

Knowledge base to FACILITATE ANTHROPOGENIC RESOURCE ASSESSMENT



MINING the
EUROPEAN
ANTHROPOSPHERE



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- (1) <http://www.minea-network.eu/>,
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This table briefly documents the report revisions. The full history of report development, including the key milestones, dates and contributors, is given on page 69.

Version	Description
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2019-07-18/19	Revision of the 2019-06-11 document, based on the discussion during the WG4 meeting in Munich [Andrea, Jacob, Julia, Mohamed, Sandra, Soraya, Teresa]. Example for chapter 3.x was provided by Jacob (Residues from municipal solid waste incineration).
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2020-03-06	Soraya Heuss-Aßbichler added section 4 and Ulrich Kral revised the section.
2020-04-06	Proofreading of section 1 and 2 [Julia Stegemann]
2020-04-10	Final review and approval by authors.

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CONTENT

1 INTRODUCTION		5
	1.1	Context 5
	1.2	Aim 6
	1.3	Scope 7
2 CURRENT KNOWLEDGE, GAPS AND NEEDS		9
	2.1	Residues from extractive industries 9
	2.1.1	Introduction 9
	2.1.2	Characterization 13
	2.1.3	Evaluation 15
	2.1.4	Classification 18
	2.2	Residues in landfills 20
	2.2.1	Characterization 20
	2.2.2	Evaluation 21
	2.2.3	Classification 25
	2.3	Residues from municipal solid waste incineration 26
	2.3.1	Characterization 26
	2.3.2	Evaluation 27
	2.3.3	Classification 29
	2.4	Residues (C&D waste) from the built environment 29
	2.4.1	Introduction 29
	2.4.2	Characterization 31
	2.4.3	Evaluation 33
	2.4.4	Classification 37
3 CASE STUDIES		39
	3.1	Residues from extractive industries 39
	3.2	Residues from landfills 42
	3.2.1	Case studies 1 to 4 42
	3.2.2	Case study 5 42
	3.3	Residues from municipal solid waste incineration 43
	3.3.1	Case study 1 43
	3.3.2	Case study 2 43
	3.3.3	Case study 3 43
	3.4	Residues (C&D waste) from buildings and infrastructure 43
	3.4.1	Case study 1 43
	3.4.2	Case study 2 44
	3.4.3	Case study 3 44
	3.4.4	Case study 4 45
	3.5	Case studies - Synthesis 45
	3.5.1	Review (details) 45
	3.5.2	Review (summary) 48
4 CONCLUSIONS AND OUTLOOK		50
ANNEXES		53
		Annex A: Case studies from extractive industries 54
		Annex B: Compilation of knowledge base across WGs 61
		Annex C: History of the report's development 69
LITERATURE		70

1 INTRODUCTION

1.1 Context

Non-energy mineral resources such as iron and ferro-alloy metals, non-ferrous metals, precious metals, industrial minerals and construction materials are essential for industrial production, the prosperity of nations and modern living standards. The scarcity, i.e. limited availability, of these commodities can be seen from two perspectives [1]. From a raw materials demand perspective, resource criticality is a prominent concept widely used to raise awareness of the vulnerability of its uninterrupted supply and is important for the development of raw material sourcing strategies [2]. From a raw materials supply perspective, estimates of the future mineability of resources are used for resource management. Both perspectives are relevant to the setting of raw materials policy [3-5].

Resource availability is fundamental for industrial production, prosperity of nations and modern living standards.

The traditional mining sector uses resource assessment and classification to estimate the mineability of natural resources. The focus of the assessment is on determining the quantity and quality of raw materials at a particular site, taking local conditions, technical feasibility and economic viability for the market, compliance with legal requirements as well as environmental and social acceptability into consideration. *Classification* involves categorizing resource quantities based on commonly agreed upon principles, terms and definitions with regard to their readiness for raw material

The mining sector estimates and communicates the future mineability of resources for project development, investment decisions and policy setting.

markets. The results of classification are communicated to investors, authorities and corporate management boards in a standardized manner, at least on a country level. This standardization is imperative for comparison of the mineability of a specific deposit over time or across different deposits. Comparability is needed to make substantial decisions about future mining investments, for managing mining project

portfolios and to help businesses and government in developing raw material sourcing strategies, as well as for better planning on the local, regional, national and transnational levels. The reliability of estimates is fundamental for building trust and acceptance among all stakeholders. Therefore, in addition to standardized classification tools, authorities and associations have developed quality assurance systems to certify experts who are qualified to reliably assess future resource capacities through education, training and experience.

