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The role of anthropogenic resource classification in supporting the transition to a Circular Economy,
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Abstract

A successful transition to a Circular Economy, as promoted by the European Commission, requires solid information on the future availability of anthropogenic resources, in analogy to natural resources. Based on a review of existing studies on the classification of anthropogenic resources, this paper investigates how and for what purpose the classification of anthropogenic resources was done in the past and how it can support the transition to a Circular Economy in the future. The review includes case studies that classify resources recovered from old landfills, built infrastructure, national secondary metal stocks, electrical and electronic waste and waste incineration residues. Five areas were identified where resource classification could have a meaningful contribution in the future**,** namely 1) to increase the knowledge on the anthropogenic resource potential for an integrated view on both anthropogenic and natural resources, 2) in supporting research to develop new technologies, 3) in supporting policy makers with designing new legislation, 4) to investigate economic viability while including social and environmental externalities and 5) to improve the marketability of recovered materials. For a Circular Economy transition, alternative consumption and production systems are needed. Resource classification can play a key role in communicating the availability, recoverability and utilization options of anthropogenic resources along the value chain, e.g. to optimize waste management operations, processes and products for enhanced resource recovery and recyclability and to compare different Circular Economy options. A standardized classification methodology including guidance on the detailed assessment for all types of anthropogenic resources is recommended, taking into account that the availability of resources does not solely depend on the material quantities, but also on the technical, operational, economic, social, environmental and regulatory conditions that enable or prevent recovery of these resources.

Keywords: Anthropogenic Resources, Secondary Raw Materials, Resource Recovery, Resource Efficiency, Sustainable Resource Management, United Nations Framework Classification for Resources (UNFC), Waste Management

1. Introduction

The European institutions have been promoting the utilization of anthropogenic resources, e.g. through the European Raw Materials Initiative (European Commission, 2008), the Circular Economy Package (European Commission, 2014) as well as various other European directives on waste management and recycling (e.g. Directive EC, 2008, 2012, 2018). Moving Europe towards a zero-pollution society is one of the ambitious goals of the recent European Green Deal (European Commission, 2019). One of the major pillars of the Circular Economy package is the EU Action Plan for the Circular Economy (European Commission, 2015), updated in 2020 (European Commission, 2020), which envisages Europe's transition from a linear ‘take-make-dispose’ economy to a Circular Economy (CE), where the value of products and materials is maintained for as long as possible and resources are preserved. The vision is to minimize waste and resource use, and to maintain the material value at the end of a product’s life. This ambitious program of action includes measures covering the whole cradle-to-cradle cycle from manufacturing and consumption to end-of-life management as well as the use of anthropogenic resources.

One of the goals of the circular economy is to return waste as "anthropogenic resources" (Winterstetter, 2016) to production as “secondary raw materials” (European Commission, 2020) in order to substitute natural resources, i.e. minerals and energy. Developing commercial activities to enable a CE, and in particular with respect to resource recovery, requires investment. The different stakeholders in a Circular Economy have different needs with respect to the sustainable implementation of anthropogenic resource recovery projects; therefore producers, investors, governments and other key stakeholders need consistent and transparent information and professional support for decision-making regarding the availability and potential for the utilization of anthropogenic resources (Kirchherr et al., 2017). The availability of natural resources is communicated based on resource classifications. In contrast, the classification of anthropogenic resources, which are stocked in the use-phase and turn into post-consumer residues, is still in its infancy. While for natural resources the focus is on security of supply and economic profitability, the management of anthropogenic resources derived from waste has a stronger emphasis on preventing harmful effects on human health and the environment (Heuss-Aßbichler et al., 2020).

The overall goal of the paper is to investigate how and for what purpose the classification of anthropogenic resources was done in the past and how it can support the transition to a Circular Economy in the future.

In this paper ‘sources’ are defined as material stocks and flows, such as old landfills or e-waste streams, out of which targeted anthropogenic resources, such as metals or phosphorus, can be extracted as commodities, i.e. ‘recovered’. A project is defined as “*a defined development or mining operation which provides the basis for economic evaluation and decision-making. In the early stages of evaluation, including exploration, the Project might be defined only in conceptual terms, whereas more mature Projects will be defined in significant detail”(UNECE, 2010).*

2. Background: Challenges of anthropogenic resource recovery & resource classification

In order to effectively use materials from anthropogenic (re-)sources within the context of CE, three main aspects - resource potential, recoverability and utilization - must be considered. We have identified the following 12 challenges, which have to be overcome:

Resource potential

1) **Unknown quantities of anthropogenic sources**, such as end-of-life products, obsolete buildings, old landfills, hibernating infrastructure, make it difficult to plan extraction activities (e.g. Graedel et al., 2002).
2) **The lack of information on the physical location, the accessibility and temporal availability** of many anthropogenic (re)sources impedes their efficient use, that is, 'urban mining' from material stocks, and recycling and reuse of obsolete products and materials (e.g. Kleemann et al., 2014). Anthropogenic resources may not occur in large, locally limited and therefore manageable reservoirs as competing geogenic resources do; the sources of anthropogenic materials are often distributed heterogeneously over time and space (Winterstetter et al., 2016b).
3) **The lack of information on the quality of anthropogenic material stocks and flows** in particular on their composition and variability, including their constituent products, components, substances, as well as potential contaminants poses a major problem for recovery. Insufficient communication between producers, manufacturers, consumers and recyclers is a barrier to effective value chain management. Design for Recycling has not yet become a core requirement in product design (Brughmans, 2019).

Recoverability

4) **Inconsistent legal framework and absent organizational infrastructure** - In many regions, an insufficient collection and recycling infrastructure leaves considerable amounts of resources uncaptured (H2020, 2019). Often the absence of a well-regulated environment for recyclers, including legislation and its enforcement, hinders the efficient collection and recovery of certain waste streams.
5) **Unclear technical feasibility and project set-up** - For some anthropogenic sources, technical procedures to recover materials and / or to remove contaminants do not exist (yet) or are immature. Further, the impacts of certain decisions for the implementation of a resource recovery project often cannot be sufficiently estimated, e.g., offsite vs onsite treatment of combustible fractions of a mined landfill on the economic viability (Blasenbauer et al., 2020).
6) **Unclear economic viability and social and environmental impacts** - The expected revenues for recovered anthropogenic resources or products do not cover the extraction costs and / or the energy input and the related emissions are not justified (Turner et al., 2015).

