i.e. anthropogenic resources (bottom-up). The factors, influencing the evaluation and classification results, are analysed for the four specific case studies and are then taken to a more generic level by comparing the case studies' results to literature on similar feasibility studies. Subsequently, the challenges and potentials for the classification of anthropogenic resources under UNFC-2009 are discussed, taking rather a framework perspective (top-down).

8.1 COMPARISON OF CASE STUDIES' RESULTS

Table 16 compares the economic results for the four case studies with two scenarios each (landfill mining ELFM, landfill mining Bornem, obsolete PCs, in use permanent magnets). While landfill mining under present conditions is not economically viable for the ELFM project (-17 €/t excavated waste), this might change in case of improving key modifying factors in the foreseeable future, i.e. doubling metal prices and decreasing sorting costs (by 20 %), and RDF disposal revenues at 10 €/t (instead of currently paying fees of 65 €/t RDF), reaching a positive Net Present Value of 3 € / t excavated waste.

For the Bornem landfill site (currently -44 €/t excavated waste), a combination of increasing land prices to 350 €/ m^2 (instead of currently 150 €/m^2) and parallel decreasing sorting costs to 15 €/t (from currently 35 €/t) would allow the project to break even (cf. Chapter 7.3.1),

Table 16: The NPVs differ for mining old landfills, obsolete PCs or permanent magnets.

	Old landfills				Obsolete PCs		Permanent magnets in wind turbines	
	ELFM Present	ELFM Potential Future	Bornem Present	Bornem Potential Future	Scenario 1 (high-income EU city)	Scenario 2 (low-income EU city)	Scenario 1 (re-use)	Scenario 2 (hydromet.)
NPV in € / t excavated waste materials / t collected PCs / t magnetic scrap	-17	3	- 44	>0	120	360	37,500	31,800
NPV in € / cap	-				0.096	0.036	0.779	0.663

However, the assumption with respect to changing key modifying factors is highly subjective. Basing the evaluation on doubling metal prices and decreasing sorting costs, but with RDF disposal fees still remaining at 20 €/t (instead of currently 65 €/t), the NPV would stay negative, namely -1.8 €/t (-29 million € in total). Even paying disposal fees of only 10 €/t would yield a negative NPV of -0.25 €/t (-4 million € in total). To break even, the required cut-off price for a landfill miner to pay is 5.7 €/t (cf. Chapter 7.3.1).

Mining materials from obsolete PCs and from permanent magnets in wind turbines (currently in-use) would both yield positive economic results. In case of the obsolete PCs, the NPV per capita shows, how the different collection rates influence the economic results favouring Scenario 1 with a higher collection rate of 800 t (vs. 100 t in Scenario 2). The NPV per ton of collected PCs makes Scenario 2 look better, due to lower labour costs. If the WEEE directive and other EU laws were implemented and enforced similarly well in the low-income city (Scenario 2), collection rates, costs for disposal of residues and avoided treatment costs were similarly high as in the high-income city (Scenario 1). A combined scenario with high collection rates and low labour cost, using a simple manual procedure to dismantle the PCs, would yield a positive overall result of 337,000 € per year, meaning 421 €/t of collected PCs and 0.337 € per capita (instead of currently 96,000 € per year in Scenario 1 vs. 36,000 € per year in Scenario 2). This means that low labour costs and high collection rates would represent an ideal situation for PC recycling.

In case of the permanent magnets from wind turbines the re-use scenario is economically clearly to be preferred over the hydrometallurgical extraction. Assuming that all installed wind turbines containing NdFeB permanent magnets in Austria are hypothetically mined within

one year under current conditions, neglects that techniques, such as hydrometallurgical extraction, might become more and more mature by the time the magnets are truly available for mining. Further, it is assumed that the REE separation plant is newly built, even though treating the relatively small amounts of materials from future obsolete Austrian wind turbines would not justify the construction of a new plant. So one would have to consider input from other sources (e.g. obsolete permanent magnets from other applications) to operate the plant economically on a permanent base.

For these four case studies, factors that influence the evaluation and thus the classification results are derived (cf. Table 17). Although these factors are quite similar, their individual weight differs in the respective case studies.

Table 17: Factors, influencing the evaluation and classification results, for different types of anthropogenic resources

	Old landfill	**Obsolete PCs**	**NdFeB permanent magnets**
Preconditions			
Availability status	• Obsolete stock	• Waste flows	• In-Use Stock
Mining / handling condition	• Pull (or Push)	• Push	• Push or Pull
System Variables			
Type & Location	• Type & location of the obsolete stock	• Type & location of the waste flow	• Type & location of the in-use stock
Volume	• Volume of landfill	• Volume of waste flow	• **Age & life-time of wind turbines / permanent magnets**
Composition	• Composition: Ash & water content, share of usable materials, combustible fraction, non-recyclables & hazardous substances, contamination of fine fraction	• Product type & size / share composing the waste flow • Composition: Share of usable materials & non-recyclables & hazardous substances	• **Technological change / substitution** • **Repair & Maintenance requirements** • Total number of wind turbines, their specific capacity & permanent magnets composing the in-use stock • Composition: Share of usable materials & non-recyclables
Legal, institutional, organizational & societal structures	• **Project partners & Public perception, no legal framework**	• **Collection & take back system** • **Consumption & disposal pattern & source separation behaviour**	
Methods & technology used for extraction & processing with specific efficiencies & maturity	• Options for excavation, sorting & valorisation	• Options for dismantling & processing	• Options for re-using magnets / separating REE from permanent magnets
	• Maturity & specific experience of technology for valorisation of materials, energy recovery	• Maturity & specific experience of technology for PC recycling	• Maturity & specific experience of technology for REE extraction / re-use of magnets
Project status	• **Project status (licenses)**		

Modifying factors			
Investment & operating costs	• Investment & operating costs (Excavation, sorting & treatment plants)	• Labour costs (Collection & sorting) • Dismantling costs	• Dismantling costs • Investment & operating costs (REE extraction & treatment plants)
Costs for external treatment & disposal	• Gate fees for energy recovery • Costs (requirements) for disposal of non-recyclables & hazardous substances	• Gate fees for end processing & energy recovery • Costs (requirements) for disposal of non-recyclables & hazardous substances	• Costs (requirements) for disposal of non-recyclables
Prices for secondary products	• **Price for regained land or landfill space** • Prices for metals (Fe, Cu, Al), construction material, soil, energy	• Prices for metals (Fe, Cu, Al) cables, hard drives, adaptors, printed circuits etc.	• Prices for Fe, B, REE or entire permanent magnets
Avoided costs	• **Avoided costs for landfill aftercare and/or remediation, partly alternative disposal**	• **Avoided alternative disposal costs**	
Monetized external effects	• CO_2 tax • Longer after care period	• **Extended Producer Responsibility scheme**	
Indirect financial effects	• **Future land tax from sold land** • **Future gate fees from newly gained landfill capacity**		

Table 17 (continued)

The following paragraphs describe the findings from the case studies as shown in Table 17. To take these results to a more general level, they are compared to similar studies. By reviewing literature on further feasibility studies, the general influencing factors for mining waste flows (including obsolete products / materials flows and residues flows) and obsolete stocks (including old buildings, hibernating products and infrastructure, tailing ponds, old landfills and slag heaps) are derived (cf. Figure 7). Influencing factors often represent sources of uncertainty and occur at various points within a mining project as shown in Figure 12 and Figure 13.

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In-Use Stocks

Type, location, volume, size and composition of in-use stocks, which can in most cases only hypothetically be mined, obviously depend on the manufacturers' production patterns and people's consumption behaviour. In-use stocks determine to a big extent the characteristics of originating waste and residues flows and / or obsolete stocks (cf. Figure 12 and Figure 13). In case of future recycling of permanent magnets contained in wind turbines, currently in use in Austria, the focus was on different technical recycling options. The choice of using hydrometallurgical methods yields a weaker economic result compared to direct re-use of permanent magnet, which is due to high REE separation costs. Prices for selling either REE or entire permanent magnets act as independent key drivers on the project's economics. Generally, the age and lifetime of an in-use stock indicates its future availability for mining. In this context also repair and maintenance requirements are essential factors (Baccini and Brunner, 2012, Lederer et al., 2016, Wallsten et al., 2013b). Technological changes and emerging substitution options might influence the type and composition of an in-use stock, being often driven by laws and policies, such as the digital switchover policy (Ongondo et al., 2011).

Evaluating hypothetical mining of in-use stocks can be a useful exercise to check, whether new laws and policies are needed due to negative economic results. For instance, McDonald and Pearce (2010) found that the economic motivation to recycle most photovoltaic (PV) modules is unfavourable, in particular for PV modules containing hazardous materials. Therefore, they plead for appropriate energy and environmental policies, including producer responsibility, for the PV manufacturing industry.

Waste Flows

As under UNFC-2009 only defined projects can be classified (UNECE, 2010), arbitrary geographical and temporal system have to be drawn for waste flows (cf. Figure 12). Waste flows can originate from in-use stocks (obsolete products / materials flows) or from processed waste or materials, resulting from previous treatment steps (residues flows), such as ash streams from municipal solid waste incineration (MSWI). In the latter case the specific technological process used (e.g. grate vs. fluidized bed incineration, wet vs. dry air pollution control) as well as the input (e.g. type of wastes incinerated) affects the flow of residues (Fellner et al., 2015). For MSWI residues the sampling procedure and type of lab analysis used to determine the grade of the targeted resource plays an essential role to gain knowledge about the flow's resource potential.

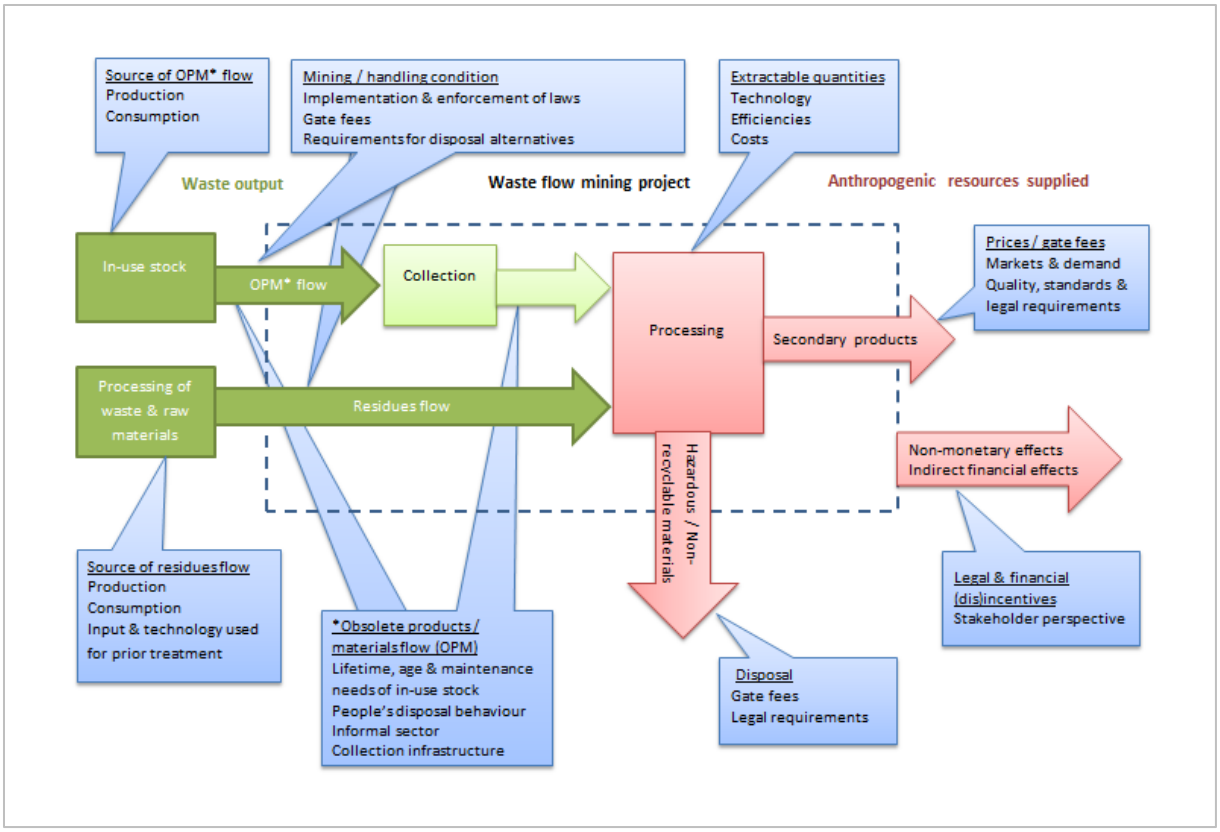

Figure 12: General influencing factors (blue boxes) within a mining project for waste flows, i.e. obsolete products / materials (OPM) flows & residues flows. System boundaries demarcate the "project".

Treating waste flows, such as waste electrical and electronic equipment (WEEE), typically represents a push situation. The EU WEEE directive specifies minimum treatment requirements for WEEE providing for the removal of specific components containing hazardous substances, such as lead in Cathode ray tubes (CRT) or chlorofluorocarbons (CFC) in cooling and freezing appliances (Huisman et al., 2008). The directive also sets the annual collection, reuse and recycling targets, and is implemented in different ways at national levels of the EU member states. Therefore, the case study at hand on treating obsolete PCs in the EU investigates two different settings of the legal, institutional, organizational and societal setting. The project feasibility of mining WEEE is dominantly influenced by the system variable "set-up of the collection and take back system". A number of stakeholders is involved with different responsibilities, such as legislators, producers, retailers, consumers, recyclers and municipalities (e.g. Huisman et al., 2008, da Cruz et al., 2014). The success of a take back system consists, amongst other things, of an appropriate infrastructure and service provision. Collection and source separation rates affect the extractable and potentially usable share of materials (e.g. Huisman et al., 2008). In Scenario 1, (high-income EU city) the public awareness of WEEE recycling is assumed to be higher, and the collection and take back infrastructure to be well organized and functioning.

Similarly, people's consumption and disposal patterns and source separation behaviour is thought to be different from a low-income city (Scenario 2) (cf. Ciocoiu et al., 2010). Equally, Ongondo et al. (2011) found that consumer variables, such as attitudes, behaviour, age, gender, employment status, storage space etc., as well as people's awareness level of take back options, play an essential role when it comes to achieving the collection and recycling goals. According to a number of authors, such as Oswald (2013), Feng et al. (2008) and Williams et al. (2008), the involvement of the informal sector plays a key role and can have a major impact on the minable waste flow.

Aside from collection, the recycling chain for WEEE consists of further succeeding steps, namely sorting, dismantling, pre-processing, and end-processing, which includes refining and disposal. Interfaces to other steps in the chain, i.e. requirements of the next processing step and also to the preceding step are of relevance (Schluep, 2009). Feng et al. (2008) identified a recycling plant's capacity and potential economies of scale as one of the decisive factors.

For the PC recycling case study at hand, most modifying factors depend on the project's legal, institutional, organizational and societal environment. Labour costs, material prices and avoided disposal costs are the main drivers of economic performance. Labour costs are higher in a high-income EU city, and (avoided) disposal costs equally tend to be higher, due to higher standards and stricter enforcement of existing laws (Scenario 1). In both scenarios prices for selling the PCs' components as secondary products and raw materials act as independent key drivers of the economic performance. The identified drivers "labour costs" and "prices of secondary materials" are in line with many other feasibility studies on E-waste recycling (e.g. Feng et al., 2008, Kang and Schoenung, 2006, Schluep, 2009, Huisman et al., 2008, Oswald, 2013).

Since PCs have to be handled anyway, the concept of avoided disposal cost plays a major role in the evaluation (Scenario 1). They strongly depend on the avoided disposal alternatives, i.e. the costs of landfilling or incineration, depending amongst others on the defined legal standards of those disposal alternatives and the enforcement of existing laws. This is valid also for other waste flows to be treated. Fellner et al. (2015), for instance, highlight, that the economic performance of Zinc recovery from incineration residues is driven by avoided waste treatment and disposal costs, rather than by the revenues from raw material valorisation.

The recovered quantities of economically interesting materials, such as glass, plastics and metals, heavily depend on the recovery efficiencies of pre-processing technologies and methods (Oswald, 2013). A number of different treatment technologies for WEEE is available, both mature and emerging ones, which alone or in combination can address the

specific needs of each product group (e.g. Dalrymple et al., 2007, Cui and Zhang, 2008, Salhofer and Tesar, 2011). Techniques with higher efficiencies are more likely chosen if markets and demand for the output fractions exist and if expected price levels for output materials are high enough to justify higher treatment costs or if disposal costs for non-recyclable remaining materials can be reduced (Schluep, 2009, Huisman et al., 2008). In the feasibility study by Kang and Schoenung (2006) for a material recovery facility in California the largest revenue source is the fee charged to the customer, which represents approximately 60% of total revenues. Metal recovery is the second largest revenue source. As the dismantling centre in the case studies at hand is a socioeconomic company, which is partly publicly funded with the aim of re-integrating people with difficulties back into the labour market, no fees are paid by municipal recycling centres for treating e-waste there (DRZ, 2016). On the cost side the main driver identified by Kang and Schoenung (2006) is the disposal of non-recyclables and hazardous substances, e.g. for Cathode ray tubes. The case study examined in this thesis is confined to PC recycling, where the disposal of capacitors represents a minor share on the costs side.

Regarding monetizing externalities, the extended producer responsibility (EPR), as for instance contained in the EU WEEE directive, is a strategy designed to integrate environmental costs, such as emissions into air, water and soil or the use of water, land and raw materials, associated with goods throughout their life cycles into the market price of the products (Lindhqvist, 1992). Further non-monetary effects integrated in the evaluation will depend upon the specific interests of involved stakeholders and the subsidies and other forms of incentives they provide. According to Schluep (2009) and Williams et al. (2008), for instance, the reuse and recycling sector has a considerable positive impact on employment and public health.

Obsolete Stocks

Obsolete stocks comprise old buildings, hibernating products and infrastructure, tailing ponds, old landfills and slag heaps (cf. Figure 7). In analogy to waste flows, obsolete stocks can originate from in-use stocks via waste flows (e.g. MSW landfill) or in direct transition (e.g. hibernating infrastructure) or from residues flows, resulting from previous treatment, e.g. ash landfills, tailing ponds and slag heaps (cf. Figure 13).

Type, location, volume, size and composition of in-use stocks depend on production (e.g. materials used for buildings and infrastructure) and people's consumption patterns (e.g. materials disposed of in landfills, hibernating products). In the case of residues flows the specific technological process used (e.g. waste incineration, aluminium refinery, smelters) as

well as the input (e.g. type of wastes incinerated) affects the flow of residues (Johansson et al., 2013, Fellner et al., 2015).

Similarly to waste flows, the in-use stock's age and lifetime determine their future availability for mining, i.e. when they turn into obsolete stocks. In this context also repair and maintenance requirements are essential factors, as shown by Wallsten et al. (2013b) for subterranean infrastructure and by Lederer et al. (2016) for Vienna's subway network.

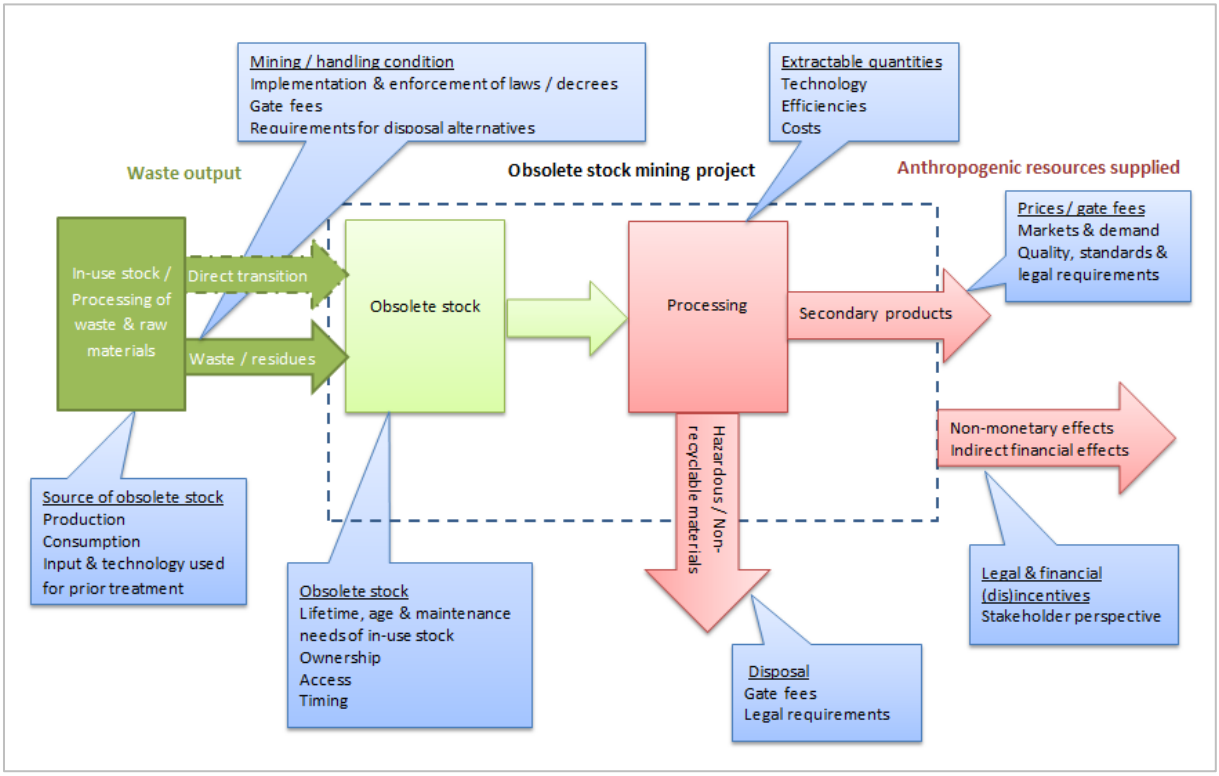

Figure 13: General influencing factors (blue boxes) for mining projects of obsolete stocks (old landfills, buildings, hibernating products & infrastructure, slag heaps, tailings). System boundaries demarcate the "project".

The alternative of mining an old landfill is usually regulated aftercare, implying that the closed landfill is left untouched and landfill facilities are maintained, with emissions being treated and monitoring activities being performed for many decades (Laner et al., 2012a). Mining obsolete stocks can either represent a push or a pull situation, as shown, for instance, by Frändegård et al. (2015). In a pull situation, mining an old landfill requires positive socioeconomic prospects either for a private investor or a public entity. As no legal LFM framework exists, individual permits and licenses are needed to advance a landfill mining project (e.g. Hermann et al., 2014, Ford et al., 2013). Some landfill mining projects were carried out with resource and energy recovery as a main focus (e.g. Zanetti and Godio, 2006, Cossu et al., 1996, Krug, 2008). However, thus far, costs generally have exceeded the revenues of recovered materials at least for MSW landfills making landfill mining not feasible

without governmental subsidies (e.g. Krook et al., 2011, Hull et al., 2005, Van Vossen and Prent, 2011, Breitenstein et al., 2016).
However, if the landfill turns out to be an immanent pollution threat to the environment, e.g. to groundwater, or if new landfill space is urgently needed, (local) authorities will oblige the former landfill operator via decrees to act, which means that the situation in that case is comparable to mining a waste flow, which has to be treated. If remediation is required, a pull situation turns into a push situation, as the choice of whether to extract the materials or not is taken away. Most of the early landfill-mining projects were primarily motivated by local pollution issues or by the need for new landfill capacities given the difficulty of getting permission to develop new landfills (e.g. van der Zee et al., 2004, Bockreis and Knapp, 2011, Hogland et al., 2004, Spencer, 1990) rather than by recovering landfilled materials as secondary resources.

Due to its local nature, a positive public perception and committed partners are very important for landfill mining projects (Craps and Sips, 2011). Landfilled wastes can be highly heterogeneous in size, shape, and condition, creating technological challenges in processing landfilled waste. It typically contains partially decomposed materials and a variety of non-recyclable fractions that can undermine the marketability of some of the landfilled materials (Prechthai et al., 2008, Wagner and Raymond, 2015, van der Zee et al., 2004, Johansson et al., 2016). Also, it is vital to account for site-specific conditions. For instance, it must be decided whether to treat the combustible waste fraction on-site (and if yes, what technology to use) or to export it to an already existing plant off-site (e.g. Ford et al., 2013). If there is a nearby incinerator willing to accept the waste at moderate gate fees, this solution might be more cost-efficient than building a new plant. Therefore, similar to a conventional mine, each landfill together with its surroundings needs to be investigated and evaluated on a case-by-case basis.

To generate knowledge on the obsolete stock’s composition and potentially extractable share of materials, for old landfills, data from samplings and test excavations together with data from logbooks on former landfilling activities (if existing) are relevant (e.g. Quaghebeur et al., 2012, Krook et al., 2012, Nispel, 2012). Efficiencies of recovery systems have a major impact on the extractable quantities of materials (Frändegård et al., 2015).They can vary widely depending upon the used techniques, from simple shovel and sieves to sensor-based sorting technologies (Hölzle, 2010). Ford et al. (2013) state that applying advanced waste separation technologies to landfilled waste might cause new problems related to separation efficiency, breakdown, blockage and high maintenance costs. The treatment and valorisation of the fine fraction is not yet mature or at least not cost-efficient, but important to reduce the amount of

residues to be re-landfilled and to gain more land or new landfill volume (Kaartinen et al., 2013). In case of smaller landfills to be mined, Fisher and Findlay (1995) suggest to select a landfill as a hub site for other nearby landfills to host excavation and screening equipment, making use of economies of scales. Hölzle (2010) and Bockreis and Knapp (2011) identified the landfill's composition (i.e. the share of valuables and non-recyclables) as well as the existing regional infrastructure as decisive factors for economic feasibility.

Although generally more homogeneous than old landfills, the influencing factors for mining slag heaps and tailing ponds are similar. In contrast, an obsolete stock of hibernating products, such as old cell phones in a drawer, can most likely only be mobilized for mining via communication campaigns and / or financial incentives (Ongondo et al., 2015). When it comes to recovering raw materials from hibernating subterranean infrastructure, the accessibility of obsolete stocks, i.e. their location and surface materials, might be a major issue. Krook et al. (2015) found that cable extraction is more expensive in city centres with asphalt or cobblestone pavements than in greenbelts. Moreover, the timing of mining decisions (e.g. together with maintenance works) can be of chief importance. For instance, integrating cable recovery as an added value to regular system upgrade projects would improve a recovery project's economic performance (Krook et al., 2015). Also in the case of old buildings, there is usually a limited time span for recovering resources before the building is torn down and turns into demolition waste flows, unless it is left abandoned (hibernation) (Kleemann et al., 2014). Additional relevant factors that might affect mining economics include the ownership of an obsolete stock (Hermann et al., 2014).

The landfill mining case studies investigated in this thesis also focus on the timing of mining, to see how future developments of key modifying factors can change the final results, and to decide, whether there are reasonable prospects for future economic extraction. On the cost side, incineration costs (transport and gate fees) as well as operational expenses for the sorting plant represent the major shares of total costs. On revenue side, avoided after care costs and metal sales represent the biggest parts. This is in line with Danthurebandara et al. (2015), Frändegård et al. (2015) and Wagner and Raymond (2015), who found the economic performance mainly dependent on parameters concerning energetic valorisation. Bernhard et al. (2011) highlight the importance of recoverable quantities and market prices of metals for a LFM project. Besides secondary products extracted from old landfills, also the regained land is of interest, which becomes obvious in the Bornem case, where the scarcity of land is the main driver of landfill mining. Correspondingly, Breitenstein et al. (2016) identified land prices together with gate fees for incineration as key factors to potentially change in the future and make LFM viable. Further, Hermann et al. (2014) and Frändegård et al. (2015) show a

considerable economic impact of landfill taxes that possibly need to be paid for re-deposited materials.

Investigating the potential mining of wood-products from solid waste landfills in Oregon, Bryden (2000) identified lacking local markets for recycling products as one of the major influencing factors. Similarly, Johansson et al. (2016) examined the market potential of excavated waste from a shredder landfill, sorted in an advanced recycling facility. While the metals could be sold, the other fractions (92%) were not accepted for incineration, as construction materials or not even for re-deposition. Similar to landfills, also for other obsolete stocks, such as recovered materials from old buildings, existing markets, and expected price levels for output materials, general demand, standards, laws and requirements for re-application are highly relevant factors (Lichtensteiger, 2006).

An evaluation is a matter of specific stakeholder interests, particularly in a pull situation (e.g. Hermann et al., 2014, Winterstetter et al., 2015a). For a private investor only direct financial effects are of interest, while non-monetary effects tend to be neglected, unless they are monetized in form of subsidies (e.g. Bockreis and Knapp, 2011). A public entity, in contrast to a private investor, is usually more interested in long-term effects, i.e. societal and environmental aspects (Graedel et al., 2012), such as the elimination of a source of local soil and water pollution (e.g. Krook et al., 2012), the avoidance of long-term landfill emissions (e.g. Bernhard et al., 2011), the public's opinion (e.g. Ford et al., 2013), the creation of new jobs (e.g. Van Passel et al., 2013) and the potentially increasing value of surrounding land (e.g. Hölzle, 2010), after mining the landfill. Thus, in addition to direct financial effects also non-monetary societal effects might be monetized and included in the evaluation. In general, Krook et al. (2015) state that the arguments for urban mining are currently more of environmental than of financial nature, e.g. for net savings in greenhouse gas (GHG) emissions due to metal recycling. Whether landfill mining increases or reduces climate impacts depends on the conditions of the economy in which it occurs. For a region more reliant on fossil fuels, combined with a landfill rich in organic waste and metals, and without a gas collection system, LFM would benefit the climate (Laner et al., 2016). In the ELFM and Bornem case studies GHG emission savings of a landfill mining project compared to a "Do-Nothing" scenario are monetized via a hypothetical CO_2 tax. However, no GHG emissions were saved, as incinerating excavated waste fractions to produce electricity resulted in higher emissions compared to the Belgian nearly emissions-free nuclear electricity sources (Winterstetter et al., 2016c, Winterstetter et al., 2015a). Further, the prevented pollution of soil, ground and surface water due to landfill mining is included via an avoided aftercare period of in total 70 years (compared to the minimum requirement of 30 years, which a

private investor would have considered). In addition, revenues from annual land taxes might be incorporated as indirect financial long-term effects for municipalities, as done in the Bornem case.

8.2 CLASSIFICATION UNDER UNFC-2009

While Figure 14 shows the classification results of the individual case studies, Table 18 displays the corresponding definitions of categories according to UNFC-2009 as applied in the four case studies. Case study specific influencing factors are contrasted to the generic definitions.

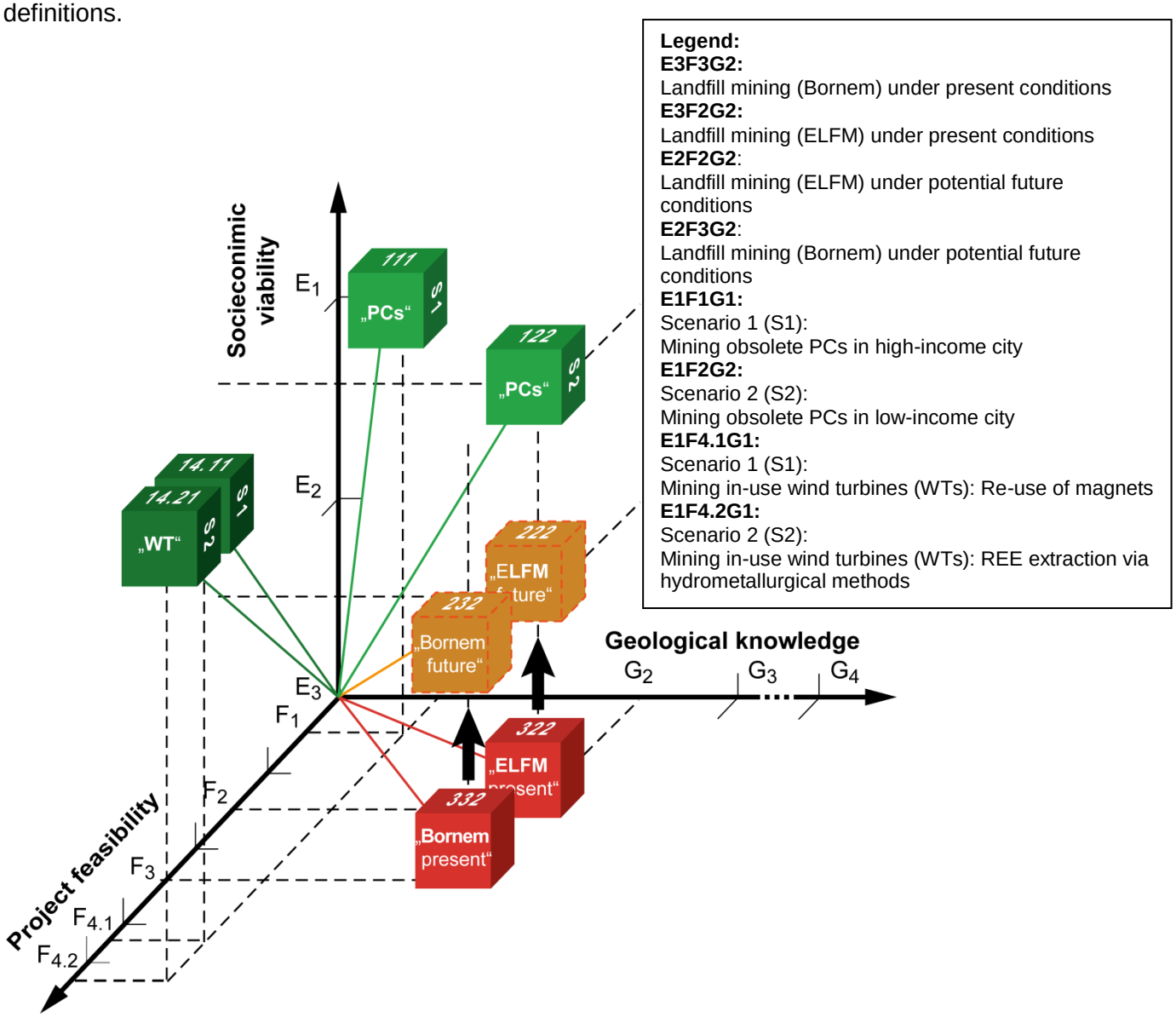

Figure 14: The applicability of UNFC-2009 is illustrated by classifying the four case studies (with two scenarios each) under UNFC-2009.

Table 18: Definitions of categories according to UNFC-2009 applied to the four case studies. While the grey boxes represent case study specific influencing factors, the white boxes display the generic definitions.