The recycling sector also requires estimates of recoverable anthropogenic resources. For this reason, various assessment tools have been developed, but a generally accepted classification for communicating the future availability of raw materials from anthropogenic sources is still missing. To overcome this gap, several actions have taken place in recent years. From 2008 onwards, individual researchers have used existing classification tools commonly used in the mining sector, and adapted and applied them to anthropogenic resources through a set of case studies on recovery potentials [6-18]. In 2015, the EU funded project *Minventory* worked on EU raw material statistics and reporting for resources and reserves [19]. The project scope included natural deposits as well as anthropogenic resources stockpiled in mine tailings, landfills and in-use stocks¹. A follow up undertaking included the EU-funded *Minerals4EU* project, which developed a European mineral information network structure [20], as well as the *Mintel4EU* project [21], which presented estimates on future resource availability.

In contrast to the mining sector, the recycling sector lacks standardized estimation and reporting of the (future) recoverability of anthropogenic resources.

¹In-use stock includes resource quantities in the use phase, such as in buildings, infrastructure and consumer goods.

In 2016, the pan-European expert network MINEA assembled eminent scholars from different disciplines across Europe to compile existing knowledge in the field of anthropogenic resource assessment. MINEA Network's mission was to initiate a process for obtaining comparable, reliable and transparent estimates of the future recoverability of anthropogenic resources. As such, it has compiled existing knowledge and built a consensus about the process required among the scholars involved. With respect to a standardized classification of anthropogenic resources, the UNECE Expert Group on Resource Management appointed a team to develop "Specifications to apply the United Nations Framework Classification (UNFC) to Anthropogenic Resources" [22], which were endorsed in 2018 [23].

MINEA Network's mission is to initiate a process to obtain comparable, reliable and transparent estimates on the future recoverability of anthropogenic resources in Europe and beyond.

This report provides knowledge for anthropogenic resource assessment.

The UNFC provides terminology, definitions and principles for aggregation and communication of assessment results, but it does not give any guidance on data collection or methods for resource assessment. Evidence-based resource assessment, including the selection of parameters for characterising resources and methods for assessing their recoverability, is essential to obtain comparable estimates over time and across scales. Within this report, the MINEA network presents a practical and user-friendly knowledge base for facilitating anthropogenic resource assessments.

1.2 Aim

The aim of this report is to provide a knowledge base that facilitates anthropogenic resource assessment. The key objectives are:

- (1) To relate current knowledge levels, gaps and future needs to assessments of viability of anthropogenic resource recovery.
- (2) To review case studies that demonstrate anthropogenic resource assessment in combination with resource classification in order to communicate the viability of anthropogenic resource recovery.

We encourage academics, businesses and government organisations to use this report for: designing and developing case studies, future planning, developing standards for characterizing resource quantities and evaluating their recoverability, and collecting and harmonizing resource statistics. Beyond this report, we see the need for further activities such as the development of quality assurance systems, including the harmonization and certification of the assessment and classification procedures, and a system for expert certification to undertake anthropogenic resource assessments and classifications. The further activities are described in detail by Heuss-Abichler *et al.* [24].