Utilization Options

7) **Legal and regulatory barriers –** Administrative burdens caused by legal and regulatory barriers can have negative impacts on the marketability for recycled materials (Johansson et al., 2017b).
8) **Environmental, health and safety concerns** - The circulation of anthropogenic materials may lead to the accumulation of hazardous substances in the cycle (cf Kral et al., 2013), and their uncontrolled dissipation in the natural and built environments due to missing legislation and / or enforcement (e.g. Achternbosch et al., 2005; Pivnenko et al., 2016; Sverdrup and Ragnarsdóttir, 2014).
9) **Uncertainty with respect to a stable secured supply of anthropogenic materials** - A stable supply depends on many factors, e.g. the quantities collected by local authorities, private waste operators and the informal sector, the separation technologies used and also consumption and disposal behaviour of individuals that influence the type and quantity of materials entering the waste stream (H2020, 2019).
10) **Marketability** - Often there is a mismatch between the quality of the recovered resources and the standards set by the manufacturers / producers, which are in many cases are based on the properties of primary raw materials rather than on the application requirements (Brughmans, 2019; Johansson et al., 2017b).

11) **Negative perception of recovered materials** – The quality of the materials recovered from anthropogenic sources is often perceived as low-quality by consumers or producers, although this is not necessarily reflected in the quality of the material (Debacker and Manshoven, 2016).
12) **Lack of comparability between anthropogenic vs natural materials** - In commodity markets, anthropogenic resources have to compete with natural resources. However, a transparent comparison on an equal footing is currently not possible, because the framework conditions for evaluation of anthropogenic resources comparable to primary raw materials are still lacking (Winterstetter, 2016).

Such challenges can in principle be considered by the concept of resource classification, an instrument to assess resource recovery projects and to support decision-making for their sustainable implementation (Blasenbauer et al., 2020; Winterstetter, 2016).

Resource classification frameworks were historically designed to manage natural materials and commodities and to make potential resource extraction projects comparable for stakeholders. Over time, numerous classification systems and reporting codes for mineral raw materials and energy resources have been developed independently all over the world in response to different sectoral needs (cf Winterstetter et al., 2016b). Resource classification systems typically consider the two dimensions of "knowledge on geological composition" and "economic feasibility of extraction", as is the case for the McKelvey code (McKelvey, 1972) and the Committee for Mineral Reserves International Reporting Standards family of codes (CRIRSCO, 2013). The United Nations Framework Classification for Resources (UNFC) uses three dimensions: 1) degree of confidence in the estimates, 2) technical feasibility and maturity, and 3) environmental-socio-economic viability (UNECE, 2010, 2020).

In 2018, specifications for application of the UNFC to anthropogenic resources were released. The specifications do not give specific operational guidance on performing the details of resource assessment in combination with resource classification (UNECE, 2018), however, first steps are currently underway to address this gap (Kral et al., 2020). Similar to resource geology, some basic information on the fundamental resource potential is required when considering 'mining' of anthropogenic deposits, that is, how much of the resource is available and when, where and how it can be accessed, and in what form. Based on this quantitative and qualitative information the recoverability can be explored, i.e., the availability of technologies for extraction and processing, their economic viability, their social and environmental impacts, and the legal framework, organizational infrastructure and project set-up. Finally, potential outlets (utilization options) can be explored.

3. Materials & Methods

This paper aims to 1) investigate how the 12 challenges related to anthropogenic resource recovery were addressed by the reviewed case studies on the classification of anthropogenic resources, and to 2) identify the potential of anthropogenic resource classification to support a Circular Economy transition.

First, a literature review was conducted using three scientific databases, Scopus, Google Scholar and Science Direct, using the key words 'resource classification UNFC', 'resource classification McKelvey', 'classification anthropogenic resources', 'resource classification circular economy', 'resource classification circularity' and 'assessment secondary resources'. The review in this paper focused exclusively on peer-reviewed studies published in scientific journals that explicitly refer to the two most widely used resource classification systems, i.e. the UNFC and the McKelvey diagram (McKelvey, 1972). The grey literature, i.e., (company) reports, conference proceedings, oral and poster presentations, were excluded from this review. (National) reporting codes from the CRIRSCO family were not included, as they were only applied to mine tailings and published as (company) reports, not as published scientific papers (e.g. Campbell et al. (2015); Cronwright et al. (2018)). However, an overview of these reports can be found in Blasenbauer et al. (2020). Only published scientific studies were considered, which performed partial or complete resource classification of anthropogenic deposits in analogy to the mining sector, and which demonstrated the application in case studies.

This review aims in a first step to identify the drivers and scope of existing studies on the classification of anthropogenic resources and to investigate to what extent (some of) the 12 challenges linked to anthropogenic resource recovery (cf Chapter 2) were addressed. In a second step, a gap analysis is performed to identify the potential of anthropogenic resource classification to support a Circular Economy transition. On the basis of the case studies, gaps are identified in relation to the currently under- or un-addressed challenges linked to anthropogenic resource recovery as well as to the updated EU Action Plan for the Circular Economy (European Commission, 2020).

4. Results & Discussion

4.1 Selected case studies on anthropogenic resource classification included for review: Drivers & scope

Case studies included for review

From a first screening of relevant papers it was found that with respect to the physical availability of anthropogenic resources there are a considerable number of studies that use system analysis tools, such as dynamic material flow analysis, to determine the overall material stocks in specific use sectors and their development over time to predict future end-of-life flows (e.g. Chen and Graedel, 2012; Pauliuk et al., 2013). Some authors evaluated the regulatory, technical, social, environmental and / or economic aspects of resource recovery projects for different types of obsolete stocks and waste flows, such as packaging waste (e.g. Ferreira et al., 2014), e-waste (e.g.Baldé et al., 2015), slags (e.g.Tian et al., 2016), old landfills (e.g. Hermann et al., 2016) or hibernating infrastructure (e.g. Wallsten et al., 2013). While a few studies compare different boundary conditions and scenarios to mine one specific deposit (e.g.Kieckhäfer et al., 2017), others compare different anthropogenic deposits as sources for one specifically sought material. Krook et al. (2011), for instance, assessed copper stocks present in the local power grids in two different Swedish cities. All these studies, to a various extent, assess the viability of recovery, but do not apply a resource classification scheme analogous to those used in the mineral resource mining sector.

Published scientific studies that were included in the review are displayed in Table 1. A similar overview is provided by Mueller et al. (2020). They all performed partial or complete resource classification of anthropogenic deposits in analogy to the mining sector, using the McKelvey or UNFC (some in slightly modified form), and demonstrated the application in case studies. Although Quina et al. (2018) do not apply any resource classification scheme to their specific case studies on technologies for resource recovery from waste incineration residues, methodological issues with respect to UNFC are extensively discussed and therefore this study was included. The same is true for Habib (2019), who presents a qualitative concept to classify different products containing permanent magnets, using the McKelvey scheme.