<table>
<tr><th></th><th>Obsolete Stocks
(Old Landfill)</th><th>Waste Flows
(Obsolete PCs)</th><th>In-Use Stock
(NdFeB Magnets)</th></tr>
<tr><td rowspan="2">E1</td><td colspan="3">Project yields positive NPV</td></tr>
<tr><td></td><td>KMF: Labour costs, avoided disposal costs, secondary raw material prices</td><td>KMF: Secondary raw material prices, REE separation costs in hydrometallurgical scenario</td></tr>
<tr><td rowspan="2">E2</td><td colspan="3">Project yields negative NPV, but due to future expected changes in key modifying factors (KMF), cut-off values might be reached</td></tr>
<tr><td><u>ELFM:</u> KMF: Treatment costs, secondary raw material prices, gate fees for energy recovery
<u>Bornem:</u> KMF: Treatment costs, land prices</td><td></td><td></td></tr>
<tr><td>E3</td><td colspan="3">Project yields negative NPV or evaluation is at too early stage to determine economic viability</td></tr>
<tr><td rowspan="2">F1</td><td colspan="3">Feasibility of extraction by a defined development project or mining operation has been confirmed
Existing legal framework
Existing societal, institutional & organizational structure
Mature technologies applied
Project status: Ongoing activities</td></tr>
<tr><td></td><td><u>Scenario 1</u>
Existing infrastructure & public awareness for PC collection via EPR (in line with WEEE directive).</td><td>-</td></tr>
<tr><td>F2</td><td colspan="3">Feasibility of extraction by a defined development project or mining operation is subject to further evaluation, at least one of the F1 criteria is not fulfilled</td></tr>
<tr><td><u>ELFM</u>
No legal framework for landfill mining
Positive public perception & committed project partners
Mainly design & planning activities ongoing
Operations only on a pilot scale.</td><td><u>Scenario 2</u>
Weakly enforced laws
Poor collection infrastructure
Low awareness about source separation
Application of established recycling methods
Interference with informal recycling sector (high uncertainties about collection rates).</td><td>-</td></tr>
<tr><td>F3</td><td colspan="2">Feasibility of extraction by a defined development project or mining operation cannot be evaluated due to limited technical data.
Extraction, processing & valorization technologies exist and are planned to be applied, but the project is not sufficiently advanced to determine the quantity & quality of potentially recoverable material, F1 criteria are widely not fulfilled</td><td>-</td></tr>
<tr><td></td><td><u>Bornem</u>
No legal framework for landfill mining</td><td></td><td></td></tr>
</table>

<table>
<tr><td></td><td>• Committed project partner
• Mainly planning activities ongoing.</td><td></td><td></td></tr>
<tr><td rowspan="2">F4</td><td colspan="3">In situ (in-place) quantities that will not be extracted by any currently defined development project or mining operation.
F1 criteria are not fulfilled, also not (yet) existing technologies
F4.1 – F4.3 describe the current state of technological development:
• F4.1: Technology under development, but no type-specific applications (yet)
• F4.2: Technology is researched, but pilot studies are not yet available
• F4.3: Technology for recovery is not currently under research or development</td></tr>
<tr><td></td><td></td><td>• In-use stocks are classified as F4 as currently not available for mining.
• No legal framework for treating obsolete wind turbines
<u>Scenario 1 (re-use)</u>
F4.1: Existing research project on the re-use of NdFeB-magnets from hybrid cars & e-vehicles
<u>Scenario 2 (hydrometallurgy)</u>
F 4.2: Technology currently being researched (e.g. Ellis et al., 1994; Itakura et al., 2006; Itoh et al., 2009),but no successful pilot studies have yet been completed / no published data</td></tr>
<tr><td rowspan="2">G1</td><td colspan="3">The stock’s / flow’s volume, composition & the applied technologies’ recovery efficiencies can be estimated with a high level of confidence to assess the share of potentially extractable & usable materials*
Alternative: P90 => Low estimate**</td></tr>
<tr><td></td><td><u>Scenario 1</u>
• Volume & composition of waste flow is well known
• Recovery efficiencies are well known</td><td>• Detailed exploration studies on magnets in wind turbines
• Knowledge about extractable materia content
• Minor uncertainties about recovery efficiencies</td></tr>
<tr><td rowspan="2">G2</td><td colspan="3">The stock’s / flow’s volume, composition & the applied technologies’ recovery efficiencies can be estimated with a medium level of confidence to assess the share of potentially extractable & usable materials*
Alternative: P50 => G1+G2 = Best estimate**</td></tr>
<tr><td><u>ELFM & Bornem</u>
• Medium level of confidence about quantity & composition of landfilled material (based on sample excavations & the landfill’s logbook data).
• Recovery efficiencies sufficiently known</td><td><u>Scenario 2</u>
• Volume & composition of waste flow well known, however significant uncertainties about collection rate due to informal sector
• Recovery efficiencies can be estimated with sufficient detail</td><td></td></tr>
<tr><td>G3</td><td colspan="3">The stock’s / flow’s volume, composition & the applied technologies’ recovery efficiencies can be estimated with a low level of confidence to assess the share of potentially extractable & usable materials*
Alternative: P10 => G1+G2+G3 = High estimate**</td></tr>
<tr><td>G4</td><td colspan="3">Quantities estimated during the exploration phase, subject to a substantial range of uncertainty & major risk that no mining operation will be implemented to extract these quantities</td></tr>
</table>

Table 18 (continued). * Incremental; ** Cumulative; KMF: Key modifying factors

The knowledge on composition and extractable material content of the in-use stock of permanent magnets in wind turbines is graded with G1. Despite minor uncertainties regarding the recovery efficiencies especially of hydrometallurgical extraction methods, there are detailed prospection and exploration studies on the in-use stock of wind turbines and on the permanent magnets contained. The same score, G1, is granted to treating obsolete PCs in a high-income EU city, as the waste flow's volume and composition can be estimated with a high level of confidence. Applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the extractable raw material potential.

Treating obsolete PCs in a low-income EU city is graded with G2, as the flow's volume and composition can be estimated only with a medium level of confidence due to the involved informal sector, implying high uncertainties about the collection rate, although the recovery efficiencies are well known.

The Enhanced Landfill Mining (ELFM) project at the Remo Milieubeheer landfill site as well as the Bornem project obtain both UNFC-2009 score G2, as the stocks' volume and composition can be estimated with a medium level of confidence, based on data from the sample excavations and the landfill's logbook. In both cases the applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the landfill's extractable raw material potential.

Regarding technical and project feasibility, the ELFM project is graded with F2. Although mature techniques are applied and there is also an established institutional structure with a number of committed partners, the project is still in the feasibility stage with mainly design and planning activities and operations only on a pilot scale. The Bornem project is graded with F3. Even though well-known technologies are applied and the institutional structure is already established with OVAM as committed partner, there are no activities on-going other than test-excavations and trial sorting. The project is still in the pre-feasibility stage with mainly planning activities and operations on a very small scale. Generally, a legal framework for landfill mining has not been developed so far and so various individual licenses are needed to advance a project.

In Scenario 1 (high-income EU city) EU legislation is presumed to be implemented and strictly enforced at national level, while in Scenario 2 (low-income EU city) it is only weakly enforced. Thus, only the most basic requirements are met (i.e. manual vs. manual-mechanical dismantling of PCs) and residues from recycling activities are assumed to be dumped. In Scenario 2, the PC collection infrastructure is assumed to be poor and the public awareness of the importance of WEEE recycling to be low. Due to the active informal sector

there are high uncertainties on collection rates. In both scenarios established technologies and methods for dismantling are applied. So while Scenario 1 is graded with F1, Scenario 2 obtains F2.

As re-using the magnets from wind turbines in their current form (Scenario 1) would be the most evident approach, the re-use scenario obtains F4.1 as the technology is currently "under active development, following successful pilot studies on other deposits, but has yet to be demonstrated to be technically feasible for the style and nature of the deposit in which that commodity or product type is located" (UNECE, 2013). The REE extraction via hydrometallurgical methods (Scenario 2) is graded with F4.2 as the technology necessary to recover some or all of these quantities is currently under research.

While neither the Bornem nor the ELFM project achieve positive results under present economic conditions, reaching cut-off values in the foreseeable future seems, however, possible for both cases. Therefore they are classified as "potentially commercial" (E2). Mining materials from obsolete PCs and from permanent magnets in wind turbines would both yield positive economic results for all investigated scenarios (E1).

8.3 Challenges & Potentials for the Classification of Anthropogenic Resources under UNFC-2009

The specific characteristics of classifying different types of anthropogenic resource deposits, can best be accounted for by UNFC-2009, rather than by any other existing code. A decisive advantage of UNFC-2009 over the two-dimensional systems (like most of the codes from the CRIRSCO family), is the additional third axis, displaying a mining project's "technical feasibility and field project status". The two-dimensional systems only account for the knowledge on composition of a deposit and the economics of a mining project. This might produce a distorted picture, especially where technologies for extraction or processing do not exist yet or are immature and therefore expensive. From a two-dimensional system, one would only get the information, that the project is "uneconomic", while the F-axis under UNFC-2009 offers a more nuanced view by potentially showing the development status of technologies applied in the project.

Further, information on the expected economic performance of mining anthropogenic materials, which are currently in-use, is highly relevant to facilitate decision-making for political and private business stakeholders. However, the classification of anthropogenic in-use stocks would not be possible under frameworks, designed primarily for public reporting purposes, such as the CRIRSCO template, but requires a broader approach, as provided by UNFC-2009.

As shown in the previous Chapter 8.2, interpreting and translating the obtained results into certain values on the different axes for final classification represents a very sensitive step. A major challenge is to account for significant differences among resource deposits, for example how exactly to compare the score “G1” granted to obsolete PCs to “G2” for an old landfill. To make potential resource extraction projects systematically comparable for interested parties, it is of utmost importance to guarantee maximum transparency and consistency. Some of the criteria cannot or hardly be quantified and thus run the risk of being assessed in a highly subjective manner. To prevent the emergence of non-transparent practices, similar to the ones existing in the mining industry, where evaluations are made by a team of experts around a “competent person”, it is vital to apply precise guidelines to evaluate anthropogenic resources in order to fit them into UNFC-2009.

The G-axis and its interpretation has been subject of intense on-going debates amongst classification experts involved with harmonization efforts (UNECE, 2016). Established approaches for geogenic resources to determine estimates for G1, G2, and G3, include deterministic, probabilistic as well as scenario approaches (Primrose, 2016). UNFC-2009, subject to commodity specific specifications, allows for discrete estimates (G1, G2, G3) (incremental method), aligning with the typical minerals approach to uncertainty. Hereby G1 means high confidence, G2 is that additional increment that can be estimated with a reasonable level of confidence, and G3 is the incremental quantities beyond G2 that can be estimated with a low level of confidence. The alternative is using a cumulative scenario approach, especially applied in petroleum, meaning that evaluators estimate low/best/high scenarios using either deterministic or probabilistic methods. Thus low estimate = G1, best estimate = G1 + G2 and high estimate = G1 + G2 + G3. In many cases the scenario method is based on probabilistic methods, where best estimate (G1+G2) is P50 from a cumulative probability distribution. Yet, there is no requirement to present evidence that a probabilistic best estimate of quantities is equivalent to a deterministic best estimate or the sum of incremental G1+G2 (UNECE, 2016).

In principle all those approaches can be applied to anthropogenic resource mining projects. Scenario approaches can be used to assess the impacts of a specific given scenario. Probabilistic methods consider uncertainties partly related to the parameter variability (ontic) and partly related to incomplete understanding and measurements (epistemic) (cf. Lloyd and Ries, 2007). To account for data quality as one of the principal sources of epistemic uncertainty, the pedigree matrix developed by Weidema and Wesnæs (1996) might be a useful tool to evaluate data based on five independent indicators, namely with respect to reliability, completeness, temporal correlation, geographical correlation and further

technological correlation. According to Frändegård et al. (2015) the uncertainties in landfill mining can be divided in scenario uncertainties, resulting from the assumptions and normative choices made (e.g. if the materials are re-deposited in the same landfill site or moved off-site), and parameter uncertainties (e.g. the amount of metals in the landfill or their recovery efficiency). Krook et al. (2012) recommend using stochastic models, e.g. in the form of Monte Carlo simulations, for complex systems and concepts with a deficit in empirically based data, which is the case for landfill mining due to the absence of successfully accomplished large-scale projects. Based on such models it can be shown, how different values for different parameters influence the final result. The parameters identified as most important can then be subject to a thorough sensitivity analysis.

As the UNFC-2009 is a project-based system, the evaluation and classification of dynamic waste flows represents a major challenge (UNECE, 2010). Here, the anthropogenic resources community might benefit from previous work and efforts made by the working group on renewable energies facing similar problems. In the UNFC-2009 specifications for renewable energies a “project” is defined as “the link between the renewable energy source and the sales quantities of energy products and provides the basis for economic evaluation and decision-making” (UNECE, 2014). Correspondingly, for a constantly renewing waste flow, such as obsolete PCs, system boundaries must be arbitrarily chosen, e.g. on a spatial and / or temporal level, in order to demarcate a mining project.

Under the CRIRSCO template, the G-axis expresses exclusively the level of geological knowledge and confidence associated with a specific part of a mineral resource deposit. However, petroleum evaluators and more recently the renewable energy community use the G-axis as a general indicator of the range of uncertainty in the quantities being reported (UNECE, 2014). Risks and rewards for the investor are clearly acknowledged as being linked to uncertainties and/or variability in the source of energy, the extraction efficiency, product prices and market conditions including policy support mechanisms (UNECE, 2014). For anthropogenic resources, the different types and sources of uncertainties within a mining project must be equally well understood (cf. Figure 12 and Figure 13). In the case studies at hand the approach used by the mineral community was followed, displaying only the knowledge on composition and the recoverable share of materials on the G-axis. Factors related to the socioeconomic sphere are represented on the E-axis, whereas factors regarding the industrial and technical domain are shown on the F-axis. However, there might be overlaps as shown in Figure 6, for instance for waste flows requiring a collection system, which is embedded in a specific legal, cultural and societal environment and which has a considerable impact on the composition and size of the minable deposit.

The feasibility of extraction by a defined development project or mining operation is reflected on the F-axis. F1 means that there is an existing and well-enforced legal framework and societal, institutional and organizational structures, fully mature technologies applied and ongoing activities. One or several of those criteria being unfulfilled will result in the lower categories F2 – F4. In the early stages of evaluation, the project might be defined only in conceptual terms, while more mature projects will be defined in greater detail. To classify currently non-extractable quantities due to, for instance, site constraints, technology limitations or other constraints, the UNFC-2009 category E3F4G1-4 ("additional quantities in place", cf. Figure 3) can be used (UNECE, 2014, UNECE, 2010). Yet, for evaluating the hypothetical mining of a certain in-use stock under current conditions, it is justified to use the E-axis' full range (E1 – E3) for the final classification, and not exclusively "E3". To indicate the in-use stock's current unavailability for mining, "F4" shall be granted by default on the F-axis, with F4.1 – F4.3 displaying the maturity of extraction and processing technologies.

Regarding the economic viability, a positive NPV will result automatically in E1 on the E-axis. In case of a negative NPV, cut-of values for key parameters decide, whether there are reasonable prospects for future economic extraction (E2) or not (E3). To determine the most likely and realistic scenario assumptions regarding future developments of key modifying factors, such as treatment costs or market prices for secondary products, it might be worthwhile to set up a panel with different independent experts. As for parts of anthropogenic materials, extraction is not (yet) economically viable under current conditions, the systematic integration of non-monetary effects will be of high priority, to create (additional) financial incentives in pull situations or to outperform the minimum legal requirements in push situations. Social and environmental externalities (e.g. eliminating sources of pollution, supply security) tend to generate additional benefits and should therefore be monetized and included in the evaluation. In light of innumerable existing non-market valuation methods, this issue is, however, far from being solved easily.

A methodological framework, including common definitions, can help to establish a knowledge base on the minable resource potential present in the anthroposphere. Coordination and networking between researchers, public authorities and private business stakeholders is indispensable to benefit from benchmarking and from sharing best practices. Standards and guidelines for a comprehensive and sustainable recovery of materials from wastes should be developed and / or harmonized. The political and legal conditions for realizing urban mining projects are to be clarified and if necessary revised (e.g. limit values for potential re-application of recovered materials in road construction). EU directives related to waste and materials should not only be implemented, but also be strictly enforced at

national levels. In addition, organizational structures have to be created, e.g. local collection infrastructure including awareness raising measures to educate people. Extensive applied and theoretical research is required in terms of technology development and innovation. Also the application of existing technologies to new resource deposits is worth to be further examined, such as the hydrometallurgical extraction of rare earth elements from permanent magnets, or sorting facilities used for excavated wastes instead of for fresh wastes.

In order to go beyond indicative or even speculative resource classifications within the framework of UNFC-2009, better communication and cooperation amongst different stakeholders along the value chain, including the wider society, is necessary. The availability of high quality data on anthropogenic stocks and flows will be crucial for future classification efforts. Therefore existing methods and practices for knowledge production and data collection on anthropogenic resources will have to be changed (or revised) and standardized. For waste flows, detailed records and cross-border communication between involved stakeholders have to be facilitated (e.g. for E-waste). Information on in-use stocks should be made available to recyclers and decision-makers to the highest possible extent (e.g. production data by manufacturers, regional data bases on built-in components and resources in buildings). For still active landfills, it has to be ensured that operators record, which wastes are placed where in a landfill and when. This will facilitate potential future mining, but also detailed modelling of landfill gas emissions, leachate production and environmental risk assessments (Ford et al., 2013).

Currently existing anthropogenic materials inventories are often produced by isolated national institutions or consultants. Frequently the resulting databases and reports lack a clear structure and – more importantly - regular updates. Therefore, it is recommendable to set up a network of competent institutions and country experts at national and EU level to report some key information on anthropogenic stocks and flows with special focus on their resource potential, such as size, composition, status regarding ongoing recycling activities etc. EU funded projects, such as SmartGround, VERAM, ProSUM and the COST action MINEA, represent first important steps to assist better-informed decision-making by political actors as well as by industry, and to increase knowledge and transparency about EU raw materials (MINEA, 2016, ProSUM, 2016, SmartGround, 2016, VERAM, 2016). Moreover, show cases and reference documents on best available techniques including regular updates should be provided by key institutions, such as the European Commission.

9. CONCLUSIONS & OUTLOOK

This chapter concludes this thesis by putting the study in a wider context, and presenting some ideas and suggestions for future research.

As an integral part of resource planning strategies, the efficient use of resources, including urban mining, recycling and re-use, and the management of waste, has gained increasing importance and will continue to do so in the upcoming decades. UNFC-2009 has proven to be highly flexible and to be subject to regular negotiations and re-definitions in response to stakeholder needs and changes in society and technology. This dissertation has presented a new methodology, which can be used to determine coherently the UNFC-2009 categories of minable materials contained in different anthropogenic deposits, in different settings and under changing conditions.

To begin with, the fundamental applicability of UNFC-2009 to anthropogenic resources has been proven successfully. By providing a first set of methods, indicators and criteria, a landfill mining project was mapped in analogy with the axes and classes of the UNFC-2009 framework. In order to broaden the classification scope by including further types of anthropogenic resources, a general evaluation concept was developed by scrutinizing the specific characteristics of various different types of anthropogenic resource deposits, to see, how they can fit into a classification system, which has originally been designed for geogenic resources. In order to prove the newly developed methodology to be operational for a range of anthropogenic resources, it was applied to case studies for landfill mining (obsolete stocks), recycling of obsolete personal computers (waste flows) and recovering materials from in-use wind turbines (in-use stocks), resulting in different classification results under UNFC-2009. Contrasting the results to previous similar feasibility studies, it turned out that the identified factors influencing the final classification can be widely generalized. Moreover, the factors were found to be similar for different types of anthropogenic resources. Yet, their individual weight differs in the respective case studies and again in the different scenarios, where the timing of mining is varied, different legal, institutional, organizational and societal settings are compared, and diverse choices for technological options are made.

Recycling the entire in-use stock of permanent magnets from wind turbines in Austria would yield the best economic results compared to mining obsolete PCs and landfill mining. Although currently not available for mining, it is crucial to know the economic performance of hypothetically mining in-use stocks under current conditions as detailed as possible, to develop suitable resource recovery strategies for future waste flows and obsolete stocks, and to avoid dissipation and dilution losses. Moreover, the information on the economic viability

of a hypothetical mining project including the availability of mature recycling technologies is of high relevance for decision makers, since expected positive economic results might make future laws and regulations on recycling obsolete. In some cases, information on the recyclability of in-use materials might be useful for manufacturers to improve their product design to facilitate future resource recovery.

PC recycling in a high-income EU member state yields overall better economic results than in a low-income EU member state, due to higher collection and source separation rates and in spite of higher labour costs. Moreover, other EU directives, such as the landfill directive, are assumed to be better enforced in a high-income country, which makes alternative disposal options unattractive and expensive. All these factors are strongly dependent on the legal, institutional, organizational and societal structures, in which a project is embedded.

In the landfill mining case studies it became clear, how future developments of key economic parameters (e.g. metal and land prices) can change the final results. These findings are of particular relevance for long-term resource planning purposes, as for parts of anthropogenic materials, mining is not (yet) economically viable under current conditions, but possibly in the foreseeable future, with changing modifying factors. However, taking adequate measures should not only start shortly before we run out of resources. It is ideally planned well in advance and carefully prepared.

This methodology will assist various stakeholders to classify anthropogenic resource deposits and prioritize potential resource extraction projects in a systematic and transparent way. This is relevant for political actors, such as governments and institutions involved with strategic resource planning to anticipate future supply, but also for private business stakeholders, such as investors interested in resource recovery undertakings. Further, waste management operators would benefit from information, on how to optimize waste management practices. By illustrating different settings of resource classification, it can be shown what political, legal or other adjustments might be needed to enhance a recovery project's performance (e.g. increasing public awareness on source separation of e-waste). Combining aspects of waste and resource management is hereby a key challenge. In this context, also the systematic integration of non-monetary effects will be of high priority to create (additional) financial incentives by monetizing social and environmental externalities (e.g. eliminating sources of pollution) via subsidies. Further research on the most suitable non-market valuation methods is needed.

Under the UN Sustainability Development Goal "Responsible consumption and production" the sustainable management and efficient use of natural resources as well as a substantial

reduction of waste generation through prevention, reduction, recycling and reuse, shall be achieved by 2030. However, the knowledge on anthropogenic resource deposits is still limited. The major contribution of this thesis is to lay a foundation for a comprehensive knowledge base of various existing potentially minable anthropogenic resources. The systematic incorporation of anthropogenic resources into the existing primary resource classification system UNFC-2009 seems like a coherent and consequent step towards a comprehensive picture of totally available and potentially minable raw materials, and will certainly help to close the knowledge gap on anthropogenic deposits. The recommendation of the UNECE Expert Group on Resource Classification to “explore the potential applicability of UNFC-2009 to anthropogenic resources and to report its findings to the eight session” (UNECE, 2016) shows that even a community, which is dominated by the primary sector, has started acknowledging the importance of anthropogenic resources. Although the beginning has been made for landfill mining and some other selected waste streams, further case studies accounting for diverse settings of mining anthropogenic resources are needed to further refine the criteria and procedures for assessing resource availability.

The ultimate aim is to obtain a complete overview of existing and potentially extractable anthropogenic resource inventories and to create a common platform for evaluating geogenic and anthropogenic resource deposits on an equal footing. Also, criticality considerations can be extended by including anthropogenic material stocks. Once established, the integration of geogenic and anthropogenic resources into one framework will facilitate comprehensive resource assessments in consideration of the raw materials present in both the lithosphere and the anthroposphere.

10. LIST OF FIGURES

11. LIST OF TABLES

12. LIST OF ABBREVIATIONS & ACRONYMS

AAPG: American Association of Petroleum Geologists

Al: Aluminum

B: Boron

CAPEX: Capital expenditures

CIM: Canadian Institute of Mining, Metallurgy and Petroleum

CMMI: Council of Mining and Metallurgical Institutes

Cu: Copper

CRIRSCO: Committee for Mineral Reserves International Reporting Standards

DCF: Discounted Cash Flow analysis

Dy: Dysprosium

ELFM: Enhanced Landfill Mining

EPR: Extended Producer Responsibility

Fe: Ferrum

IAEA / NEA: International Atomic Energy Agency / Nuclear Energy Agency

ICM: International Council on Mining and Metal

IW: Industrial Waste

JORC: Joint Ore Reserves Committee

LCA: Life-cycle assessment

LFM: Landfill Mining

MFA: Material Flow Analysis

MSW: Municipal Solid Waste

NAEN: National Association for Subsoil Use Auditing

Nd: Neodymium

NF-metals: Non-ferrous metals

NPD: Norwegian Petroleum Directorate

NPV: Net Present Value

OPEX: Operating expenses

OVAM: Public Waste Agency of Flanders

PC: Personal computer

PERC: Pan-European Reserves and Resources Reporting Committee

Pr: Praseodymium

PRMS: Petroleum Resources Management System

PRO: China Petroleum Reserves Office

RDF: Refuse Derived Fuel

REE: Rare earth elements

SAMREC: South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves

SI: Supplementary Information

SPE: Society of Petroleum Engineers

SPEE: Society of Petroleum Evaluation Engineers

SME: Society for Mining, Metallurgy, and Exploration, Inc

SRF: Solid Recovered Fuel

UNECE: United Nations Economic Commission for Europe

UNEP: United Nations Environment Programme

UNDP: United Nations Development Programme

UNFC-2009: United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009

USSR: Union of Soviet Socialist Republics

USGS: United States Geological Survey

WEEE: Waste electrical and electronic equipment

WPC: World Petroleum Council

WT: Wind turbines

Zn: Zinc

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14. ANNEX (PAPERS I – III)

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Framework for the evaluation of anthropogenic resources: A landfill mining case study – Resource or reserve?

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ABSTRACT

The goal of this study is to apply the natural resource classification framework UNFC-2009 to a landfill-mining project to identify the landfilled materials as potential anthropogenic 'resources' (reasonable prospects for eventual economic extraction in the foreseeable future) or 'reserves' (current economic extraction possible), and to reveal critical factors for the classification of the project. Based on data from a landfill-mining project in Belgium, the focus of the evaluation was set on technological options and economics, with a material flow analysis quantifying relevant material and energy flows and a discounted cash flow analysis including Monte Carlo simulations, exploring the project's socioeconomic viability. Four scenarios have been investigated, representing different alternatives for the combustible waste fraction's thermal treatment (gas-plasma technology vs. incineration) and for specific stakeholder interests (public vs. private perspective). The net present values were found to be negative for all four scenarios, implying that none of the project's variations is currently economically viable. The main drivers of the economic performance are parameters related to the thermal treatment of the combustible waste fraction as well as to the sales of recovered metals. Based on required future price increases for non-ferrous metals or electricity to make the project economically viable, the scenarios resulted in different final resource classifications. Although the applicability of UNFC-2009 to landfill mining has been proven successfully, further research is needed to define generally suitable criteria for categorizing various kinds of anthropogenic resources under UNFC-2009. This will allow for fair comparisons between naturally occurring and anthropogenic resource deposits.

1. Introduction

While the exploration and subsequent evaluation of primary resource deposits is a well-established discipline, the knowledge on anthropogenic resource stocks and their availability for reuse and recycling is very limited. To forecast supply coverage of specific raw materials, studies often compare the total amount of anthropogenic resources to only that geological stock estimated to be economically extractable, i.e. the reserves. This is, however, an asymmetrical comparison, as there are materials also in the anthroposphere that are not even hypothetically extractable. Various authors, such as Johansson et al. (2013), Weber (2013) or Wallsten et al. (2013) have advocated for establishing a link between mining virgin materials and mining anthropogenic resources. Furthermore, there have been concrete attempts to map anthropogenic resources in classification codes for natural resources, amongst others by Lederer et al. (2014) and Mueller et al. (2014). The integration of anthropogenic resources into the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) (UNECE, 2004, 2013) would facilitate comparisons between countries' total natural and anthropogenic inventories and hence lead to better estimates of total world stocks.

The commodity-specific specifications for solid minerals under UNFC-2009 (CRIRSCO, 2013) define mineral resources as "concentration of naturally occurring materials in or on the Earth's crust

Abbreviations: DCF, discounted cash flow analysis; ELFM, enhanced landfill mining; GP, gas-plasma technology; INC, incineration; IW, industrial waste; LCA, life cycle assessment; LFG, landfill gas; LFM, landfill mining; MFA, material flow analysis; MSW, municipal solid waste; NFM, non-ferrous metals; NPV, net present value; PV, present value; RDF, refused-derived fuel.

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[1] http://iwr.tuwien.ac.at/anthropogenic-resources/home.html.

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with reasonable prospects for eventual economic extraction, either currently or at some point in the future". Mineral reserves are resources that are "known to be economically feasible for extraction under present conditions". Modifying factors (legal, market, economic, technological etc.) determine the permanently evolving boundaries between 'resources' and 'reserves'.

Whether this concept can be applied to anthropogenic deposits in a similar way to distinguish 'resources' from 'reserves', will be attempted in a first case study on landfill mining: mining of waste deposits, compared to other resource recovery undertakings, exhibits the most similarities with traditional mining projects. Moreover, in the EU there is a considerable potential of between 150,000 and 500,000 historic landfills, which could deliver a significant stream of secondary materials and energy, justifying the exploration and subsequent evaluation of landfill mining projects (Jones et al., 2013; Krook et al., 2012). The first report of a landfill-mining project dates back to 1953 in Israel, aiming to excavate the waste of an old landfill and process it for use as a soil amendment (Savage et al., 1993). This project stayed the single documentation of landfill mining until the 1980s. Most of the following early landfill-mining projects were primarily motivated by local pollution issues or increase of landfill capacities (Bockreis and Knapp, 2011; Hogland et al., 2004) rather than by recovering landfilled materials as secondary resources. Until today landfill mining focusing chiefly on resource recovery has not been commercialized on a large scale. This is mainly due to the fact that factors modifying the socioeconomic viability of landfill-mining projects differ for each site and are often linked to high uncertainties (Hogland et al., 2010; Kaartinen et al., 2013). Therefore, similar to a conventional mine, each landfill needs to be investigated on a case-by-case basis, ideally following a standardized procedure.

The goal of this study is to apply the universal primary resource classification framework UNFC-2009 to a landfill-mining project in order to categorize the landfilled materials either as anthropogenic 'resources' or 'reserves' and to identify critical factors for the resource classification of the project. Therefore, an operative evaluation procedure has been developed and applied to a case study on enhanced landfill mining (ELFM) (ELFM, 2013; Jones et al., 2013). Four scenarios have been investigated, representing different technological alternatives for the combustible waste fraction's thermal treatment (gas-plasma technology vs. incineration) and for specific stakeholder interests (public vs. private perspective). Material flow analysis (MFA) is used to quantify the extractable and potentially usable share of the landfill's resource potential. Subsequently, the economic viability of mining the identified extractable raw materials is explored from different stakeholders' perspectives, based on a discounted cash flow (DCF) analysis, including an uncertainty and sensitivity analysis by using Monte Carlo simulations. Finally, the classification of the four scenarios is attempted under UNFC-2009.

2. Materials and methods

2.1. Conceptual evaluation framework

To identify the landfill's resource potential, being economically feasible for extraction under present conditions ('reserves') or in the foreseeable future ('resources'), three basic dimensions need to be considered: first, the knowledge about the composition and size of the resource stock, second, the technical feasibility of extraction in terms of quantity and quality, and third, the socioeconomic viability based on a financial evaluation including also not directly monetized effects, the so-called "modifying factors", such as environmental, social, legal or market aspects (CRIRSCO, 2013). These three dimensions are reflected in the generic principle-based

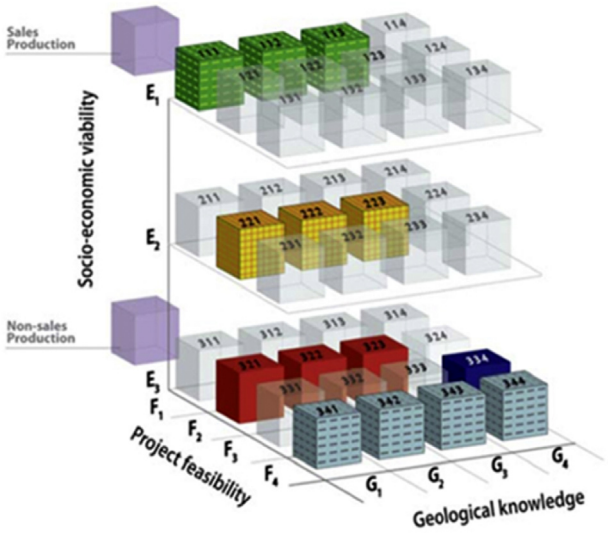

Fig. 1. United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) (UNECE, 2013). 1st digit (E) – "Socio-economic viability"; 2nd digit (F) – "Field project status and technical feasibility"; 3rd digit (G) – "Knowledge on geological composition". Reproduced courtesy of the United Nations Economic Commission for Europe.

UNFC-2009 classification system, which can either be directly applied or used as a bridging tool to harmonize, for instance, existing different national resource codes. Like in the two-dimensional systems based on USGS (1980), there are axes describing "socioeconomic viability" (E) and "knowledge on geological composition" (G), but UNFC-2009 includes an additional third axis relating to the "field project status and technical feasibility" (F). These criteria are each subdivided into categories and sub-categories, which are then combined in the form of classes or sub-classes, creating a three-dimensional system by using a numerical coding scheme (UNECE, 2013) (see Fig. 1). Detailed explanations and definitions of the single categories F1–4, E1–3 and G1–4 can be found in Annex 1 of UNECE (2013).

In concrete terms, UNFC-2009 is applied to the case study on enhanced landfill mining (ELFM) by first developing four alternative scenarios, representing different technological options for the combustible waste fraction's thermal treatment (gas-plasma technology vs. incineration) and for specific stakeholder interests (public vs. private perspective). To classify a natural resource deposit before starting actual mining activities, the stages "prospection", "exploration" and "evaluation" have to be run through (Torries, 1998). In Table 1 those four phases are linked to the goals of a landfill-mining project and then mapped each to the respective UNFC axis considered as suitable. Material flow analysis (MFA) (Brunner and Rechberger, 2004) is a suitable tool for the first two phases in order to identify and later characterize relevant anthropogenic stocks and flows (Lederer et al., 2014; Wallsten et al., 2013). Skipping the prospection phase in this study, MFA first quantifies the landfill's total resource potential, and then the extractable and potentially usable share of materials as a basis for the following economic analysis. The socioeconomic viability of mining the identified extractable raw materials is explored, based on a discounted cash flow (DCF) analysis. At first, only direct costs and revenues, representing a private investor's micro perspective are included, while in a second step, non-monetary modifying factors that might significantly impact the project's economic viability are evaluated in a public entity's macro view. Specifically, greenhouse gas (GHG) emissions of the landfill-mining project are compared to a "Do-Nothing" scenario. Additionally, the impact of extended landfill aftercare obligations is investigated, and a conservative discount

Table 1
Operative procedure for evaluating a landfill-mining project.

Evaluation steps	Goal	Localization in UNFC-2009	Methods for decision foundation	Preliminary classification indicators
Prospection	First estimates on resource potential: selection of a project	–	Macro scale MFA; analysis & evaluation of landfill statistics & literature data on waste composition	Behets et al. (2013) (1) Type of landfill (2) Period of landfilling (3) Volume of the landfill (4) Land use of the landfill site (5) Distance to roads, navigable waterways and railway depots (6) Proximity to other landfills
Exploration	Gain knowledge on size & composition of a specific deposit: landfill's total resource potential	G-axis	Detailed investigation of a specific landfill: data from waste disposal log book & waste sampling & analysis	(1) Landfill's content & the uncertainties about it
	Field project status & technical feasibility of recovery & valorization regarding quantities & quality: amount of extractable & potentially usable resources	F-axis	Micro scale MFA with specific recovery efficiencies & modeling of technological alternatives	(1) Uncertainties regarding project feasibility (2) Maturity of technology (for extraction & valorization of materials)
Evaluation	Socioeconomic viability including direct financial effects & non-monetary modifying factors	E-axis	DCF analysis & cut-off values for key parameters	(1) Net present values (NPV) (a) NPV > 0: reserve (b) NPV < 0: resource or not? Factors to reach cut-off values for key parameters realistic?
Classification	Combination of all criteria & classification under UNFC-2009			

MFA = material flow analysis, DCF = discounted cash flow analysis.

rate is assumed. Uncertainties originating from model input parameters of the economic analysis are considered in an uncertainty and sensitivity analysis by performing Monte Carlo simulations. Combining all previous criteria the four scenarios are finally classified under UNFC-2009. The preliminary classification indicators shown in Table 1 are discussed in Section 3.3.

2.2. The enhanced landfill mining (ELFM) case study

An evaluation of landfilled materials with special focus on various technological options and economics is carried out for the enhanced landfill mining (ELFM) project at the Remo Milieubeheer landfill site in Houthalen-Helchteren, Belgium (ELFM, 2013; Jones et al., 2013), in the following called "ELFM project". Due to its scale, the open communication strategy and the detailed level of documentation, this project has been chosen as a case study for this work. Moreover, ELFM is not only aiming to stabilize the waste materials, but to valorize to the maximum extent possible the various waste streams either as material or as energy (Jones et al., 2012). The landfill received over 16 million metric tons of waste from the 1970s onwards and covers today an area of 1.3 km^2. It contains a roughly equal share of municipal (MSW) and industrial (IW) solid waste and is engineered in compliance with Flemish legislation and the EU Landfill Directive.

The landfilled waste is planned to be almost entirely excavated over a period of 20 years, with operations starting in 2017 (Jones et al., 2013). The present study makes some assumptions that diverge from the ELFM consortium's plans: metals (ferrous and non-ferrous) as well as the stone fraction will be sold after recovery, while paper, plastics, wood and textiles will be entirely converted into refused-derived fuel (RDF) and energetically recovered exclusively for electricity generation in a newly built on-site waste-to energy plant. In one scenario a gas-plasma technology is used, like in the ELFM project (Bosmans et al., 2012), and in an alternative scenario RDF is thermally treated in a state-of the art fluidized bed incinerator. In the ELFM project, the vitrified slag resulting from the gas-plasma process is used as construction material. However, as this has not been proven beyond laboratory tests yet (Spooren et al., 2013), this study assumes that the vitrified slag is, at least temporarily, re-landfilled. At the end of excavation activities the regained land will be sold, while the ELFM project restores nature without any land sales (Van Passel et al., 2013). Within the ELFM project extensive sampling activities and characterization studies of the waste samples have been performed to gain knowledge about the landfill body's quantitative and qualitative composition (Quaghebeur et al., 2012). In addition, consistency checks have been completed based on the available log book data on the waste deposition at the site (ELFM, 2013). Table 2 presents the average composition of the landfill. The fine fraction of the industrial waste contains a 6 ± 1% share of fine metals, while the MSW fine fraction only contains 3 ± 1%. Those fine metals are composed of 97% ferrous and 3% non-ferrous metals. The unknown fraction is most probable a mixture of degraded organic materials and sand (Quaghebeur et al., 2012).

Table 2
Average composition of the landfill (Spooren et al., 2012) presented as mean values and absolute standard deviations for municipal solid waste (MSW) and industrial waste (IW).

	MSW (mean value ± std. dev. abs., wt%)	IW (mean value ± std. dev. abs., wt%)
Plastics	20 ± 8	5 ± 5
Textiles	7 ± 6	2 ± 1
Paper/Cardboard	8 ± 6	2 ± 1
Wood	7 ± 2	7 ± 2
Glass/Ceramics	1 ± 1	1 ± 1
Metals	3 ± 1[a]	3 ± 3[a]
Minerals/Stones	10 ± 4	10 ± 10
Fines <10 mm	40 ± 7[b]	62 ± 7[b]
Unknown	4 ± 4	8 ± 6

Wt% = dry weight percentage. Uncertainty ranges are based on own assumptions.

[a] 2.4% ferrous metals, 0.6% non-ferrous metals (Quaghebeur et al., 2012), out of which 30% are assumed to be copper and 70% aluminum (e.g. Mitterbauer et al., 2009).

[b] IW fine fraction: 6 ± 1% of fine metals, MSW fine fraction: 3 ± 1% (Quaghebeur et al., 2012). Fine metals are composed of 97% ferrous and 3% non-ferrous metals. While the copper share is given (Quaghebeur et al., 2012), we assume a 3:7 copper:aluminum ratio (e.g. Mitterbauer et al., 2009).