1.3 Scope

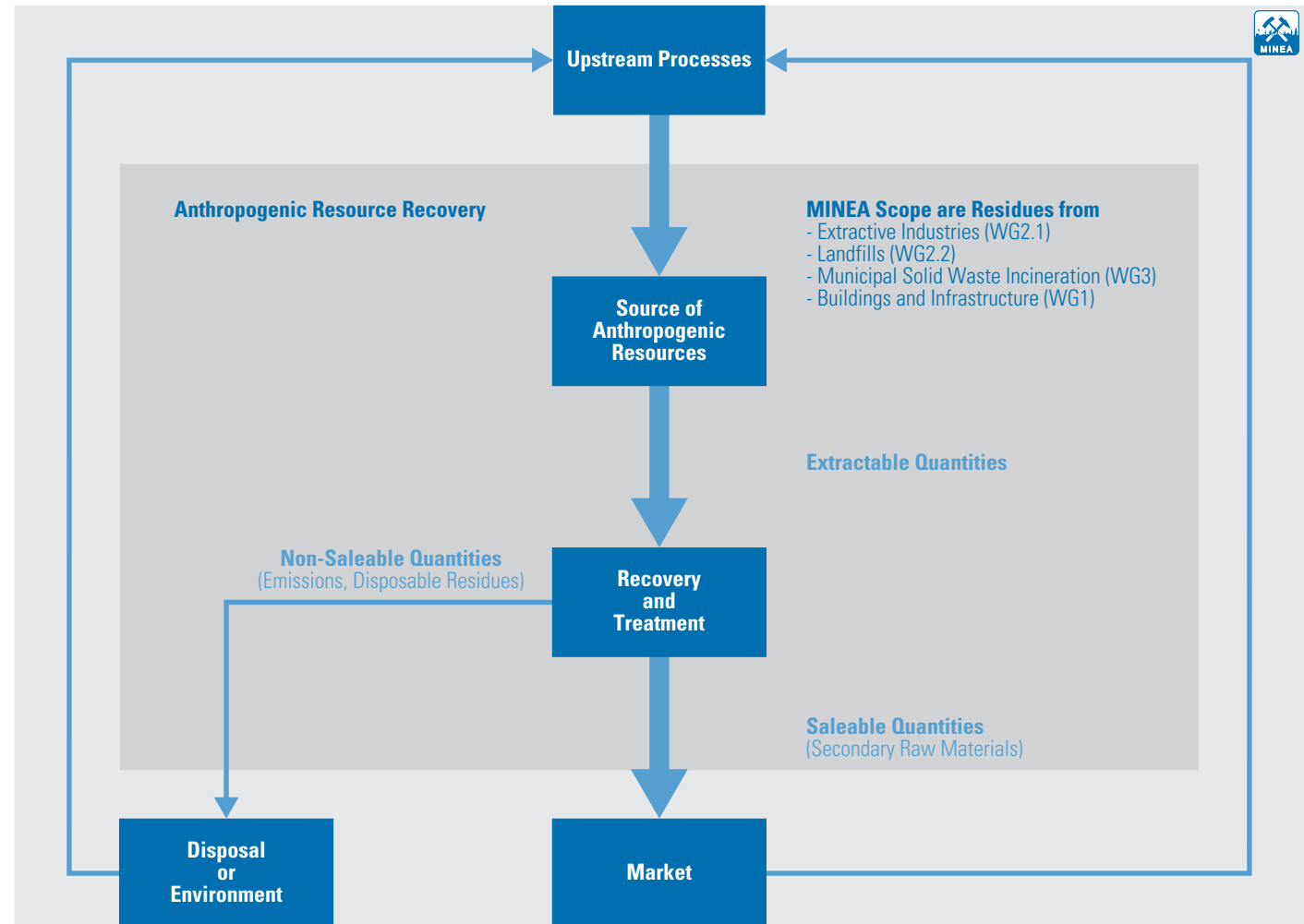
The knowledge base is aligned with the four MINEA Working Groups, each focusing on resource recovery from a specific anthropogenic source (FIGURE 1). It should be noted that the terms *anthropogenic source*, *waste* and *residue* are effectively synonymous in this report, and each may be used according to the convention for the given sector.

FIGURE 1
Scope of the report.



A common denominator across all MINEA Working Groups is the material flow perspective for anthropogenic resource recovery. As shown in **FIGURE 2**, resource recovery starts with the “source of anthropogenic resources”. It is noted that the material quantities at the source are static for old waste in landfills and extractive industry deposits (MINEA WG 2.1 and 2.2) but change over time for construction and demolition (C&D) waste and residues from municipal solid waste incineration (MSWI) (MINEA WG1 and WG 3). Next, during “treatment and recovery”, valuable materials are extracted from the source and converted into saleable and non-saleable quantities. In fact, “anthropogenic resource recovery” is driven by the contextual boundary conditions such as institutional setting, costs and benefits, market and social acceptance, environmental impacts and legal compliance. This report addresses many of the individual factors that affect the viability of anthropogenic resource recovery.