Table 1: Research papers included in the review

Type of anthropogenic source	Source(s)	Spatial system boundaries	Resource(s) targeted	Classification concept used	Reference
Old landfills	Landfills (ash & MSW), steel and iron slags, waterbodies, soil, construction materials, households & infrastructure	National level: Various stocks in Austria	P	McKelvey	Lederer et al. (2014)
	One historical landfill comprising MSW and industrial waste	Project level: Landfill site located in Flanders, Belgium	Fe, Cu, Al, minerals and stones, RDF / energy, land, avoided aftercare cost & CO2 tax	UNFC	Winterstetter et al. (2015)
	A number of small historical MSW landfills	Project level/ regional level: Landfill sites located all over Flanders, Belgium	Fe, Cu, Al RDF, soil, construction materials, avoided aftercare cost & CO2 tax, future land tax for municipality	UNFC	Winterstetter et al. (2018)
Waste Incineration Residues	MSWI APC residues & bottom ash	EU level: APC residues & bottom ash in EU-28+ Norway+ Switzerland	Zn, avoided disposal costs for MSWI residues	McKelvey	Fellner et al. (2015)
	MSWI fly ash	Project level / city level: Fly ash in Vienna, Austria	Metals (Fe, Zn, Pb, Cu, Cd), mineral materials (gypsum, limestone, clay, quartz), salt, monetized avoided environmental impacts	UNFC	Huber and Fellner (2018)
	MSWI fly ash incl. APC residues	Supranational level: residues in Europe	Mineral fraction, Zn, REE, salt	UNFC	Quina et al. (2018)
	MSWI bottom ash	Project level/ regional level: 5 MSWI plants & 2 recovery plants in Kanton Zurich, Switzerland	Fe, non-ferrous metals, stainless steel, glass	UNFC	Mueller et al. (2020)

Type of anthropogenic source	Source(s)	Spatial system boundaries	Resource(s) targeted	Classification concept used	Reference
WEEE	NdFeB permanent magnet from electrical cars, fluorescent lamp with Eu phosphors, fibre optic cables with Er	National level, Switzerland	Nd, Er, Eu	UNFC	Mueller et al. (2015)
	Obsolete computers, NdFeB permanent magnets in wind turbines, old landfill	Project level/ national level: Magnets in wind turbines in Austria, Project level / city level: Obsolete computers in Vienna Project level: Old landfill in Belgium	Computers: Fe, Al, Cu, printed circuit boards & contacts, plastic, others Wind turbines: Magnet for reuse, vs. recovery of Nd, Fe, B, Dy, Pr Landfill: Fe, Cu, Al, construction materials, RDF, land, avoided aftercare	UNFC	Winterstetter et al. (2016a)
	NdFeB permanent magnets	Product level / national level: Denmark	NdFeB permanent magnets for reuse, refurbishment, remanufacturing, vs. recycling of REEs	McKelvey	Habib (2019)
Built infra-structure	Subway Network	City level: Vienna, Austria	Concrete, gravel, bricks, Fe, Cu, Al	McKelvey	Lederer et al. (2016)
Metals	All types of Cu sources in the economy	International level: China, Germany, Italy, Japan, Korean Republic, Spain, USA	Cu	McKelvey	Maung et al. (2017a)
	All types of Al sources in the economy	International level: Argentina, Australia, Austria, Belgium, Brazil, China, France, Germany, India, Italy, Japan, Netherlands, Norway, Russia, South Africa, Spain,	Al	McKelvey	Maung et al. (2017b)

Type of anthropogenic source	Source(s)	Spatial system boundaries	Resource(s) targeted	Classification concept used	Reference
		Switzerland, UK, USA			
	All types of Zn sources in the economy	International level: China, France, Germany, Italy, Japan, USA	Zn	McKelvey	Maung et al. (2019)

Al = Aluminum, APC = Air-pollution-control, B = Boron, Cd = Cadmium, Cu = Copper, Dy = Dysprosium, Er = Erbium, Eu = Europium, Fe = Ferrous metals (Iron), MSW(I) = Municipal solid waste (incineration), Nd = Neodymium, P = Phosphorus, Pb = Lead, Pr = Praseodymium, REE = Rare earth elements, RDF = Refused Derived Fuel, WEEE = Waste Electrical and Electronic Equipment, Zn = Zinc

McKelvey = US Geological Survey Classification (McKelvey, 1972); UNFC = United Nations Framework Classification for Resources (UNECE, 2010)

Drivers of anthropogenic resource classification in existing case studies

The result of the review shows that resource classification in previous case studies had very diverse drivers (cf Table 2 and SI):

Table 2: Drivers of anthropogenic resource classification in existing case studies

Drivers	Case studies
• **Establish an inventory of available and accessible anthropogenic (re)sources at regional / national level**	Lederer et al. (2014); e.g. Maung et al. (2017a); Maung et al. (2019); Maung et al. (2017b)
• **Compare different alternatives and scenarios for resource recovery projects** ○ Compare different anthropogenic sources ○ Compare the recovery of materials from anthropogenic and natural sources ○ Compare different evaluation perspectives ○ Compare different technologies and / or methods for resource recovery ○ Compare different circular economy options ○ Compare different utilization options for recovered anthropogenic resources	e.g. Winterstetter et al. (2016a) e.g. Mueller et al. (2015) e.g. Winterstetter et al. (2015) Mueller et al. (2020); e.g. Quina et al. (2018). Habib (2019), Winterstetter et al. (2016a) Huber and Fellner (2018)
• **Determine key parameters for the success of a recovery project** ○ Determine the right timing of mining by identifying key parameters that are likely to change in the near future to make the project economically viable ○ Identify specific factors and settings related to site, project and system that are favorable or represent a barrier for resource recovery projects	e.g. Winterstetter et al. (2015) e.g. Fellner et al. (2015); Mueller et al. (2020); Winterstetter et al. (2018).
• **Optimize waste management operations for enhanced resource recovery at project and system level** ○ Identify the best upstream combination of waste combustion, APC and ash collection technologies for Zn recovery ○ Improve the waste collection systems and invest in public awareness for source separation of waste	Fellner et al. (2015), Winterstetter et al. (2016a)

o Change landfilling practices for future P recovery	Lederer et al. (2014).
• **Internalize environmental and social externalities in the financial evaluation either via legislation or concepts of monetization**	e.g. Huber and Fellner (2018).
• **Optimize design of products with respect to recoverability of materials and ease of collection**	Habib (2019).

As shown in Table 2, the drivers were mainly about anthropogenic resource recovery, i.e. to identify the resource potential and to investigating the recoverability of anthropogenic resources. In this context also different circular economy options (reuse vs. recycling) and different utilization options for recovered anthropogenic resources were compared. In addition, considerations on how to optimize waste management and product design for future resource recovery played a role, and how to internalize environmental externalities.