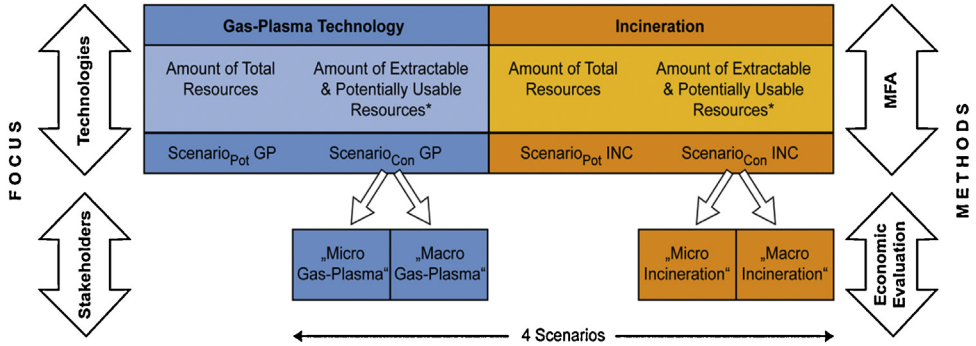

Fig. 2. Investigated scenarios focusing on technological options and stakeholder interests. In the conservative scenarios state of the art transfer coefficients were applied (*).

2.3. Scenario and uncertainty analysis

Based on the data and information available from the ELFM project, in total four alternative scenarios representing different technological options and stakeholder interests have been developed and investigated (see Fig. 2). Transfer coefficients have been defined for the processes contained in the material flow model, determining for each scenario the material and energy flows of the landfill-mining project. The transfer coefficients are specified on the level of material fractions defining the partitioning of the material and energy inputs to the various output flows of a process (see Supplementary Information (SI), Tables 1 and 2).

"Potential" scenarios (Scenario$_{Pot}$) are developed to quantify the landfill's total resource potential, whereas the "conservative" scenarios (Scenario$_{Con}$) express the share of the resource potential, which is extractable and potentially usable as secondary raw materials under present technological conditions.

The conservative scenarios serve as a basis for the subsequent economic evaluations, distinguishing between the gas-plasma technology and incineration as possible alternatives for energy recovery. As the economic analysis should be based on present technological and market conditions, the scenarios displaying the landfill's total resource potential are not further investigated.

For each thermal recovery option – for a gas-plasma technology, as planned for the ELFM project, and for a fluidized bed incineration as alternative scenario – an economic evaluation from a private investor's micro perspective and from a public entity's macro view, by including non-monetary modifying factors, is carried out (see Fig. 2). The focus was deliberately put on energy recovery options to contrast a more established method (incineration) to the still immature gas-plasma technology envisaged in the original project. To facilitate a direct comparison, the incinerator – just like the gas-plasma technology in the ELFM project – is assumed to be newly built on-site, instead of exporting the combustible waste fraction to an already existing plant off-site. As there is no market for district heating in Belgium, instead of using a combined heat and power incinerator, a plant with maximum electricity output is assumed. Modeling different separation and material processing technologies, however, is beyond the scope of this study.

Since many model input parameters of the evaluation are associated with large uncertainties, an uncertainty and sensitivity analysis has been carried out by performing Monte Carlo simulations in @Risk (Palisade Corporation, 1997). Uncertainties in recovered material quantities, in estimates for costs and prices are considered and analyzed. Plausible data ranges have been defined based on literature, expert interviews as well as on own estimates. Detailed assumptions on the parameters' distributions are presented in SI, Table 4. By identifying the main drivers of economic performance the robustness of the evaluation is tested. Also discount rates are defined as uncertain model parameters in order to investigate the influence of discount rate variation on the outcomes of the economic analyses.

2.4. Material flow analysis

Based on the ELFM project's data the physical models of all relevant material and energy flows have been set up (see Fig. 3 and SI, Fig. 1), following the method of material flow analysis (MFA) (Brunner and Rechberger, 2004) and using the STAN software (Cencic and Rechberger, 2008).

Scenario$_{Pot}$ GP (see SI, Fig. 1) assumes ideal conditions, with maximum separation and sorting efficiencies for the material flows and optimal energy recovery via an on-site gas-plasma technology and electricity generation. The fine fraction is treated such that a high-calorific fraction is recovered for RDF production (approximately 8% of total fines, Quaghebeur et al., 2012). Besides, a maximum recovery efficiency of fine metals for material recovery is assumed. The remaining fines are washed in a chemical–physical treatment process and sold as construction material. Scenario$_{Pot}$ INC assumes the same, except that in this case RDF is thermally treated in a state-of-the art fluidized bed incinerator on-site.

In Scenario$_{Con}$ GP and Scenario$_{Con}$ INC, that part of the resource potential, which is under current, established technological conditions extractable and potentially usable, is determined, again for both thermal treatment options, gas-plasma technology and incineration. Efficiencies have been applied for the MFA process *Excavation*, *Separation & Sorting*, similar to those of the first process step in a mechanical biological treatment plant (Busschaert, 2014). Also for the processes *Preparation RDF*, *Treatment Fines* and *Monoincineration* transfer coefficients referring to state-of-the-art plants are used. In this case fine metals are only partially recovered (50%, Quaghebeur et al., 2012). Currently, the expected poor economic return does not justify the use of further fine treatment technologies. As the remaining fines are highly contaminated and cannot be used as construction material without further treatment (Spooren et al., 2013), they need to be re-landfilled on site.

For simplicity reasons the annual amount of wastes being excavated together with the composition of wastes are assumed to be constant over the whole operation period of 20 years (807 kt/a).

2.5. Economic evaluation and modifying factors

The above-mentioned scenarios focus primarily on recovery efficiencies of materials from the landfill and the technological options for thermal treatment of the combustible waste fraction. In order to examine also the socioeconomic viability of mining the identified extractable and potentially usable raw materials, a discounted cash flow (DCF) analysis is performed, by calculating the net present values (NPV) before taxes for each scenario, based on

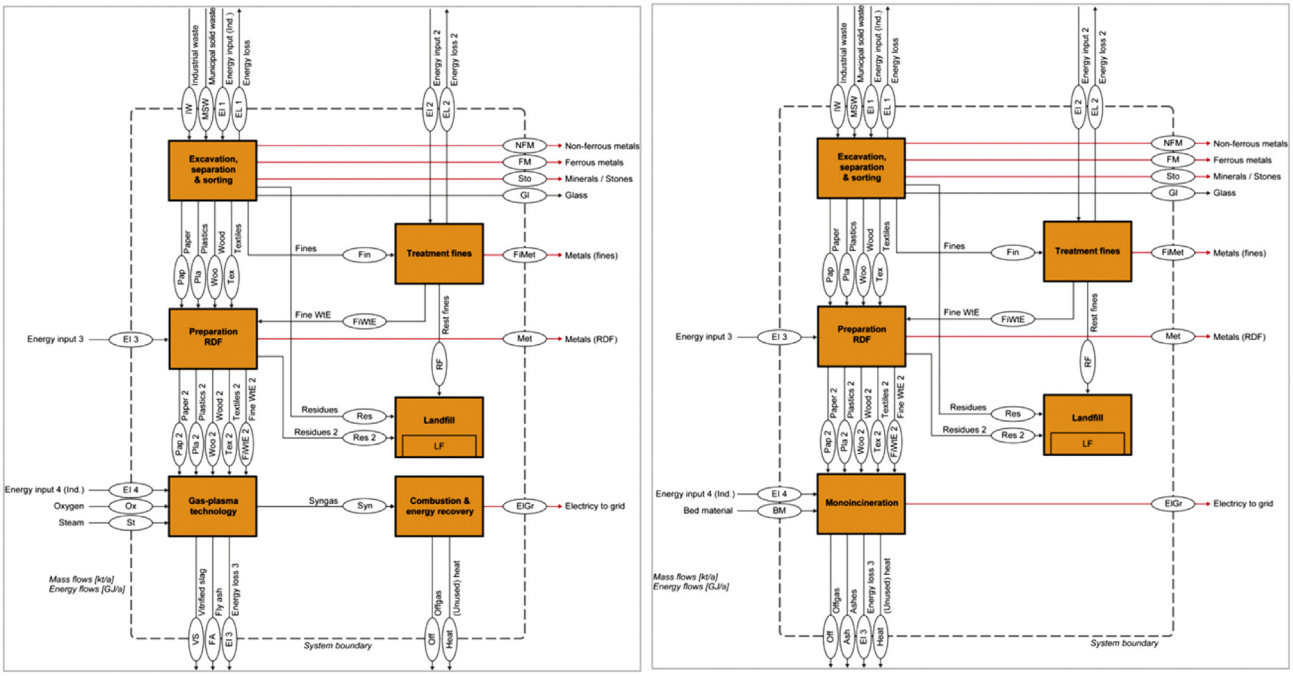

Fig. 3. Illustration of the qualitative material flow models for the conservative scenarios for gas-plasma technology ($Scenario_{Con}$ GP, l.) and incineration ($Scenario_{Con}$ INC, r.): under present, established technological conditions extractable and potentially usable secondary raw materials. Ind. = Indirect, i.e. does not change energy content of flow.

material and energy flows from the conservative MFA models (see Fig. 3).

For each energetic valorization option, i.e. for gas-plasma technology ($Scenario_{Con}$ GP) and incineration as alternative scenario ($Scenario_{Con}$ INC), an economic evaluation from a private investor's micro perspective and from a public entity's macro view, by including non-monetary modifying factors, has been performed.

Using a DCF analysis, which is also widely used in the evaluation of mining projects of primary resources (Torries, 1998), it is shown if and under which conditions the whole landfill mining project can be classified as a 'reserve' or a 'resource'. In the mining sector, the term 'reasonable prospects for eventual economic extraction' implies according to CRIRSCO (2013) an expert judgment by a so-called "competent person" "in respect of the technical and economic factors that are likely to influence the prospect of economic extraction, including the approximate mining parameters". This is, however, a quite intransparent and non-standardized procedure relying heavily on the personal experience of the respective competent person. According to Sinclair and Blackwell (2002) "optimal procedures for resource/reserve estimation are not cut and dried, but contain an element of 'art' based on experience, that supplements technical routine and scientific theory."

Eq. (1): discounted cash flow (DCF) analysis: formula net present value (NPV) (Fisher, 1965)

$$\mathrm{NPV} = -C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_r}{(1+r)^T} \quad (1)$$

The NPV is computed by subtracting the initial investment cost ($-C_0$) from the sum of the discounted cash flows (C) and can be seen as the expected profit of the investment (Eq. (1)). It takes the time value of money (T = time given in years) and all the relevant cash flow elements over a pre-defined period into account, which are discounted by the discount rate r. From the structure of this formula it is evident that present values of cash flows are lower the farther they lie in the future and the higher the discount rate is chosen.

A positive NPV implies that a project is economically viable. Consequently, the deposit to be evaluated can be classified a 'reserve'. In this context feasibility studies in the mining sector often provide the "cut-off grade", which is defined as the level of mineral that is used to discriminate between ore and waste within a given ore body, i.e. the level below which extraction is not economically viable (Dagdelen, 1993). With increasing costs of mining the "cut-off grade" increases, whereas it decreases in light of rising commodity prices, as high prices justify mining also low-grade deposits. Thus, the cut-off grade reacts to and reflects the boundary conditions of mining. Generally speaking, a value for a relevant parameter is calculated, which, depending on modifying factors, represents a threshold between positive and negative NPVs. In the study at hand this concept is applied to the landfill: the cut-off prices of non-ferrous metals and of electricity are calculated. If the NPV turns out to be negative, ruling out the deposit to be a 'reserve', the calculated "cut-off grade" serves as a basis for assessing whether the deposit can be labeled a 'resource' or not.

By comparing the cut-off prices to the respective actual prices, it becomes clear how these parameters need to change to turn the NPV at least into "0" and so to reach the break-even point. Based on historical and prospected future price developments, the calculated factor for a neutral NPV can be judged realistic or not to reach in the near future.

Thus, the cut-off grade allows making predictions about whether there are reasonable prospects for economic extraction in the foreseeable future or not, and serves therefore as decisive indicator for the following resource classification.

In the micro evaluation only direct, i.e. purely financial, costs and revenues on the microeconomic level are covered, while non-monetary effects and also potentially existing subsidies or other forms of financial incentives are intentionally neglected. Subsequently, the evaluation from the macro perspective of a public entity is performed to quantify the effects of external effects on the economics of the project, in natural resource classification systems called "modifying factors" (CRIRSCO, 2013). The macro perspective can highlight relevant factors that need to be included

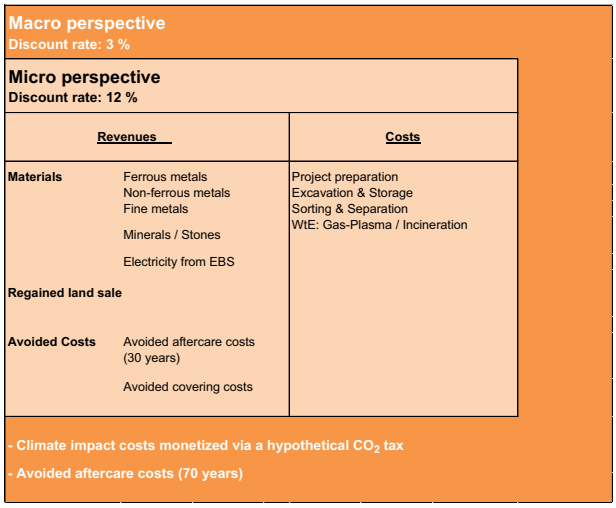

Fig. 4. Micro vs. macro perspective: costs & revenues.

(i.e. monetized) in the economic assessment to create (additional) economic incentives for landfill mining. In the study at hand potential greenhouse gas (GHG) emission savings of a landfill mining project compared to a "Do-Nothing" scenario are valued with a hypothetical CO_2 tax at 10 €/t CO_2 equiv., to show exemplarily how modifying factors can be included in the evaluation (see Fig. 4). In addition, a lower discount rate is applied and longer aftercare obligations in the "Do-Nothing" scenario are assumed, meaning that the avoided emissions and the avoided aftercare costs are higher due to landfill mining and can be considered as revenues.

The NPVs before taxes are calculated based on literature data on the economics of landfill mining (a.o. Ford et al., 2013; Rettenberger, 1995; Van Passel et al., 2013; Van Vossen and Prent, 2011), including costs for project preparation and licenses, capital expenses (CAPEX) and operating expenses (OPEX) for the thermal treatment plant (incinerator vs. gas-plasma technology), as well as CAPEX and OPEX for the separation and sorting plant (Van Vossen and Prent, 2011) and the excavation activities.

Revenues are generated from the sales of ferrous and non-ferrous metals from the fine and coarse fraction, the mineral/stone fraction as well as the on-site production of electricity from RDF, consisting of paper, plastics, wood and textiles, with an average heating value of 19 MJ/kg. At the end of the excavation activities the regained land[2] will be sold. Table 4 of SI presents the detailed costs and revenues together with the recovered material and energy quantities.

Further, it is assumed that the landfill operator, before starting landfilling activities, had made provisions for future aftercare obligations that can be liquidated after successfully mining the landfill. Those avoided aftercare costs (including costs for area maintenance, water treatment, monitoring, analyzing and sampling) can thus be accounted for on the revenue side for a period of 30 years in the micro perspective scenario, which corresponds to the minimum period for which aftercare funding has to be accrued (Directive, 1999) and for 70 years in the macro perspective scenario, to show the effect of an extended aftercare obligation period. Moreover, with a discount rate of 10–15% the avoided aftercare and covering costs appear to be only marginal (therefore only 30 years were chosen for the micro scenario), while a lower discount rate (0–5%) grants higher weight to cash flows occurring far in the future. However, the difference between 70 and 100 years is not that significant anymore (cf. Beaven et al., 2014).

Another assumption is that in a "Do-Nothing" scenario the landfill would be covered after 20 years, with the fugitive emissions from the landfill and the associated aftercare cost decreasing significantly afterwards. No extra costs for re-landfilling residues and their aftercare are assumed, except for costs for a one-meter thick soil cover being subtracted from the costs that are avoided by not covering the landfill due to landfill mining.

According to Michel (2001) for a private firm "the discount rate is simply the rate of return on an investment with a similar risk as the proposed project". To reflect a high risk investment decision, a discount rate between 10 and 15% is chosen for the project at hand (Baurens, 2010). For public entities there are basically two options how to determine their discount rate: for projects that are financed by taxes a discount rate equal to the real, long-term interest rate is set, representing an "exchange rate" that mirrors society's preference for exchanging present for future consumption. Projects that are financed by bonds are given a discount rate that is equal to the real interest rate on the government's bonds of similar maturity (Michel, 2001). In any case, the discount rate is significantly lower than the one applied by a private investor, ranging between 0 and 5%. The effect of a private investor's discount rate, compared to a public entity's rate on the present value of cash flows is shown in SI, Table 4.

In order to account for GHG emissions in the macro evaluation, the global warming potential (GWP_{100}) was calculated for all relevant project activities and processes, using a life cycle approach. Global warming potential is the mass-based equivalent of the greenhouse effect of greenhouse gases expressed in CO_2 equivalents. Due to characteristics of greenhouse gases and different retention periods in the atmosphere, the GWP is a time integral over a certain period, in this study given for 100 years (Umweltbundesamt Deutschland and Ökoinstitut, 2013).

Data for processes outside the foreground system (i.e. the landfill mining scenario) was extracted from the PROBAS database provided by the German environmental agency (Umweltbundesamt Deutschland and Ökoinstitut, 2013). Emissions caused by landfill mining activities and subsequent thermal treatment of the combustible waste fractions are compared to emissions that can be avoided due to the landfill mining project. Specifically, emissions occurring during the excavation activities, for sorting the waste fractions and processing RDF are accounted for. Also, emissions caused by the thermal treatment of RDF (gas-plasma technology vs. incineration) are included, while emissions associated with the construction of processing facilities are neglected. For the calculation of GHG emissions attributed to thermal treatment, the plants' own energy consumption as well as process-specific features are considered, such as the input of pure oxygen for the gas-plasma technology. Moreover, the composition of RDF is taken into account, discriminating between fossil and biogenic emissions. All fossil emissions plus the biogenic emissions originating from the thermal treatment of materials that would not have been degraded under anaerobic conditions (i.e. wood and textiles) are accounted for, as they would otherwise have been sequestered in the landfill.

On the saving side the electricity gained from thermal treatment, replacing the Belgian marginal electric energy source natural gas (European Commission, 2007), as well as the saved production emissions for copper, aluminum and steel are considered, by subtracting the GWP_{100} of primary metal production from the GWP_{100} of the secondary metal production (assuming full substitution). Also, emissions from the landfill itself, which will gradually cease being emitted during the landfill-mining project and in the aftermath, are compared to a "Do-Nothing" scenario over a period of 70 years, since after that the gas production is quite low (see SI, Fig. 3). Those emissions are assessed with the landfill gas emission model

[2] Net area that is actually gained after re-landfilling residues, which could not be valorized during the LFM project, such as residual materials after the treatment of fines.

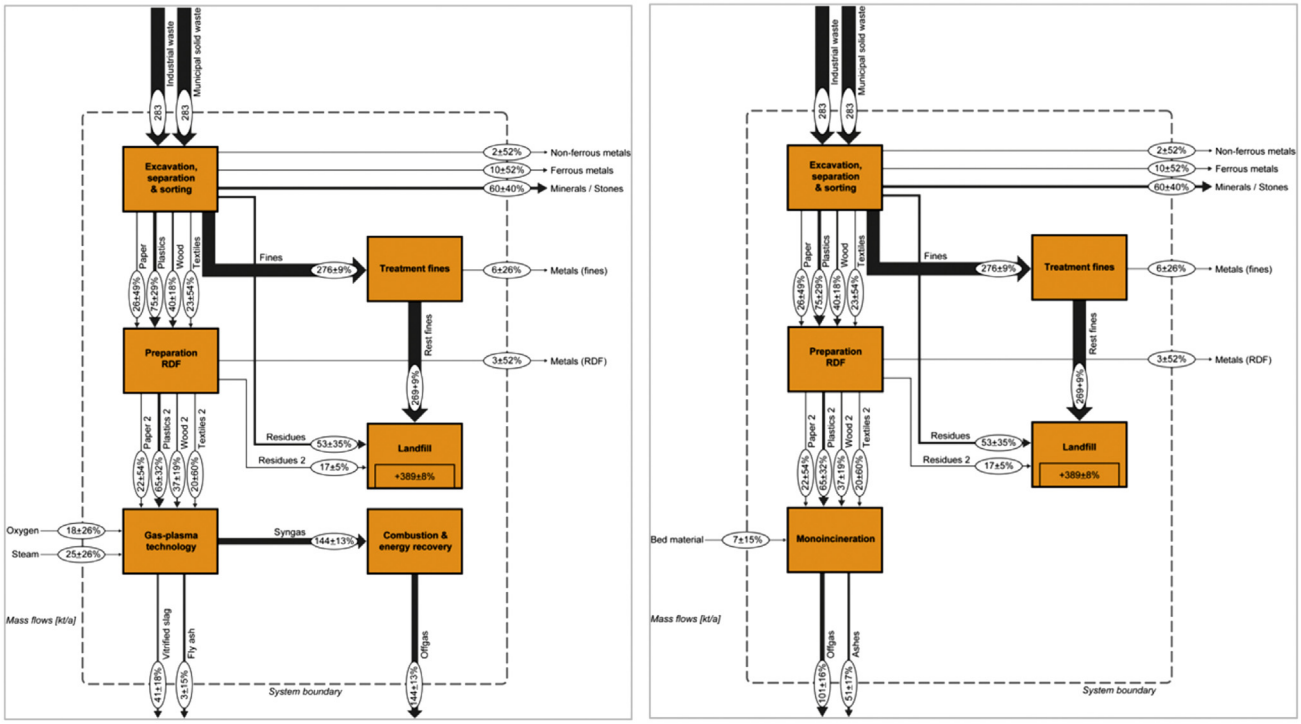

Fig. 5. Material flows for the conservative scenarios gas-plasma technology ($Scenario_{Con}$ GP, l.) and incineration ($Scenario_{Con}$ INC, r.): under present, established technological conditions extractable and potentially usable secondary raw materials.

(LandGEM) of the US Environmental Protection Agency (Alexander et al., 2005). In the first order model used by LandGEM, this study assumes a CH_4 generation rate (k) of 0.04 $year^{-1}$. The potential CH_4 generation capacity L_o is 100 m^3 per t of wet waste, and M_i, the mass of solid waste disposed in the ith year, equals 16.1 million metric tons in total, deposited between 1975 and 2003.

Also GHG emission savings related to leachate treatment are calculated. Fig. 3 of SI compares the leachate generation in a landfill-mining scenario compared to a "Do-Nothing" scenario. Assuming 5 kWh for the treatment of 1 m^3 leachate (Robinson, 2005) the saved energy for leachate treatment was converted into saved emissions, using again the Belgian marginal electric energy source natural gas.

3. Results

3.1. Material flow analysis

Flows are given in 1000 metric tons per year. While in the MFA models for simplicity reasons dry matter was modeled, in the economic analysis an original moisture content of 30% was assumed, decreasing to 15% after drying in the RDF preparation process.

Fig. 5 presents the conservative scenarios, $Scenario_{Con}$ GP and $Scenario_{Con}$ INC, which assume that after the partial recovery of fine metals and no recovery of high-calorific fines, the remaining fines are still highly contaminated and can therefore not be used as construction material, given currently existing treatment methods (Spooren et al., 2013).

In $Scenario_{Pot}$ GP and $Scenario_{Pot}$ INC the landfill's total annual resource potential amounts to 807 kt per year (=565 kt dry matter, cf. Fig. 5) over an operation period of 20 years, equaling the annual amount of waste to be excavated and entirely recovered (see SI, Fig. 2). This implies that there is no fraction of unknown wastes present and no impurities in the recovered waste streams. Moreover, these scenarios assume 100% separation and sorting efficiencies for the material flows and optimal energy recovery via incineration/gas-plasma technology and electricity generation. All input and output flows (materials and energy) for the conservative and potential MFA scenarios are shown in SI, Table 3.

The sum of extractable secondary raw materials amounts to 286 ± 50 kt wet matter per year (cf. Fig. 5: RDF and valuable material outputs). Relating the conservative to the potential scenarios (cf. SI, Fig. 2), this means that only 35 ± 7% of the total resources present in the landfill are actually extractable and usable under current, state-of-the-art technological conditions, mainly due to the quantitative importance of fines <10 mm, accounting for more than half of the excavated wastes.

3.2. Economic evaluation and modifying factors

For the analysis of the macro perspective the global warming potential (GWP_{100}) is investigated for the two scenarios. Fig. 6

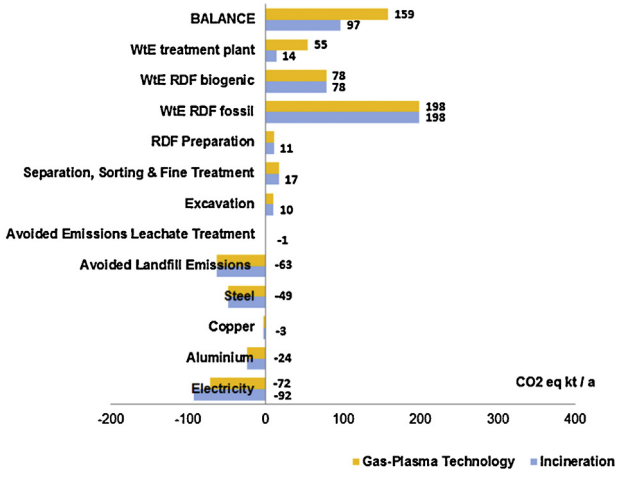

Fig. 6. Landfill mining and subsequent thermal treatment: savings vs. new emissions.

Table 3
Specific costs & revenues (undiscounted) shown for each scenario in € per *t* of excavated waste. Net costs as difference between costs and revenues. P90 (P50, P10) means that 90% (50%, 10%) of the results from Monte Carlo simulations are above this value.

All costs and revenues in €/*t* waste		Scenario			
		"Micro Incineration"	"Macro Incineration"	"Micro Gas-Plasma"	"Macro Gas-Plasma"
Specific costs	P90	47	47	46	46
	P50	52	52	54	54
	P10	58	58	62	62
Specific revenues	P90	32	33	25	26
	P50	37	39	34	35
	P10	43	46	43	45
Net costs	P90	15	14	21	20
	P50	15	13	20	19
	P10	15	12	19	17

shows that thermal treatment of RDF (WtE treatment plant plus RDF's fossil and partly biogenic emissions) causes by far the highest emissions. 27% of total thermal treatment emissions originate from biogenic sources (carbon release from biogenic materials that would not have been degraded under anaerobic landfill conditions) in the incineration scenario and 24% in the gas-plasma scenario. Incineration still achieves better results than the gas-plasma technology due to the latter's high own energy consumption as well as the required input of pure oxygen and steam. On the saving side mainly avoided production emissions for steel as well as avoided landfill emissions and the substitution of marginal Belgian electricity (natural gas with 397 g CO_2 equiv./kWh; Umweltbundesamt Deutschland and Ökoinstitut, 2013) play major roles. The difference between newly caused and saved emissions yields annually 97 kt CO_2 equiv. for incineration and 159 kt CO_2 equiv. per year for the gas-plasma technology, meaning that for none of the two scenarios there are actually GHG savings.

Regarding economics, average specific landfill mining costs have been calculated in the course of a discounted cash flow (DCF) analysis. Considering all the above-mentioned costs and revenues, average specific landfill mining net[3] costs lie between 13 and 20 € per ton of waste (P50 values from Monte Carlo Simulations), depending on the specific scenario (see Table 3). In all four scenarios, costs exceed revenues by far, indicating economic inefficiency.

Also, the actual NPVs for all four scenarios turned out to be negative, even though on different levels, as shown in Fig. 7. However, the ranking amongst the scenarios changes when looking at the two indicators: while under the specific cost–revenue ratio (Table 3), where undiscounted cash flows are considered, the macro scenario for each thermal treatment is performing better, the micro scenarios are ahead when the NPVs are taken as indicators. The reason for this phenomenon is that the DCF analysis takes the time value of money into account and distinguishes between different points in time where certain cash flows occur. For instance, revenues from land sales together with avoided covering and aftercare costs occur only at the end of landfill mining activities after 20 years. Thus, this quantitatively important cash flow is highly sensitive to the chosen discount rate; the higher the discount rate, the lower the value of future cash flows at present. Capital investment costs, accordingly, are assumed to be fully paid at the very beginning of landfill mining operations and have therefore a comparatively high present value (see Fig. 7).

In the macro scenarios the GHG emissions valued with a hypothetical CO_2 tax at 10 €/t CO_2 equiv. appear as additional cost, as no emissions are saved. Unlike the other cash flows this tax is not discounted, as the value of GHG emissions is considered to be independent of time. Therefore, the macro scenarios perform worse when using discounted cash flows than the specific cost–revenue ratio (undiscounted), as the GHG emission costs become more important relative to revenues lying far in the future, when using the DCF method.

On the revenue side, ferrous and non-ferrous metals sales play a very important role, in both the fine fraction and in the coarse fraction. While in the micro scenarios metal sales amount to approximately 40% of total revenues, in the macro scenarios their share is only 30%, due to comparatively higher avoided aftercare costs and lower discount rates, as aftercare obligations are assumed to be longer in this scenario. Land reclamation at a mean price of 40 €/m^2 (Van Passel et al., 2013) turns out to be of minor importance. Gains from electricity production for incineration account for 50% of total revenues (macro 36%) in the incineration scenario, and for 38% (macro 30%) in the gas-plasma scenario. The share of total thermal treatment costs is 51% (macro 46%) for incineration and 75% (macro 48%) for the gas-plasma scenario due to its higher operational costs. Another major share is cost for sorting and separation. GHG emission costs represent a relatively small share, compared to total costs.

The sensitivity analysis using Monte Carlo simulations in @Risk (see SI, Table 5) identifies the amount of produced electricity as well as (non-)ferrous metals and their market prices as main drivers on the revenue side, and the amount of RDF to be thermally treated as main driver on the cost side. As for all four scenarios the NPVs turned out negative, the cut-off values for non-ferrous metal as well as for electricity prices are calculated. The calculated factors for electricity prices are equally valid for the amount of electricity produced due to potentially increased efficiencies, but not due to increased amounts of RDF, implying no additional costs for electricity generation. To reach the break-even point, i.e. a neutral NPV, in the "Micro Incineration" scenario non-ferrous metal prices have to increase 11.6-fold, whereas for scenario "Micro Gas-Plasma" they need to rise 14.6-fold, compared to current price levels. Electricity prices, for being one of the identified economic drivers, have to increase 4-fold (incineration) or 6-fold (gas-plasma technology) in the micro analysis. In scenario "Macro Gas-Plasma" non-ferrous metal prices have to be 8.5 times higher and in scenario "Macro Incineration" they need to be 6.6 times higher than current prices (Table 4). With regard to electricity prices in the macro analysis, they have to increase by a factor 3.7 (gas-plasma technology) or by a factor 2.6 (incineration) to make the scenarios economically viable.

These results might seem counterintuitive at first, as for the macro scenarios the cut-off values are lower, even though they have strongly negative NPVs. This is due to the lower discount rate resulting in a more balanced distribution of revenues over time. The results from this economic analysis including the global warming potential provide the foundation for the following classification of each single scenario under UNFC-2009.

[3] Accounting for costs and revenues, not discounted yet.

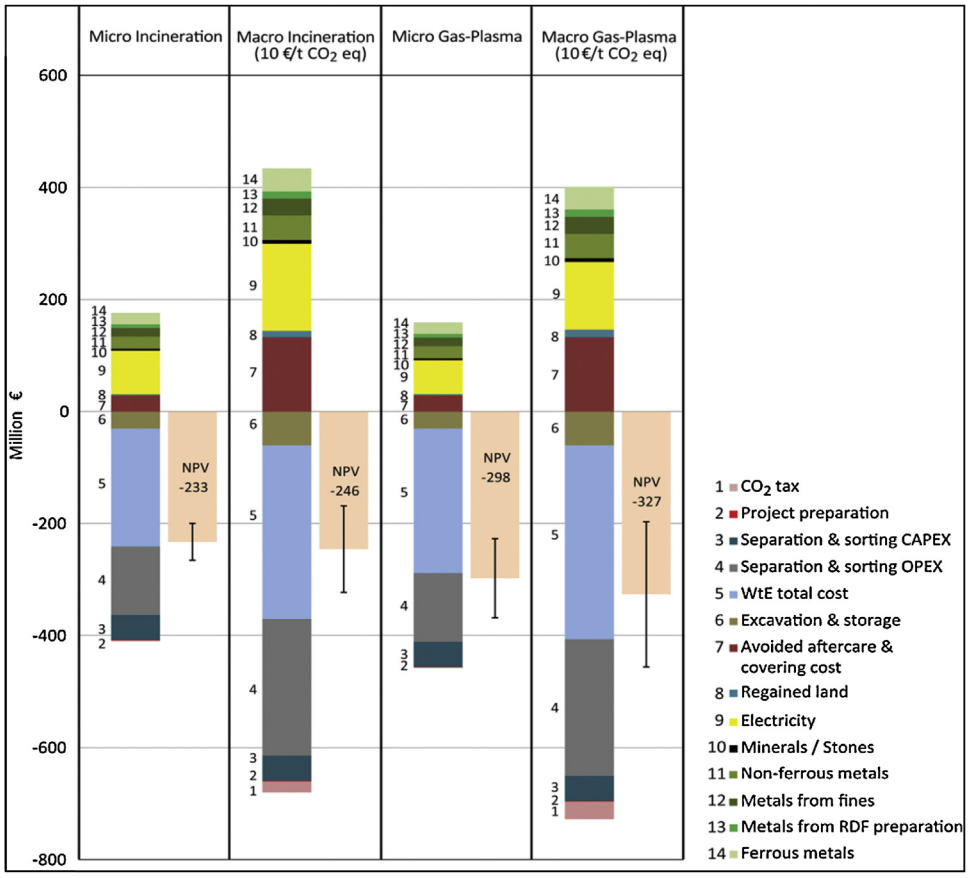

Fig. 7. Composition of costs and revenues discounted over 20 years and total net present values (NPV) as difference between cost and revenue cash flows for 4 scenarios.

3.3. *Resource classification*

The applicability of UNFC-2009 for the classification of anthropogenic stock resources is shown in Fig. 8. The preliminary indicators used for mapping the four landfill-mining scenarios in the UNFC-2009 system are listed in Table 1 and will need stepwise refinement. Using the framework's numerical coding scheme, the scenarios "Macro Incineration" and "Macro Gas-Plasma" are graded with "2" for "socioeconomic viability"(1st digit), as there are realistic chances for future economic extraction, as indicated by the cut-off values, even though their NPV is currently negative (see Fig. 7). The limit between grades "2" and "3" regarding socioeconomic viability has been defined by different factors, describing the increases in prices which are necessary to reach cut-off values: if revenues from non-ferrous metal recovery are assumed to be the economic driver, the limit factor for realistic price increase within the next 20 years has been set to 10. If revenues from electricity generation are considered, the realistic factor to reach cut-off values has been set to 4. Therefore the scenarios "Micro Incineration" and "Micro Gas-Plasma" obtain grade "3", because their factors to reach cut-off values are above 10 for non-ferrous metal prices and 4 or higher for electricity prices. As it can be judged as unrealistic that non-ferrous metal prices will increase by more than 10-fold, this means that there are no reasonable prospects for economic extraction in the foreseeable future.

If the pure NPVs and their respective cut-off values are used as indicators for socioeconomic viability, the scenarios "Macro Incineration" and "Macro Gas-Plasma" are graded with "2". However, those very scenarios which are supposed to monetize positive environmental effects emit actually more (!) GHG emissions compared to a "Do-Nothing" scenario, mainly due to the fact that emissions per unit of electricity generated are higher (incineration: 850 g CO_2 equiv./kWh; gas-plasma technology: 1440 g CO_2 equiv./kWh) than the replaced Belgian marginal energy source natural gas with 397 g CO_2 equiv./kWh (Umweltbundesamt Deutschland and Ökoinstitut, 2013). Thus, further research is needed how to handle such a situation in the evaluation process.

The second digit standing for "field project status and technical feasibility" grants to both gas-plasma scenarios grade "2", while the incineration scenarios are graded "1": current information and data on the project as a whole can be estimated as sufficiently detailed for making an educated decision. Also technologies for extracting and sorting the landfill's materials are relatively well-known and established. However, compared to the not entirely mature

Table 4
Scenario "Macro Incineration": cut-off values for different parameters.

	Actual price (average)	Cut-off price	Factor to reach the cut-off price
Non-ferrous metals (30% Cu, 70% Al)	1220 €/t[a]	8074 €/t	6.6
Electricity price (Feed-in, Belgium)	45 €/MWh[a]	116 €/MWh	2.6
Land price	40 €/m^2	917 €/m^2	23

[a] Average price for the period 2010–2014.