FIGURE 2
 Recovery of anthropogenic resources in a material flow perspective.



2 CURRENT KNOWLEDGE, GAPS AND NEEDS

Anthropogenic resource assessment is used to estimate the viability of resource recovery from by-products, wastes and residues. Existing case studies apply different concepts and terminologies to define the methodological steps of resource assessment [24]. Despite the differences, we looked for a unifying concept for use by each Working group to structure the current knowledge, gaps and needs in this report. We discussed the generic concept during MINEA Workshops [25, 26] and concluded that anthropogenic resource assessment can be divided into the two steps “characterization” and “evaluation”, which are then combined with the third step “classification”:

- (1) Characterization of materials at the source (quantity, quality, location).
- (2) Evaluation of material recoverability under defined boundary conditions.
- (3) Classification of the material quantities in analogy to natural resource classification.

The following sections address material quantities in the anthropogenic sources that were the focus of the MINEA Working Groups, and make use of the three steps (characterization, evaluation and classification) to map the current knowledge, gaps and needs to assess the material quantities available from these sources. It is noted that each subsection finishes with a table that gives a comprehensive overview of current knowledge, gaps and needs. All the tables are merged in the Annex B: Compilation of knowledge base across WGs.

2.1 Residues from extractive industries

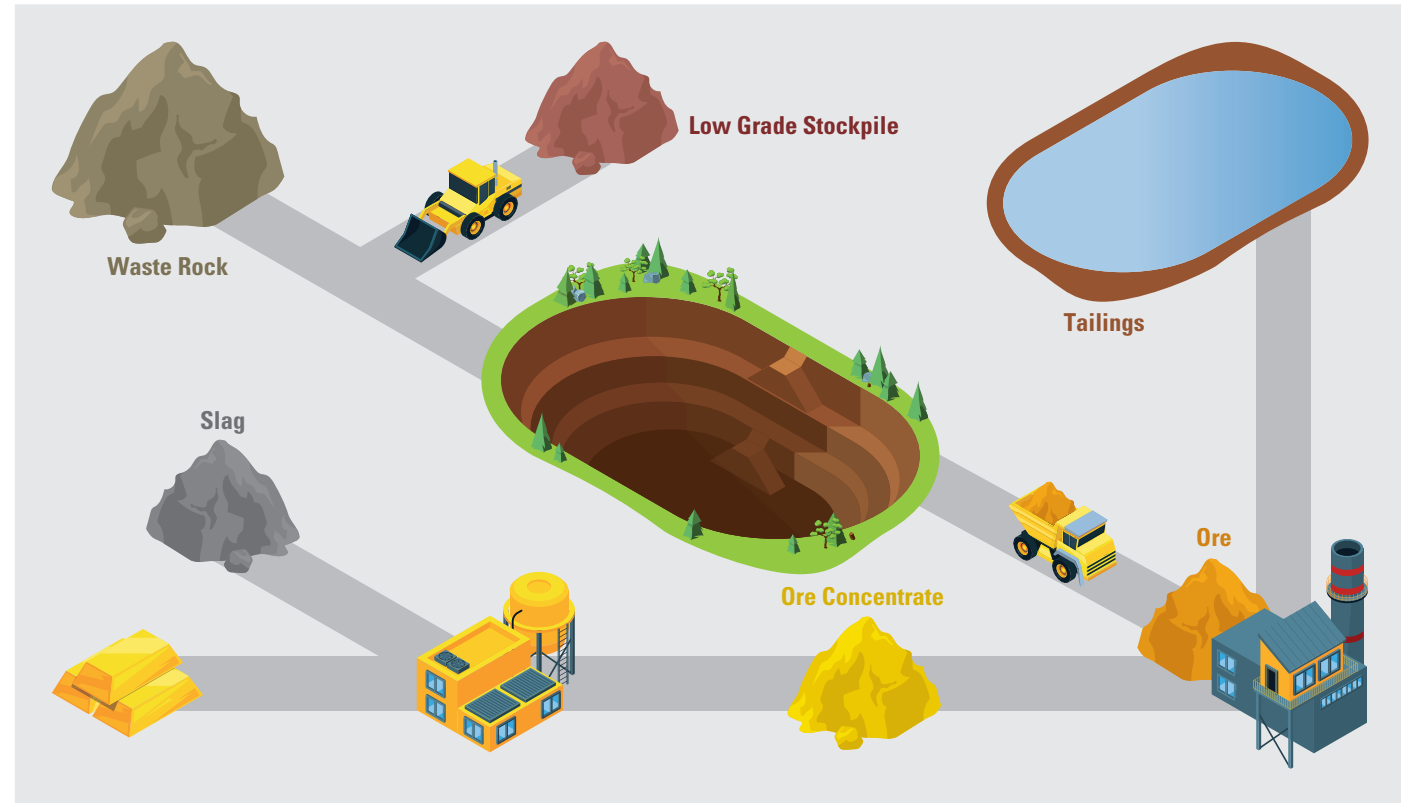
2.1.1 Introduction

Extractive industry wastes/residues (subsequently referred to as “mining/metallurgical residue”) are the non-valuable materials resulting from the exploration, mining and processing of mineralized rocks when subject to any modification other than crushing (yielding ordinary mining waste, which is simply unusable mineral materials) or processed to varying degrees during the ore-processing and hydrometallurgical or pyrometallurgical enrichment phases (thus often containing chemical, inorganic and organic additives). These residues include waste rock, low-grade stockpiles, tailings, slags, etc., as shown in [FIGURE 3](#). Previously discarded, they may now be of economic interest due to:

- technological innovations in mineral processing that allow for the production of raw materials from lower grade materials;
- the development of innovative construction materials whose production is based upon mining/metallurgical residues;
- the increasing demand for a variety of new (and usually critical) raw materials used in electronic devices, electric vehicles, the renewable energy sector, etc.



FIGURE 3
A simplified material flow chart
in extractive industries and
associated wastes and residues.
Picture adapted from [27]



During the last 10 years, many projects have addressed the creation of a knowledge base for raw materials, including both natural and anthropogenic resources [28], all of them highlighting the lack of information in relation to the classification of mining/metallurgical residues.

In spite of the presence of high-grade minerals in mining/metallurgical residues [29, 30], very little is known about these anthropogenic deposits, apart from environmental and safety-related information required as part of existing regulatory frameworks², as they have been considered to be unwanted waste.