Scope of existing case studies on anthropogenic resource classification

The 14 reviewed studies cover resource recovery from old landfills (Lederer et al., 2014; Winterstetter et al., 2015; Winterstetter et al., 2018), from waste incineration residues (Fellner et al., 2015; Huber and Fellner, 2018; Mueller et al., 2020; Quina et al., 2018), from Waste Electrical and Electronic Equipment (WEEE) (Habib, 2019; Mueller et al., 2015; Winterstetter et al., 2016a), from built infrastructure, (Lederer et al., 2016) and the recovery of metals from all sources in the economy (Maung et al., 2017a; Maung et al., 2019; Maung et al., 2017b)(cf. Table 1).

The resources recovered from the deposits comprise elements such as phosphorus (P), aluminum (Al), copper (Cu), zinc (Zn), rare earth elements (REE), ferrous metals (Fe), as well as components, such as magnets from wind turbines or motherboards from obsolete computers. Some recovery efforts target materials such as salt, soil, gravel, a fine mineral fraction, refused derived fuel (RDF). Further, depending on the level of granularity, some case studies include other valuables, such as reclaimed land after landfill mining and / or avoided aftercare (e.g. Winterstetter et al., 2015), future land tax for a municipality (Winterstetter et al., 2018), avoided costs for disposal alternatives (e.g.Fellner et al., 2015) or monetized positive environmental impacts (e.g. Huber and Fellner, 2018).

As shown in Table 1, half of the studies use the three dimensions of the UNFC; the other half use the two dimensions of the McKelvey diagram (McKelvey, 1972). Those using the McKelvey diagram focus on investigating the resource potential and on establishing an inventory of available and accessible anthropogenic (re)sources at regional / national level, while the studies using UNFC rather focus on the recoverability at the level of a defined project with specific technologies and project set-ups.

Mueller et al. (2020) traced the historic development of actual resource recovery projects from municipal solid waste incineration (MSWI) residues. The majority of the reviewed studies are forward-looking, meaning that resource recovery activities are actively planned, or at least considered, for some point in the future. Although most of the assumptions made in these case studies are linked to high uncertainties (e.g. on future price developments etc) and knowledge gaps, only half of the reviewed studies included any estimates of uncertainty. Geographically the main focus of the previous case studies has been Europe, i.e., Belgium, Austria, Denmark, Switzerland, with the studies by Maung and colleagues being the exceptions by also including data from outside of Europe, mainly the USA, Japan and China. Details on the methodological differences between the case studies can be found in Kral et al. (2020).

4.2 How the reviewed case studies addressed challenges related to anthropogenic resource recovery

Based on the review findings this chapter describes to what extent the existing case studies on the classification of anthropogenic resources addressed the 12 challenges linked to anthropogenic resource recovery (cf Chapter 2).

Challenges related to Resource Potential

Information on the fundamental resource potential is required when considering anthropogenic resource recovery, that is, how much of the resource is available, when, where and how it can be accessed, and in what form.

Unknown quantities of anthropogenic sources

To quantify the available and recoverable resources, information on the anthropogenic source(s) has to be collected within the set spatial system boundaries in a first step.

Eight out of fourteen studies (Huber and Fellner, 2018; Lederer et al., 2016; Mueller et al., 2020; Mueller et al., 2015; Quina et al., 2018; Winterstetter et al., 2015; Winterstetter et al., 2016a; Winterstetter et al., 2018) focus on the source, that is, on one specific deposit (e.g. on a specific landfill) or a certain type of source (e.g., MSWI residues), out of which one or multiple different materials are extracted, rather than targeting one specific single commodity. Four macro-level studies target specific commodities, that is, phosphorus (Lederer et al., 2014) and various metals (Maung et al., 2017a; Maung et al., 2019; Maung et al., 2017b) by looking at various potential sources at national or even international levels. Fellner et al. (2015) and Habib (2019) use a hybrid approach by narrowing down the number of investigated types of sources in advance, to target only one specific resource. Fellner et al. (2015) focuses on MSWI residues, i.e. air pollution control (APC) residues and bottom ashes, to recover zinc, while Habib (2019) compares NdBFe magnets from different devices to recover REE.

Lack of information on the physical location, accessibility and temporal availability of (re)sources

The physical location, the accessibility and the temporal availability of a resource can vary depending on whether the material is contained in anthropogenic stocks and flows and strongly depends on the regulatory environment. Both the macro-level type of studies focusing mainly on the resource potential, as well as the case studies considering the details of resource recovery (project-specific), need to deal with the temporal availability of (re)sources. The location and specific physical accessibility are, however, more relevant to the project-specific studies.

Four studies focus on obsolete or in-use material stocks, i.e., on landfills and on built infrastructure. Obsolete stocks come closest to natural deposits/mines, as they are usually immobile and finite. A landfill-mining project can usually be well defined and resources are depleted over time. The drivers to mine landfills can be diverse, e.g., for materials resource and / or land recovery (Winterstetter et al., 2015) or for soil remediation (Winterstetter et al., 2018). If no remediation for environmental reasons is required, mainly the economic profitability will determine whether or not a historic landfill will be mined (Winterstetter, 2016). Accessing built-in materials in infrastructure for resource recovery is typically only feasible in combination with maintenance and / or replacement (Wallsten et al., 2015). For Vienna's subway infrastructure, Lederer et al. (2016) found that about 3 % of the materials have to be replaced within the next 100 years, and therefore have the potential to be recovered as resources.

Seven of the reviewed case studies focus on present or future waste flows, i.e., WEEE and MSWI residues. As in the case for stocks, the revenues from resource recovery can help to reduce the costs of waste treatment. The collection and recycling of obsolete personal computers (PCs), as described by Winterstetter et al. (2016a), is required under the EU WEEE directive (Directive EC, 2012). Since waste flows are dynamic as compared to stocks, the temporal and spatial system boundaries of the ‘project’, as defined under UNFC, had to be drawn artificially and arbitrarily in this study, namely for a period of one year and a defined city of 1 million inhabitants.

Unlike for WEEE, there is no EU Directive in place yet to specify the collection and treatment of permanent magnets in wind turbines. Winterstetter et al. (2016a) classify NdBFe magnets in wind turbines which are currently in use. Habib (2019) compares the resource potential of NdBFe magnets currently in use in different devices to recover REE from potential future waste flows, taking into account their size, location, lifetimes and how easily they can be collected.

For MSWI residues, there is no legislation in place that prescribes resource recovery. Thus resources are only recovered if, for instance, explicit decisions are made at governmental level (Mueller et al. (2020), or in case of positive economics, which are more likely if the costs of disposal alternatives are relatively high (Fellner et al., 2015).