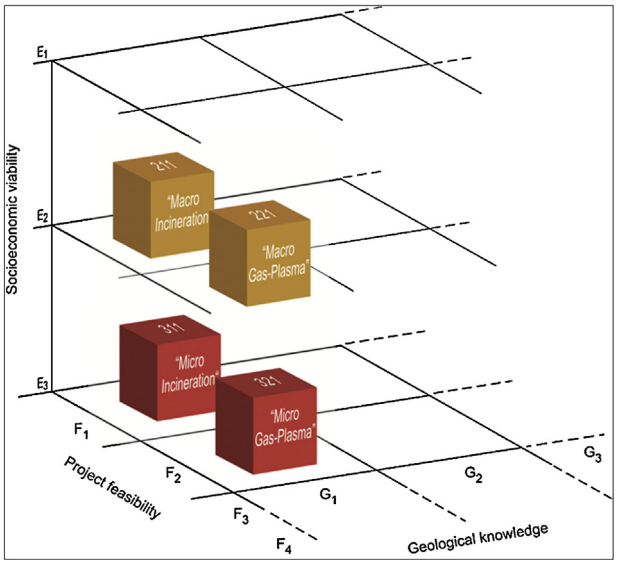

Fig. 8. The applicability of UNFC-2009 is illustrated by classifying the 4 scenarios of the original landfill-mining project. 1st digit – "Socioeconomic viability"; 2nd digit – "Field project status and technical feasibility"; 3rd digit – "Knowledge on composition".

gas-plasma technology, incineration is a more established thermal treatment option and obtains therefore a higher score. In terms of "geological" knowledge, all scenarios are graded with "1" (3rd digit), as the quantities contained in the landfill can be estimated with a high level of confidence deduced from both the sample excavations and the landfill's logbook data. Combining those three criteria, scenario "Macro Incineration" is categorized as 211, "Macro Gas-Plasma" as 221, "Micro Incineration" as 311 and "Micro Gas-Plasma" 321 (see Fig. 8).

The classification as 'resource' or 'reserve' (or none of both) depends on a number of factors. Only extending the system boundaries of the evaluation from a micro to a macro perspective and including some non-monetary modifying factors (while neglecting others) might have a significant impact on the final results. The decision for on-site thermal treatment of the combustible waste fraction and the choice of a specific technology together with associated costs, revenues and emissions plays an equally decisive role. The evaluation outcome might change, for instance, if the gas-plasma technology is further developed, with operational costs decreasing, while increasing the amount of electricity produced.

4. Discussion

Main difficulties in evaluating costs and benefits of landfill-mining projects arise from the fact that modifying factors affecting the project's socioeconomic viability differ for each site and are often linked to high uncertainties. For example, costs for the potential treatment of the fine fraction are largely depending on its level of contamination and thus on the landfill's specific composition.

Besides uncertainties about input data and model parameter values, there are also uncertainties originating from the chosen evaluation scenarios and the related assumptions. When developing alternative evaluation scenarios, it is important to identify the main drivers of the project's economic performance and to account for site-specific conditions. For instance, it must be decided whether to treat the combustible waste fraction on-site (and if yes, what technology to use) or to export it to an already existing plant off-site. In case there is a nearby incinerator willing to accept the waste at moderate gate fees, this solution might be more cost-efficient than building a new plant. Therefore, similar to a conventional mine, each landfill together with its surroundings needs to be investigated and evaluated on a case-by-case basis, ideally following a standardized procedure, such as the one presented in this study.

In this study, the amount of produced electricity as well as (fine) metals and their market prices are identified as main drivers on the revenue side, and the amount of RDF to be thermally treated as main driver on the cost side (see SI, Table 5). This is in line with Van Passel et al. (2013), who found the economic performance mainly dependent on parameters concerning energetic valorization, and also with Bernhardt et al. (2011) who highlight the importance of recoverable quantities and market prices of metals for a LFM project.

Moreover, parameter values and system conditions are likely to change over time, which should be taken into consideration. Especially, expected revenues for materials to be sold, heavily depend on future commodity price developments. In this study, increasing prices were anticipated in the final classification under UNFC-2009 by calculating factors to reach the cut-off prices.

However, this classification is primarily to be seen as an example of how results from economic evaluations of anthropogenic deposits can be mapped into the UNFC-2009 system. Thus, the limits between two categories (e.g. E2 and E3), i.e. between price levels that are "realistic to reach" vs. "unrealistic to reach" in the foreseeable future, are chosen quite arbitrarily and will need further refinement. Moreover, the focus on only one parameter when calculating cut-off prices neglects possibly existing correlations, for instance, between increasing metal prices and increasing operating costs due to higher energy prices. Another issue to be addressed in future research is that there are several related parameters influencing the revenues (and therefore the cut-off values). For metals, for instance, the separation efficiencies and the metal prices could change both, meaning that less dramatic changes in several such related parameters could magnify and result in the same effect as large changes in one specific parameter value.

Regarding the project's GHG emission saving potential compared to a "Do-Nothing" scenario, it was found, that for none of the two scenarios there are actually net emission savings, with incineration still achieving better results than the gas-plasma technology. Thermal treatment of RDF causes by far the highest emissions in the whole project, which is also confirmed by Danthurebandara et al. (2013) and Frändegård et al. (2013).

In this study, all fossil emissions plus the biogenic emissions originating from the incineration/gasification of materials that would not have been degraded under anaerobic conditions (i.e. wood and textiles of biogenic origin) have been accounted for, since the latter would otherwise have been sequestered in the landfill. In case of the incineration scenario, neglecting all biogenic CO_2 emissions would result in a reduction of 80% for the net balance of CO_2 equivalents. For the gas-plasma scenario the exclusion of all biogenic emissions would lead to 50% lower net overall emissions. However, in that case the NPVs would only increase by 7% (incineration) and 5% (gas-plasma technology), due to lower additional costs for the CO_2 tax (10 €/t CO_2 equiv.).

The consumption of electricity was modeled based on the marginal electricity source for Belgium, namely natural gas with 397 g CO_2 equiv./kWh. Applying the emission-poor Belgian average electricity mix (approximately 50% nuclear energy) with 214 g CO_2 equiv./kWh (Umweltbundesamt Deutschland and Ökoinstitut, 2013), would increase net overall emissions for the incineration scenario by 19% due to lower amount of replaced energy emissions, and reduce emissions for the gas-plasma scenario by 4%, which is mainly due to the gas-plasma technology's high own energy consumption. In contrast to this study, Danthurebandara et al. (2013) applied the Belgian average energy mix and assumed the

valorization of the residues from the gas-plasma technology, replacing geopolymer or blended cement. They also assumed a higher content of extractable fine metals in the industrial waste fraction (40% compared to 6% in this study) and the rest fines being recovered as sand, soil and aggregates. Therefore, they obtain a positive overall result regarding environmental benefits.

As there are no GHG emission savings, the additional emissions, valued with 10 €/t CO_2 equiv., appear in the macro scenarios as additional cost (instead of additional revenues), representing, however, a relatively small share, compared to total cost. If those monetized emissions were excluded from the macro analysis, the NPV of the scenario "Macro Incineration" would improve by 8% and for "Macro Gas-Plasma" by 10%.

Regarding UNFC-2009, the three axes with their respective criteria offer great potential to classify not only various types of naturally occurring commodities, but also anthropogenic resources from landfill mining projects.

The socioeconomic viability of a LFM project can be measured and expressed via a discounted cash flow analysis including non-monetary modifying factors (social, environmental, legal etc.).

Similar to natural resource deposits, cut-off values can be calculated for key parameters in a landfill-mining project below which mining is not economically feasible in order to distinguish 'resources' from 'reserves'. Particularly, if the net present value turns out negative the respective cut-off value determine whether there are realistic chances for future economic extraction or not.

Also the UNFC-2009 axes "knowledge on (geological) composition" and "project status and technical feasibility" offer suitable classification criteria. Both can be illustrated with MFA models, showing first the knowledge on the landfill's full resource potential, and in a second step the actual technical feasibility of resource recovery by applying state-of the art transfer coefficients to all relevant processes. In addition, alternative valorization and treatment methods can be shown and compared in separate MFA models.

There are no real limitations of applying the UNFC-2009 system to anthropogenic resource deposits, because of its rather general nature as a classification framework, which does not specify how exactly to perform the actual evaluation. The classification indicators used in this study (Table 1) to fit the LFM project into UNFC-2009 will have to be further refined, for instance how exactly "geological" uncertainty of an anthropogenic deposit can be quantified (in comparison to a primary deposit) or how the maturity of extraction technologies can be measured. Also the issue of changing modifying factors as well as setting the limits for realistic changes for future economic extraction will need to be addressed in future research.

5. Conclusions

In this study, the natural resource classification framework UNFC-2009 was applied to the enhanced landfill-mining project in Belgium to identify the landfilled materials as potential anthropogenic 'resources' or 'reserves', and to reveal critical factors for the resource classification of the project.

Similar to the mining industry, cut-off prices (alternatively also cut-off quantities or costs) were calculated for important economic performance parameters, to determine under which conditions an anthropogenic deposit can be labeled a 'resource' or a 'reserve'. The classification as 'resource' or 'reserve' (or none of both) depends on a number of factors. Only by extending the system boundaries of the evaluation from a micro to a macro perspective as well as the choice of certain technological options can have a significant impact on the final results. This study shows exemplarily the inclusion of GHG emissions and longer aftercare obligations. However, by investigating the global warming potential, the list of non-monetary effects owing to landfill mining, and to be included in a macro evaluation, has been by no means treated exhaustively. Incorporating further modifying factors can rapidly move the boundaries separating 'resources' from 'reserves'. Those factors comprise newly created landfill capacity (Hermann et al., 2014), the increase in value of surrounding land (Van Passel et al., 2013) or mitigation of imminent environmental pollution threats, to name just a few. They depend on the landfill's location, its site-specific characteristics and particular interests of involved stakeholders. In general, it can be stated, also in accordance with Bockreis and Knapp (2011), Hogland et al. (2010), Kaartinen et al. (2013) and numerous other authors, that factors affecting the socioeconomic viability of landfill-mining projects differ for each site and need to be examined and evaluated on an individual basis.

In conclusion, the applicability of UNFC-2009 for a first classification of recovered materials from an old landfill has been proven successfully in this study. We presented an approach to evaluate landfill mining from a resource classification perspective, which can be used to estimate coherently the actual material 'resources' and 'reserves' contained in old landfills for different sites and under different conditions. To establish a standardized procedure, further research should focus the definition of specific, quantifiable criteria and indicators for categorizing landfill-mining projects and other kinds of anthropogenic deposits, analogous with the axes and classes of the UNFC-2009 framework. This will allow for systematic comparisons between different types of anthropogenic stock and flow resources. The ultimate goal is to create a common platform for describing and evaluating naturally occurring and anthropogenic resource deposits.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2015.01.004.

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SUPPLEMENTARY INFORMATION

1. MATERIAL FLOW ANALYSIS

*Table 1: Transfer Coefficients (TC) for the "**conservative"** scenarios as used in the Material Flow Analysis in STAN, based on Busschaert (2014).*

Process: Excavation, Separation & Sorting				
Material Flows	**RDF Preparation Streams**	**Ferrous Metals**	**Non-Ferrous Metals**	**Other Streams**
Paper / Cardboard	0.8			0.2 > Res
Glass / Ceramics	0.05			0.95 > Sto
Plastics	0.86			0.14 > Res
Metals	0.2	0.6	0.1	0.1 > Res
Minerals / Stones	0.02			0.98 > Sto
Wood	0.91			0.09 > Res
Textiles	0.8			0.2 > Res
Fines consisting of Fine Metals, Fine WtE & Rest Fines	0.05			0.95 > Fin
Unknown				1 > Res

Process: Preparation RDF			
Material Flows	**Waste-to-Energy (WtE)**	**Residues (Res)**	**Metals**
Paper / Cardboard	0.95	0.05	
Glass / Ceramics	0.2	0.8	
Plastics	0.95	0.05	
Metals	0	0.05	0.95
Minerals / Stones	0.1	0.9	
Wood	1	0	
Textiles	0.95	0.05	
Fines consisting of Fine Metals, Fine WtE & Rest Fines	0.3	0.7	

Process: Treatment Fines			
Material Flows	**Metals**	**Rest Fines**	**WtE** (ad RDF Preparation)
Fine Metals	0.5	0.5	0
WtE Fines	0	1	0
Rest Fines (Contaminated, ad Landfill)	0	1	0

The fractions of Municipal Solid Waste (MSW) and Industrial Waste (IW) are modeled in STAN on the level of "subgoods": The process *Excavation, Separation & Sorting* directs 80 % of the paper fraction into the stream "Pap". During the process *Preparation RDF* again 95 % of this goes into "Pap2". Correspondingly, 95 % of the plastic fraction goes into the stream "Pla", and then 95 % into "Pla2". 100 % of the wood fraction goes to "Woo" and then fully into "Woo2". 95 % of the textiles go to "Tex" and then 95 % of this to Tex2". Other fractions, such as stones or part of the fines, are allocated to the streams "Pap"/"Pap2", "Pla"/"Pla2", "Woo"/Woo2", and to "Tex"/"Tex2" according to the size of the respective stream.

*Table 2: Transfer Coefficients (TC) for the **"potential"** scenarios as used in the Material Flow Analysis in STAN*

Process: Excavation, Separation & Sorting				
Material Flows	**RDF Preparation Streams**	**Ferrous Metals**	**Non-Ferrous Metals**	**Other Streams**
Paper / Cardboard	1			
Glass / Ceramics	0			1 > Gla
Plastics	1			
Metals	0	0.8	0.2	
Minerals / Stones	0			1 > Sto
Wood	1			
Textiles	1			
Fines consisting of Fine Metals, Fine WtE & Rest Fines	0			1 > Fin
Unknown	0			1 > Res

Process: Preparation RDF	
Material Flows	**Waste-to-Energy (WtE)**
Paper / Cardboard	1
Glass / Ceramics	-
Plastics	1
Metals	-
Minerals / Stones	-
Wood	1
Textiles	1
WtE fines	1

Process: Treatment Fines			
Material Flows	**Metals**	**Rest Fines**	**WtE** (ad RDF Preparation)
Fine Metals	1	0	0
WtE Fines	0	0	1
Rest Fines (Decontaminated, ad Construction Material)	0	1	0

The "potential" scenarios (Scenario $_{Pot}$) are developed to quantify the landfill's total resource potential. They assume ideal conditions, with maximum separation and sorting efficiencies for the material flows and optimal energy recovery via an on-site WtE plant and electricity generation. The fine fraction is treated such that a high-calorific fraction is recovered for RDF production. Besides, a maximum recovery efficiency of fine metals for material recovery is assumed.

The "conservative" scenarios (Scenario $_{Con}$) show that part of the resource potential, which is under current, established technological conditions extractable and potentially usable. Realistic efficiencies have been applied for the MFA process *Excavation, Separation & Sorting*, similar to those of the first process step in a mechanical biological treatment plant (Busschaert, 2014). Also for the processes *Preparation RDF*, *Treatment Fines* and *Monoincineration* transfer coefficients referring to state-of-the-art plants are used. In this case fine metals are only partially recovered.

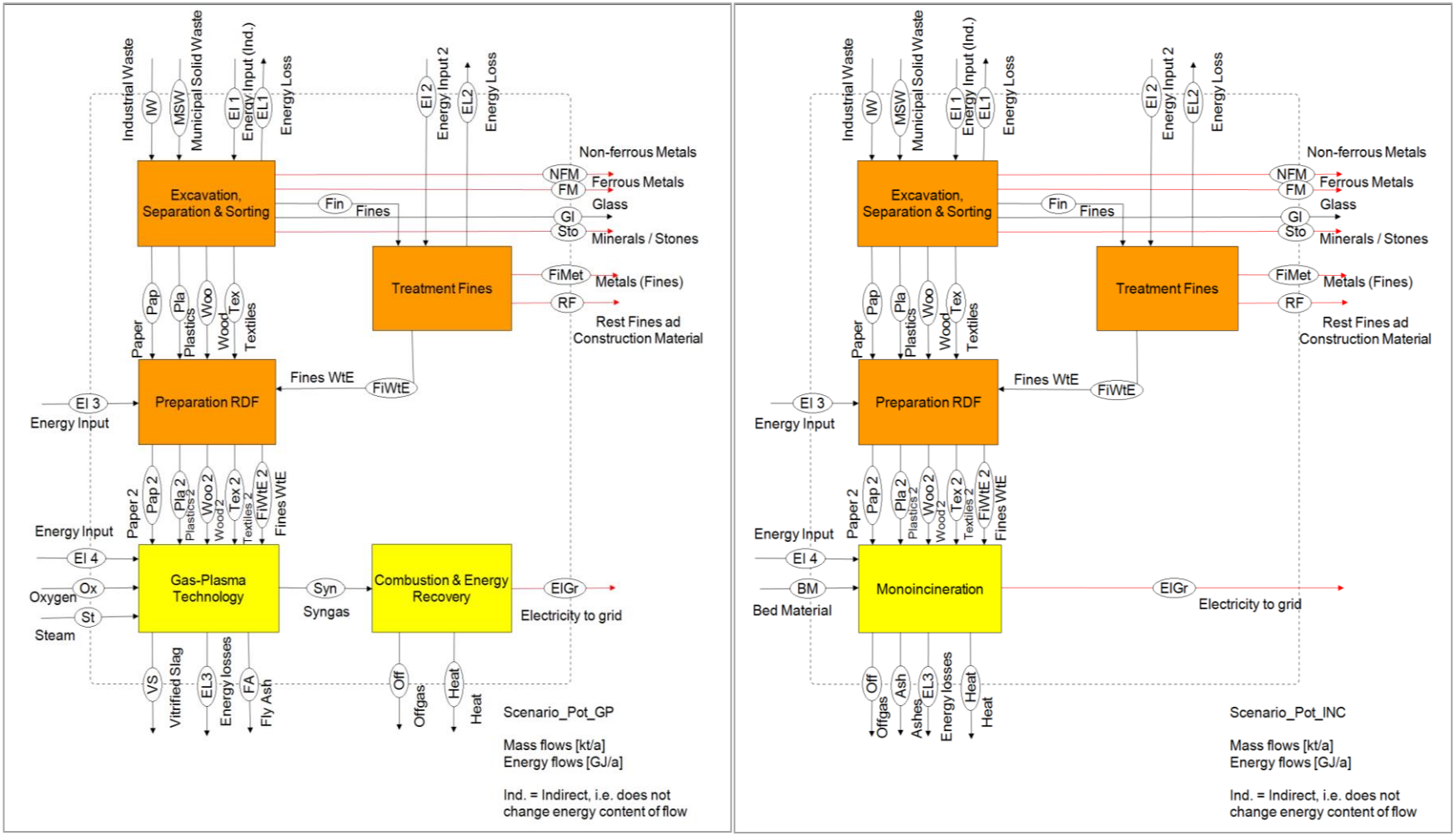


Figure 1: Illustration of the qualitative material flow models for the potential scenarios for gas-plasma technology (Scenario $_{Pot}$ GP, l.) and incineration (Scenario $_{Pot}$ INC, r.): The landfill's total resource potential.

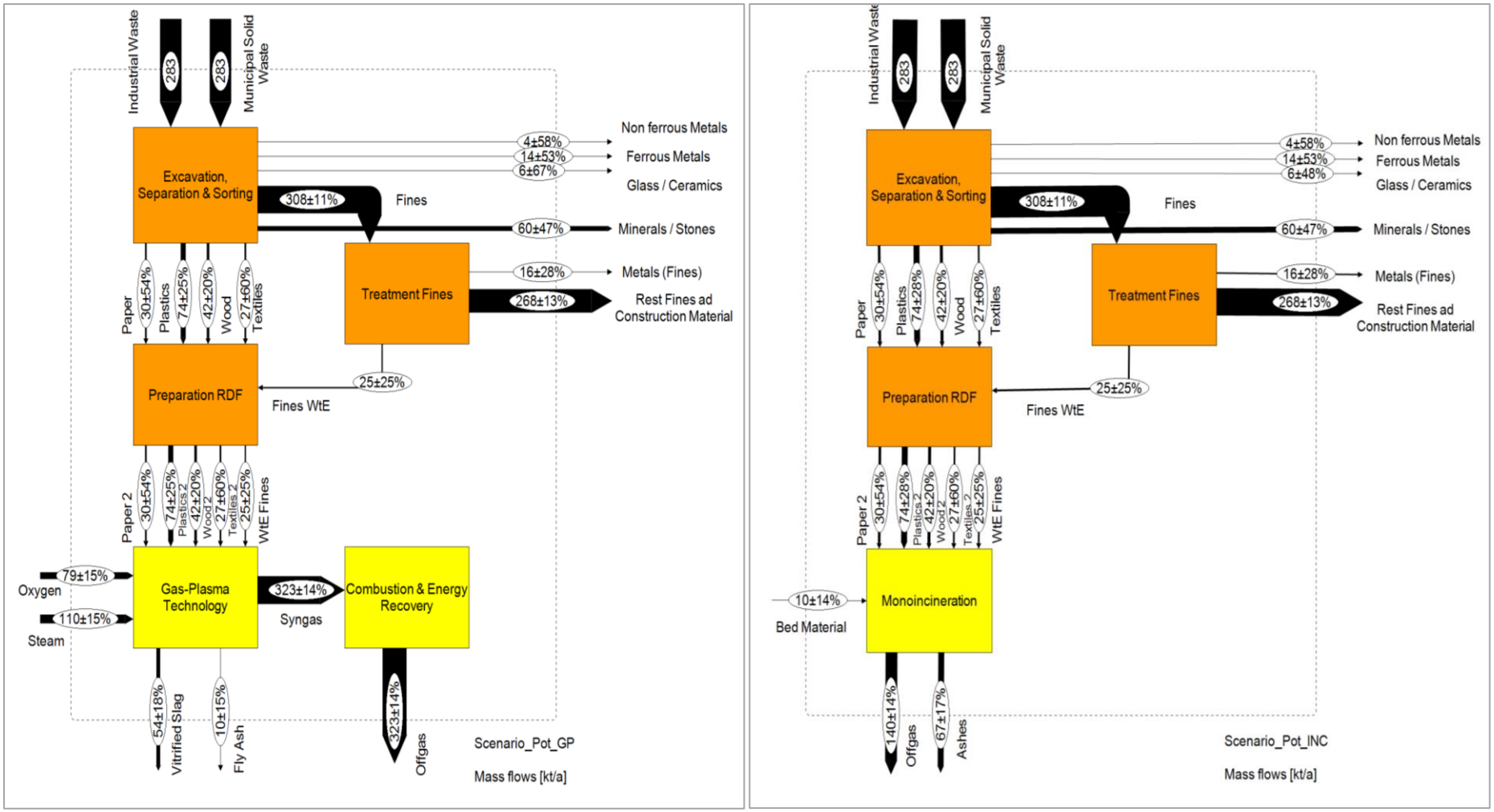


Figure 2: Material flows for the potential scenarios gas-plasma technology (Scenario $_{Pot}$ GP, l.) and incineration (Scenario $_{Pot}$ INC, r.): The landfill's total resource potential. Flows are given as dry matter in 1000 tons per year.

Table 3: Input & output flows for 4 MFA scenarios: "Potential Gas-Plasma" vs. "Conservative Gas-Plasma", "Potential Incineration" vs. "Conservative Incineration".

Material flow (dry matter) [kt/a] Energy flow [GJ/a] Specific Energy [GJ/t]			Scenario $_{Pot}$ GP	Scenario $_{Con}$ GP	Scenario $_{Pot}$ INC	Scenario $_{Con}$ INC	Specific Energy $_{Con}$ [GJ/t]	Specific Energy $_{Pot}$ [GJ/t][i]
Flow	**Flow name in MFA model**							
Inputs		***Units***						
IW	**Industrial Waste (dry)**[a]	[kt/a]	282.5					
MSW	**Municipal Solid Waste (dry)**[a]	[kt/a]	282.5					
EI 1	**Energy Input (Indirect)**[b]	[GJ/a]	90,949	90,949	90,949	90,949		
EI 2	**Energy Input 2 (Indirect)**[c]	[GJ/a]	45,744 - 53,481	40,423 - 48,419	45,744 - 53,481	40,423 - 48,419		
EI 3	**Energy Input**	[GJ/a]	102,529 - 141,441	82,765 - 126,618	102,529 - 141,441	82,765 - 126,618		
EI 4	**Energy Input (Indirect)**[d]	[GJ/a]	376,603 - 507,235	238,532 - 410,086	120,133 - 165,166	86,291 - 133,112		
Valuable Outputs								
ElGr	**Electricity to grid**[e]	[GJ/a]	814,079 - 2,038,916	529,341 - 1,225,879	1,354,172 - 1,891,111	657,820 - 987,699		
FM	**Ferrous Metals**	[kt/a]	7 - 22	5 - 15	7 - 22	5 - 15		
FiMet	**Metals (Fines)**	[kt/a]	11 - 20	5 - 8	11 - 20	5 - 8		
Met	**Metals (RDF)**	[kt/a]	0	2 - 5	0	2 - 5		
NFM	**Non-ferrous Metals**	[kt/a]	2 - 6	1 - 3	2 - 6	1 - 3		
Sto	**Minerals / Stones**	[kt/a]	32 - 88	36 - 83	32 - 88	36 - 83		
VS	**Vitrified Slag**[f]	[kt/a]	44 - 64	34 - 48	0	0		
GL	**Glass**	[kt/a]	2 - 10	0	2 - 10	0		
RF	**Rest Fines**[g]	[kt/a]	233 - 302	244 - 294	233 - 302	244 - 294		
Pap 2	**Paper 2**	[kt/a]	14 - 45	10 - 34	14 - 45	10 - 34	8.4	8.7
Pla 2	**Plastics 2**	[kt/a]	56 - 92	44 - 86	56 - 92	44 - 86	25.1	25.8
Tex 2	**Textiles 2**	[kt/a]	11 - 43	8 - 32	11 - 43	8 - 32	17.6	18.1
Woo 2	**Wood 2**	[kt/a]	34 - 51	30 - 44	34 - 51	30 - 44	15.3	15.7
FiWtE 2	**Fine WtE**	[kt/a]	18 - 31	0	18 - 31	0	-	10.1
	Total RDF[h]	[kt/a]	166 - 229	134 - 205	166 - 229	134 - 205		

Explanations Table 3:

[a] In the STAN models dry matter was modeled. In the economic analysis an original moisture content of 30 % was assumed, decreasing to 15 % after drying in the RDF preparation process.

[b] No uncertainty range applied because energy input for the process *Excavation, Sorting & Separation* (31.3 kWh / t, Rettenberger, 1995) depends on amount of excavated waste, which is assumed to be fixed.

[c] Based on Rettenberger (1995): 31.3 kWh / t

[d] Energy demand of gas-plasma technology: 400 - 845 kWh / t (Bosmans et al., 2012). Energy demand of a state-of the art waste incinerator: 4 % of total RDF energy input (Stubenvoll et al., 2002).

[e] Conservative scenarios: Cross electrical efficiency of incineration (excluding own demand): Incineration: 30 % (Ramboll, Personal Communication); Gas-Plasma Technology: 32 % (Taylor et al., 2013).
Potential scenarios: Cross electrical efficiency of incineration (excluding own demand): Incineration: 46 % (based on Kabelac, 2009); Gas-Plasma Technology: 40 ± 20 %, (based on Geysen, Personal Communication).

[f] Potential scenario: Construction material / Conservative scenario: Temporarily stored on site

[g] Potential scenario: Construction material / Conservative scenario: Temporarily stored on site

[h] RDF = Sum of flows “Pap2”, “Pla2”, “Tex2”,”Woo2”. Heating Value (wet): 19 MJ / t

[i] The potential scenarios’ flows are slightly higher as there are no impurities (TCs always 100 % (see Table 2) and no unknown wastes are assumed to be present. Thus, the unknown fraction of about 10 % is allocated to all streams according to their size. Specific energy is modeled also in STAN with an original moisture content of 30 %, decreasing to 15 % after drying in the RDF preparation process.

2. EOCONOMIC EVALUATION & MODIFYING FACTORS

Table 4: Present values of costs & revenues, discounted with rates of 12%, 3% and 0 % taking the timing of cash flows into account.

	REVENUES		Price per Unit [€/t, €/m2, €/MWh,€/a]	Distribution in @Risk	Reference	Quantity (based on STAN models, normally distributed) [t/a, m2, MWh/a]	Cashflows with discount rate 12 % (Mean Values) ,[€]	Cashflows with discount rate 3 % (Mean Values), [€]	Undiscounted Cashflow (Mean Values), [€]	Duration [a]	Comment
MATERIALS	**Ferrous Metals**		170 - 214	Uniform	Letsrecycle.com 2014a; Letsrecycle.com 2014b.	6,926 - 21,982	20,513,105	40,857,555	54,925,380	20	
	Metals RDF Preparation		170 - 214	Uniform		2,193 - 6,961	6,495,794	12,938,181	17,392,980	20	
	Metals from Fines		221* (mean)	Uniform		7,165 - 11,321	15,251,256	30,377,120	40,836,400	20	97 % Ferrous Metals, 2,1 % Al, 0,09 % Cu
	Non-Ferrous Metals		1220* (mean)	Uniform		1,154 - 3,664	21,952,545	43,724,601	58,779,600	20	70 % Al, 30 % Cu *Al Price: 600 - 980 *Cu Price: 1300 - 3400
	Minerals / Stones		4 - 6	Normal	Kies & Sand ServiceGmbH 2014	51,110 - 119,630	3,188,331	6,350,449	8,537,000	20	
ENERGY	**Electricity produced from RDF**	**Incineration**	35 - 55	Triangle	Busschaert 2014	131,164 - 200,897	78,325,693	156,007,406	149,427,620	20	
		Gas-Plasma Technology	35 - 55	Triangle		44,336 - 259,938	60,777,208	121,054,718	136,923,500	20	
LAND SALES	**Regained land**	**Incineration**	3 - 80	Triangle	Van Passel, Dubois et al. 2013	489,200 - 553,200	1,929,683	11,206,827	20,848,000	1	Gained in 2037
		Gas-Plasma Technology	3 - 80	Triangle		599,000 - 655,000	2,321,395	13,481,736	25,080,000	1	Gained in 2037
	AVOIDED AFTERCARE COST										
	Avoided Aftercare (Maintenance area, water treatment, monitoring, analysing & sampling)		5 - 7	Normal	Geysen 2013.	61,750 - 68,250	20,450,435	55,253,692	81,900,000	20	Every year increasing by 65000 m2 x 6 €
	Avoided Aftercare	**10 years after LFM**	0.8 - 1.2	Normal	Own estimates**	1,300,000	1,203,275	-	13,000,000	1	** 1/6 of original costs after covering the landfill in a "Do-Nothing" Scenario Gained in 2037 for 10 years after LFM (Micro)
		50 years after LFM	0.8 - 1.2	Normal		1,300,000	-	34,940,703	65,000,000	1	Gained in 2037 for 50 years after LFM (Macro)
	Avoided Covering Cost		50 - 75	Normal	Geysen 2013.	1,300,000	7,444,662	43,235,626	80,431,000	1	Gained in 2037

Table 4 (continued)

	COST									
EXCAVATION & PRE-TREATMENT										
PROJECT PREPARATION	**Investigative Studies, Permits & Unforeseen costs**	900,200 - 1,100,300	Triangle	Based on Van Vossen & Prent 2011.		1,000,280	1,000,280	1,000,280	1	Paid once in 2016
EXCAVATION & STORAGE	**Excavation & Storage**	4.5 - 5.5	Normal	Van Vossen & Prent 2011; Van Passel et al. 2013	807,000	30,139,205	60,030,611	80,700,000	20	Annually excavated amount: 16.1 Mio t / 20
SORTING & SEPARATION	**Separation & Sorting CAPEX**	38,000,000 - 60,000,000	Triangle	Bernhardt et al. 2011 Ford et al. 2013		45,000,000	45,000,000	45,000,000	1	Paid once in 2016
	Non-MSW	0.9 - 1.1	Normal	Based on Van Vossen & Prent 2011.	1,440 - 3,346	17,875	35,604	47,860	20	Cumulated cost per ton of treated fraction
	Other	13 - 15	Normal		27,360 - 63,580	4,754,898	9,470,703	12,731,540	20	
	Fines	13 - 15	Normal		358,115 - 430,343	41,225,353	82,111,759	110,384,000	20	
	Metals Fine treament	8 - 10	Normal		7,165 - 11,321	628,277	1,251,389	1,682,260	20	
	Ferrous metal	16 - 19	Normal		6,926 - 21,982	1,851,571	3,687,919	4,957,720	20	
	Paper / Cardboard	22 - 26	Normal		14,422 - 48,618	5,685,801	11,324,855	15,224,160	20	
	Non-ferrous metals	28 -33	Normal		1,154 - 3,664	544,410	1,084,345	1,450,220	20	
	Minerals / Stones	32 - 38	Normal		51,110 - 119,630	22,318,319	44,453,141	59,758,980	20	
	Textiles	32 - 38	Normal		11,256 - 45,434	7,410,296	14,759,666	19,841,620	20	
	Plastic	32 - 38	Normal		63,538 - 123,330	24,426,574	48,652,317	65,404,000	20	
	Wood	32 - 38	Normal		42,588 - 63,172	13,824,340	27,535,018	37,015,720	20	
WASTE - TO - ENERGY										
INCINERATION	**Incineration CAPEX**	95,000,000 - 115,000,000	Triangle	Linz AG 2012		110,000,000	110,000,000	110,000,000	1	Paid once in 2016
	Incineration Maintenance	2,850,000 - 3,450,000	Triangle	Stubenvoll et al. 2002		24,649,164	49,095,667	66,000,000	20	3 % of CAPEX, annually paid
	Incineration OPEX	50 - 80	Triangle		137,533 - 203,087	76,096,237	151,566,824	203,753,420	20	
GAS-PLASMA TECHNOLOGY	**Gas-Plasma CAPEX**	137,533,000 - 203,087,000	Normal	Danthurebandara 2014		169,794,522	169,794,522	169,794,522	1	Paid once in 2016
	Gas-Plasma OPEX	60 - 90	Triangle		137,533 - 203,087	88,778,943	176,827,961	237,712,331	20	

Table 5: Driving factors of NPV

	Scenario:			
	"Micro Incineration"	**"Macro Incineration"**	**"Micro Gas-Plasma"**	**"Macro Gas-Plasma"**
1	Electricity Produced	Electricity Produced	RDF Amount to be treated (-)	Electricity Produced
2	RDF Amount to be treated (-)	RDF Amount to be treated (-)	Electricity Produced	RDF Amount to be treated (-)
3	Non-Ferrous Metals Amount for Sale	Non-Ferrous Metals Amount for Sale	Non-Ferrous Metals Amount for Sale	Non-Ferrous Metals Amount for Sale
4	Ferrous Metals Amount for Sale	Ferrous Metals Amount for Sale	Ferrous Metals Amount for Sale	Ferrous Metals Amount for Sale
5	Minerals / Stones Amount to be separated (-)	Minerals / Stones Amount to be separated (-)	Minerals / Stones Separation OPEX (-)	Minerals / Stones Amount to be separated (-)
6	Incineration OPEX (-)	Plastics Amount to be separated (-)	Gas-Plasma OPEX (-)	Plastics Amount to be separated (-)

As many parameters of the landfill-mining project are associated with large uncertainties, an uncertainty and sensitivity analysis was performed in @Risk (Palisade Corporation, 1997), with recovered material quantities, discount rates, costs and prices being considered and analyzed. The results are based on a Monte Carlo Simulation with 10,000 runs, i.e., the simulation was run 10,000 times and for each run, new random samples for all input parameters were generated.

The sensitivity analysis (Table 5) identifies the amount of produced electricity as well as the amount of non-ferrous metals as main drivers on the revenue side, and the amount of RDF to be thermally treated as main driver on the cost side. Minerals / stones as well as plastics are among the main drivers because they represent relatively large fractions to be treated with high uncertainties.

While most factors correlate positively with the Net Present Value ("the higher, the better"), "(-)" means that those factors have a negative correlation with the NPV ("the higher, the worse")

3. BASELINE EMISSIONS: „DO-NOTHING" SCENARIO

The "Do-Nothing" scenario supposes that no landfill mining activities are undertaken: During the first 10 years after closure electricity is generated from landfill gas (LFG) with a gas collection rate of 50 %, while 25 % of the LFG is oxidized within the landfill cover and a share of 25 % is emitted to the atmosphere, possessing a global warming potential *(see Figure 3).* The electricity produced replaces the Belgian marginal energy emission equivalents, namely natural gas with 397 g CO_2 eq./ kWh (Umweltbundesamt Deutschland and Ökoinstitut, 2013). After those first ten years, LFG is simply burnt, with equally 25 % being emitted and 25 % oxidized within the landfill cover. After 20 years after closure, the landfill is covered and therefore LFG emissions are reduced: For the following 50 years, only 15 % of total LFG is emitted to the atmosphere (see *Figure 3*). After this period of overall 70 years, LFG emissions are already at a very low level and are neglected in this study. However, methane emissions due to landfill gas generation have been modelled for a period of 170 years (*see Figure 4*) to show that the release of methane after 2087 contributes only very little to the total CH_4 emissions from the landfill in the "Do-Nothing" scenario. The overall greenhouse gas emissions would increase by less than 10%, which would not have a major

impact on the total saved net emissions of the landfill-mining scenarios, as they remain negative.

For the landfill-mining project, in contrast, emissions look slightly different during the first 20 years: During the first 10 years electricity is generated from LFG with a gas collection rate of 50 %, replacing natural gas as mentioned above, (later from year 10 to year 20 LFG is simply burnt), while 25 % of LNG is emitted to the atmosphere and 25 % oxidized. Due to mining, however, LFG production is constantly decreasing and ends after 20 years. It is assumed that the re-landfilled residues do not possess any greenhouse gas potential. In the first order model used by LandGEM (cf. methane production in *Figure 4*), this study assumes a CH_4 generation rate (k) of 0.04 $year^{-1}$. The potential CH_4 generation capacity L_o is 100 m^3 per t of wet waste, and M_i, the mass of solid waste disposed in the i^{th} year, equals 16.1 million metric tons in total, deposited between 1975 and 2003.