Most of the mining/metallurgical residue treatment plants currently operating worldwide produce the same commodities originally extracted by the mine (thus leaving in place other valuable minerals), mainly due to the localized knowledge of processing plant efficiency and monitoring activities (mass balances, sampling, chemical and mineralogical analysis, etc.), which provides the information required to assess mineability.

Residues from extractive industries

²Zibret, Lemière, Mendez, Cormio, Sinnett, Cleall, Szabo and Carvalho National mineral waste databases as an information source for assessing material recovery potential from mine waste, tailings and metallurgical waste. Manuscript submitted to Minerals, MDPI.

Nonetheless, demand for commodities changes over time and minerals associated with those originally extracted could become of interest. However, often nothing or very little is known about their content in mining/metallurgical residues. Several drivers may be considered to foster mining and metallurgical residue characterization and further evaluation and classification, such as:

- mandatory remediation operations due to impacts on environmental and human health (whereby residue mining and reprocessing partly covers remediation costs) [32, 33];
- land value (whereby the economic viability of residue mining may increase due to land recovery for further uses) [34].
- inaccessibility of geogenic deposits, whether because they are in areas unfavourable for humans to work (i.e., ultra-deep deposits, under the sea, etc.) or where current land use prevents mining (whereby residue mining is a cost-effective alternative raw materials sourcing).

However, assessment of the feasibility of each of these options requires specific information. With this in mind, and using an approach similar to that presented in Panagiotopoulou et al. [35], MINEA WG 2.1 defined a list of “key factors” which should be known to enable assessment of the recoverability of mining/metallurgical residues. These factors can be divided into the following three groups:

- ‘basic’ information related to the mining/metallurgical residue deposit (location, type of material, data collection methods, history of mine, etc.) as well as the main drivers and barriers for resource recovery (e.g., legislation, land use restrictions, data availability, etc.);
- ‘mineral-centric’ information about crucial properties of mining/metallurgical residues that should be considered in relation to the potential for further extraction of valuable minerals/metals. The chemical and mineralogical composition of the tailings determines the potential metallurgical or chemical extraction process, while the physico-chemical properties influence the pre-processing activities (drying, grinding, additives, homogenisation, separation, etc.) needed before commodity extraction;
- ‘material-centric’ information required to assess the feasibility of using mining/metallurgical residues for new materials (e.g., concrete, geopolymers and other construction materials). The residue elemental and mineral composition determines its ability to react as a binder or form clinker minerals during the production process, as well as whether other specific additives are needed. Physico-chemical properties allow us to estimate the equipment needed to pre-process source material (grinding, separation, screening etc.) for desired end-products.