Six of the reviewed studies compare both material stocks and present and / or future waste flows. This is done by the studies following a commodity-specific approach, as they are comparing a range of potential sources to identify the most suitable options for mining the targeted resource (e.g. Lederer et al., 2014). Maung et al. (2017a); and Maung et al. (2019); Maung et al. (2017b) rely on the two-dimensional McKelvey diagram to describe the resource potential of various stock and flow resources in an economy. They assume that the recovery of Zn, Al and Cu is technically feasible and economically viable by default for products currently in-use, based on past scrap recycling rates (‘future reserves’). Product waste flows emerging in the specific year are labeled ‘reserves’, while past wastes in landfills and dissociated materials are assumed not to be economically feasible for mining, although the authors admit that there might be exceptions.

Two case studies use the UNFC and compare (past) materials stocks and (future) waste flows to recover resources at project level: Mueller et al. (2015) compare different anthropogenic REE sources in Switzerland, that is, magnets from end-of-life vehicles, fluorescent lamps (both present and future waste flows), and underground fiber-optic cables (in-use material stocks), which will be available for potential mining as of 2030. Their location is, however, widely unknown. Winterstetter et al. (2016a) compare projects for the recovery of materials from an old landfill (obsolete stock), from obsolete PCs (present and future waste flows), and from in-use wind turbines (future waste flows) under UNFC.

Lack of information on the quality of anthropogenic material stocks and flows

In general, there is insufficient information on the quality of anthropogenic sources, that is, on their composition and variability, including their constituent products, components, substances, as well as potential contaminants.

This is true for the reviewed studies focusing on old landfills, where information mainly relies on log books and in some cases on test excavations and sampling (Winterstetter et al., 2015; Winterstetter et al., 2018). The former do not usually provide details necessary for material recovery, and the latter provide only an incomplete picture, because of the difficulty and expense of conducting this kind of sampling at a statistically relevant level. The material composition of the subway network is assumed based on historical articles and books as well as on documents and plans for the newer subway lines obtained from the construction companies and the subway operator (Lederer et al., 2016). The WEEE case studies typically use literature data about the composition of products and components (Habib, 2019; Mueller et al., 2015; Winterstetter et al., 2016a). Due to the nature of the commodity-specific national and international studies, knowledge on the composition of the broad range of anthropogenic sources relies on a variety of different data sources, e.g., from (international) national statistics and literature (Lederer et al., 2014; Maung et al., 2017a; Maung et al., 2019; Maung et al., 2017b), and are therefore insufficiently detailed to support project-level classification. Only the data on metal concentrations from waste incineration residues is comparatively solid, as it is often based on the plants’ own sampling activities (Mueller et al., 2020).

Some of the reviewed studies give recommendations on how to change and influence the composition of anthropogenic resource deposits to facilitate future resource recovery. Especially, the composition of waste flows can be influenced by decisions taken upstream. For instance, PC collection for enhanced resource recovery can be improved by increased public awareness of source separation or stricter controls on the informal sector to avoid ‘çherry-picking’ of valuable materials, which leaves behind other resources that are uneconomic to recover on their own (Winterstetter et al., 2016a). Fellner et al. (2015) found that grate combustion of waste in combination with wet APC and separate collection of boiler and filter ash is the best technological combination for Zn recovery. Quina et al. (2018) identified important factors for the resource potential, that is, the type of waste incinerated, the incinerator technology, as well as the APC system. Lederer et al. (2014) state that the extractable amount of P could have been much higher if P-rich materials were not mixed with low-grade materials during landfilling.

Challenges related to Recoverability

Once the resource potential is known, setting up a specific resource recovery project requires the analysis of specific framework settings, such as legislation and enforcement or the organizational infrastructure, to enable planning for the use of appropriate technologies, and the assessment of the associated recoverable quantities, economic viability, and social and environmental impacts.

Inconsistent legal framework and absent organizational infrastructure

Legislation and enforcement together with the required organizational infrastructure are often needed to safeguard the public and the environment, and to provide stable conditions for recyclers and resource recovery activities.

The collection and treatment of obsolete PCs in the EU, for instance, is regulated by the WEEE directive (Directive EC, 2012). Depending on how well EU legislation is implemented and enforced in the member states – including the organization of collection and the public awareness on source separation - resource recovery becomes more or less economically viable, as shown by Winterstetter et al. (2016a). Habib (2019) also used the ease of collection, including (not yet) existing legislation and collection infrastructure, as one of the criteria to distinguish between three product groups to make predictions on the economics of extraction: For wind turbines there are usually special agreements between their producers/owners/managers and the waste handling companies; end-of-life, vehicles and washing machines are usually dropped off by individual consumers at waste collection sites due to their big size, while small WEEE usually have lower collection rates, as they end up as hibernating stocks due to their small size (e.g., old phones in drawers).

Legal requirements can play an important role in making disposal alternatives more expensive, and thus certain resource recovery activities more attractive, as shown in the case studies on MSWI residues by Huber and Fellner (2018), Fellner et al. (2015) and Mueller et al. (2020). Fellner et al. (2015) found that the widely variable economics of Zn recovery from MSWI residues depend on the alternative disposal costs which are driven by legislation. The legislation in that case differs, however, from one EU member state to the other, as there is no EU directive in place.

Unclear technical feasibility and project set-up

Setting up a resource recovery project requires the planning for the use of appropriate technologies and project-set-ups as well as anticipating the impacts on the economic viability to be expected.

Half of the reviewed studies include the comparison of different technology options. Quina et al. (2018) compared six technology options for derivation of various secondary products from MSWI APC residue (lightweight aggregates, glass-ceramics and cement) and raw materials (zinc, REE salts). Similarly, Huber and Fellner (2018) compared four different technology options for MSWI fly ash utilization, i.e., the FLUREC process and cement clinker production, both with and without salt recovery, making use of the 3rd axis under UNFC ('technical feasibility and maturity') to illustrate their maturity level. Mueller et al. (2020) conducted a retrospective investigation of the different development phases of a project to recover different materials from MSWI bottom ash, also comparing two technology options, i.e., dry and wet bottom-ash treatment.