In addition, greenhouse gas emission savings related to leachate treatment are calculated, using the hydrologic balance method (with 847 mm annual mean precipitation for Belgium) to calculate the whole amount of leachate that would have been produced in a "Do-Nothing" scenario, assuming an aftercare period of 70 years. In the "Do-Nothing" scenario a top-sealing is placed after 20 years after closure, and therefore leachate production is reduced from 29 % to 5 % of the annual precipitation (see *Figure 3*).

In contrast, in a landfill-mining scenario the amount of generated leachate decreases with every year of landfill mining and stops at the end of mining activities (re-landfilled residues are assumed not to produce leachate that needs to be treated). Assuming 5 kWh for the treatment of 1 m^3 leachate (Robinson, 2005) the saved energy for avoided leachate treatment was converted into saved CO_2 eq. emissions, again assuming the marginal Belgian energy source (natural gas with 397 g CO2 eq./ kWh, Umweltbundesamt Deutschland and Ökoinstitut, 2013) for the calculation of emissions.

Figure 3: Annual methane emissions and leachate amount in landfill mining compared to a "Do-Nothing" scenario.

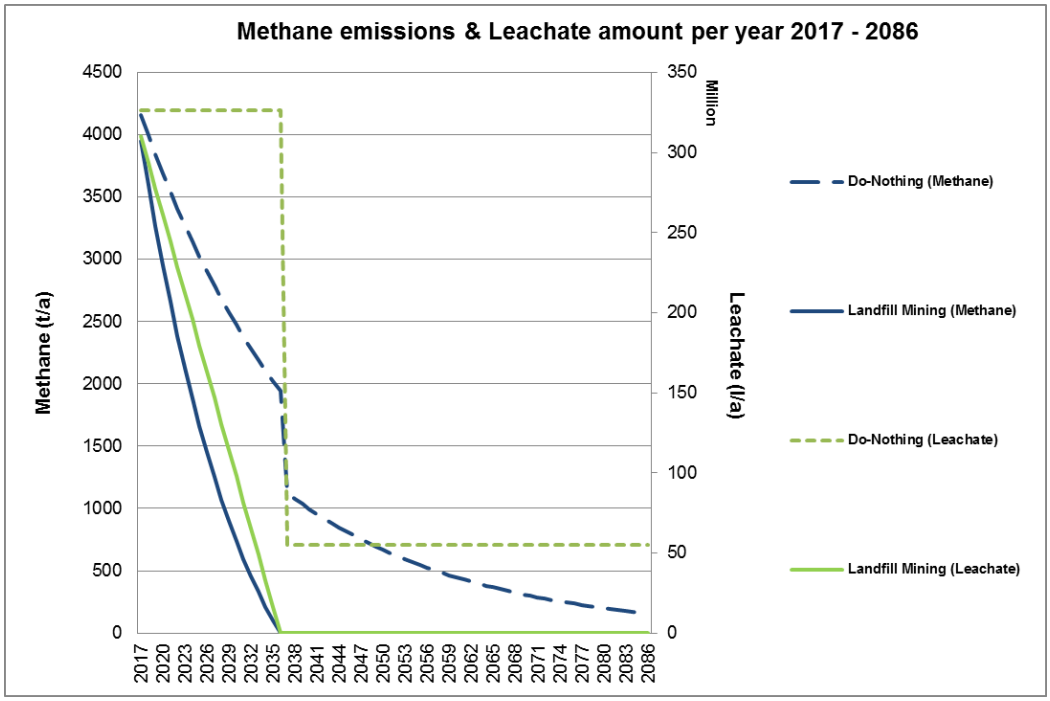
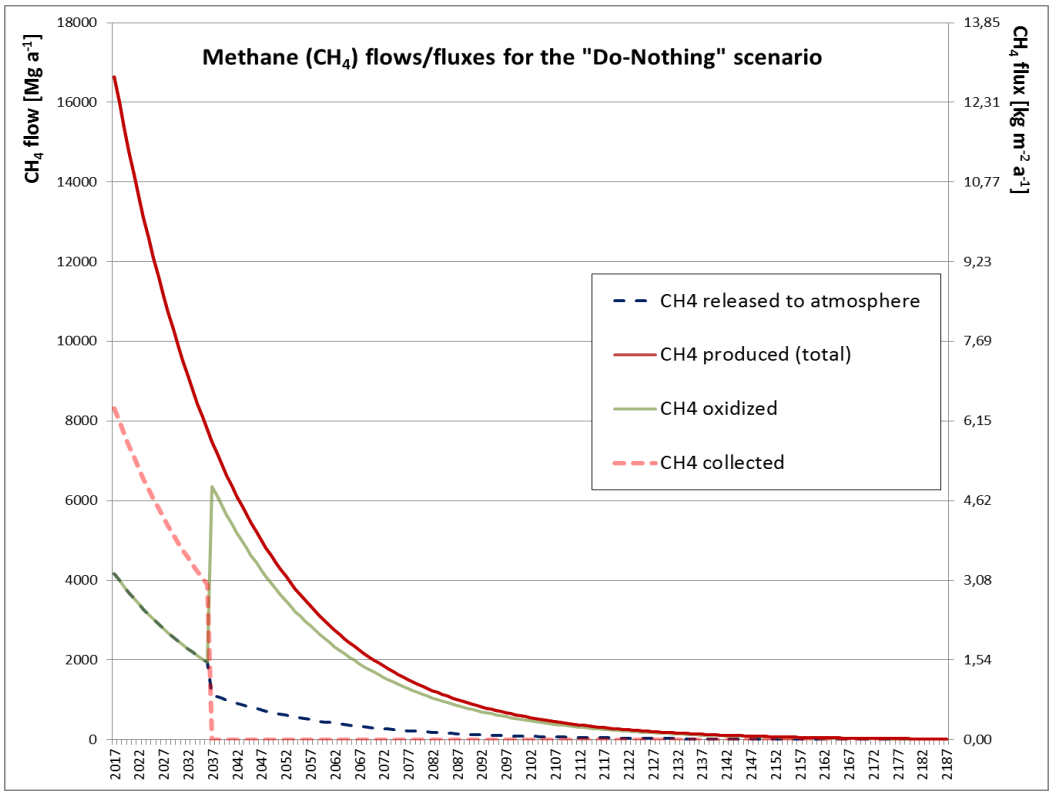


Figure 4 shows the total methane emissions produced until the year 2187. The oxidation rate amounts to 25 % in the first 20 years and to 85 % after the landfill is covered. 50 % of total methane emissions are collected, but only during the first 20 years. Methane emissions released to the atmosphere amount to 25 % until covering the landfill and 15 % afterwards. However, because the methane flux (methane flow per area of landfill cover) is already very low after 2087, it could be expected that methane oxidation rates would even increase further and thereby the landfill may practically not emit greenhouse gases on the long term. In any case, the contribution of long-term methane emissions to the total amount of emitted methane from the landfill is most probably small.

Figure 4: Annual methane emissions in a "Do-Nothing" scenario



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Integrating anthropogenic material stocks and flows into a modern resource classification framework: Challenges and potentials

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ABSTRACT

In light of various policy initiatives promoting the efficient use of resources, this study investigates how anthropogenic resources could be classified under the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009). Compared to geogenic resources, anthropogenic deposits are more heterogeneous and subject to various dynamics, due to the human impact on their genesis. Often they must be assessed not only under aspects of resource recovery, but with respect to alternative waste treatment and disposal options. Factors, which are influencing the classification of anthropogenic resources, vary during the individual phases of resource classification, namely prospection, exploration and evaluation. During the (pre)prospection phase, the preconditions defining the setting for the following resource classification are checked, i.e. the deposit's status of availability for mining ("in-use stocks", "obsolete stocks" or "waste flows") as well as the specific handling and mining condition. System variables, which determine the potentially extractable amount of materials, play a major role during the exploration phase, e.g. technological choices for recovery. In the evaluation phase, modifying factors with direct impact on the project's economics are investigated, such as prices for secondary products, (avoided) costs and possibly monetized externalities. Challenges and potentials of classifying different types of anthropogenic resources under UNFC-2009 are illustrated for two different cases: Mining an old landfill (obsolete stock) is contrasted in a qualitative discussion to mining E-waste (waste flow). Finally, an operative evaluation procedure is outlined, which is still to be refined and illustrated via case studies.

1. Introduction

Rapidly increasing population and growing wealth have resulted in an excessive demand for resources over the past 25 years, leading to growing waste generation and concerns over securing future supplies of raw materials, as some of these resources are concentrated in only few regions of the world. Therefore, international organizations, European institutions as well as national governments have been increasingly promoting improvements in resource efficiency as well as in the utilization of so-called 'anthropogenic resources', as the UN Sustainable Development Goals (UNDP, 2015) or the European Raw Materials Initiative show (European Commission, 2008). Moreover, by recovering materials from obsolete stocks and flows, the need for final sinks, such as landfills, will decrease or at least not increase along with growing waste quantities (Kral and Brunner, 2014). In addition, the secondary production of metals, for instance, is generally less polluting for the immediate environment (Ayres et al., 2013) and considerably less energy intensive than primary production, leading to reduced greenhouse gas emissions (UNEP, 2013). As a consequence, the prospection (i.e. the search for material deposits) and the exploration (i.e. the process of finding deposits being commercially viable for extraction) of anthropogenic resources have gained increasing attention in scientific literature. In this study the term "anthropogenic resources" is defined as stocks and flows of materials created by humans or caused by human activity, which can be potentially drawn upon when needed.

Static material flow analyses have been performed to quantify material turnovers and provide bottom-up estimates of in-use stocks (e.g. Chen and Graedel, 2012), while dynamic material flow

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analyses have been primarily used to determine the overall material stocks in specific use sectors, their development over time and consequent material flows (e.g. Buchner et al., 2015; Mü;ller et al., 2014). A number of authors (e.g. Hashimoto et al., 2009; Kleemann et al., 2014; Lichtensteiger, 2006) have specifically investigated the resource potential of buildings. Several studies (e.g. Kapur and Graedel, 2006; Krook et al., 2012) conclude that anthropogenic deposits, such as landfills, old buildings and hibernating infrastructure, are comparable in size to the remaining natural stock of certain metals. UNEP (2010) finds that half of the previously extracted primary materials are no longer in use. Rettenberger (2009) underlines the relevance and size of the anthropogenic stock for certain materials contained in German landfills. Exploring the resource potential of milling and smelting wastes, Gordon (2002) identifies mill tailings as the single largest source of copper in anthropogenic deposits in the US copper cycle.

But not only the size of exploitable anthropogenic stocks is comparable to virgin material deposits, but also the grade of minerals. Ongondo et al. (2011), for instance, argue that the concentration of gold in old cell phones is two orders of magnitude higher than in natural ores.

To manage scarce raw materials and to facilitate comparisons between anthropogenic and geogenic resources, potential resource extraction projects must be made comparable for involved stakeholders. 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. Furthermore, there have been concrete attempts to map anthropogenic resources into classification codes for natural resources, amongst others by Lederer et al. (2014), based on the examples of Phosphorus stocks in Austria, and Mueller et al. (2015) taking the example of waste electrical and electronic equipment (WEEE).

Although highly relevant for strategic resource planning, only few studies (e.g. Fellner et al., 2015; Wallsten et al., 2013; Krook et al., 2011, 2015, Winterstetter et. al., 2016b) compare different types of anthropogenic material deposits with the aim to prioritize potential extraction projects under economic and/or ecological aspects and specific constraints.

Winterstetter et al. (2015a) demonstrate the applicability of United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to anthropogenic stock resources by classifying recovered materials from an old landfill. They conclude that UNFC-2009 does not only integrate various kinds of primary resources and related extractive activities, but, that it also offers a consistent framework for the analogous classification of diverse anthropogenic resources.

However, UNFC-2009 just like all the other resource classification codes and standards, serves for classification means only, meaning that it does not provide specific guidelines for assessing a mining project. Therefore, the goal of this study is to outline an operative procedure for the classification of different kinds of anthropogenic resources under UNFC-2009, which has been encouraged at the sixth and seventh session of the UNECE expert group on resource classification (UNECE, 2015; Winterstetter et al., 2015b; UNECE, 2016, Winterstetter et. al., 2016a).

After describing the historical development of resource classification systems in general (chapter 2.1.), and of UNFC-2009 in particular (chapter 2.2.), the differences between anthropogenic and geogenic resource assessments are analyzed (chapter 2.3.). Due to the heterogeneity of anthropogenic material deposits, it is of utmost importance to understand and systemize factors, which influence their evaluation and classification. After drafting a concept on how to integrate anthropogenic resources into UNFC-2009 by developing an operative evaluation procedure (chapter 2.4.), different settings of anthropogenic resource classification are illustrated based on two cases: Mining an old landfill, representing an anthropogenic obsolete stock, is contrasted in a qualitative discussion to mining E-waste, an example for mining a waste flow (chapter 2.5.). Finally, challenges and potentials for the integration of anthropogenic resources into UNFC-2009 are discussed (chapter 3), and future research needs are briefly outlined (chapter 4).

2. On how to integrate anthropogenic resources into a modern resource classification framework

The characteristic element of resource classification systems, having evolved over time, is managing scarce resources, and making potential resource extraction projects comparable for involved stakeholders, such as governments or private investors. In order to identify the framework being most suitable for the integration of anthropogenic resources, currently existing resource classification systems and their historical development are reviewed in the following sections.

2.1. The historical development of resource classification systems

The classification of natural resources looks back on a long history (cf. Fig. 1). Starting in the early 18th century in Europe, the perception of temporary scarcity of key raw materials provoked first reflections on a more sustainable use of natural resources. Around 1700, an acute scarcity of wood threatened the livelihood of thousands in Saxony, as the mining industry and smelting of ores had used up entire forests. Rising timber prices resulted in bankruptcy and closure of parts of the mining industry. Influenced by this environment Hans Carl von Carlowitz was the first one to formulate the concept of sustainability in forestry (Von Carlowitz, 1713). Over half a century later, Thomas Robert Malthus focused on the availability of food, forecasting a forced return to subsistence-level conditions, once population growth had outperformed agricultural production, without, however, deriving concrete instructions on how to solve this issue (Malthus, 1798). In the mid-nineteenth century, during the industrial revolution, when the British economy was heavily dependent on coal for energy, Jevons (1865) warned against dwindling coal deposits and rising coal prices for having the potential to undermine economic activity and to end the British supremacy. In this context Jevons covered various issues fundamental to sustainability, such as limits to growth, resource peaking, taxation of energy resources and renewable energy alternatives.

In the United States the U.S. Geological Survey (USGS) (founded in 1879 and originally charged with the classification of public lands) and the U.S. Bureau of Mines (founded in 1920) have conducted modest continuing programs in coal resource estimation, starting already from their early years of existence. In 1972, Vincent E. McKelvey, at that time USGS director, adapted and extended an old and long-used way to classify mineral reserves by the U.S. Bureau of Mines, including all of the undiscovered deposits that might be out there (McKelvey, 1972). In 1976 his work was adopted with minor changes for joint use by the U.S. Bureau of Mines and U.S. Geological Survey (Wood et al., 1983).

In the petroleum industry international efforts to standardize the definitions and estimation methods started in the 1930s. Based on work done by the Society of Petroleum Evaluation Engineers (SPEE), the Society of Petroleum Engineers (SPE) released definitions for all Reserves categories in 1987. In the same year, the World Petroleum Council (WPC) published independently definitions that were quite similar. In 1997, the two organizations jointly published a single set of definitions for Reserves for global use (Definitions, 1997). In 2000, the American Association of Petroleum Geologists

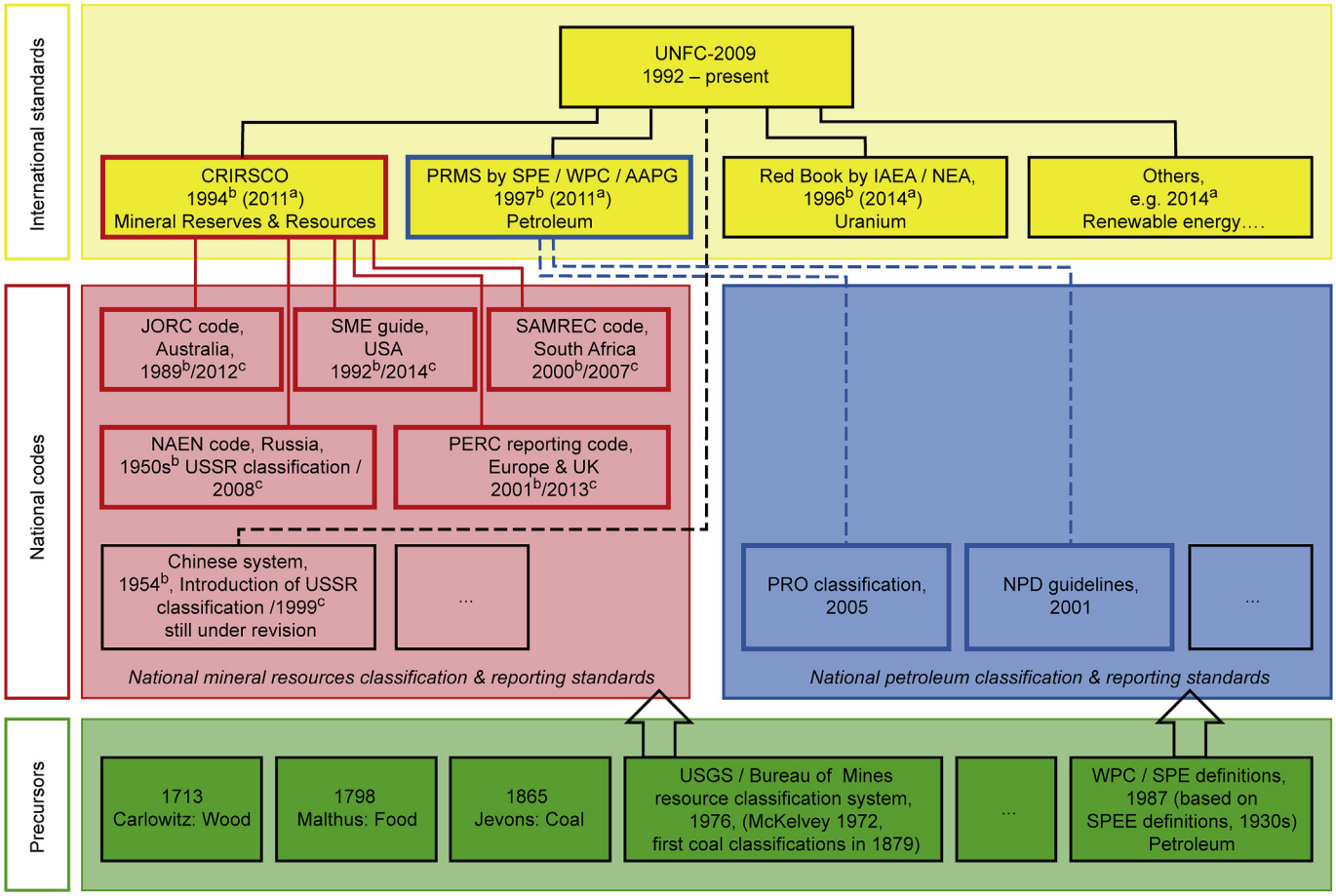

Fig. 1. History of resource classification. Legend: [a] Date of official alignment with UNFC-2009; [b] Date of creation; [c] Last revised version.
AAPG: American Association of Petroleum Geologists, CIM: Canadian Institute of Mining, Metallurgy and Petroleum, CRIRSCO: Committee for Mineral Reserves International Reporting Standards, IAEA/NEA: International Atomic Energy Agency/Nuclear Energy Agency, JORC: Joint Ore Reserves Committee, NAEN: National Association for Subsoil Use Auditing, NPD: Norwegian Petroleum Directorate, PERC: Pan-European Reserves and Resources Reporting Committee, PRMS: Petroleum Resources Management System, PRO: China Petroleum Reserves Office, SAMREC: South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves, SPE: Society of Petroleum Engineers, SPEE: Society of Petroleum Evaluation Engineers, SME: Society for Mining, Metallurgy, and Exploration, Inc., USSR: Union of Soviet Socialist Republics, USGS: United States Geological Survey, WPC: World Petroleum Council.

(AAPG), SPE, and WPC jointly released a classification system for all petroleum resources (PRMS).

Unlike the top-down development in the petroleum industry, in the mineral resource sector over time various parallel mineral resources classification systems have been developed at national level (Weber, 2013). By now, almost all major mining nations as well as economies that heavily depend on mineral resource imports have developed their own national classification code. However, as the mining industry has become more and more of a global business, starting from the 1990s on, there have been increased efforts to harmonize those codes in order to create transparency and comparability in the reporting of primary raw materials (CRIRSCO, 2013; UNECE, 2010).

The Committee for Mineral Reserves International Reporting Standards (CRIRSCO) was established by the Council of Mining and Metallurgical Institutes (CMMI) in 1994. Agreeing on the definitions of the two major categories, 'resources' and 'reserves', and their respective sub-categories (measured, indicated, inferred mineral, proved and probable), the CRIRSCO family currently includes the following national codes and standards: JORC (Australasia), NI43-101 & CIM Definition Standards (Canada), SAMREC (South Africa), PERC (Europe), SME (United States), Comisión Minera de Chile (Chile), NAEN (Russia) as well as several other candidate member countries (CRIRSCO, 2013).

2.2. Striving for harmonization: United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009)

In 1992 after the collapse of the Soviet Union the German Government proposed a new classification system to the UNECE Working Party on Coal to compare the vast resources in the previously centrally planned economies to those in the market economies (UNECE, 2013). Therefore the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) has been initiated by the UN Economic Commission for Europe (UNECE) under a global mandate from the UN Economic and Social Council. In order to facilitate comprehensive worldwide application, in 2009 a revised and simpler version of the classification system was prepared, known as UNFC-2009.

In 1999 an agreement between UNECE and CMMI CRIRSCO was made in order to harmonize terms that had previously often been used incoherently. The CRIRSCO template provides the commodity-specific specifications for solid minerals under UNFC-2009, defining mineral resources as "concentration of naturally occurring materials in or on the Earth's crust with reasonable prospects

for eventual economic extraction, either currently or at some point in the future" (CRIRSCO, 2013). Mineral reserves are defined as resources that are known to be economically feasible for extraction under present conditions. Modifying factors (legal, market, economic, technological etc.) determine the constantly moving boundaries between resources and reserves (CRIRSCO, 2013). As a result of the alignment and mapping work that has been done so far, since 2011, quantities reported under the two-dimensional CRIRSCO template can also be reported under UNFC-2009 with its numerical codes. UNFC-2009 can either be applied directly or used as a harmonizing tool (UNECE, 2010).

The CRIRSCO template was primarily created to ensure consistent standards of public reporting in an international setting, for mining companies, financial institutions, stock exchange regulators and shareholders. It excludes the categories "undiscovered", "unrecoverable" and "uneconomic", which may be relevant for other purposes, e.g. information on national resource inventories (CRIRSCO, 2013; Henley, 2011). Governments, for instance, have to be able to understand and report their full resource base, especially for long-term planning purposes. UNFC-2009 fulfills both governmental as well as to a certain extent corporate stakeholders' requirements.

UNFC is a generic principle based system in which quantities are classified on the basis of the three fundamental criteria of "socio-economic viability" (E1 – E3), "field project status and feasibility" (F1 – F4), and "geological knowledge" (G1 – G4), with E1F1G1 being the best category. These criteria are each subdivided into categories and sub-categories, which are then combined in the form of classes or sub-classes, creating a three-dimensional system by using a numerical coding scheme (UNECE, 2010) (cf. Fig. 2).

UNFC-2009 serves for classification means only, meaning that it does not provide detailed evaluation guidelines for assessing a commodity or a mining project. For instance, it does not prescribe standardized methods and techniques on how to account for modifying factors or on how to report a mine's by-products (Weber, 2013). The actual evaluation for the purpose of public reporting is done at an earlier stage, often by a team of experts around a "competent person". According to the CRIRSCO family codes, those evaluators must possess an appropriate level of expertise and relevant experience in the estimation of quantities associated with the type of deposit under evaluation. Also, they must be a member of a recognized professional organization with a code of ethics and disciplinary procedures (CRIRSCO, 2013). However, none of the existing codes forbids estimates from the mining companies' own competent persons. Internal evaluation procedures differ from one company to another and rely heavily on the personal experience of the respective competent person, resulting in a substantial lack of transparency and objectivity (e.g. Falcone et al., 2013; Sinclair and Blackwell, 2002).

Although UNFC-2009 had been originally designed to address specific primary mineral resource deposits and fossil fuels, this framework has proven to be quite flexible and to be subject to regular negotiations and re-definitions in response to stakeholder needs and changes in society and technology. As a major mining nation China has been actively participating in designing UNFC from 1999 on (UNECE, 2015). The Petroleum Resources Management System (PRMS) was officially aligned with UNFC-2009 in 2011 and the Red Book on Uranium in 2014 (cf. Fig. 1). This means that quantities can be estimated either in the "aligned systems or directly under UNFC (UNECE, 2010).

Recently, efforts have been made to integrate renewable energies into UNFC-2009 in order to compare renewable energy resources with non-renewable resources (Falcone et al., 2013; UNECE, 2014). The endeavor of creating precise specifications and

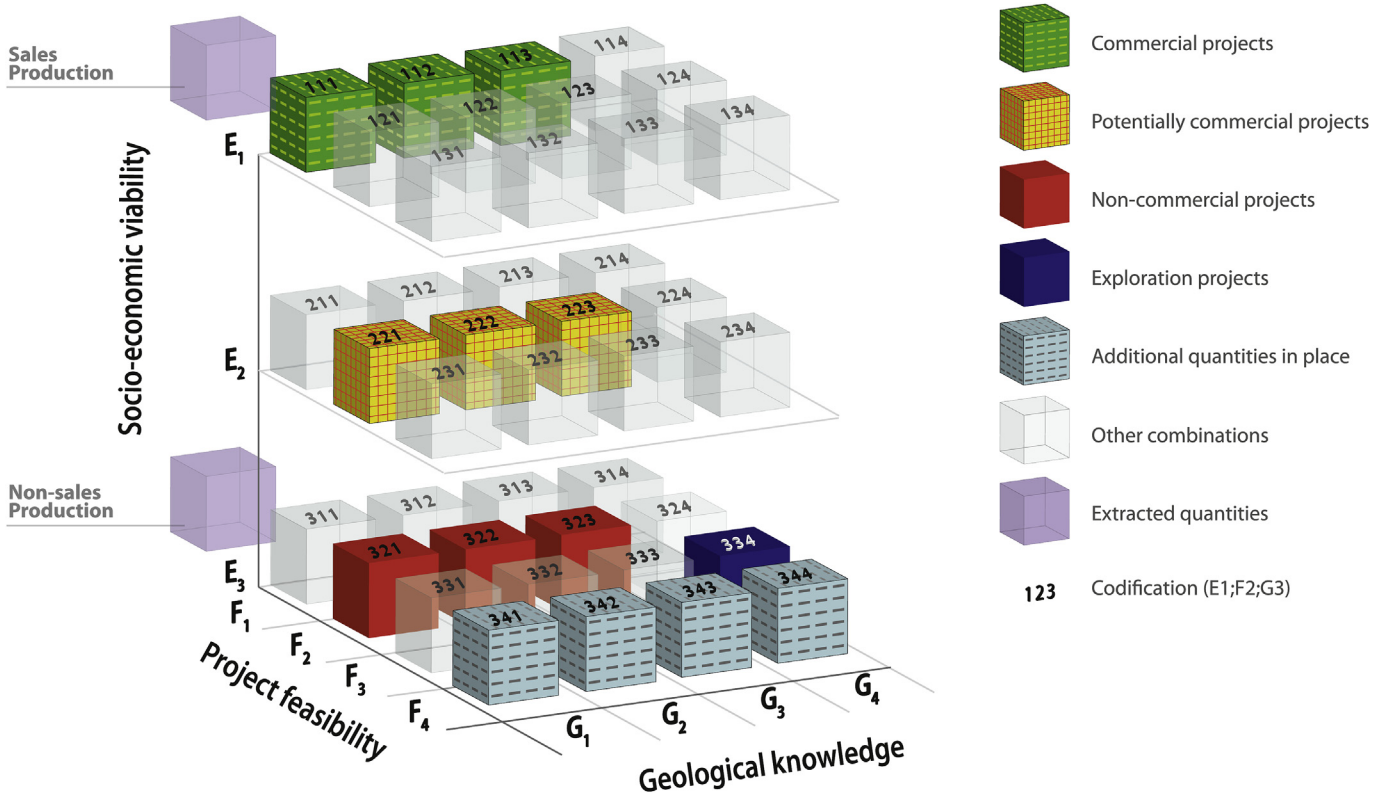

Fig. 2. United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009). Reproduced courtesy of the United Nations Economic Commission for Europe.

guidelines to fit anthropogenic resources into UNFC-2009 has been encouraged at the sixth session of the UNECE expert group on resource classification (UNECE, 2015; Winterstetter et al., 2015b).

At the seventh session the Expert Group recommended "that, […] a small sub-group be established to explore the potential applicability of UNFC-2009 to anthropogenic resources and to report its findings to the eight session" (UNECE, 2016).

2.3. Anthropogenic vs. geogenic resources

Evaluating anthropogenic resources requires a somewhat different approach compared to geogenic deposits (cf. Fig. 3).

Factors, which directly or indirectly influence the classification process, differ or have at least different priorities and implications. There are seven key aspects to be considered when mining anthropogenic material stocks and flows:

(1) **Human influence** on deposit formation: Production, consumption and disposal embedded in a specific system (e.g. laws)
(2) **Diverse and scattered sources** of anthropogenic materials (e.g. E-waste vs. old landfill)
(3) **Many diverse recoverable fractions** within one anthropogenic mining project
(4) **Time** of genesis shorter
(5) **High uncertainties** (legal and technological framework, quality of the materials)
(6) Anticipating future obsolete stocks and waste flows **by investigating in-use stocks**
(7) **Often positive externalities** (e.g. removing source of pollution, greenhouse gas emission savings)

Of utmost importance is the human influence (1) on the creation of anthropogenic deposits, whereas the genesis of geogenic resource deposits and also renewable primary energies entirely depends on natural conditions and processes (cf. Fig. 3). The formation of anthropogenic material deposits depends on various aspects of production, consumption and disposal occurring in a system, which is defined by, amongst others, the cultural, economic, and legal context, resulting in very diverse and scattered sources of anthropogenic materials (2). Manufacturers determine the design of products that have to be disposed of later on, e.g. obsolete personal computers. On the one hand they are subject to the influence of consumers and their buying patterns, and on the other hand they are regulated via laws and policies, for instance on integrated waste management, eco-design or design for recycling (e.g. McCann and Wittmann, 2015; Oswald, 2013). Consumers do not only put pressure on producers through their buying behaviour, but do also play a key role when it comes to waste disposal. For instance, their awareness about source separation of wastes or their timing of discard decisions potentially increases (or deceases) the quantity, quality and grade of minable materials, which is obviously not possible for a natural ore deposit. In this context also profit-seeking recyclers play a central role, being subject on the one hand to laws and policies and on the other hand to commodity markets. Those recycling companies are usually much smaller, compared to internationally operating mining companies in the primary sector, and lack therefore political power and influence.

It is inherent to human cultures that they are constantly developing. Therefore parameter values and system conditions are not static, but likely to change over time. Old landfills, for instance, are witnesses of changing production, consumption and disposal behaviours as well as changing waste management laws and policies over a certain period of time (Bockreis and Knapp, 2011; Gäth and Nispel, 2012; Hölzle, 2010). Technological changes on both the production and the disposal side are amongst the most powerful forces. On the one hand they influence the demand and prices for certain raw materials and on the other hand they potentially improve technical feasibility of recycling due to decreasing costs.

In the primary sector each mine has commonly only few main products and some by-products, such as selenium in copper mines, which, however, are usually not reported (Winterstetter et al.,

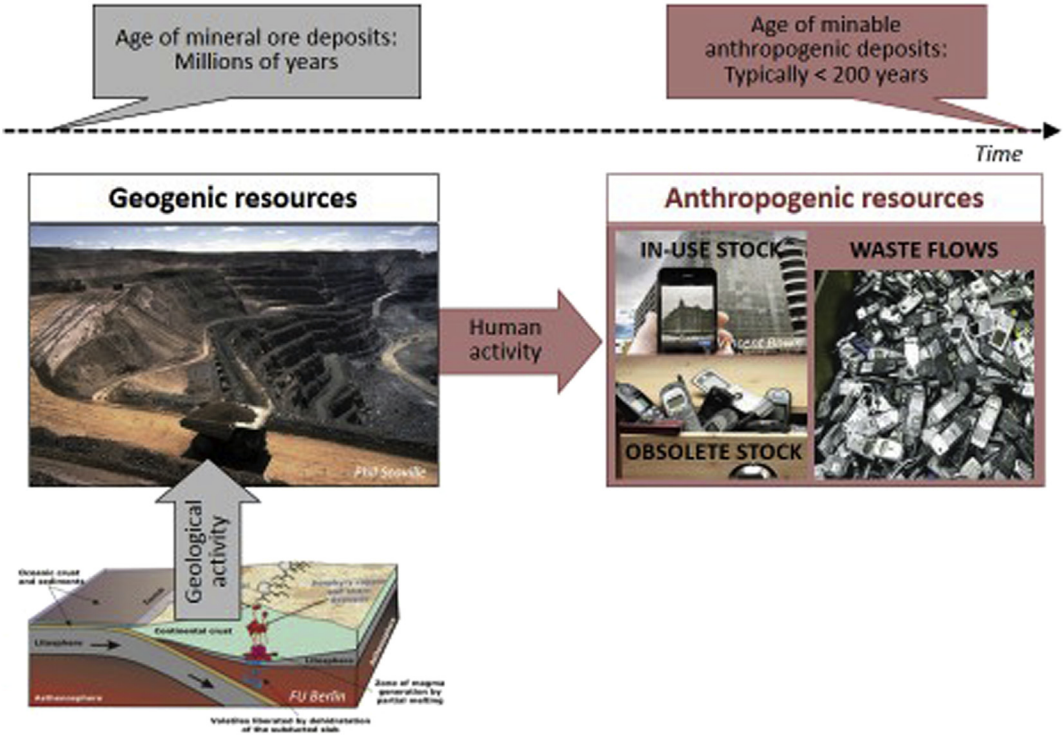

Fig. 3. Geogenic vs. anthropogenic material deposits.

2015b; Weber, 2013). In an anthropogenic mine there are many diverse fractions to be recovered within one project. Within a landfill mining project, for instance, usually a soil-like fraction is recovered, together with ferrous and non-ferrous metals and a combustible fraction. Also selling regained land or newly created landfill capacity together with avoided costs for the landfill's aftercare contributes to the revenues. Revenues for selling all those raw materials and secondary products have to be evaluated as one single project, while markets for each fraction might be very different (3).

While geogenic resources have built up over geologic periods of time, i.e. millions of years, the genesis of anthropogenic stocks occurs over shorter time spans (4) and is subject to various transforming dynamics, such as changing waste legislation, implying high uncertainties (5) for the planning of mining activities. Uncertainties also stem from a potentially changing legal environment or technological developments and sometimes from concerns over qualities of the recovered materials (e.g. fines from landfill mining). While extraction technologies for geogenic resources tend to be well established, for anthropogenic resources often the utilization of new technology or applying existing technology to new materials is associated with high uncertainties (e.g. Bosmans et al., 2013). For some end-of-life materials, such as rare earth elements in permanent magnets, extraction or processing technologies are not available at all or have only been tested at laboratory scale (e.g. Angerer et al., 2009; Schüler et al., 2011).

While mining companies are mainly interested in the commercially recoverable share of the resources, i.e. the reserves, many anthropogenic material deposits are currently likely to be classified as “potentially commercial” (‘resource’). The distinction for anthropogenic resources between non-resources and resources is relevant to support decisions on specific treatments or storage for potential future extraction (6), provided that there are reasonable prospects for future economic extraction. Information on the future mining potential of in-use materials can be useful to manufacturers to increase their products' recyclability and thereby improve future resource availability.

Unlike geogenic resources, anthropogenic deposits often must be assessed not only under aspects of resource recovery, but also in view of alternative waste treatment and disposal costs, and including non-monetary externalities (7). Fellner et al. (2015), for instance, highlight, that the economic performance of Zinc recovery from incineration residues is driven by avoided waste treatment and disposal costs, rather than by the revenues from raw material valorization. Furthermore, in the mining industry non-monetary effects are mainly considered in order to show potential threats to the economic performance of a project in form of looming additional costs, for instance, due to uncertainties concerning new environmental regulations, regulatory inconsistencies, native land claims and protected areas, infrastructure, socioeconomic agreements, political stability, labour issues and security (McMahon and Cervantes, 2011). For anthropogenic deposits, in contrast, those non-monetary effects tend to generate additional benefits and should therefore be monetized and included in the evaluation, for instance the value of eliminating sources of pollution or saved greenhouse gas emissions (e.g. Hermann et al., 2014; Hogland et al., 2010; Frändegård et al., 2015; Van Passel et al., 2013).

2.4. Operative procedure for the evaluation & classification of anthropogenic resources

As shown in the previous chapters, the common feature of both early and contemporary resource classification systems is managing scarce raw materials. For this purpose involved stakeholders, such as governments or investors, must be provided with an operative tool to compare and prioritize potential resource extraction projects.