The basic factors are relevant for system definition and resource evaluation, while the mineral-centric and material-centric factors enable characterization according to the project goals (e.g., remediation, land recovery, minerals supply, production of new materials).

Residues from extractive industries

TABLE 1 maps the 3 groups of factors with the corresponding assessment stages.

TABLE 1
Mining/metallurgical residues
key factors for assessment stages.

Assessment stage	Factors	Basic	Mineral centric	Material centric	
Characterization	Location, history, mining and processing technology of the site	X			
	Volume, area and structure of the existing tailings	X			
	Reason for which the mine was abandoned	X			
	Homogeneity of the tailings	X			
	Methodology of data collection	X			
	Chemical and mineralogical composition	Matrix (bulk elements)		X	
		Commodity elements		X	
		Trace elements		X	
		Type and content of alkali ions			X
		Type and content of alkaline earth ions			X
		Type and content of silica			X
		Type and content of potentially toxic elements			X
		Type and content of organic substances			X
	Physico-chemical properties	Moisture content		X	X
		Grain size distribution		X	X
		Redox state at different pH values		X	
		Mechanical properties			X
Thermal properties				X	
Evaluation	Environmental impacts of mine waste deposit	Current physical impacts	X		
		Potential physical impacts	X		
		Current chemical impacts	X		
		Potential chemical impacts	X		
		Need for remediation	X		
		Remediation costs	X		
	Land availability to reallocate processed waste to a new facility	X			
	Legislative barriers for resource recovery from mine waste	Ownership	X		
		Special permits required	X		
		Land use restrictions	X		
		Other legislative barriers	X		
	Data availability	Data managing authority	X		
		Language(s)	X		

Residues from extractive industries

The present report is based on information gathered in:

- Mining waste deposit inventories (created due to the EU Directive 2006/21/EC);
- Mining site cadastres/inventories, which mainly provide “basic” factors data and collected from 66 case studies (at the end of March 2020, [TABLE 15](#)) included in:
- Technical reports for investors, in accordance with CRIRSCO / UNFC standards;
- Reports and databases of research projects dealing with the production of raw materials from mining/metallurgical residues;
- Reports from international organizations and research centers;
- Scientific papers published in international journals;
- Academic theses.

The case studies reviewed cover the whole knowledge chain, from assessment to evaluation and classification, as well as industrial applications. Nevertheless, most of the studies are aimed at characterisation of the environmental impacts of mining/metallurgical residues, and only a few are focused on resources. They include a wide variety of metals (Co, Cu, F, Fe, Li, Zn, W), minerals (bauxite, dolomite, quartzite, salt), steel slags and red muds. Four case studies deal with the recoverability of materials for use in the construction sector (e.g., geopolymers). Few examples of industrial case studies were found. A first case of an industrial application of biohydrometallurgy and a case of fresh tailings processing were analysed. Socio-political acceptance was addressed only in three case studies. This is an important gap since public opposition, and even community violence, has been experienced at several sites.

2.1.2 Characterization

This chapter presents the current knowledge, knowledge gaps and needs identified by MINEA WG 2.1 for appropriate characterization of mining/metallurgical residues, with the primary intention of evaluating the potential for material recovery, as summarized in [TABLE 2](#).