For WEEE, Mueller et al. (2015) compared technology options at different maturity levels to recover different rare earth elements (REE). Commercial recovery of Eu from lamps has started in 2012, whereas recycling of NdFeB permanent magnets recycling is currently under research, but there is no commercial plant yet. Habib (2019) compared CE options, i.e. reuse, refurbishment, remanufacturing, and the recovery of REE, for different NdFeB permanent magnet types in different devices. Winterstetter et al. (2016a) compared the direct reuse of NdFeB permanent magnets from wind turbines to hydrometallurgical extraction of Nd, Fe, B, Dy and Pr. In the PC recycling case manual dismantling of PCs was compared to mechanical recycling. The excavated waste from landfill mining was sent into a state-of-the-art material-recycling-facility (MRF) and the combustible fraction was sent to an off-site WtE plant; for that Winterstetter et al. (2015) compared two technology options, i.e. gas-plasma technology vs incineration. The latter study also illustrates that other decisions in setting up a resource recovery project might have an impact on the economic viability, e.g., whether the combustible fraction of a mined landfill is treated offsite or onsite (Winterstetter et al., 2015), or whether a mobile or a stationary unit is chosen for the sorting of the excavated waste (Winterstetter et al., 2018).

Unclear economic viability and social and environmental impacts

The economic viability of recovery projects is addressed by 10 out of the 14 reviewed case studies, although to a varying level of detail. The macro-level studies typically apply rough extraction costs and compare them with anthropogenic resource prices, to estimate the economic viability. But to estimate extraction costs, they also have to make assumptions about the applied technologies. For instance, Lederer et al. (2014) assumed a hypothetical technology to produce P fertilizer from all anthropogenic P sources in the Austrian economy. Fellner et al. (2015) assumed an existing technology for the recovery of Zn used in Switzerland to be used for the whole EU. To determine economic viability, they simply took the ratio of the Zn recovery costs of the FLUREC technology, compared to the 5-year average market price for metallic Zn, and subtracted the avoided alternative disposal costs for incineration residues. Following a more conservative approach, Maung et al. (2017a); Maung et al. (2019); Maung et al. (2017b) based their assumptions on the technical feasibility as well as the economic viability for future resource recovery on past scrap recycling data.

The studies that assess the economics of resource recovery at the level of individual projects with a defined duration typically apply a Discounted Cash Flow analysis (Winterstetter et al. (2015), Winterstetter et al. (2016a), Huber and Fellner (2018); Winterstetter et al. (2018)). Winterstetter et al. (2015) evaluated the economics for four possible landfill-mining scenarios and also determined the 'cut-off values' for key parameters that will have to change in the future for the project to break even. Also Winterstetter et al. (2018) found that - while landfill-mining under current conditions is not economically viable - the final results might look different with future changes in key economic parameters, such as increases in land prices. Winterstetter et al. (2016a) compared the economics of recovering materials from an old landfill, from obsolete PCs, and from in-use wind turbines. The 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. Huber and Fellner (2018) performed a similar Discounted Cash Flow analysis to compare the utilization of MSWI fly ash in cement production, to metal recovery and de-icing salt production.

Two studies address the economics rather indirectly without performing their own calculations. Habib (2019) classified different products containing NdBFe permanent magnets under a modified McKelvey diagram, based on increasing resource recovery challenges and increasing resource amount per unit, lifetime and economic feasibility. Mueller et al. (2020) retrospectively evaluated the socioeconomic viability based on a number of qualitative factors, including the profitability as reported by the plant operator, and whether the social license to operate including environmental permits was obtained.

In general, social aspects of resource recovery were not addressed in depth by any of the reviewed studies. Mueller et al. (2020) used the concept of 'social license to operate' similarly to how it is used in the mining sector, meaning that the local municipalities were consulted to avoid public opposition to the project. Winterstetter et al. (2018) also qualitatively integrated the factor 'public perception' of the planned landfill-mining project in the assessment of the project feasibility.

With respect to the consideration of environmental impacts for landfill-mining, Winterstetter et al. (2015) and Winterstetter et al. (2018) accounted for avoided aftercare costs that would have occurred in a 'Do-Nothing' scenario for a duration of at least 30 years, as specified in the EU Landfill Directive, as well as for avoided greenhouse gas emissions monetized via a hypothetical carbon tax. Huber and Fellner (2018) also included the environmental impacts of the recycling options that they examined for MSWI fly ash via an extensive Life Cycle Assessment (LCA). After looking at the impacts on human health, ecosystem quality, resources and climate change, they monetized them in the evaluation via the social cost of carbon.

In this context it makes a difference whether the evaluation is conducted from the perspective of a public entity or private investors (Winterstetter et al. (2016a), Winterstetter et al. (2018), Huber and Fellner (2018)). A public entity is assumed to make decisions not only for their own profit, as is the case for a private investor, but on behalf of society overall. Therefore, environmental and social externalities are more likely to be included in the financial evaluation.

Challenges related to Utilization Options

A crucial point when planning for a resource recovery project is to consider potential outlets (utilization options) for the resources extracted.

Legal and regulatory barriers to marketability for recovered materials

In terms of legal and regulatory barriers which can constrain markets for recycled materials by imposing administrative burdens Huber and Fellner (2018) pointed out that even within Europe there are different national legal frameworks regarding the utilization of fly ash. And also Quina et al. (2018) stressed the importance of legislation and legal requirements for the use and marketability of materials recovered from anthropogenic sources.

Environmental, health and safety concerns of recovered materials

None of the reviewed case studies addressed the issue of the potential accumulation of hazardous substances in the cycle, which are not (yet) regulated by legislation.

Uncertainty with respect to a stable secured supply of anthropogenic materials

For potential markets it is important to have a constant and stable supply of materials, as addressed by Mueller et al. (2020).

Marketability

In most case studies, the quality of recovered anthropogenic resources and their marketability is insufficiently addressed. All the prospective studies reviewed rely on assumptions about the quality of recovered materials and the existence of markets. In some cases these assumptions are more justified as previous similar resource recovery activities exist and mature technology is applied. For instance, for WEEE recycling - at least for known waste flows such as PCs - the quality of recovered materials and components is typically known. For REE recovery from permanent magnets similar approaches as in the extraction of primary materials are assumed to work, as well as reuse for bigger magnets (Habib, 2019; Winterstetter et al., 2016a). The quality of materials and secondary products recovered from MSWI residues depends on the technology applied and its maturity (Huber and Fellner, 2018; Quina et al., 2018). With respect to markets for anthropogenic resources, Quina et al. (2018) highlighted the importance of existing local infrastructure, e.g., whether there are nearby metal smelters or a cement clinker plant.

The macro-level studies hardly touch upon the issue of the final marketability of recovered materials. In the studies on metal recovery, the quality of future resources is implicitly assumed based on past scrap recycling data (Maung et al., 2017a; Maung et al., 2019; Maung et al., 2017b). For the landfill-mining case studies, the marketability of extracted resources is assumed, as there are not many real-life projects with suitable data available (Johansson et al., 2017b). There is also not much knowledge on the quality of materials to be recovered from underground infrastructure, such as fiber optic cables, due to missing previous experience (Mueller et al., 2015). For the subway network in Vienna the quality of the recovered materials is assumed to be consistent with existing secondary raw materials markets, e.g., scrap metal prices (Lederer et al., 2016).