Factors that influence the classification of anthropogenic resources (in the following called ‘influencing factors’) can be divided into A) preconditions, B) system variables and C) modifying factors. They play different roles during the single phases of resource classification, being displayed on the three axes of UNFC-2009 (cf. Fig. 4).

In the pre-prospection phase, the deposit's status of availability for mining, discriminating between “in-use stocks”, “obsolete stocks” and “waste flows”, as well as the specific handling and mining condition (push vs. pull) represent exclusion criteria for potential mining activities. Those preconditions define the setting for the following classification (cf. Fig. 4).

System variables play a major role in the prospection and exploration phase, being displayed on the G- and F-axis respectively under UNFC-2009. They determine the amount of potentially extractable and usable materials and provide the basis for the following evaluation phase (cf. Fig. 4). To account for different (possible) sets of system variables, scenario analysis can be used, e.g. to investigate different project set-ups. However, throughout a specific evaluation process, the system variables are exogenously given.

During the actual socioeconomic evaluation the ‘modifying factors’ (CRIRSCO, 2013) are investigated, being reflected on the E-axis under UNFC-2009. They have a direct impact on the project's socioeconomic viability and can hardly be influenced by individual stakeholders, but may change over time (cf. Fig. 4).

2.4.1. Pre-prospection

The goal of the pre-prospection phase is to select a specific mining project by screening existing data bases and reports on diverse anthropogenic deposits (Behets, 2013). To obtain a rough overview of relevant anthropogenic stocks and flows, the method of Material Flow Analysis (MFA) can be used, for instance, to visualize national E-waste flows. MFA is a systematic quantification of the flows and stocks of materials within a defined system (in space and time), connecting the sources, the pathways and the sinks of a material (Brunner and Rechberger, 2004).

In this phase the preconditions for mining are investigated, i.e. the deposit's status of availability for mining, and the specific handling and mining condition, defining the setting for the following classification. Anthropogenic resources can be structured according to their status of availability, namely along the lines of obsolete stocks (potentially available for mining) and waste flows (treatment often required). They both originate from in-use stocks of anthropogenic resources, which are currently by definition not available for mining.

Two types of situations, i.e. specific conditions for handling and mining, may arise, push vs. pull, each changing the focus and goal of the following phases of exploration, evaluation and final classification (cf. Fig. 4). In a pull situation, materials are mined only if the evaluation of the project's socioeconomic viability is positive and otherwise left untouched, similar to mining geogenic resources. Therefore the main focus is on the modifying factors, even though system variables are examined in a first step to determine the amount of extractable materials. In a push situation no “yes-or-no”-mining decision can be made, as the anthropogenic materials have to be managed in any case due to legal requirements, like in the case of E-waste flows. This may include material recovery to reduce costs. It basically means that in the following exploration phase the socioeconomically optimal alternative is sought via scenario analysis within the given legal constraints.

Evaluating the economics of hypothetically mining the current in-use stock can be useful for producers to increase their products'

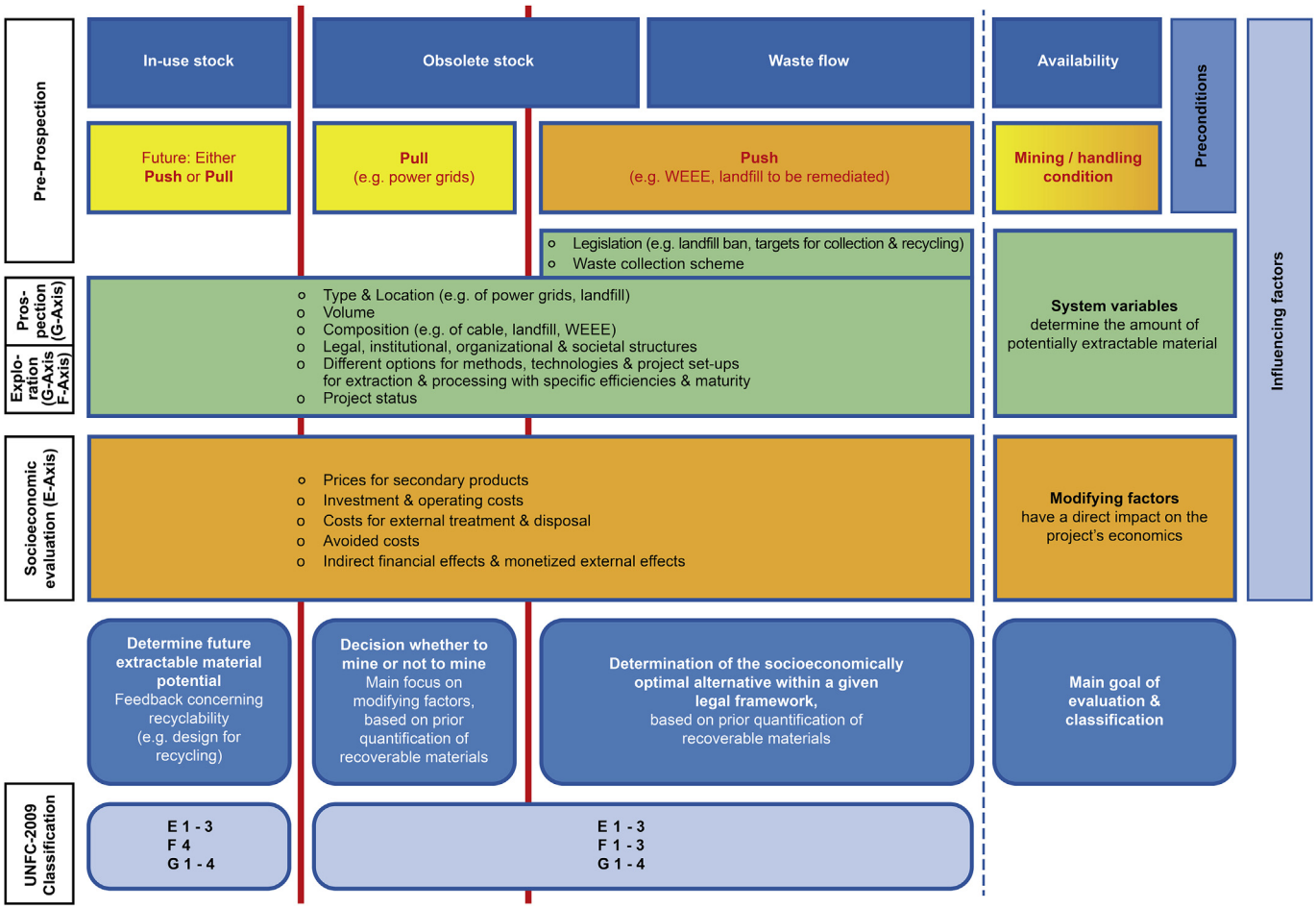

Fig. 4. Each classification phase requires a different focus on influencing factors (preconditions, system variables and modifying factors).

recyclability and to forecast future obsolete stocks and flows. If laws do not exist yet, like in the case of obsolete wind turbines or solar panels, the evaluation outcome will tell decision makers, whether a legal framework for treatment is necessary (push) or not, in case of positive economics (pull).

2.4.2. Prospection

During the prospection phase (displayed on the G-axis), mainly information on a specific resource deposit's type, location, volume and composition shall be gained, allowing first estimates on the resource potential (cf. Fig. 4).

2.4.3. Exploration

In the exploration phase (reflected on the G- and F-axis), the knowledge on the deposit's resource potential has to be deepened (cf. Fig. 4). To identify the potentially extractable and usable share of materials as a function of different technology alternatives and project set-up options, the effect of changing system variables on the final outcome can be investigated. Different sets of system variables are considered via alternative scenarios, e.g. different technology assumptions in terms of material recovery efficiencies.

Based on the respective project's data (e.g. on a landfill's logbook), MFA models of all relevant material flows – and if applicable also energy flows – can be set up for each scenario.

Data on the state-of the art material efficiencies of the relevant processes define that part of the resource potential, which is under current technological conditions extractable and potentially usable. Using MFA further allows to model different project set-ups as well as different options for extraction methods and sorting and processing technologies along with their specific recovery efficiencies.

2.4.4. Evaluation

In the actual evaluation step, the socioeconomic viability of extracting and utilizing the identified extractable raw materials is explored and displayed on the E-axis (cf. Fig. 4). Within a Discounted Cash Flow (DCF) analysis, the project's Net Present Value (NPV) is computed by subtracting the investment cost from the sum of discounted cash flows over a certain period of time. This method is also widely used for the evaluation for mining projects of geogenic resources (Torries, 1998).

Taking into account the choices (e.g. technological) made in the previous phases along with their implications, the main focus of the evaluation phase is on the modifying factors. Having a direct impact on the project's socioeconomic viability, they can potentially move the classification status of a given material deposit along the E-axis of UNFC-2009 from “non-commercial” to “potentially commercial” (resource) to “commercial” (reserve).

A positive NPV implies that a project is economically viable. Consequently, the evaluated materials can be classified as ‘reserve’. If the NPV turns out to be negative, however, one has to judge, whether there are reasonable prospects for economic extraction in the foreseeable future. Whether the deposit can be labeled a ‘resource’ or not, can be decided by anticipating realistic changes of key parameters, by calculating the so-called “cut-off values”, i.e.

required changes in prices or costs to reach the break-even point (NPV = 0) (cf. Winterstetter et al., 2015a).

In the mining industry modifying factors "include, but are not restricted to mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors" (CRIRSCO, 2013).

Modifying factors comprise costs linked to the use of a specific technology or the choice of a specific mining method (e.g. open pit vs. underground mine), commodity prices or certain laws having an immediate impact on the economics (e.g. laws regarding environmental protection or workers' rights).

This looks similar for anthropogenic resources. Here, modifying factors comprise prices for secondary products (e.g. recovered metals or energy), investment and operating costs, costs for external treatment and disposal of residues, avoided costs (e.g. for a landfill's aftercare) and monetized external effects. As stated in Chapter 2.3., mining anthropogenic deposits tends to generate additional positive externalities, such as preventing groundwater pollution or saving greenhouse gas emissions. Depending on the evaluator's perspective and interests, non-monetary effects might be considered and monetized, for instance, via a hypothetical carbon tax (Winterstetter et al., 2015a).

In pull situations, where a deposit can (but does not have to) be mined, legislation and policy can strongly influence the evaluation outcome, for instance by creating financial government incentives or by imposing costly licensing procedures. In push situations, where material extraction from the deposit takes place in any case, alternative costs for disposal and treatment, which can be avoided due to mining and recovery activities, can have a major impact on the project's economics.

2.4.5. Classification under UNFC-2009

Finally, all of the aforementioned criteria are combined and used as a basis for the classification under UNFC-2009 (cf. Fig. 4). The E-axis reflects the socioeconomic viability of a resource recovery project (E1 − E3). While obsolete stocks and waste flows can potentially be classified within the entire range of existing UNFC-2009 categories (E1 − E3, F1 − 3, G1 − 4), in-use stocks fall into lower classes on the F-axis, displaying a mining project's technical feasibility and project status. They are currently not available for mining, but will become waste flows or obsolete stocks in the foreseeable future. Therefore, by definition, in-use stocks are classified as F4, with the subclasses F4.1 − F4.3 describing the current state of technological development (UNECE, 2013).

Categories on the G-axis (G1 − G4), reflecting the knowledge on a deposit's composition and extractable material content, may be applied in cumulative form to express low (G1), best (G1 + G2) and high estimates (G1 + G2 + G3), as commonly used for recoverable fluids. Discrete classification is used for solid minerals, reflecting the level of geological knowledge and confidence, associated with a specific deposit (UNECE, 2010).

2.5. Illustrating examples: E-Waste vs. old landfill

Treating waste flows, such as waste electrical and electronic equipment (WEEE), typically represents a push situation. The management of WEEE flows in the European Union is mainly regulated and driven by laws, in particular by the EU directive 2012/19/EU. This EU directive sets the annual collection, reuse and recycling targets, which is implemented in different ways at national levels of the EU member states. Under the extended producer responsibility (EPR) producers are obliged to finance the take back of WEEE from consumers, ensure their safe disposal and to comply with the set recycling targets (European Commission, 2003, 2012). Thus, here the question is not whether to mine or not to mine WEEE, but rather on how to fulfill legal requirements in a socio-economically optimal way. The project feasibility of mining WEEE is dominantly influenced by the system variable "set-up of the collection and recycling system". A number of stakeholders is involved with different responsibilities, such as legislators, producers, retailers, consumers, recyclers and municipalities (e.g. Huisman et al., 2008). The success of a take back system consists, amongst other things, of an appropriate infrastructure and service provision. Moreover, consumer variables, such as attitudes, behaviour, age, gender, employment status, storage space etc., as well as their awareness level of take back options play an essential role when it comes to achieving the collection and recycling goals (e.g. Ongondo et al., 2011), which again determines the quantity of minable/extractable materials. Aside from collection, the recycling chain for WEEE consists of further succeeding steps, namely sorting, dismantling, pre-processing, and end-processing, which includes refining and disposal. The EU directive specifies minimum treatment requirements for WEEE providing for the removal of specific components containing hazardous substances. As WEEE have to be handled anyway, the concept of avoided disposal cost plays a major role in the evaluation. They will strongly depend on the avoided disposal alternatives, i.e. the costs of landfilling or incineration, depending amongst others on the defined legal standards of those disposal alternatives. A number of different treatment technologies for WEEE are available, both mature and emerging ones, which alone or in combination can address the specific needs of each product group (e.g. Cui and Zhang, 2008; Dalrymple et al., 2007; Salhofer and Tesar, 2011). The recovered quantities of economically interesting materials, such as glass, plastics and metals (Cu, Al, Au, Ag etc.), heavily depend on the recovery efficiencies of pre-processing technologies and methods (Oswald, 2013). Techniques with higher efficiencies are more likely chosen if markets for the output fractions exist and if expected price levels for output materials are high enough to justify higher treatment costs or if disposal costs for non-recyclable remaining materials can be reduced.

Mining stocks can either represent a push or a pull situation, as shown, for instance, by Frändegård et al. (2015). The alternative of mining a landfill is usually regulated aftercare, implying that the closed landfill is left untouched and landfill facilities are maintained, with emissions being treated and monitoring activities being performed for many decades (Laner et al., 2012). Mining an old landfill therefore requires positive socioeconomic prospects either for a private investor or a public entity, representing a pull situation. For a private investor only direct financial effects are of interest, while non-monetary effects tend to be neglected, unless they are monetized in form of subsidies (e.g. Bockreis and Knapp, 2011). A public entity, in contrast, is more interested in long-term effects, i.e. societal and environmental aspects (Graedel et al., 2012), such as the elimination of a source of local soil and water pollution (e.g. Krook et al., 2012), the avoidance of long-term landfill emissions (e.g. Bernhard et al., 2011), the public's perception (e.g. Ford et al., 2013), the creation of new jobs (e.g. Van Passel et al., 2013) and the potentially increasing value of surrounding land (e.g. Hölzle, 2010), after mining the landfill. Some landfill mining projects were carried out with resource and energy recovery as a main focus (e.g. Cossu et al., 1996; Krug, 2008; Zanetti and Godio, 2006). However, if the landfill turns out to be an immanent pollution threat to the environment, e.g. to groundwater, or if new landfill space is urgently needed, authorities will oblige the former landfill operator to act, which means that the situation in that case is comparable to mining a waste flow that has to be treated. In other words the stock turns into a flow, a pull into a push situation, as the choice of whether to extract the material or not is taken away. Most of the early landfill-mining projects were primarily motivated by

local pollution issues or by the need for new landfill capacities given the difficulty of getting permission to develop new landfills (e.g. Bockreis and Knapp, 2011; Hogland et al., 2004; Spencer, 1990; van der Zee et al., 2004) rather than by recovering landfilled materials as secondary resources.

3. Discussion: challenges and potentials for the classification of anthropogenic resources under UNFC-2009

Under the UN Sustainability Development Goal "Responsible consumption and production", amongst others, the sustainable management and efficient use of natural resources as well as a substantial reduction of waste generation through prevention, reduction, recycling and reuse, shall be achieved by 2030. Therefore, the incorporation of anthropogenic resources into UNFC-2009 seems like a coherent and consequent next step towards a comprehensive picture of available and potentially minable geogenic and anthropogenic raw materials.

In order to make potential resource extraction projects comparable for interested parties, transparency and consistency are of utmost importance. To prevent the emergence of untransparent and rather subjective practices, similar to the ones existing in the mining industry, where evaluations are made by a team of experts around a "competent person", it is important to create precise guidelines to evaluate anthropogenic resources in order to fit them into UNFC-2009.

A methodological framework, including common definitions, might help to enhance the knowledge base on the resource potential present in the anthroposphere, by standardizing the data collection processes, facilitating cross-border communication between involved stakeholders (e.g. for E-waste records), and to finally harmonize practices, standards and guidelines for a comprehensive and sustainable recovery of materials from wastes.

Due to the heterogeneous nature of anthropogenic resources, their classification has several specific characteristics (cf. chapter 2.3 ff.), which – in our opinion – can best be accounted for by UNFC-2009, rather than by any other existing code.

For instance, the classification of anthropogenic in-use stocks would be impossible under frameworks, designed primarily for public reporting purposes, such as the CRIRSCO template, but requires a broader approach, as offered by UNFC-2009. To classify currently non-extractable quantities due to, for instance, site constraints, technology limitations or other constraints, the UNFC-2009 category E3F4G1-4 ("additional quantities in place") can be used (UNECE, 2014; UNECE, 2010).

However, we consider, that for evaluating the hypothetical mining of a certain in-use stock under current conditions, it is justified to use the E-axis' full range (E1 – E3) for the final classification, and not exclusively "E3". Information on the projected economic performance of mining anthropogenic materials, which are currently in-use, is highly relevant to facilitate decision-making for political and private business stakeholders. To indicate the in-use stock's current unavailability for mining, "F4" is granted by default on the F-axis, with F4.1 – F4.2 displaying the maturity of extraction and processing technologies.

As for parts of anthropogenic materials, extraction is not (yet) economically viable under current conditions, the systematic integration of non-monetary effects will be of high priority, to create (additional) financial incentives in pull situations or to outperform the minimum legal requirements in push situations. Social and environmental externalities (e.g. eliminating sources of pollution, supply security) tend to generate additional benefits and should therefore be monetized and included in the evaluation. Combining aspects of waste and resource management is hereby a key challenge. In light of innumerable existing non-market valuation methods, this issue is, however, far from being solved easily.

A decisive advantage of UNFC-2009 over the two-dimensional systems (like most of the codes from the CRIRSCO family), is the additional third axis, displaying a mining project's "technical feasibility and field project status". The two-dimensional systems only account for the knowledge on composition of a deposit and the economics of a mining project. This might produce a distorted picture, especially where technologies for extraction or processing do not exist yet or are immature and therefore expensive. From a two-dimensional system, one would only get the information, that the project is "uneconomic", while the F-axis under UNFC-2009 offers a more nuanced view by potentially showing the development status of technologies applied in the project.

Another major challenge is the evaluation and classification of dynamic waste flows. Under UNFC-2009 only defined projects can be evaluated and classified (UNECE, 2010). Therefore, for a constantly renewing waste flow, such as obsolete PCs, system boundaries must be arbitrarily chosen, e.g. on a spatial and/or temporal level. Alternatively, an entirely new way of integrating them under UNFC-2009 will have to be established.

4. Conclusion & outlook

UNFC-2009 offers a consistent framework for the classification of different kinds of anthropogenic resources, in analogy with geogenic resources. The operative evaluation procedure, developed in this study, accounts for the specific properties of anthropogenic resources. Compared to geogenic resources, anthropogenic deposits are often more scattered and more heterogeneous, containing diverse recoverable fractions. They are created and altered by human activities via the production, consumption and disposal of materials and goods, and are renewed over drastically shorter time spans than geogenic resources. Due to various dynamics, the planning of mining activities is linked to high uncertainties, with respect to the legal and technological framework, as well as to the quality of the materials. Moreover, anthropogenic deposits often must be assessed not only under aspects of resource recovery, but also regarding alternative waste treatment and disposal options, and including non-monetary externalities. Besides classifying obsolete stocks and waste flows, information on the future mining potential of in-use materials can help manufacturers to increase their products' recyclability and so improve future resource availability.

In order to obtain a comprehensive overview of various anthropogenic resources and to allow their full integration into UNFC-2009, the operative evaluation procedure outlined in this study needs to be refined. Once established, the integration of geogenic and anthropogenic resources into one framework, will facilitate quantitative resource assessments in consideration of the raw materials present in natural deposits as well as raw materials present in the anthroposphere. On this basis, complete and comprehensive assessments of raw material supply can be made. Also, criticality considerations can be extended by including anthropogenic material stocks. Although the groundwork has been laid for landfill mining and some other selected waste streams, further case studies accounting for diverse settings of mining anthropogenic resources are needed to further refine the criteria and procedures for assessing resource availability.

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Abbreviations

AAPG	American Association of Petroleum Geologists
CIM	Canadian Institute of Mining, Metallurgy and Petroleum
CMMI	Council of Mining and Metallurgical Institutes
ICM	International Council on Mining and Metal
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
IAEA/NEA	International Atomic Energy Agency/Nuclear Energy Agency
JORC	Joint Ore Reserves Committee
NAEN	National Association for Subsoil Use Auditing
NPD	Norwegian Petroleum Directorate
PERC	Pan-European Reserves and Resources Reporting Committee
PRMS	Petroleum Resources Management System
PRO	China Petroleum Reserves Office
SAMREC	South African Code for Reporting of Exploration Results, Mineral Resources and Mineral Reserves
SPE	Society of Petroleum Engineers
SPEE	Society of Petroleum Evaluation Engineers
SME	Society for Mining, Metallurgy, and Exploration, Inc
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNDP	United Nations Development Programme
UNFC-2009	United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009
USSR	Union of Soviet Socialist Republics
USGS	United States Geological Survey
WEEE	waste electrical and electronic equipment
WPC	World Petroleum Council

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Credits of pictures used in Fig. 3

Adelaide's lost buildings: Self-guided walking tour by Vincent brown, https://commons.wikimedia.org/wiki/File:2011_adelaide_5706042946.jpg.
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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

Table 1
Classification of mining an anthropogenic material deposit under UNF-2009 (based on Winterstetter et al. (2016)).

Phases & UNFC-2009 axes	Goal	Influencing factors	Methods for decision foundation
1. Pre-Prospection	Selection of a deposit to be mined	A) Preconditions a) Availability status • In-use stock: Currently not available for mining, but at some point in the future • Obsolete stock: Potentially available for mining, sometimes even required • Waste flows: Treatment often required b) Mining/handling condition • Pull: Deposit can be mined • Push: Materials must be extracted from the deposit due to system constraints	Analysis & evaluation of reports/data bases on anthropogenic deposits: Macro Scale MFA
2. Prospection G-Axis	Knowledge on the deposit's resource potential	B) System Variables[a] a) Type & Location b) Volume c) Composition	Detailed investigation of the deposit (e.g. log books, sampling, analysis)
3. Exploration G-Axis F-Axis	Knowledge on the deposit's share of extractable & potentially usable materials Technical feasibility & Project status: Identify options for technologies & project set-ups	d) Legal, institutional, organizational & societal structures e) Different options for methods, technologies & project set-ups for extraction & processing with specific efficiencies & maturity f) Project status	Micro scale MFA with specific recovery efficiencies Technology assessment, policy framework analysis, stakeholder analysis
4. Evaluation E-Axis	Socioeconomic viability of extraction & utilization	C) Modifying factors[b] a) Prices for secondary products b) Costs c) Avoided costs d) Indirect financial effects e) Monetized external effects	DCF analysis & cut-off values for key parameters Net Present Values (NPV) a) NPV > 0: Reserve b) NPV < 0: Resource or not?
5. Classification	Combination of all criteria & classification under UNFC-2009		

MFA = Material Flow Analysis.
DCF = Discounted Cash Flow Analysis.
[a] Determine the physical amount of potentially extractable materials.
[b] Direct impact on the project's economics, but not within the domain of a single stakeholder.

socioeconomic viability and can potentially move the classification status of a given material deposit along the E-axis of UNFC-2009 from "non-commercial" to "potentially commercial" (resource) to "commercial" (reserve). They can hardly be influenced by individual stakeholders, but may change over time. Finally, all of the aforementioned criteria are combined and used as a basis for the classification under UNFC-2009 (Winterstetter et al., 2016).

2.2. Case studies

To illustrate different settings of anthropogenic resource classification, the extraction and utilization of anthropogenic materials from an old landfill (obsolete stock) is contrasted to recovering materials form obsolete PCs (waste flow), and from permanent magnets in wind turbines (in-use stock).

Compared to other resource recovery undertakings, mining resources from obsolete stocks exhibits the most similarities with conventional primary resource mining projects. The alternative of mining a landfill is usually regulated aftercare, implying that the closed landfill is left untouched and landfill facilities are maintained, emissions treated, and monitoring is carried on for many decades in case of municipal solid waste (MSW) landfills (Laner et al., 2012).

By choosing end-of-life personal computers (PC) as opposed to an old landfill, we explore how mining a waste flow differs from mining an obsolete stock. In a pull situation, mining an old landfill requires positive socioeconomic prospects either for a private investor or a public entity. However, if the landfill turns out to be an immanent pollution threat to the environment, e.g. to groundwater, the former landfill operator will be obliged to act, which means that the situation in that case is comparable to mining a waste flow that has to be treated due to legal constraints, and where alternative disposal costs play a more prominent role. Treating waste flows, such as obsolete PCs, typically represents a push situation. The management of e-waste flows in the European Union is mainly regulated and driven by laws, in particular by the European WEEE directive 2002/96/EC and 2012/19/EU, determining the annual collection, reuse and recycling targets. The directive specifies minimum treatment requirements for e-waste providing for the removal of specific components containing hazardous substances. Under the Extended Producer Responsibility (EPR) system all economic operators, putting electrical and electronic equipment on the market, are responsible for their management and recovery (cf. da Cruz et al., 2014). This implies that they have to finance the take back of WEEE, classified in ten categories, from consumers, and ensure their safe disposal (European Commission, 2003, 2012; Zoeteman et al., 2010).

Moreover, information on the current status and size of in-use stocks is highly relevant with regard to future minable waste flows and obsolete stocks. In 2008, rare earth permanent magnets accounted for 21% of total rare earth elements (REE) use in terms of volume and 37% in terms of value (Kingsnorth, 2010), with wind turbines being one of the most important drivers for the NdFeB permanent magnet demand (Schüler et al., 2011). Depending on whether there will be future constraints, such as laws and policies, and how the general framework will look like, mining REE materials or entire magnets can potentially become a push or a pull situation.

2.2.1. Obsolete stock: the case of landfill mining

For the first case study an evaluation of landfilled materials with special focus on the economics (pull situation) is performed for the Enhanced Landfill Mining (ELFM) project in Flanders, Belgium.

From the 1970 s until 2003, more than 16 million metric tons of wastes were landfilled on 1.3 square kilometers. It contains a roughly equal share of municipal and industrial solid waste (cf. Table 2) and is engineered in compliance with Belgian legislation and the EU Landfill Directive.

The landfilled waste is planned to be almost entirely excavated over a period of 20 years, with operations starting in 2017 (Jones et al., 2013). The present study makes some assumptions that differ from the ELFM consortium's plans: Metals (ferrous and non-ferrous) as well as the stone fraction will be sold after recovery, while paper, plastics, wood and textiles will be entirely converted into Refuse Derived Fuel (RDF) and exported to an offsite incineration plant for electricity generation. At the end of excavation activities the regained land will be sold. A considerable share of materials has to be re-landfilled due to high contamination levels. To carry out a landfill mining project, it is highly important to know all involved stakeholders, such as the landfill's former operator and its current owner (private investors vs. public authority) (e.g. Diener et al., 2015; Hermann et al., 2014). In this case the evaluation is performed from a public entity's macro view. The greenhouse gas emission saving potential compared to a "Do-Nothing" scenario was quantified through a Life Cycle Assessment (LCA) and then monetized via a hypothetical CO_2 tax at 10 €/t CO_2 eq., exemplarily for a non-monetary long term effect. This corresponds to the average price of carbon emission futures between 2010 and 2015 (Investing.com, 2016). Detailed calculations of newly emitted and avoided emissions of a LFM project can be found in Winterstetter et al. (2015). In addition, a rather low discount rate of 3% (cf. SI, Section 1) is applied and aftercare obligations in the "Do-Nothing" scenario are assumed to be 70 years (minimum requirement under the landfill directive is 30 years), which implies that both avoided emissions and avoided aftercare costs are higher due to landfill mining and can be considered as revenues (Winterstetter et al., 2015). Discounted costs and revenues are considered for 20 years with investment costs being depreciated over ten years (own assumption). Table 3 shows system variables and modifying factors considered in the case study.

2.2.2. Waste flow: the case of end-of life personal computers

Under UNFC-2009 only defined projects can be evaluated and classified (UNECE, 2010). Therefore, for a constantly renewing waste flow, such as obsolete PCs, system boundaries must be arbitrarily chosen. In this case study, two different scenarios of handling obsolete PCs are evaluated for a European city of 1 million inhabitants (cf. Table 4).

The main focus lies on the WEEE EU directive and its enforcement, as well as on the population's waste collection and source separation behavior, which affects the waste flow's volume, as well as on the technical options for dismantling obsolete PCs. Scenario 1 reflects the situation of treating obsolete computers in a city of a high-income EU member state, where the EU directive 2002/96/EC is fully implemented in national law and strictly enforced. The average amount of WEEE collected in 2012 in Austria (taken as pars pro toto high-income EU member state) accounted for 9.6 kg (cap/a) (Eurostat, 2015). In 2012, a share of 8% out of the total collected WEEE in Austria is assumed to be obsolete PCs, yielding 0.8 kg/(cap/

Table 2
Composition of the landfill presented in mean values and absolute standard deviations (Quaghebeur et al., 2012). Wt % = Dry weight percentage.

	Municipal Solid Waste (Mean value ± std. dev. abs., wt-%)	Industrial Waste (Mean value ± std. dev. abs., wt-%)
Plastics	20 ± 8	5 ± 5
Textiles	7 ± 6	2 ± 1
Paper / Cardboard	8 ± 6	2 ± 1
Wood	7 ± 2	7 ± 2
Glass / Ceramics	1 ± 1	1 ± 1
Metals (Cu, Al, Fe-metals)	3 ± 1	3 ± 3
Minerals / Stones	10 ± 4	10 ± 10
Fines <10 mm	40 ± 7	62 ± 7
Unknown	4 ± 4	8 ± 6

Table 3
Mining of materials from an old landfill: system variables and modifying factors.

	Landfill Mining
Main Goal	• Determine the socioeconomic viability from a public entity's perspective
System variables	
Availability status	• Obsolete stock
Specific mining condition	• Mined for resource recovery (pull situation)
Type & Location	• MSW / IW landfill in Flanders (Belgium)
Volume & Composition	• Data from the sample excavations & the landfill's logbook
Legal, institutional, organizational & societal structures	• No legal framework existing, but established institutional structure with a number of committed partners, positive public perception
Project set-up for thermal treatment	• Offsite incineration of the combustible waste fraction
Project Status	• Project is still in the feasibility stage with mainly design & planning activities, operations only on a pilot scale
Modifying factors	
Investment & operating costs	• Costs for licenses & permits • Costs for excavation & storage • Costs for separation & drying (CAPEX & OPEX)[a]
Prices for secondary products	• Prices for secondary products: Fe-metals, Cu, Al, stones, regained land
Costs for external treatment & disposal	• Costs for transport, baling & gate fees for energy recovery
Avoided costs	• Avoided costs for final landfill cover & after care for 70 years
Monetized external effects	Hypothetical CO_2 -tax

CAPEX: Capital expenditures (used by a company to acquire or upgrade physical assets such as property, industrial buildings or equipment).
[a] OPEX: Operating expenses (ongoing costs a company pays to run its basic business).

Table 4
Mining of materials from end-of-life PCs for two different scenarios: System variables and modifying factors.

Obsolete PCs	Scenario 1	Scenario 2
Main Goal	Determine the economic performance within a given legal, institutional, organizational & societal structures	
System variables		
Availability status	• Waste flow	
Specific mining /handling condition	• PCs have to be treated under EU directive (push situation)	
Type & location	• PCs with similar composition & weight • European city with 1 million inhabitants	
Volume & Composition	WEEE collection in 2012: 9.6 kg(cap/a) (Austria) Separate collection of obsolete PCs: 0.8 kg(cap/a) => 800 t PCs/a	WEEE collection in 2012: 1.2 kg(cap/a) (Romania) Separate collection of obsolete PCs: 0.1 kg(cap/a) => 100 t PCs/a
Legal, institutional, organizational & societal structures	High income EU member state Full compliance with EU laws: High public awareness, good infrastructure	Low income EU member state Weak compliance with EU laws: Low public awareness, weak infrastructure
Different options for dismantling with specific efficiencies	Mechanical treatment & further manual dismantling	Manual dismantling
Modifying factors		
Investment & operating costs	• Costs for sorting, transport & dismantling (CAPEX & OPEX)	
Prices for secondary products	• Prices for Fe-metals, Al, Cu, cables, fine fraction, adaptors, (granulated) printed circuits, contacts, brass, processors	• Prices for Fe-metals Al, printed circuits, (hard) drives, adaptors, contacts, processors
Costs for external treatment & disposal	• Disposal of capacitors	
Avoided costs	• Avoided disposal costs of PCs	

a) separately collected PCs (based on ReUse-Computer e.V, 2013, same share assumed in both cities). Thus, for a city of 1 million inhabitants an annual PC waste flow of 800 t can be calculated. Regarding processing, Scenario 1 represents a hybrid scenario of mechanical processing and manual disassembly, as shown in SI, Fig. 1 (Salhofer and Spitzbart, 2009).

In Scenario 2, obsolete PCs are collected and treated in a city of a low-income EU member state, where the EU directive is implemented, but weakly enforced. In 2012 in Romania (representative low-income EU member state) the average amount of WEEE collected accounted for 1.2 kg/(cap/a) (Eurostat, 2015). Annually, 0.1 kg of waste PCs are separately collected per person. Thus, for a city of 1 million inhabitants the annual PC waste flow amounts to 100 t. In this scenario the obsolete PCs are manually dismantled in a single step, meeting only the basic requirements under the EU directive. Economically interesting materials are recovered, while a considerable share of residues is dumped.

The waste flow in a city of a high-income EU country is assumed to be composed of PCs, which are discarded after an average period of five years. In a city of a low-income EU country, such as Romania, according to Ciocoiu et al. (2010), PCs are used longer than recommended by the manufacturer, which is due to the weaker economic situation. However, neither the composition nor the weight of individual PCs has changed significantly since the 2000 s, as shown in the study by Nagai (2011) (cf. Table 5). Discounted costs and revenues are considered for one year with investment costs being depreciated over ten years (cf. case study on landfill mining).

Table 5
Composition of an old desktop PC without monitor dating from 2006, in weight % (based on Salhofer and Spitzbart, 2009).

	Average content (% of total weight) of materials in a PC produced after the year 2000
Iron/Steel	70%
Aluminum	5%
Copper	1%
Printed circuits/Contacts	10%
Plastics	9%
Other	5%

2.2.3. In-use stock: the case of NdFeB permanent magnets in wind turbines

In this case study two different options for a future utilization of end-of-life permanent magnets in wind turbines, which are currently in use, are investigated, namely the re-use of permanent magnets (Scenario 1) and the recovery of Neodymium (Nd), Ferrum (Fe), Boron (B), Dysprosium (Dy) and Praseodymium (Pr) via hydrometallurgical methods (Scenario 2).

A report by Gattringer (2012) provides detailed information and data regarding the in-use stock of recoverable materials in wind turbines in Austria. Based on an installed capacity of 214 MW in 2011, Gattringer (2012) assumed increasing new annual installations, resulting in 277 MW installed wind power at the end of 2014 in form of wind turbines containing NdFeB permanent magnets. Calculating with 0.6 kg NdFeB per installed kW (Hatch, 2008; Wuppertal Institut, 2014) the overall resource potential of in-use wind turbines in Austria in 2014 amounts to 166 t NdFeB materials. Magnet scrap consists typically of 24% of Nd (Prakash et al., 2014), representing twice the concentration of natural ore deposits (Bleiwas and Gambogi, 2013). The Dy share amounts to approximately 4%, Pr up to 5% and Fe varies between 62 and 69%, while the B content is usually around 1% (Prakash et al., 2014).

Regarding the project's technical feasibility, two sets of system variables are evaluated in two different scenarios (cf. Table 6).

In Scenario 1, NdFeB permanent magnets are re-used in their current form and shape. Separating the permanent magnets from the wind turbines' nacelles as well as demagnetizing and then re-magnetizing them represent hereby the key steps (Binnemans et al., 2013).

In Scenario 2, a hydrometallurgical method was selected to separate rare earth elements (REE) from the magnet scrap. When mining REE from primary ores this is the most common chemical extraction method to produce concentrates, which are then leached with aqueous nitric, sulfuric or hydrochloric acids. Given the variety of different hydrometallurgical methods, for this case study the aqueous process developed by Lyman and Palmer (1992) was chosen. After leaching and entirely dissolving the magnetic scrap in an aqueous H_2SO_4 solution, a salt of an alkali element or ammonium is added to the solution of dissolved rare earth

Table 6
Potential future mining of materials from permanent magnets in wind turbines for two different scenarios: system variables and modifying factors.