Little is generally known about the physical and chemical characteristics of mining/metallurgical residues, mainly in older deposits. This is particularly true for their composition and homogeneity below the surface and for the effects of any secondary processes following deposition. The lack of reliable data about these deposits, combined with the ambiguity in many countries regarding which legislation takes precedence for resource recovery from mining/metallurgical residue deposits (i.e., mineral extraction, waste management, environmental protection, etc.) seems to present a barrier to their large-scale reuse [31]. To examine the potential for resource recovery from mining/metallurgical residues, it is therefore essential that a detailed understanding of the composition and properties of these residues be developed.

a) Current knowledge

One potential source of the composition data and properties of mining/metallurgical residues is the inventory of mining waste deposits, produced by each EU member state under EU Directive 2006/21/EC. The main objective of this Directive was to map these deposits and to assess risks and potential impacts associated with various environmental parameters (e.g., concentrations of potentially toxic elements, results of leaching tests, sediment mobilization, etc.), aiming to identify those in most urgent need of remediation. The determination of the potential for future resource utilization was of minor interest³.

MINEA WG 2.1 analyzed the inventories of seven Member States (France, Hungary, Italy, Portugal, Slovenia, Spain, UK). Mining residue deposits were generally classified as low or high risk, depending on their potential to release harmful substances. Higher risk sites were then assessed in more detail and, as a result, more data are available for these sites. This approach was taken by the majority of countries.

³ibid.

Residues from extractive industries

b) Gaps

With regard to the recovery of valuable minerals / materials, the national mining waste inventories under EU Directive 2006/21/EC are an incomplete and inconsistent data source because of their focus on environmental parameters. This is especially the case in France, Hungary and the UK, but the information collected varies considerably from country to country. The most useful information contained in the inventories for this purpose is the location of the deposit, the general description of the material, usually focused on the main commodity of original interest, and the estimated quantity of such material (e.g., tailings deposit volume). Among the countries considered by WG 2.1, it is apparent that only Italy and Spain have detailed information regarding all listed mining sites in the inventory.

Some 'mineral-centric' and 'material-centric' key factors are generally available for larger and high-risk sites, but limited to potentially toxic elements. Moreover, the mining residue deposits can be very heterogeneous, depending on the history of ore extraction and processing as well as the occurrence of alteration processes in the waste column, while the information of potentially toxic element levels are generally available only from surface sampling [36]. This also limits the usefulness of mining waste registries as a source of information for metal extraction beyond the provision of basic brief information to plan more detailed investigations. Moreover, national mining waste registries generally do not contain information about metals that are not classified as potentially toxic elements, but are regarded as critical elements today (e.g., Li, Ge or rare earth elements).

Even less information is available for the 'material-centric' key parameters. Except for a few cases (e.g., the Italian inventory), information such as the content of alkali ions, redox potential, silicon, organic substance etc. has not been assessed at all.

While reviewing specific datasets from the national registries, it also became evident that different countries have different data access policies. Although the majority of countries provide information about locations of mining residue deposits and basic characteristics, it is still very hard to access detailed reports that contain the information needed for the potential assessment of resource recovery from mining residues. Even if such reports are publicly available, they cannot be found in one place, but are generally scattered across different locations (i.e., web pages, libraries etc.). Another barrier for the use of the mining waste registries as a source of information for potential stakeholders is language as the information and reports are, with the exception of Hungary, provided only in the national language.

b) Needs

In most cases, national mining waste registries do not provide sufficient data to assess projects for minerals / materials recovery from mining residues.

As a consequence, it is recommended to use the national mining waste registries to obtain general information (location, volume, pollutants, etc.) about existing anthropogenic deposits, and then to consult other sources (mining / industrial activity registries from Geological Surveys, regional or local authorities, historical archives, etc.) to gather relevant information for minerals / materials recoverability assessment, including homogeneity, grain size distribution or content of substances that are not regarded as pollutants but are important for the assessment of potential future recovery of resources (see [TABLE 1](#)). Nevertheless, it is apparent that gathering information from different sources, e.g., chemistry from environmental impact studies and tonnage from national registries, may not be consistent for grade mapping or resource estimates, and requires a good knowledge of each site. In many cases, additional characterization is needed for confident evaluation and classification of a project.

Residues from extractive industries

TABLE 2
Characterization knowledge
for residues from extractive
industries.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> National mining waste inventories with environmental parameters (e.g., potentially toxic elements). 	<ul style="list-style-type: none"> Information in national mining waste inventories (e.g., critical elements occurrence and grade, contents in alkali ions, silicon, organic substances, etc.) useful to assess the potential for minerals and materials recovery. Harmonization of information in European countries. 	<ul style="list-style-type: none"> Access to organized and detailed reports with information needed for mineral and materials recovery. National inventory information in English.