Negative perception of recovered materials
None of the reviewed studies addressed the issue of negative perceptions of the quality of recovered materials by potential end-users (whether or not such perceptions are correct).

Lack of comparability between anthropogenic vs natural materials
On commodity markets, anthropogenic resources have to compete with primary resources. Only Mueller et al. (2015) compared three anthropogenic REE sources and one natural deposit, finding that the anthropogenic deposits have a higher concentration of REE than the evaluated natural deposit, without, however, comparing the marketability of anthropogenic resources as compared to geogenic resources.

4.3 How anthropogenic resource classification can support the transition to a Circular Economy in the future

This chapter describes the gap between what has been done so far in the existing reviewed case studies, and what could be done in the future with respect to the currently un- or under-addressed challenges linked to anthropogenic resource recovery (cf Chapter 4.2 & 2) as well as the updated EU Action Plan for the Circular Economy.

With respect to the 12 challenges identified for anthropogenic resource recovery, five fields were identified where future case studies on resource classification could have a meaningful contribution:

1) Resource potential

Although a number of the reviewed case studies are investigating the resource potential contained in anthropogenic sources at regional or national level, none of them does it with the motivation to develop a comprehensive resource strategy that integrates both natural and anthropogenic resources by putting all resources on an equal footing.

Establishing integrated inventories of both available and accessible anthropogenic (re)sources and natural resources can be useful for strategic resource planning at (inter)national, regional and city level. Further, securing the local supply of critical raw materials for national key industries can be extended by including anthropogenic material stocks (Winterstetter, 2016). Similar to the mining industry, the role of governments and public authorities is crucial especially in the large scale prospection phase, when mapping and collecting sound data on resources, i.e. on the quantities, physical location, accessibility, temporal availability and quality. By gathering information on domestic anthropogenic resource deposits, hotspots for recovery can be identified and data and information provided to project developers in order to select promising resource recovery projects. For private business stakeholders, e.g. from the manufacturing industry, the information provided by governments and resource planning entities on the overall resource potential available in an economy is of use, for instance, to develop sustainable material sourcing strategies and mitigate supply risks (Heuss-Aßbichler et al., 2020).

2) Technical feasibility

While half of the reviewed case studies are exploring different options for technologies and project-set-ups, this is mainly done with the motivation to select the most suitable and cost-efficient alternative in the context of a specific project. In that case resource classification is used to compare scenarios with different technologies and how this impacts the project's overall environmental, social and economic viability.

However, resource classification and in particular UNFC with the additional axis ‘technical feasibility and maturity’ can be useful to assess resources for which extraction technologies are not yet existing, are immature, or mature but so far have been only applied in different fields / contexts. One step further, it could even support and accompany the development of new technologies via a continuous and iterative classification. This would help to guide research and innovation in a CE context (Winterstetter, 2016).

3) Legislation

Many of the reviewed case studies found that legislation is key and can either be an obstacle (as in the case of usage of MSWI residues) or act in favor of anthropogenic resource recovery by protecting public health and the environment (as in the case of the WEEE directive) or by making disposal alternatives less attractive.

Beyond the existing case studies resource classification could be used even more intensively to help policy makers understand the impacts of specific new laws and regulations to be introduced and to develop different scenarios with respect to setting the right framework conditions for anthropogenic resource recovery, e.g. by designing suitable legal and regulatory framework and / or by setting (financial) (dis)incentives (Heuss-Aßbichler et al., 2020).

4) Economic viability and social and environmental impacts

While almost all reviewed case studies addressed the economic viability of recovery projects, considerably fewer studies considered also environmental and social impacts. Those case studies with environmental considerations, mainly focus on avoided greenhouse gas emissions treating them subordinate to economic viability. Most of the reviewed studies did not address social aspects at all, and if, then only as a contingency of potential public resistance to a planned resource recovery project.

A systematic inclusion of social and environmental externalities would also be of interest for the primary mining sector. Currently existing classification systems for primary resources fail to fully integrate these aspects (UNECE, 2017). Only recently, there have been attempts to account for the environmental and social sustainability of mining projects in line with the Sustainable Development Goals.

The costs of recycling and recovering anthropogenic resources are often higher than that for mining natural resources, since externalities - both positive or negative - are not priced by commodity markets, allowing for the linear economy to be more profitable for many products and materials (Johansson et al., 2017a). Having a harmonized classification approach would help to bridge the gap between natural and anthropogenic resources and put them on a more equal footing.

Although the EU Action Plan for the Circular Economy stipulates circularity as a prerequisite for climate neutrality, it should be noted that the Action Plan has been initiated primarily by the EU Commission's Directorate-General Grow and has a clear focus on material savings, job creation and innovation and competitiveness potentials. Also social inclusion is mentioned prominently (European Commission, 2020). With respect to innovation and competitiveness resource classification can be useful to attract external funding to upscale new and innovative technology for resource recovery, e.g. by assessing new technologies for plastics recycling. This can be beneficial for both sides the technology developers, such as research institutes or private companies, but also funding entities, such as banks and investors.

5) Marketability

Most of the reviewed case studies do not address the final marketability of recovered anthropogenic resources.

This topic is, however, key for the success of anthropogenic resource recovery projects and also considered of paramount importance in the EU Action Plan for the Circular Economy. For recyclers, for instance, it is crucial to identify markets for their recovered materials. To compete with virgin raw materials it is key to decrease the costs of the supply chain, while increasing the revenues from selling recyclables (Brughmans, 2019). Resource classification offers the opportunity to show externally that a stable quantitative material supply is possible and at the same time qualitative requirements can be met, while internally it can facilitate decision making in collection, treatment and processing.

This can also help to change the sometimes bad reputation of anthropogenic resources as they are often perceived as inferior by consumers or producers, regardless of their actual quality. Moreover, improved communication along the value chain can also help to avoid the accumulation of hazardous substances in the cycle (Brughmans, 2019).

The European Commission’s CE program of action includes measures covering the whole cradle-to-cradle cycle from manufacturing, production and consumption to end-of-life management as well as the use of anthropogenic resources. Research and innovation are considered key in all stages.

The reviewed case studies mainly addressed the CE areas ‘end-of life management’, while ‘the use of secondary raw materials’ has not been covered extensively. The areas ‘manufacturing, production and consumption’ have only been touched upon in some of the studies’ discussion part. Thus, beyond the challenges related to anthropogenic resource recovery, there is still a big potential for resource classification to be explored in an even broader Circular Economy context.