NdFeB permanent magnets from wind turbines	Scenario 1	Scenario 2
Main Goal	Determine the extractable material potential, which might become available in the future	
System variables		
Availability status	• In-use stock	
Specific mining / handling condition	• Hypothetically mined within one year under current conditions (push or pull situation, depending on whether there will be future constraints, such as laws and policies)	
Type & Location	• NdFeB permanent magnets in wind turbines in Austria	
Volume & Composition	• Estimates based on data on production and installation of wind turbines and their capacity in Austria	
Legal, institutional, organizational & societal structures	• No legal framework existing. It is very likely that a wind park operator replaces the permanent magnet in case of a defect.	
Different recycling options with specific efficiencies	• Re-use of permanent magnets	• Hydrometallurgical method (Lyman and Palmer, 1992) to extract Nd,Fe,B, Dy & Pr
Modifying factors		
Investment & operating costs	• Costs of separating magnets out of wind turbines & demagnetization	• Costs of separating magnets out of wind turbines & demagnetization • REE extraction from magnet (CAPEX & OPEX of separation plant)
Prices for secondary products	• Price of used permanent magnets	• Prices of REE and metals

elements, iron and boron, in order to selectively precipitate and finally separate an insoluble double sulfate salt of the rare earth element and the alkali element or ammonium from the solution (Lyman and Palmer, 1992).

As under UNFC-2009 only defined projects can be classified (UNECE, 2010), system boundaries must be chosen in order to evaluate in-use stocks that are currently not available for mining. Similar to mining materials from obsolete PCs this can be done on a geographical and temporal level. Due to high uncertainties and for simplicity reasons, NdFeB permanent magnets from wind turbines in Austria are assumed to be mined under current conditions within one year.

For the hypothetical recovery of materials from in-use wind turbines in Austria, treatment costs (OPEX) are based on the market prices of acids, which are required to extract REE from permanent magnets as tested in own laboratory scale experiences. Further, it is assumed that the REE separation plant is newly built, even though treating the relatively small amounts of materials from future obsolete Austrian wind turbines would not justify the construction of a new plant. Estimated investment costs are downscaled from facilities used for the separation of REE from primary ores (Sykes, 2013). Investment costs of the mobile unit are depreciated over ten years (cf. case study on landfill mining). Costs for separating permanent magnets from wind turbines and demagnetizing them are almost negligible (Stiesdal, 2015).

2.3. Scenario modeling

2.3.1. Prospection & exploration

Based on the respective project's data, the physical models of all relevant material flows and in case of the LFM project also energy flows have been set up for each scenario, following the method of Material Flow Analysis (MFA). MFA is a systematic quantification of the flows and stocks of materials within a defined system (in space and time), connecting the sources, the pathways and the sinks of a material (Brunner and Rechberger, 2004). State-of the art transfer coefficients for all involved processes determine that part of the resource potential, which is under current, established technological conditions extractable and potentially usable. Using MFA further allows to model different options for extraction methods and processing technologies with their specific recovery efficiencies, as well as different project set-ups.

2.3.2. Economic evaluation

To compare the socioeconomic viability of mining the identified extractable and potentially usable raw materials in different scenarios, a Discounted Cash Flow (DCF) Analysis is performed by calculating the Net Present Values (NPV) before taxes, based on material and energy flows from the previously created MFA models, to decide whether a project can be classified as a ‘reserve’ or a ‘resource’. DCF analyses are also widely used in the evaluation of mining projects of primary resources (Torries, 1998) and takes the time value of money into account (Fisher, 1930):

$$NPV = -C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_r}{(1+r)^T}$$

It is computed by subtracting the initial investment cost ($-C_0$) from the sum of the cash flows (C) over a pre-defined period of time (T = time given in years), which are discounted by the discount rate r.

A positive NPV implies that a project is economically viable. Consequently, the evaluated materials can be classified as ‘reserve’. If the NPV turns out to be negative, however, one has to judge, whether there are reasonable prospects for economic extraction in the foreseeable future. Whether the deposit can be labeled a ‘resource’ or not, can be decided by anticipating realistic changes of key modifying factors, for instance by calculating the so-called “cut-off values”, i.e. required changes (e.g. in prices or costs) to reach at least a neutral NPV. Chosen discount rates vary according to the “miner's” perspective: A private investor will apply higher discount rates, while a public entity in charge of the mining project will use a lower discount rate (cf. Winterstetter et al., 2015).

2.3.3. Classification

Finally, all of the aforementioned steps' results are used as a basis for the classification under UNFC-2009. Projects are classified on the basis of three fundamental criteria, namely “socioeconomic viability” (E1 – E3), “field project status and technical feasibility” (F1 – F4), and “knowledge on composition and extractable material content” (G1 – G4), with E1F1G1 being the best category (UNECE, 2010). Table 7 shows the UNFC-2009 definitions of the different single categories.

Categories on the G-axis, reflecting the knowledge on composition and extractable material content of an anthropogenic deposit, may be applied in cumulative form to express low (G1), best (G1 + G2) and high estimates (G1 + G2 + G3), as commonly used for recoverable fluids. P90, P50 and P10, representing these

categories, mean that the estimated value is exceeded with a probability of 90%, 50% and 10%. Discrete classification is used for solid minerals (UNECE, 2010). In this case each discrete estimate reflects the level of geological knowledge and confidence associated with a specific part of the deposit.

The F-axis shows the technical feasibility and project status of a mining project. By definition, in-use stocks are classified as F4, in order to indicate that they are currently not available for mining. In terms of socioeconomic viability (E-axis), a positive NPV results in the score E1. If the NPV is negative, the potential future development of key modifying factors is investigated. If the breakeven point can be reached based on plausible assumptions, there are reasonable prospects for the project to become economically viable (E2). A negative NPV without realistic chances to become economically viable would imply a UNFC-2009 score of E3. In a pull situation, like in the landfill mining project, where no (legal) pressure for remediation and/or recovering materials exist, the E-category will decide, whether to (potentially) mine (E1, E2) or not to mine (E3). In a push situation this score will indicate, whether the minimum legal requirements are outperformed due to positive economics.

3. Results

The following sub-chapters present the results structured according to the three types of anthropogenic deposits examined.

3.1. Obsolete stock: landfill mining

3.1.1. Prospection & exploration

Table 8 shows a range of estimates regarding the landfill's potentially recoverable and usable fractions. In line with the Petroleum Resources Management System (PRMS) specifications for petroleum under UNFC-2009 the G-categories can be used to cumulatively express low, best and high estimates of potentially recoverable and usable quantities of materials and energy.

3.1.2. Economic evaluation

Discounting the project's cash flows over 20 years with a discount rate of 3%, the landfill mining project yields a negative NPV of −277 million € (−17 €/t excavated material) (cf. Fig. 1), implying that under current conditions the project is not economically viable, and the landfill cannot be classified as reserve (cf. Winterstetter et al., 2015; SI, Table 4).

On the cost side, incineration costs, comprising transport and gate fees (35%) as well as operational expenses for the sorting plant (44%) represent the major shares of total costs. The greenhouse gas emission saving potential compared to a “Do-Nothing” scenario turned out to be negative and therefore appears on the cost side.

On revenue side, avoided aftercare costs for 50 years after closure (48%) and ferrous metals, including the metals from RDF

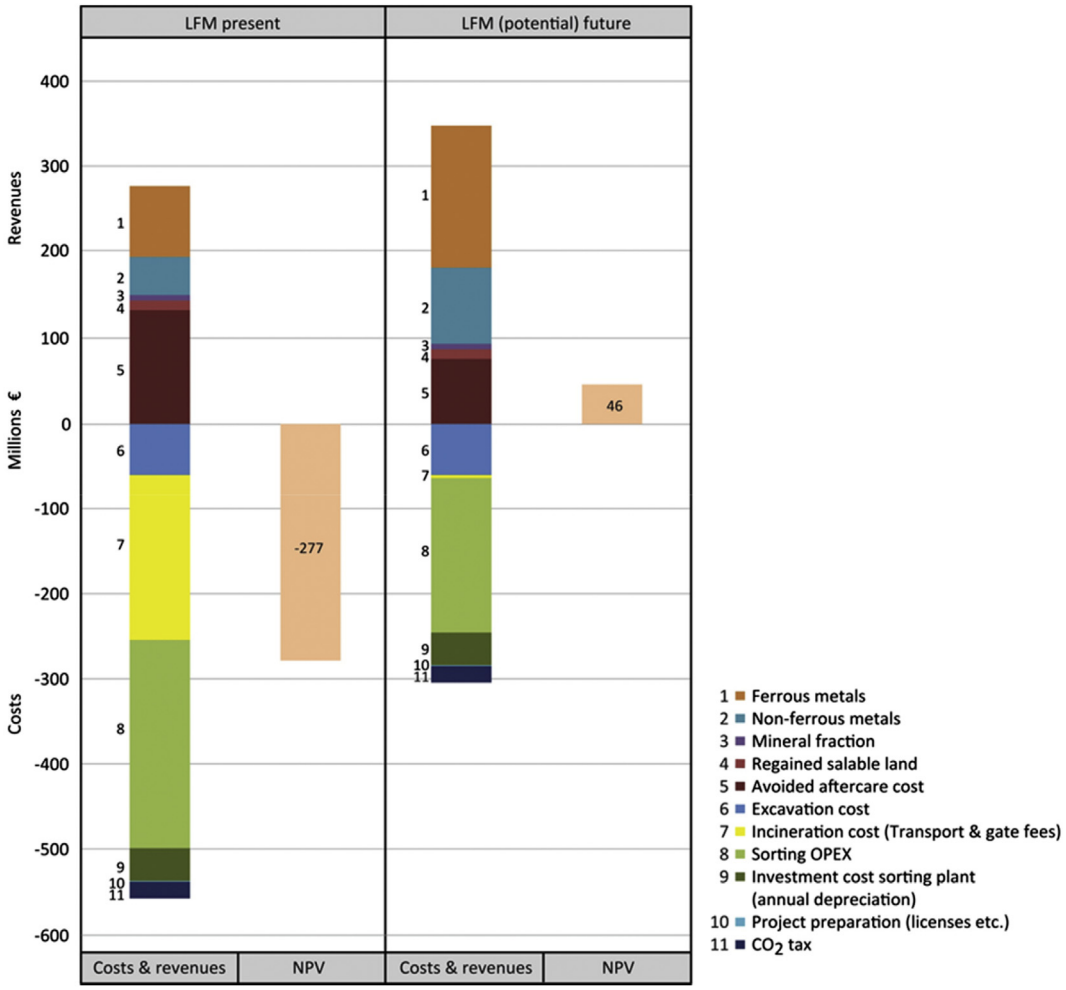

Fig. 1. Costs and revenues of a landfill-mining project, discounted over 20 years with a discount rate of 3% (comparing present and potential future conditions).

Table 7
Definitions of categories according to UNFC-2009 (UNECE, 2013).

E1	Extraction & sale has been confirmed to be economically viable[b]
E2	Extraction & sale is expected to become economically viable[b] in the foreseeable future[a]
E3	Extraction & sale is not expected to become economically viable[b] in the foreseeable future[a] or evaluation is at too early stage to determine economic viability
F1	Feasibility of extraction by a defined development project or mining operation has been confirmed
F2	Feasibility of extraction by a defined development project or mining operation is subject to further evaluation
F3	Feasibility of extraction by a defined development project or mining operation cannot be evaluated due to limited technical data. Extraction, processing & valorization technologies already exist, but projects are not sufficiently advanced to determine the quantity & quality of potentially recoverable material
F4	In situ (in-place) quantities that will not be extracted by any currently defined development project or mining operation. Not (yet) existing technologies F4.1 − F4.3 describe the current state of technological development
G1	The stock's / flow's composition & share of potentially extractable & usable materials can be estimated with a high level of confidence, Alternative: P90 => Low estimate[c]
G2	The stock's / flow's composition & share of potentially extractable & usable materials can be estimated with a medium level of confidence Alternative: P50 => G1+G2 = Best estimate[c]
G3	The stock's / flow's composition & share of potentially extractable & usable materials can be estimated with a low level of confidence Alternative: P10 => G1+G2+G3 = High estimate[c]
G4	Quantities estimated during the exploration phase, subject to a substantial range of uncertainty & major risk that no mining operation will be implemented to extract these quantities

[a] The length of "foreseeable future" can vary, depending on the commodity. Typically it is 20 years.
[b] "Economically viable" includes the "consideration of prices, costs, legal /fiscal framework, environment, social and all other non-technical factors that could directly impact the viability" (UNECE 2013).
[c] As commonly used for recoverable fluids, the cumulative form (G1+G2+G3) expresses "high / best / low estimates". P90 (P50, P10) means that the estimated value is exceeded with a probability of 90% (50%, 10%).

Table 8
Potentially recoverable and usable quantities from an old landfill (total), expressed in a cumulative way.

	Unit	G1 Low estimate	G1+G2 Best estimate	G1+G2+G3 High estimate
Regained salable land	[m^2]	490,000	520,000	550,000
Off-Site incineration: RDF transported to external incinerator	[kt]	2,600	3,400	4,200
Salable net electricity (produced in a plant with 30 % efficiency)	[GWh]	3,600	4,700	5,800
Stones/minerals	[kt]	1,000	1,700	2,400
Non-ferrous metals (Al, Cu)		28	54	79
Ferrous metals		320	550	810
Amount of materials to be re-landfilled (fines, sorting residues, incineration ash)		11,200	9,600	8,000

preparation and the fine fraction, (30%) and non-ferrous metals (16%) are the biggest parts.

To determine under which conditions landfill mining can be labeled "potentially commercial" or "non-commercial", cut-off values are calculated under consideration of potential future changes of a set of key modifying factors. Nispel (2012), for instance, assumes that within 20 years ferrous and non-ferrous metal prices will double and operators of incineration plants will pay, due to overcapacity, at least 10 € per ton of RDF made from the landfill's combustible materials. Additionally, he forecasts operating costs of sorting plants to decrease by 20%, due to the use of more energy efficient technologies. Moreover, avoided aftercare costs for 30 years instead of 50 years after closure are assumed, as the landfill-mining project will be postponed by 20 years into the future and aftercare costs have to be paid in the meantime. Given all these hypothetical assumptions, the landfill-mining project would yield a positive NPV of in average 46 million € (2.9 €/t) (cf. Fig. 1). In fact, keeping doubling metal prices and 20% lower sorting costs, a landfill miner could still pay a cut-off price of 5.7 €/t for the incineration of RDF to reach at least the break-even point (with NPV = 0).

3.1.3. Classification

In terms of "knowledge on the landfill's composition and its extractable material content", the project is graded with G2,[1] as the quantities contained in the landfill can be estimated with a medium level of confidence based on data from both the sample excavations and the landfill's logbook data. In addition, the applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the landfill's extractable raw material potential.

The F-axis indicates a project's "field project status and technical feasibility". Even though only well-known technologies are applied and the institutional structure is already established, meaning that the current landfill owner is seriously planning the project with a number of committed partners, the LFM project is still in the feasibility stage with mainly design and planning activities and operations on a pilot scale. Generally, a legal framework for landfill mining has not been developed so far and so various individual licenses are needed to advance the project. Therefore, the project is classified as "potentially feasible" (F2).

While the landfill-mining project does not achieve positive results under present economic conditions, reaching cut-off values in the foreseeable future seems, however, possible. Therefore it is classified as "potentially commercial" (E2). Combining those three criteria, the landfill-mining project is categorized as E2F2G2 ("resource").

3.2. Waste flow: end-of-life personal computers

3.2.1. Prospection & exploration

Table 9 shows the potentially recoverable and usable quantities of materials from obsolete PCs collected in a city of 1 million inhabitants in a high-income EU country with an annual collection rate of 800 tons PCs and advanced mechanical-manual dismantling (Scenario 1), compared to a low-income EU city with an annual

[1] Discrete (not cumulative) classification, as usually used for classifying solid minerals.

collection rate of 100 tons PCs (due to weak enforcement of existing laws) and only one manual dismantling step (Scenario 2).

3.2.2. Economic evaluation

Discounting the project's cash flows over one year with a discount rate of 3%, both scenarios treating obsolete PCs yield positive net present values, with Scenario 1 resulting in 96,000 € and Scenario 2 in 34,000 € (cf. Fig. 2 and SI, Table 1).

This corresponds to 120 € NPV per ton of collected PCs for Scenario 1 and 340 € NPV per ton of collected PCs for Scenario 2, which is due to the higher costs in Scenario 1, namely 530 € compared to 230 € per ton of collected PCs in Scenario 2. Discounted revenues in contrast are not that different, namely 650 € (Scenario 1) and 570 € per ton of collected PCs (Scenario 2).

For both scenarios the main drivers on the revenue side are recovered printed circuits (50% in Scenario 1, and 60% in Scenario 2). In Scenario 1 (high income country) costs for sorting PCs from other IT devices is the biggest share of total costs (81%) due to assumed labor costs of 17 € per hour, while in Scenario 2 (low income country) labor costs of 6 € per hour are assumed, amounting to 66% of total costs. Compared to Scenario 2, a higher number of fractions for potential sale is generated in Scenario 1, due to several dismantling steps, resulting in slightly higher revenues, while requiring a higher number of working hours (7.4 h vs. 6 h). On the revenues side of Scenario 2 no avoided disposal costs are assumed (representing 10% in Scenario 1). The alternative would be dumping, as in this case also other European laws, such as the landfill directive, are assumed to be weakly enforced.

3.2.3. Classification

In terms of "knowledge on the obsolete PCs waste flow's composition and its extractable material content", Scenario 1 is graded with G1, as the flow's volume and composition of obsolete PCs can be estimated with a high level of confidence and the applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the extractable raw material potential. Scenario 2 obtains G2, as the flow's volume and composition can be estimated only with a medium level of confidence due to the informal collection and recycling activities, implying high uncertainties about the collection rate.

Regarding "field project status and technical feasibility" (F-axis), well-known techniques for dismantling and treatment are applied in both scenarios. In Scenario 1 the institutional and organizational infrastructure for collecting WEEE and financing take back systems via EPR schemes in line with the EU WEEE directive is already established. While Scenario 1 is therefore graded with F1, Scenario 2 is classified as potentially feasible (F2). Despite existing EU and national laws, their enforcement is weak. The WEEE collection infrastructure is poor and people and local governments have not yet realized the importance of source separation and recycling

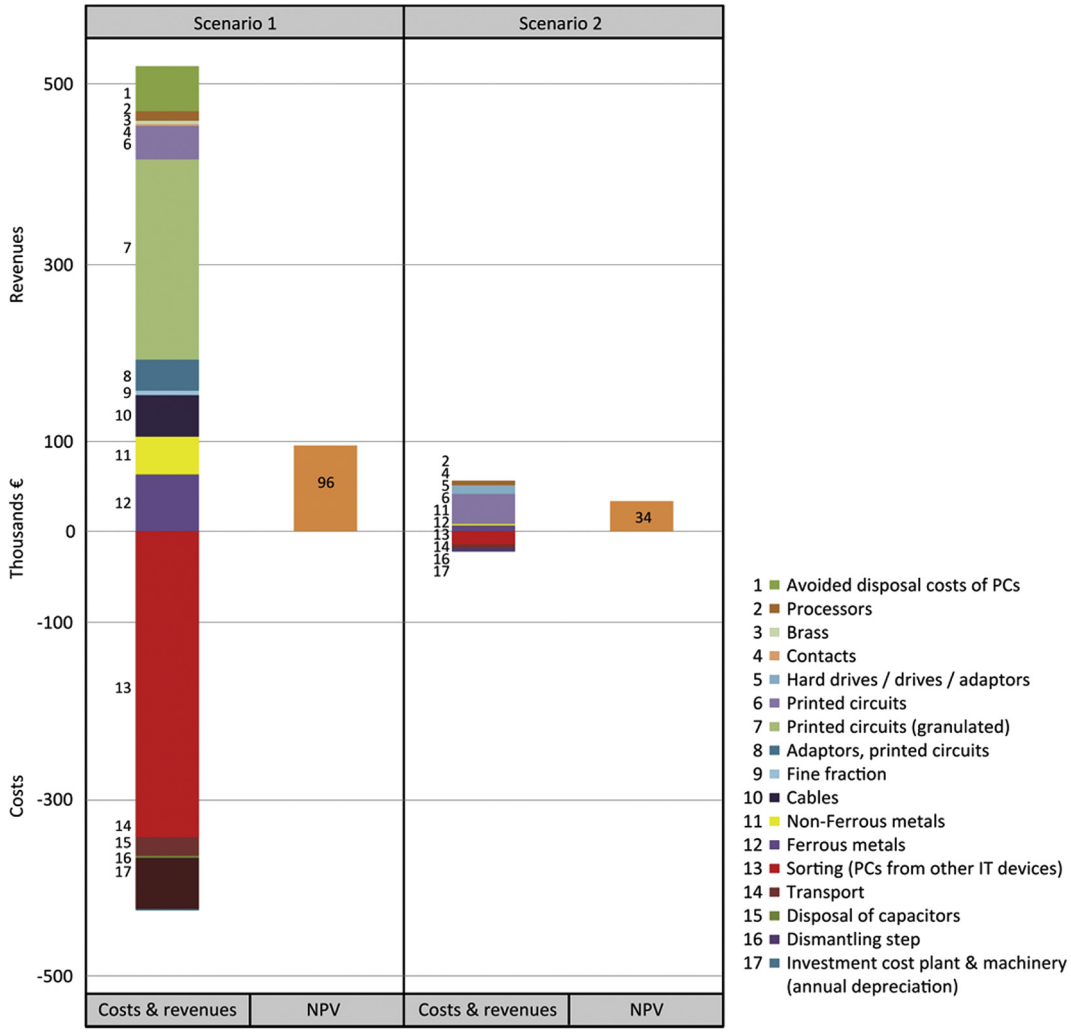

Fig. 2. Costs and revenues for Scenario 1 and Scenario 2, discounted over 1 year with a discount rate of 3%.

Table 9
Potentially recoverable and usable material quantities from obsolete PCs in a high-income EU city (Scenario 1) and a low-income EU city (Scenario 2) within one year (own calculations based on Salhofer and Spitzbart (2009).

Output flows[a]	Unit	Scenario 1 (800 t PCs collected/a)	Scenario 2 (100 t PCs collected/a)
Ferrous metals		579	59
Non-ferrous metals	[t]	25	1.4
Printed circuits		54	7
Hard drives, disk drives, drives, adaptors			22
Adaptors, printed circuits		23	
Cables		27	
Contacts		2.2	0.5
Brass		1.3	
Processors		0.3	0.2
Fine fraction		6	
Capacitors to be disposed of		4	
Other fractions to be disposed of (plastics, residues...)		78	10

[a] Impurities are included cf. SI, Tables 2 and 3.

Table 10
Potentially recoverable and usable quantities of materials from wind turbines in Austria (own calculations).

	Unit	Scenario 1 (re-use)	Scenario 2 (hydrometallurgy)
Nd	[t]		39
Fe			98
B			1.6
Dy			6.5
Pr			3.2
Used NeFeB permanent magnets		166	

electrical and electronic equipment. Also, potentially existing laws on the disposal of (hazardous) wastes are poorly enforced, and due to the informal recycling activities there are high uncertainties on PC collection.

In terms of economic viability, both scenarios are graded with E1 due to positive NPVs. Thus, the overall classification for Scenario 1 is E1F1G1 and E1F2G2 for Scenario 2.

3.3. In-use stock: NdFeB permanent magnets in wind turbines

3.3.1. Prospection & exploration

Table 10 shows the potentially recoverable and usable quantities of materials from NdFeB permanent magnets in wind turbines, which are currently in use, for the total installed capacity of 277 MW in 2014 in Austria. In Scenario 1, the magnets are directly re-used, while in Scenario 2 Nd, Fe, B, Dy and Pr are extracted via hydrometallurgical methods (cf. SI, Table 6).

3.3.2. Economic evaluation

166 t of materials are assumed to be extracted and treated from future obsolete wind turbines in Austria. Discounting the project's cash flows over one year with a discount rate of 3%, both scenarios clearly yield positive NPVs, with Scenario 1 (re-use) resulting in 6.2 million €, and Scenario 2 (hydrometallurgy) in 5.3 million € (cf. Fig. 3 and SI, Table 5).

This corresponds to about 37,500 € per ton of magnetic scrap in Scenario 1, and 31,800 € per ton in Scenario 2.

Economic drivers on the revenue side of the re-use Scenario 1 are obviously the prices of permanent magnets (40 €; /kg, Stiesdal (2014)), and in Scenario 2 the prices of Nd, Pr and Dy, for which average prices between 2008 and 2015 were assumed. Nd represents 36%, Pr 24% and Dy 40% of total revenues.

The costs for separating permanent magnets from wind turbines as well as for their subsequent re-magnetization could almost be neglected (Stiesdal, 2015), representing 2% of overall cost in Scenario 2. In Scenario 2, the assumed investment costs of the REE separation plant (22% of total cost) and its operating costs (75% of total cost) are linked to uncertainties. It seems, however, highly plausible that treatment costs are lower than the extraction of REE from primary ores due to higher concentrations of REE in magnets (24% Nd compared to 12% in primary ores (Bleiwas and Gambogi, 2013)), which are additionally less compound and therefore easier soluble. Thus, lower amounts of acids and energy are needed, resulting in lower operating costs compared to primary REE extraction.

3.3.3. Classification

In terms of “knowledge on the in-use wind turbines'/permanent magnets' composition and the extractable material content”, both scenarios are graded with G1, as the stock's size and composition can be estimated with a high level of confidence, based on detailed prospection and exploration studies on the in-use stock. However, there are some uncertainties on the recovery efficiencies in Scenario 2.

Regarding technical and project feasibility, re-using the magnets in their current form (Scenario 1) would be the most evident approach for large and easily accessible magnets used in wind turbines and large electric motors and generators in hybrid and electric vehicles, according to Binnemans et al. (2013) and Stiesdal (2015). Siemens initiated a research project on the re-use of NdFeB-magnets from hybrid cars and e-vehicles (Binnemans et al., 2013). Therefore the re-use of permanent magnets from wind turbines obtains F4.1 as the technology is currently “under active development, following successful pilot studies on other deposits, but has yet to be demonstrated to be technically feasible for the style and nature of the deposit in which that commodity or product type is located” (UNECE, 2013). The REE extraction via hydrometallurgical methods (Scenario 2) is graded with F4.2 as the technology necessary to recover some or all of these quantities is currently being researched (e.g. Ellis et al., 1994; Itakura et al., 2006; Itoh et al., 2009), but no successful pilot studies have yet been completed” (UNECE, 2013) or at least there are no published data.

In terms of economic viability both scenarios are graded with E1 due to positive NPVs. Thus, the overall classification for Scenario 1

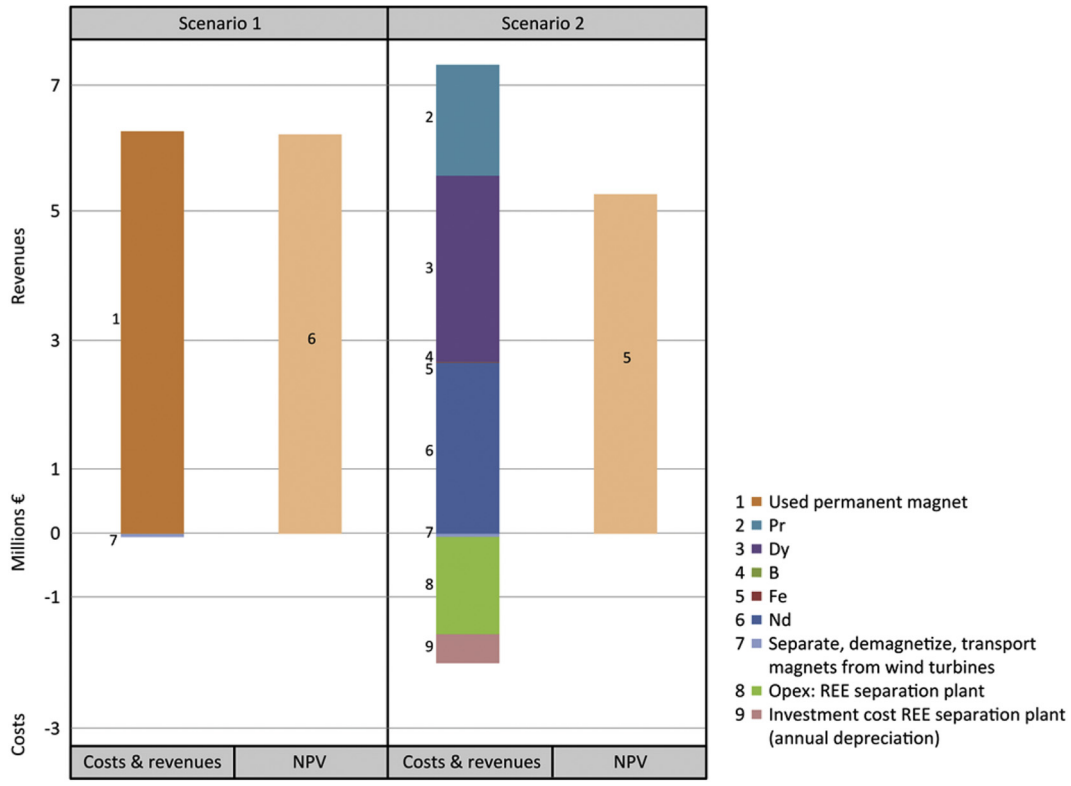

Fig. 3. Costs and revenues for Scenario 1 (re-use) and Scenario 2 (hydrometallurgy), discounted over 1 year with a discount rate of 3%.

(re-use) is E1F4.1G1, and for Scenario 2 (hydrometallurgy) E1F4.2G2.

4. Comparison of results & discussion

In the following sub-chapters the economic results as well as factors, influencing the evaluation and classification results, are compared for the three case studies.

4.1. Comparison of economic results

Table 11 compares the economic results for the three case studies. While landfill mining under present conditions is not economically viable, this might change in case of improving key modifying factors in the foreseeable future. Mining materials from obsolete PCs and from permanent magnets in wind turbines (currently in-use) would both yield positive economic results.

In case of the obsolete PCs, the NPV per capita shows, how the different collection rates influence the economic results favoring Scenario 1 with a higher collection rate of 800 t in Scenario 1 (vs. 100 t in Scenario 2). The NPV per ton of collected PCs makes Scenario 2 look better, due to lower labor costs. In case of the permanent magnets from wind turbines the re-use scenario is economically clearly to be preferred over the hydrometallurgical extraction.

4.2. Comparison of influencing factors & their importance

Based on these three case studies the general influencing factors for old landfills (obsolete stocks), obsolete PCs (waste flows) and permanent magnets in wind turbines (in-use stocks) are derived and subsequently analyzed for similarities and differences (cf. Table 12).

In general, the factors which are influencing the final classification are quite similar for different types of anthropogenic resources. The type, location, size, composition and methods and technologies used for extraction, sorting and utilization (material or energetic) and their respective recovery efficiencies are of high importance in all three cases, as they determine the pre-conditions and the final amount of recovered materials. However, their individual weight differs in the respective case studies.

For the case study on treating obsolete PCs in the EU, regulated by the EU WEEE directive (European Commission, 2012), the focus is on different settings of the legal, institutional, organizational and societal structure. This affects the extractable and potentially usable materials via collection and source separation rates and the involvement of the informal sector. In a high income EU country, the public awareness of WEEE recycling and people's consumption, disposal and source separation behavior is assumed to be higher, and the collection and take back infrastructure to be well organized and functioning. Also the modifying factors depend on a project's legal, institutional, organizational and societal setting. Labor costs are higher in a high income EU country, and avoided disposal costs equally tend to be higher, due to higher standards and stricter enforcement of existing laws. Prices for selling the PCs' components act as independent key drivers of the economic performance.

In case of future recycling of permanent magnets contained in wind turbines, currently in use in Austria, the focus was on technical feasibility. The choice of using hydrometallurgical methods yields a weaker economic result compared to direct re-use of permanent magnet, which is due to high REE separation costs. Prices for selling either REE or entire permanent magnets act as independent key drivers on the project's economics. Knowing the age and lifetime of an in-use stock gives hints about their future availability for mining.

Due to its local nature, for the landfill mining (LFM) a positive public perception and committed partners are very important

Table 11
The NPVs differ for mining an old landfill, obsolete PCs or permanent magnets.

	Old landfill		Obsolete PCs		NdFeB permanent magnets from wind turbines	
	Present	Potential future	Scenario 1 (high income EU country)	Scenario 2 (low income EU country)	Scenario 1 (re-use)	Scenario 2 (hydrometallurgy)
NPV in €/t excavated waste materials/t collected PCs/t magnetic scrap	−17	2.9	120	340	37,500	31,800
NPV in €/cap			0.096	0.034	0.779	0.663

(Craps and Sips, 2011). As no legal LFM framework exists, individual decrees and licenses by (local) authorities are needed to advance the project. Besides secondary products extracted from old landfills, in this case also the regained land is of interest. But due to the assumed price of 40 € per m^2 it is not of high importance here.

In this case study the focus is on modifying factors, to see how future developments of key drivers, i.e. metal prices and costs for sorting and energy recovery, can change the final result and to decide whether there are reasonable prospects for future economic extraction.

An evaluation is a matter of specific stakeholder interests. From a public entity's view, in addition to direct financial effects also non-monetary societal effects might be monetized and included in the evaluation. In this case greenhouse gas emission savings of a landfill mining project compared to a "Do-Nothing" scenario are quantified via a LCA and then monetized through a hypothetical CO_2 tax, however, appearing due to additional emissions caused by LFM on the cost side. Further, the prevented pollution of soil, ground and surface water due to landfill mining is included via an avoided aftercare period of in total 70 years (compared to minimum

Table 12
Factors, influencing the evaluation and classification results, for different types of anthropogenic resources.

	Old landfill	Obsolete PCs	NdFeB permanent magnets
Preconditions			
Availability status	• Obsolete stock	• Waste flows	• In-Use Stock
Mining/handling condition	• Pull (or Push)	• Push	• Push (or Pull)
System variables			
Type & Location	• Type & location of the obsolete stock	• Type & location of the waste flow	• Type & location of the in-use stock
Volume	• Volume of landfill	• Volume of waste flow • Product type & size composing the waste flow	• Age & life-time of wind turbines / permanent magnets • Total number of wind turbines, their specific capacity & permanent magnets composing the in-use stock
Composition	• Composition: Ash & water content, share of usable materials, combustible fraction, non-recyclables & hazardous substances, contamination of fine fraction	• Composition: Share of usable materials & non-recyclables & hazardous substances	• Composition: Share of usable materials & non-recyclables
Legal, institutional, organizational & societal structures	• Project partners & Public perception, no legal framework	• Collection & take back system • Consumption & disposal pattern & source separation behavior	
Methods & technology used for extraction & valorization with specific efficiencies	• Options for excavation, sorting & valorization • Maturity & specific experience of technology for valorization of materials, energy recovery	• Options for dismantling & processing • Maturity & specific experience of technology for PC recycling	• Options for re-using magnets / separating REE from permanent magnets • Maturity & specific experience of technology for REE extraction / re-use of magnets
Project status	• Project status (licenses)		
Modifying factors			
Investment & operating costs	• Investment & operating costs (Excavation, sorting & treatment plants)	• Labor costs (Collection & sorting) • Dismantling costs	• Dismantling costs • Investment & operating costs (REE extraction & treatment plants)
Costs for external treatment & disposal	• Gate fees for energy recovery • Costs (requirements) for disposal of non-recyclables & hazardous substances	• Gate fees for end processing & energy recovery • Costs (requirements) for disposal of non-recyclables & hazardous substances	• Costs (requirements) for disposal of non-recyclables
Prices for secondary products	• Price for regained land or landfill space Prices for metals (Fe, Al, Cu), construction material, soil, energy	• Prices for metals (Fe, Al, Cu) cables, hard drives, adaptors, printed circuits etc.	• Prices for Fe, B, REE or entire permanent magnets
Avoided costs	• Avoided costs for landfill aftercare and/or remediation, partly alternative disposal	• Avoided alternative disposal costs	
Monetized external effects	• CO_2 tax • Longer after care period		
Indirect financial effects	• Future land tax from sold land • Future gate fees from newly gained landfill capacity		

requirement of 30 years, which a private investor would have considered).

4.3. Criteria & challenges for the classification under UNFC-2009

The main goal of this study is to provide criteria to distinguish between the different categories, in order to map different types of anthropogenic resources under UNFC-2009. In Table 13 the general definitions of UNFC-2009 classes along the three axes are applied to the case studies' specific examples (cf. chapter 3).

4.3.1. G-axis

For the G-axis, displaying the knowledge on composition and extractable material content of an anthropogenic deposit, the two main indicators are 1) data on volume and composition and 2) data on recovery efficiencies of applied technologies and methods for extraction and valorization.

Under UNFC-2009 the level of confidence (high, medium, low) are not specified more precisely at a generic level, as there are fundamental differences between the approaches that are used for commodities extracted as solids and those extracted as fluids. For anthropogenic resources, G-categories may be applied in cumulative form (e.g. G1 + G2 + G3) to express low, best and high estimates, as commonly used for recoverable fluids, or discretely, mainly used for classifying solid minerals. In the following discrete will be favored over cumulative classification.

Despite minor uncertainties regarding the recovery efficiencies especially of hydrometallurgical extraction methods, there are detailed prospection and exploration studies on the in-use stock of wind turbines and permanent magnets, resulting therefore in G1. The same score is granted to treating obsolete PCs in a high income EU country, as the waste flow's volume and composition can be estimated with a high level of confidence. Applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the extractable raw material potential.