Some case studies give recommendations on how to optimize upstream waste management operations and processes for enhanced resource recovery, some compare different Circular Economy options (reuse vs. recycling) and different utilization options for recovered anthropogenic resources (cf Table 2 & SI). Future resource classification case studies could look into these topics in even greater detail and for a wide range of anthropogenic material stocks and flows. Taking this one step further, resource classification can help to facilitate the communication between key stakeholders, e.g. between manufacturers and recyclers, by giving feedback and recommendations to design more circular products (Habib, 2019) and industry processes in the future (Huber and Fellner, 2018). Resource classification could show different scenarios for the recoverability of anthropogenic resources depending on different product and / or process designs. The design of products and upstream processes has an impact on the efforts for collecting and dismantling of products, selecting appropriate extraction technologies as well as on the environmental-socio-economic viability of resource recovery.

In the EU Action Plan for the Circular Economy Product design is considered an important element in shifting to alternative systems of consumption and production and will be also key to making progress on waste prevention (European Commission, 2020). The newly proposed sustainable product policy legislative initiative aims to widen the Ecodesign Directive to make it deliver on circularity. This includes, amongst other things, *“improving product durability, reusability, upgradability and reparability, addressing the presence of hazardous chemicals in products, and increasing their energy and resource efficiency”, increasing recycled content in products, while ensuring their performance and safety and enabling remanufacturing and high-quality recycling”.* So, resource classification could support recyclers to feed back valuable information to manufacturers on a product’s design for recycling and on the ease of collection. This can also be of use for manufacturers for the reporting of the sustainability of their products and, based on the feedback, they can make adjustments with respect to collection/ take-back schemes and / or on the design.

Product groups that have so far not been addressed in any resource classification study, but which are explicitly mentioned by the updated EU Action Plan for the Circular Economy (European Commission, 2020) include, e.g., batteries, textiles and high impact intermediary products such as steel and cement. Also, end-of-life vehicles as well as plastics, construction and buildings, food (waste) and nutrients have not been covered. Future case studies could, for example, focus on the plastics value chain, on reversible buildings, on new business models for batteries or on innovative P recycling technologies, to name just a few examples.

5. Conclusions & Outlook

Based on a review of selected case studies, this work aimed to find out how and for what purpose the classification of anthropogenic resources was done in the past and how it can support the transition to a wider Circular Economy in the future.

The review included case studies that classify resources recovered from old landfills, built infrastructure, national secondary metal stocks, electrical and electronic waste and waste incineration residues. Existing anthropogenic resource classification studies mainly addressed resource recovery from material stocks and waste flows. Half of the studies use the three dimensions of the UNFC; the other half rely on the two dimensions of the McKelvey diagram. Those using the McKelvey diagram tend to focus on investigating the resource potential, rather than focusing on the recoverability at the level of a defined project with specific technologies and project set-ups. The drivers of the reviewed case studies were mainly related to resource recovery, that is, to identify the resource potential at national / regional level and to investigate the recoverability of anthropogenic resources for different scenarios, e.g. for different technologies and project set-ups. In this context also different circular economy options (reuse vs. recycling) and different utilization options for recovered anthropogenic resources were compared. In addition, considerations on how to optimize waste management operations and processes, and product design for future resource recovery played a role, and how to internalize environmental externalities.

With respect to the 12 challenges identified for anthropogenic resource recovery, five areas have been identified where resource classification could have a meaningful contribution in the future**,** namely to 1) increase the knowledge on the anthropogenic resource potential for an integrated view on both anthropogenic and natural resources, 2) in supporting support research to develop new technologies and innovative recovery methods, 3) in supporting policy makers with designing new legislation, 4) to investigate the economic viability while including social and environmental externalities and 5) to improve the marketability of recovered materials.

For the transition to a Circular Economy, a standardized methodology for all types of anthropogenic resources is recommended, which considers individual resource recovery activities as part of a wider system, taking into account that the availability of resources does not solely depend on the material quantities and qualities, but also on the technical, operational, economic, social, environmental and regulatory conditions that enable or prevent recovery of these resources.

To achieve the transition to a circular economy there is a need to move towards alternative systems for consumption (e.g. sharing, reuse) and production (e.g. repair, remanufacturing) (European Commission, 2020). Resource classification can play a key role in communicating the availability, recoverability and utilization options of anthropogenic resources along the value chain. While past studies on resource classification mainly addressed the resource recovery from material stocks and waste flows, there is also a big potential role in the future, e.g. to optimize waste management operations, industry processes and products for enhanced resource recovery and recyclability and to compare different CE options (e.g. reuse, remanufacturing vs. recycling).

A standardized classification methodology including guidance on the detailed assessment will contribute to a harmonized collection of data and information, not only on the resource potential, but also on the recoverability and the utilization of anthropogenic resources. The classification should be performed by independent experts with a solid background regarding the anthropogenic commodity in question, similar to a ‘competent person’ (UNECE, 2020) as existing in the mining sector. This will be also relevant with respect to the European Commission’s plans to establish market observatories for key secondary materials, similar to the ones exising for key food commodities, allowing to better cope with market volatility and read market signals (European Commission, 2020).

Key CE stakeholders could in one way or another benefit from a standardized anthropogenic resource classification system. Resource-planning entities at macro level, such as governments or geological surveys, can benefit from harmonization to get a comprehensive overview of resources in an economy, mainly with respect to the overall resource potential, but also with respect to setting the right framework conditions for anthropogenic resource recovery. This is, however, only possible if “ground-level” entities and project developers follow a standardized approach to facilitate the systematic and transparent aggregation of individual recovery projects.(Heuss-Aßbichler et al., 2020). Finally, a harmonized and standardized classification approach would be also useful for all those CE stakeholders whose decisions on product design and upstream processes in the value chain can enhance resource recovery and even more importantly facilitate the utilization of anthropogenic resources at a later stage, namely manufacturers and the waste management sector.

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7. Abbreviations and Acronyms

Al: Aluminum
B: Boron
CE: Circular Economy
Cu: Copper
CRIRSCO: Committee for Mineral Reserves International Reporting Standards
DCF: Discounted Cash Flow analysis
Dy: Dysprosium
Fe: Ferrum
LCA: Life-cycle assessment
LFM: Landfill Mining
MFA: Material Flow Analysis
MSW: Municipal Solid Waste
MSWI: Municipal Solid Waste Incineration
Nd: Neodymium
NF-metals: Non-ferrous metals
NPV: Net Present Value
PC: Personal computer
Pr: Praseodymium
RDF: Refuse Derived Fuel
REE: Rare earth elements
SI: Supplementary Information
UNECE: United Nations Economic Commission for Europe
UNFC: United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources
USGS: United States Geological Survey
WEEE: Waste electrical and electronic equipment
Zn: Zinc

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