Treating obsolete PCs in a low income EU country is graded with G2, as the flow's volume and composition can be estimated only with a medium level of confidence due to the involved informal sector, implying high uncertainties about the collection rate, although the recovery efficiencies are well known.

The landfill mining project obtains UNFC-2009 score G2, as the stock's volume and composition can be estimated with a medium level of confidence based on data from the sample excavations and the landfill's logbook. The applied technologies' recovery efficiencies can be estimated with sufficient detail for assessing the landfill's extractable raw material potential.

4.3.2. F-axis

The technical feasibility and project status of a mining project, shown on the F-axis, is indicated by 1) the maturity of applied techniques for extraction and valorization and by 2) the legal, institutional, organizational and societal structures as well as by 3) the specific project status. In a push situation, such as treating obsolete PCs in the European Union, laws define minimum standards for treatment and collection and can be considered as prescribing system variables. In Scenario 1 (high income EU country) EU legislation is presumed to be implemented and strictly enforced at national level, while in Scenario 2 (low-income EU country) it is only weakly enforced. Thus, only the most basic requirements are met (i.e. manual vs. manual-mechanical dismantling of PCs) and residues from recycling activities are assumed to be dumped.

In Scenario 2, the PC collection infrastructure is assumed to be poor and the public awareness of the importance of WEEE recycling to be low. Due to the active informal sector there are high uncertainties on collection rates. Here it becomes evident, that a sharp distinction between the single UNFC-2009 axes, and especially between the G- and the F-axis is not always clear-cut, as the collection system has an influence on the waste flow's volume and composition, but also on the project feasibility. Factors such as the involvement of the informal sector or general source separation behavior are strongly dependent on the legal, institutional, organizational and societal structures, in which a project is embedded, being reflected on the F-axis. Therefore, G- and F- categories are often interdependent particularly for waste flows.

In both scenarios established technologies and methods are applied. So while Scenario 1 is graded with F1, Scenario 2 obtains F2.

The landfill mining project is equally graded with F2. Although mature techniques are applied and there is also an established institutional structure with a number of committed partners, the project is still in the feasibility stage with mainly design and planning activities and operations only on a pilot scale. Moreover, the legal framework for landfill mining has not been developed so far.

For in-use stocks to be mined in the future, the main question is, whether extraction and valorization technologies do currently exist or not and how the general framework will look like. It can potentially become a push or a pull situation and is generally scored with F4 to indicate its current unavailability for mining, comparable to in-situ quantities in the mining industry (UNECE, 2013). The sub-categories F4.1 – F4.3 describe the current state of technological development. A clear distinction between the individual categories on the F-axis is often difficult and dependent on the evaluator's subjective assessment, as they cannot or only hardly be quantified.

4.3.3. E-axis

The socioeconomic viability of a mining project (E-Axis) is expressed by one main indicator, namely by a positive NPV, considering investment and operating costs, costs for external treatment and disposal, prices for secondary products, avoided costs and monetized external effects. In case of a negative NPV, it shall be investigated whether there are reasonable prospects to become economically viable in the foreseeable future.

However, the distinction between the categories “expected to become economically viable in the foreseeable future (E2)” and “not expected to become economically viable (E3)” is based on specific assumptions, which can be considered as realistic by some experts, while others might have a completely different view. Each of the three case studies has project specific key modifying factors, which have to be considered for calculating the cut-off values, i.e. how they have to change to reach a neutral NPV.

Moreover, there are also uncertainties originating from the chosen evaluation scenarios and the related assumptions. As under UNFC-2009 only defined projects can be evaluated and classified, arbitrary system boundaries will have to be chosen, e.g. on a spatial and/or temporal level, which is obviously easier for a confined landfill mining project than for a continuous flow of obsolete PCs or the in-use wind turbines. Projects of mining obsolete stocks, such as an old landfill, are comparatively easy to plan ahead. Therefore, depending on the project's size, project durations can be assumed to be similar to the mining industry. In contrast, waste flows, such as obsolete PCs, underlie more complex dynamics and fluctuations, making it seem unsound to set such projects' temporal system boundaries at longer than ten years. The same is true for in-use stocks: Since there are typically high uncertainties on the in-use materials' future availability for mining, on the stock's size and composition, on the technical feasibility of recovery as well as the future legal framework, the planning horizon of such projects should be kept rather short, unless reliable information and data are available. Hypothetical mining is assumed under current

Table 13
Definitions of categories according to UNFC-2009 are applied to the three show cases. While the gray boxes represent case study specific influencing factors, the white boxes display the generic definitions.

	Obsolete Stocks	Waste Flows	In-Use Stock
	Old Landfill	Obsolete PCs	NdFeB Magnets
E1	Project yields positive NPV		
		KMF: Labor costs, avoided disposal costs, secondary raw material prices	*KMF: Secondary raw material prices, REE separation costs in hydrometallurgical scenario*
E2	Project yields negative NPV, but due to future expected changes in key modifying factors (KMF), cut-off values might be reached		
	KMF: Treatment costs, secondary raw material prices, gate fees for energy recovery		
E3	Project yields negative NPV or evaluation is at too early stage to determine economic viability		
F1	Feasibility of extraction by a defined development project or mining operation has been confirmed • Existing legal framework • Existing societal, institutional & organizational structure • Mature technologies applied • Project status: Ongoing activities		
		Scenario 1 *Existing infrastructure & public awareness for PC collection via EPR (in line with WEEE directive)*	–
F2	Feasibility of extraction by a defined development project or mining operation is subject to further evaluation, at least one of the F1 criteria is not fulfilled		
	• *No legal framework for landfill mining* • *Positive public perception* • *Mainly design & planning activities ongoing* • *Operations only on a pilot scale*	Scenario 2 • *Weakly enforced laws* • *Poor collection infrastructure* • *Low awareness about source separation* • *Application of established recycling methods* • *Interference with informal recycling sector (high uncertainties about collection rates)*	–
F3	• Feasibility of extraction by a defined development project or mining operation cannot be evaluated due to limited technical data. • Extraction, processing & valorization technologies exist and are planned to be applied, but the project is not sufficiently advanced to determine the quantity & quality of potentially recoverable material, F1 criteria are widely not fulfilled		
F4	In situ (in-place) quantities that will not be extracted by any currently defined development project or mining operation. • F1 criteria are not fulfilled, also not (yet) existing technologies • F4.1 – F4.3 describe the current state of technological development: F4.1: Technology under development, but no type-specific applications (yet) F4.2: Technology is researched, but pilot studies are not yet available F4.3: Technology for recovery is not currently under research or development		
			•*In-use stocks are classified as F4 as they are currently not available for mining.* •*No legal framework for treating obsolete wind turbines* *Scenario 1 (re-use)* *F4.1: Existing research project on the re-use of NdFeB-magnets from hybrid cars & e-vehicles* *Scenario 2 (hydrometallurgy)* *F 4.2: Technology currently being researched (e.g. Ellis et al., 1994; Itakura et al., 2006; Itoh et al., 2009),but no successful pilot studies have yet been completed / no published data*

Table 13 (*continued*)

	Obsolete Stocks	Waste Flows	In-Use Stock
	Old Landfill	Obsolete PCs	NdFeB Magnets
G1	The stock's / flow's volume, composition & the applied technologies' recovery efficiencies can be estimated with a high level of confidence to assess the share of potentially extractable & usable materials[a] Alternative: P90 => Low estimate[b]		
		Scenario 1 • *Volume & composition of PC waste flow is well known* • *Recovery efficiencies are well known*	• *Detailed exploration studies on magnets in wind turbines* • *Knowledge about extractable material content* • *Minor uncertainties about recovery efficiencies*
G2	The stock's / flow's volume, composition & the applied technologies' recovery efficiencies can be estimated with a medium level of confidence to assess the share of potentially extractable & usable materials[a] Alternative: P50 => G1+G2 = Best estimate[b]		
	• *Medium level of confidence about quantity & composition of landfilled material (based on sample excavations & the landfill's logbook data)* • *Recovery efficiencies sufficiently known*	*Scenario 2* • *Volume & composition of waste flow is well known, however significant uncertainties about collection rate due to informal sector* • *Recovery efficiencies can be estimated with sufficient detail*	
G3	The stock's / flow's volume, composition & the applied technologies' recovery efficiencies can be estimated with a low level of confidence to assess the share of potentially extractable & usable materials[a] Alternative: P10 => G1+G2+G3 = High estimate[b]		
G4	Quantities estimated during the exploration phase, subject to a substantial range of uncertainty & major risk that no mining operation will be implemented to extract these quantities		

KMF: Key modifying factors.
[a] Discrete classification.
[b] Cumulative form.

technical and economic conditions, in order to check whether this stock may represent a future resource or not.

To investigate a project's socioeconomic viability the systematic integration of non-monetary effects will be of high priority, as for many anthropogenic materials extraction is not (yet) economically viable under current conditions. Social and environmental externalities (e.g. eliminating sources of pollution) tend to generate additional benefits and should therefore be monetized and included in the evaluation. Combining aspects of waste and resource management is hereby a key challenge. For this purpose various existing concepts of non-market valuation can be useful. Ferreira et al. (2014), for instance, quantified environmental impacts of packaging waste recycling via a LCA and subsequently converted them into monetary values for inclusion into the financial-economic assessment. Non-marketed assets (i.e. environmental quality) were valued by using stated preference studies (i.e. willingness-to-pay estimates), while valuing the depletion of natural assets and loss of production with the good's respective market price. However, what non-monetary effects to finally include in the evaluation will depend also on the specific perspective of the stakeholder interested in performing a certain mining project (private vs. public).

Fig. 4 shows how all the before-mentioned criteria are combined and used to classify the three case studies and their scenario variations on the three axes of UNFC-2009.

5. Conclusion

In conclusion, the applicability of UNFC-2009 to different types of anthropogenic resource recovery projects for the purpose of comparing and prioritizing them, has been proven successfully in this study. To illustrate different settings of anthropogenic resource classification, mining anthropogenic resources from an old landfill (obsolete stock), from obsolete PCs (waste flow) and from wind turbines (in-use stock) was investigated exemplarily, resulting in different evaluation results and therefore in different classifications under UNFC-2009. The factors which are influencing the final classification are similar for different types of anthropogenic resources, but their individual weight differs in the respective case studies.

When treating obsolete PCs in the EU, the focus is on different settings of the legal, institutional, organizational and societal structure, affecting the extractable and potentially usable materials via collection and source separation rates, but also influencing the modifying factors (e.g. labor costs). In the LFM case study the focus was on the timing of mining and on modifying factors, to see how future developments of key drivers (e.g. metal prices) can change the final result and to decide whether there are reasonable prospects for future economic extraction. In case of future potential recycling of permanent magnets contained in wind turbines, currently in use in Austria, the focus was on how the choice of recycling technology could affect the economic results.

Recycling the entire in-use stock of permanent magnets from wind turbines in Austria within one year would yield the best economic results compared to mining obsolete PCs and landfill mining. Although currently not available for mining, it is crucial to know the economic performance of hypothetically mining the in-use stock's resource potential under current conditions as detailed as possible, in order to develop suitable recovery strategies for future waste flows and obsolete stocks. In some cases, information on the recyclability of in-use materials might be useful for

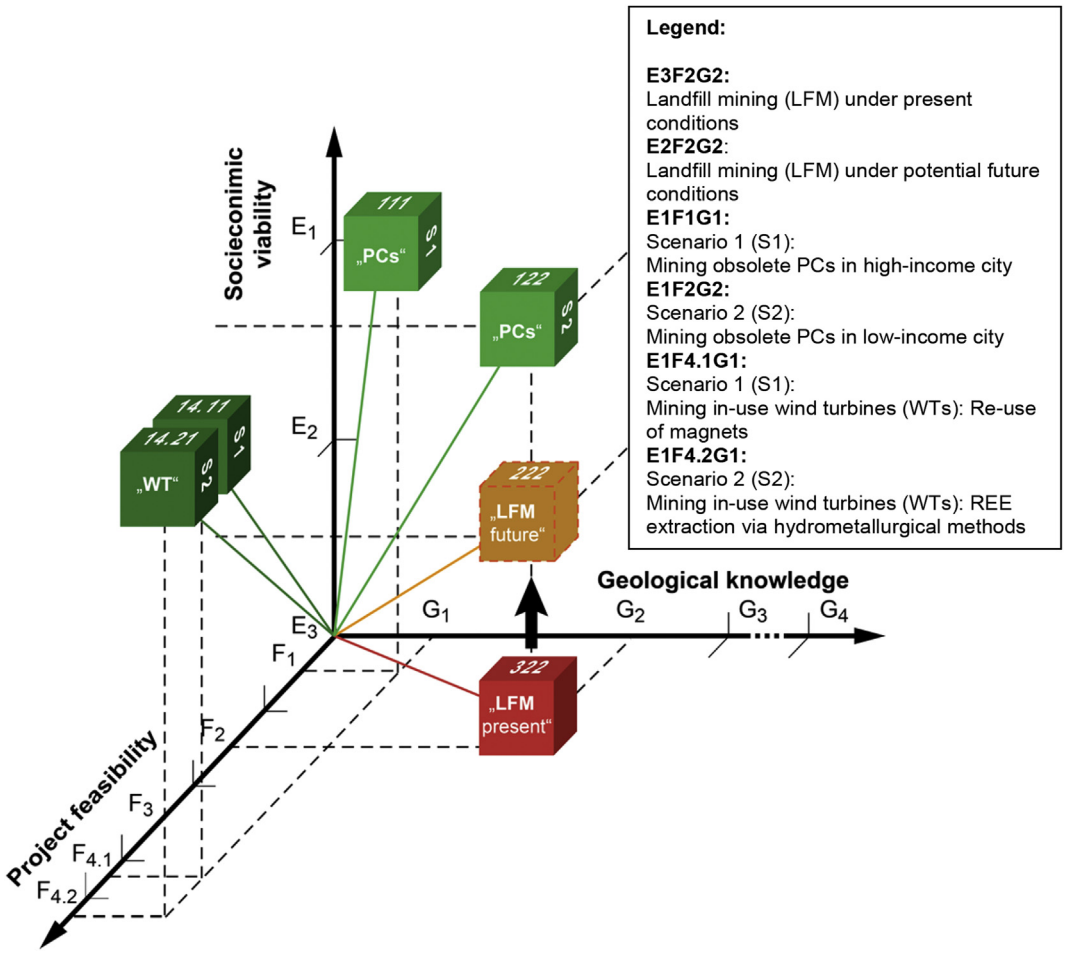

Fig. 4. The applicability of UNFC-2009 is illustrated by classifying the three case studies under UNFC-2009.

manufacturers to improve their product design. Moreover, the information on the economic viability of a hypothetical mining project is of high relevance for decision makers, since expected positive economic results might make future laws on recycling obsolete.

This method will assist governments, potential investors and waste management companies in the future to classify anthropogenic resource deposits and prioritize potential extraction projects in a systematic and transparent way. We presented an evaluation approach, which can be used to determine coherently the UNFC-2009 categories of materials contained in different anthropogenic deposits and under different conditions. Based on the three case studies, criteria for the classification of anthropogenic resources under UNFC-2009 were developed in order to distinguish between the framework's different categories.

To demonstrate the practicality and robustness of the presented method, it needs to be applied to further types of anthropogenic resources, such as to obsolete buildings, in the future.

As some of the criteria cannot or hardly be quantified and thus run the risk of being assessed in a highly subjective manner, the biggest challenge is to require utmost transparency when evaluating and classifying anthropogenic resources. The availability of high quality data on anthropogenic stocks and flows will be crucial for future classification efforts. The ultimate aim is to obtain a comprehensive overview of existing and potentially extractable anthropogenic resource inventories and to create a common platform for evaluating geogenic and anthropogenic resource deposits on an equal footing.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.05.083.

Abbreviations

B	Boron
CAPEX	Capital expenditures
DCF	Discounted Cash Flow analysis
Dy	Dysprosium
EPR	Extended Producer Responsibility
Fe	Ferrum
LFM	Landfill Mining
MFA	Material Flow Analysis
MSW	Municipal Solid Waste
Nd	Neodymium
NF-metals	Nonferrous metals
NPV	Net Present Value

OPEX Operating expenses
PC Personal computer
Pr Praseodymium
RDF Refuse Derived Fuel
REE Rare earth elements
SI Supplementary Information
UNECE United Nations Economic Commission for Europe
UNFC-2009 United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009
WEEE Waste electrical and electronic equipment
WT Wind turbines

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SUPPLEMENTARY INFORMATION

related to

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

by

A. Winterstetter, D. Laner, H. Rechberger, J. Fellner

Content

The bases for the economic evaluation of the three case studies and their respective scenarios are described and shown in Table 1 (PC waste flows), Table 4 (landfill mining) and Table 5 (permanent magnets), including salable quantities, prices, costs as well as discounted and undiscounted cash flows.

A detailed overview of transfer coefficients applied in the MFA models can be found in Table 2 and Table 3 (PC waste flows) and Table 6 (permanent magnets).

Figure 1 illustrates the qualitative material flow model for the mechanical-manual dismantling of obsolete PCs. The STAN models underlying the economic evaluation for the landfill mining case study as well as a detailed overview of applied transfer coefficients can be found in Winterstetter et al. (2015). Figure 2 shows the 3 axes of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC-2009).

1. GENERAL INFORMATION ON THE ECONOMIC EVALUATION

A private firm chooses a discount rate, which is “simply the rate of return on an investment with a similar risk as the proposed project” (Baurens, 2010). For public entities there are two options how to define their discount rate: For projects that are financed by taxes a discount rate equal to the real, long-term interest rate is set. Projects that are financed by bonds are given a discount rate that is equal to the real interest rate on the government’s bonds of similar maturity (Michel, 2001). In the landfill mining case study (situated in Belgium with a project period of 20 years) we assume the latter financing option: The yields of Belgian government bonds with a maturity of 20-years amount in average between 2000 and 2015 to 3 % (Investing.com, 2016a). For reasons of comparability we apply the same discount rate also to the PC waste flows and the permanent magnets from wind turbines, although both recovery projects last only 1 year (1-year bonds have usually lower yields). Therefore, in addition to the discounted cash flows, also undiscounted cash flows are shown in Table 1 (PC waste flows), Table 4 (landfill mining) and Table 5 (permanent magnets). Similarly, the period of depreciation is assumed to be 10 years in all three case studies.

2. PC WASTE FLOWS

Table 1: Present values of costs & revenues, discounted with 3% and 0 % taking the timing of cash flows into account.

REVENUES	Quantity [t] Scenario 1 800 t of PCs	Quantity [t] Scenario 2 100 t o PCs	Average Price [€/t]	Cashflows with discount rate 3 % (Mean Values), [€], 1 year	Undiscounted Cashflow (Mean Values), [€], 1 year	Cashflows with discount rate 3 % (Mean Values), [€], 1 year	Undiscounted Cashflow (Mean Values), [€], 1 year	Reference / Comment
				Scenario 1		Scenario 2		
Ferrous metals	579	59	113	63.552	65.459	6.424	6.617	Letsrecycle.com 2015a (light iron 2013/2015)
Aluminum	19	1.4	1.175	21.538	22.184	1.555	1.602	Letsrecycle.com 2015b (aluminum alloy cuttings 2013/2015)
Copper	3	-	5.250	17.534	18.060	-	-	Letsrecycle.com 2015c (heavy copper 2013/2015)
Mixed metals	3	-	1.175	3.285	3.384	-	-	Fe 36 % + 33 % Al, Au, Ag, Pa: Assume pure Al price due to Au, Ag, Pa
Cables	27	-	1.800	46.555	47.952	-	-	Scheideanstalt 2015
Fine fraction	6	-	1.000	5.052	5.920	-	-	Scheideanstalt 2015
Adaptors, printed circuits	23	-	1.556	34.796	35.840	-	-	Scheideanstalt 2015
Printed circuits (granulated)	46	-	5.000	224.466	231.200	-	-	Scheideanstalt 2015; Expert interview
Printed circuits	8	7	5.000	37.670	38.800	35.491	36.556	Scheideanstalt 2015
Contacts	2.2	0.5	1.000	2.097	2.160	493	508	Scheideanstalt 2015
Brass	1.3	-	2.876	3.574	3.681	-	-	Letsrecycle.com 2015d (mixed brass2013/2015)
Processors	0.3	0.2	35.000	10.874	11.200	5.422	5.585	Scheideanstalt 2015
Hard drives,disk drives, drives, adaptors		22	433	-	-	9.409	9.691	Scheideanstalt 2015
AVOIDED COST								
Total amount of PCs	800	0	65	50.485	52000	0	0	Avoided cost for incineration

Table 1 (continued)

COST			Average Cost [€/t PC]					
Sorting (PCs from other IT devices) *Scenario 1*	800	-	-442	-343.301	-353.600	-	-	It takes 26 h to sort 10 t of scrap with 10 % PCs => 26 h to sort 1 t PCs (assumption based on expert interview), assumed labor cost Scenario 1: 17 € /h Scenario 2: 6 € /h, Eurostat 2011
Scenario 2	-	100	-156	-	-	-15.146	-15.600	
Transport from collection point to dismantling	800	100	-8	-6.214	-6.400	-777	-800	100 km, 0,08 € / tkm
Disposal of capacitors	4	-	-600 €/t capac.	-2.423	-2.496	-	-	Assumption based on expert interview
Transport to specialized treatment or disposal	106	30	-88	-14.459	-14.893	-3.136	-3.230	Processors, Contacts, Hard Drives, Motherboards = 1100 km / Rest (Fe, Al, Cu, Others): 100 km, 0,08 € / tkm
	694	70	-8					
Dismantling step *Scenario 1 (mechanical-manual)*	800	-	-74	-57.339	-59.060	-	-	After first mechanical dismantling step, 25% of input dismantled manually , 7.4 h for dismantling step, 17 € /h, Salhofer & Spitzbart 2009
Scenario 2 (manual)	-	100	-40	-	-	-3.845	-3.960	One manual dismantling step, 6.6 h, 6 € /h
Investment cost for storage space, sorting & dismantling facilities (annual depreciation) *Scenario 1 (mechanical-manual)*	800	-	-2	-1.709	-1.760	-	-	220,000 € for a plant of 10,000 t /a capacity, i.e. 120,000 € for machinery (smasher, mill, sieve, magnetic separator) + 100,000 € for buildings, storage etc, assume depreciation over 10 years
Scenario 2 (manual)	-	100	-1	-	-	-97	-100	100,000 € for buildings, storage etc, assume depreciation over 10 years

Table 2: Transfer coefficients [-] for the manual dismantling (Scenario 2) as used in the Material Flow Analysis in STAN, based on Salhofer and Spitzbart, 2009.

Outputs	**Mixed Scrap**	**Hard drives, disk drives, drives, adaptors**				**Iron /Steel**	**Al**	**Contacts**	**Printed Circuit Boards**	**Processors**	**Other fractions to be disposed of (plastics, residues...)**
Subgoods		**Hard drive**	**Disk drive**	**Drive**	**Adaptors**						
Steel / Iron	0.003	0.02	0.03	0.06	0.09	0.8					
Aluminum	0.01	0.34	0.02		0.36		0.27				
Copper	0.05	0.12	0.08	0.11	0.64						
Printed Circuit Boards / Contacts		0.03	0.02	0.05	0.10			0.05	0.73	0.02	
Plastics	0.02	0.01	0.03	0.15	0.12	0.14					0.53
Other											1

Table 3: Transfer coefficients [-] for the mechanical-manual dismantling (Scenario 1) as used in the Material Flow Analysis in STAN, own calculations based on Salhofer and Spitzbart, 2009.

Outputs	Iron / Steel	Al	Cu	Cables	Mixed Metals (30 % Al, 30 % Fe)	Diverse Metals (18 % Fe)	Adaptors / Printed Circuit	Printed Circuits granulated	Printed Circuits	Contacts	Brass	Processors	Other fractions to be disposed of				
Subgoods													Fine fraction	Plastics	Diverse Fractions (20 %Fe, 50 % Al)	Capacitors	Dust
Steel / Iron	0.98			0.0006	0.0017	0.002	0.01		0.006				0.003		0.002		
Aluminum	0.36	0.47			0.02	0.07									0.073		
Copper			0.39	0.25			0.25	0.0364	0.073								
Printed Circuit Boards / Contacts	0.0040				0.01		0.045	0.5798	0.045	0.027	0.016	0.04	0.043		0.022	0.0525	0.144
Plastics				0.16										0.843			
Other	0.26			0.32		0.067	0.334		0.089				0.018				

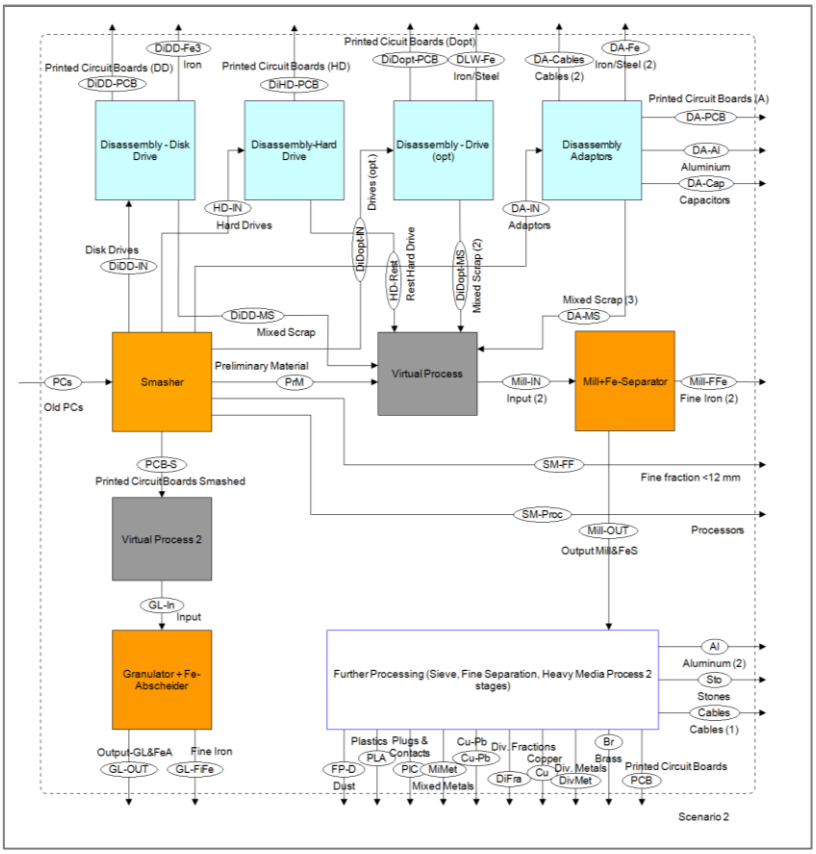

Figure 1: Illustration of the qualitative material flow model for the mechanical-manual dismantling (Scenario 1)

The fractions of Steel / Iron, Aluminum, Copper, Printed Circuit Boards / Contacts, Plastics and Others are modeled in STAN on the level of “subgoods”. In Scenario 2 (cf. Table 2) the only process “Manual Dismantling” directs, for instance, 1 % of the Aluminum to the output flow “Mixed Scrap”, 34 % to “Hard Drives”, 2 % to “Disk Drives”, 36 % to “Adaptors” and 27 % to the actual Aluminum output flow.

In contrast, Scenario 1 represents a hybrid scenario of mechanical processing and manual disassembly, as shown in Figure 1.

First, the old PCs are processed in a smasher after removing the detachable components. All (hard, disk) drives and adaptors are removed and then manually dismantled. The remaining mixed fraction is crushed and subsequently mechanically processed. Together with the materials from the smasher it goes to the mill, which includes a Fe-separator, where about 80% are discharged as fine fraction and iron. The rest is discharged for further mechanical processing. Almost 60 % of the overall input fraction of printed circuit boards is granulated (cf. Table 3).

The transfer coefficients for the combination of mechanical and manual treatment of old PCs are shown in Table 3. Based on the overall content of aluminum present in the input, a total of approximately 47% of the subgood is discharged in an unmixed fraction. The rest can mainly be found in iron and mixed metal outputs.

3. LANDFILL MINING

Table 4: Present values of costs & revenues, discounted with 3% and 0 % taking the timing of cash flows into account.

REVENUES	Quantity [t, m2] LFM Present	Average Price [t] LFM (potential) future	Average Price per Unit [€/t, €/m2, €/MWh,€/a]	Cashflows with discount rate 3 % (Mean Values), [€], 20 year	Undiscounted Cashflow (Mean Values), [€], 20 years	Cashflows with discount rate 3 % (Mean Values), [€], 20 years	Undiscounted Cashflow (Mean Values), [€], 20 years	Reference / Comment
				LFM Present		LFM (potential) future		
Ferrous Metals	14.454	380	190	40.857.555	54.925.200	81.714.828	109.850.400	In Scenario "Potential future LFM" metals (Fe & Non-Fe) are expected to double.
Metals RDF Preparation	4.577	380	190	12.938.181	17.392.980	25.876.362	34.785.960	*97 % Ferrous Metals, 2,1 % Al, 0,09 % Cu **70 % Al, 30 % Cu with Al Price: 800, Cu Price: 2200, own assumptions due to unknown metal quality Letsrecycle.com 2015a (light iron 2013/2015)
Metals from Fines*	9.243	442	221	30.377.120	40.836.392	60.754.240	81.672.785	
Non-Ferrous Metals**	2.409	2.440	1.220	43.724.601	58.779.600	87.449.202	117.559.200	
Minerals / Stones	85.370	5	5	6.350.449	8.536.998	6.350.449	8.536.998	Kies & Sand ServiceGmbH 2014
Regained salable land	521.200	40	40	11.206.827	20.848.000	11.206.827	20.848.000	Gained only at the end of LFM activities in year 20. Van Passel et al. 2013;
AVOIDED COST								
Avoided aftercare cost	65.000	6	6	55.253.692	81.900.000	55.253.692	81.900.000	Maintenance area, water treatment, monitoring, analysing & sampling, Annually increasing by 65,000 m2 x 6 €; Geysen 2013.
Avoided aftercare costs for the last 30 years	1.300.000	1	-	-	-	20.964.422	39.000.000	Gained at the end of LFM activities in year 20, for 30 years after LFM (as LFM was 20 years postponed into the future); Own assumption
Avoided aftercare costs for the last 50 years	1.300.000	-	1	34.940.703	65.000.000	-	-	Gained at the end of LFM activities in year 20, for 50 years after LFM; Own assumption
Avoided Covering Cost	1.300.000	-	63	43.235.626	80.431.000	-	-	Gained only at the end of LFM activities in year 20, in Scenario "Potential future LFM" the landfill has to be covered due to postponed LFM activities Geysen 2013.

Table 4 (continued).

COST		Average Cost [€/t]						
Excavation & storage co	807.000	-5	-5	-60.030.611	-80.700.000	-60.030.611	-80.700.000	Annually excavated amount: 16.1 Mio t / 20; Van Vossen & Prent 2011; Van Passel et al. 2013
Incineration cost: Transport	169.795	0	0	-16.167.128	-21.733.699	-16.167.128	-21.733.699	80 km with 0.08 €/tkm, own assumption
Incineration cost: Baling	169.795	-5	-5	-12.630.569	-16.979.452	-12.630.569	-16.979.452	Own assumption
Incineration cost: Gate fees	169.795	10	-65	-164.197.393	-220.732.878	25.261.137	33.958.904	In Scenario "Potential future LFM" gate fees are expected to decrease from 65 €/t to -10 €/t. Letsrecycle.com 2014a
Sorting & separation OPEX	807.000	-18	-23	-244.366.715	-328.498.080	-180.830.029	-243.092.367	In Scenario "Potential future LFM" sorting costs are expected to decrease by 20 %. Based on Van Vossen & Prent 2011.
Investment cost sorting & separation plant	-	-	-	-38.385.913	-45.000.000	-38.385.913	-45.000.000	Paid over the first 10 years. Bernhardt et al. 2011, Ford et al. 2013;
Project preparation (licenses etc.)	-	-	-	-1.000.280	-1.000.280	-1.000.280	-1.000.280	Paid in year 1. Based on Van Vossen & Prent 2011.
CO2 tax	-	-	-	-19.482.658	-19.482.658	-19.482.658	-19.482.658	Paid in year 1. For detailed LCA see Winterstetter et al. 2015.

4. PERMANENT MAGNETS FROM WIND TURBINES

Table 5: Present values of costs & revenues, discounted with 3% and 0 % taking the timing of cash flows into account.

REVENUES	Quantity [t] Scenario 1 Re-use	Quantity [t] Scenario 2 Hydromet. extraction	Average Price [€/t]	Cashflows with discount rate 3 % (Mean Values), [€], 1	Undiscounted Cashflow (Mean Values), [€], 1 year	Cashflows with discount rate 3 % (Mean Values), [€], 1	Undiscounted Cashflow (Mean Values), [€], 1 year	Reference / Comment
				Scenario 1		Scenario 2		
Nd	-	39	70.284	-	-	2.669.048	2.749.119	Av. price 2008 - 2015, Molycorp 2013
Fe	-	98	113	-	-	10.755	11.078	Av. price 2013 - 2015, Letsrecycle.com 2015a (light iron 2013/2015)
B	-	2	641	-	-	1.014	1.044	Av. price 2011 - 13, USGS 2013
Dy	-	7	459.703	-	-	2.909.536	2.996.822	Av. price 2008 - 2015, Molycorp 2013
Pr	-	3	546.863	-	-	1.730.591	1.782.509	Av. price 2008 - 2015, Molycorp 2013
Used permanent magnet	166	0	38.925	6.284.762	6.473.305	-	-	Expert interview, Stiesdal 2015
COST			Average Cost [€/t of permanent magnet]; [€/a]					
Device to separate & demagnetize magnets from wind turbines (annual depreciation)	-	-	-51.330	-49.835	-51.330	-49.835	-51.330	Expert interview, Stiesdal 2015, approx. 500,000 € for a mobile device, assume depreciation over 10 years
Investment cost REE separation plant (annual depreciation)	-	-	-466.228	-452.648	-466.228	-	-	498 mio $ for REE separation plant with capacity of 16000 t / a, Chadwick 2012, => 5.2 mio $ for 166 t, 0.5 mio $ with assumed depreciation over 10 years
*REE separation plant (OPEX)***								*Quantities of acids used are based on own laboratory experiments ** dominated by input of acids
Sulphuric acid (H2SO4)	-	166	-3	-	-	-477	-491	160 $ / t, Alibaba 2015a
Sodium hydroxide (NaOH)	-	166	-1	-	-	-101	-104	435 $/t, Alibaba 2015b
Hydrogen peroxide (H2O2)	-	166	-0.12	-	-	-20	-21	460 $ / t, Alibaba 2015c
Hydrofluoric (HF) acid	-	166	-6	-	-	-921	-948	800 $ / t, Alibaba 2015d

Table 6: Transfer coefficients for the hydrometallurgical extraction of REE, Fe and B (Scenario 2) as used in the Material Flow Analysis in STAN, own calculations based on Prakash et al. 2014.

	Nd	Fe	B	Dy	Pr	Others / residues
Permanent magnets	0.235	0.589	0.098	0.0392	0.00196	0.107

According to Prakash et al. (2014) a magnet's composition is assumed with 24 % of Nd, 65.5 % of Fe, 1 % of B, 4 % of Dy and 2 % of Pr. Under consideration of the specific REE recovery efficiencies based on own assumptions, Scenario 2's only process "Hydrometallurgical extraction" directs around 23.5 % of the overall permanent magnets to the output flow "Neodymium", 58.9 % to "Ferrum (Fe)", 0.098 % to "Boron (B)", 3.92 % to "Dysprosium (Dy)" and 1.96 % to "Praseodymium (Pr)" (cf. Table 6).

5. THE UNITED NATIONS FRAMEWORK CLASSIFICATION FOR FOSSIL ENERGY AND MINERAL RESERVES AND RESOURCES (UNFC-2009)

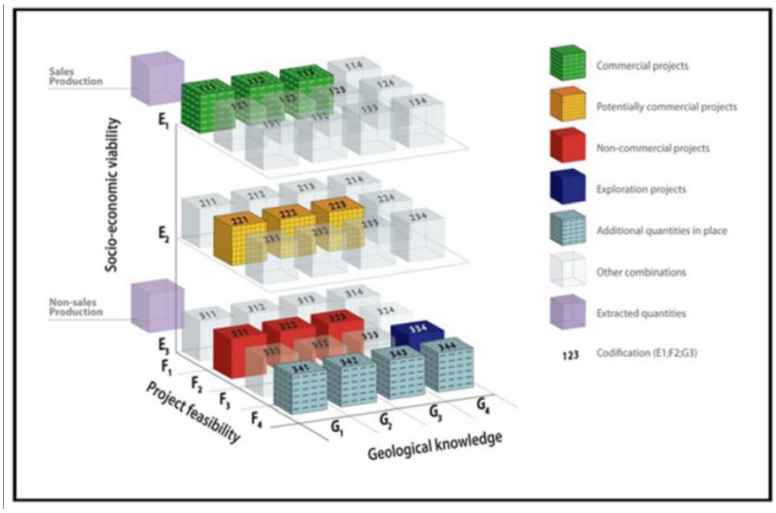

Figure 2: United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009). Reproduced courtesy of the United Nations Economic Commission for Europe (UNECE, 2010).

Under UNFC-2009 quantities are classified on the basis of the three fundamental criteria, namely "socioeconomic viability" (E1 – E3), "field project status and technical feasibility" (F1 – F4), and "knowledge on composition" (G1 – G4), with E1F1G1 being the best category (cf. Figure 2) (UNECE, 2013).

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