2.1.3 Evaluation

Most of the available information for resource evaluation, beyond national inventories, comes from technical reports (usually according to CRIRSCO and UNFC standards) and from research project reports. In Europe, information typically comes from project reports, Master or PhD theses, studies and reports from research institutions (such as the French Bureau de Recherches Géologiques et Minières and the European Joint Research Centre).

In the following, we list and describe factors that affect the viability of resource recovery:

Legal accessibility to the source

Local policies and regulations pertaining to resource recovery from mining/metallurgical residues are almost completely disregarded in the national inventories. A very important aspect in raw materials recovery assessment is the ownership of the tailings (e.g., state, county, municipality, private entity, etc.) as well as the indication of key legislation and policy which regulates mining/metallurgical residues exploitation and processing (i.e., mining legislation, spatial planning on national and local level, environmental protection, waste management, etc.).

National inventories usually allow the identification of ownership of residues deposits, but it is not always possible to obtain legal access due to safety or environmental restrictions.

Although sometimes conflicting, the information about existing policies and regulations are accessible and can be considered in the evaluation phase. It is, therefore, necessary to harmonize policies and regulations at national and EU level.

Technical recoverability

As mineral processing and metallurgical technology in the past were not as efficient as they are today, what was regarded as waste in the past can often be regarded as quality ore today. For example, Mudd [37] reported that the average grade of mined Cu ore in Australia was 15-25% from 1842 to 1880, then gradually decreased to around 4% between 1880 and 1940, dropping to around 2% by 2008, while during this time, the production of Cu ore and waste rock were steadily increasing. The largest Cu open pit mines can economically extract Cu ores with grade below 1%. A similar pattern is also observed for Au. In Australia ore with 15-30 g/t Au were extracted during 1850 to 1910, dropping to around 15 g/t during 1910 to 1940, and steadily decreasing to 1-2 g/t in 2008 [37].

Very efficient minerallurgical, pyrometallurgical and hydrometallurgical processes have been developed for the recovery of metals from low-grade ores and mining wastes in the last two decades [38-42].

Residues from extractive industries

Some recovery techniques, which facilitate or allow subsequent exploitation, were classified as either i) indirect material recovery through decontamination, ii) indirect material recovery through changing the physicochemical nature of the residues and iii) indirect land recovery [41].

One method of particular interest is the application of electrokinetic techniques, which have potential applicability to the fine-grained materials often found in extractive industry residues. This type of 16 / 91 approach has the potential to convert waste materials into assets by transforming them into viable ore deposits [43].

Infrastructure

General purpose databases/maps allow for easy gathering of information about transport infrastructures and the energy & water supply network. However, the information provided is usually incomplete for mining sites in remote areas where local infrastructures have not been mapped. Moreover, in situ surveys may be needed at closed or abandoned mining sites to verify whether the existing infrastructures are still working.

Environmental impact

Environmental impacts from mining/metallurgical residues are associated with site location (proximity to urban, protected or culturally relevant areas), land use, emissions of dusts and leachates, and bursts and collapses of tailings and/or waste-rock management facilities, which can cause severe environmental damage and even loss of human life [44]. As a consequence of large environmental disasters from a number of abandoned and active mine tailings, such as the Aznalcollar tailings dam collapse [45] or the Baia Mare cyanide spill [46], the EU adopted the 'Mining Waste Directive' (2006/21/EC) [47]. This Directive obliged every EU country to produce a database of mining waste deposits in their countries.

These deposits are usually located next to historic mines where the natural environment has undergone many changes in the past and could act as a potential source for future dispersion of pollutants into the environment. Therefore, there may be an advantage to combining resource recovery from mining/metallurgical residues deposits with site rehabilitation processes. This has also been recognized by the EU, which funded several projects dealing with material recovery from mining/metallurgical residues, such as the Horizon 2020 programs like Smart Ground [48], NEMO [49] and Remediate projects or the EIT Raw Material network RIS-RECOVER [50], RIS-CuRE projects [51], or the Interreg project REGENERATIS [52].

Legal compliance

Currently, it seems that many relevant regulations apply, including those related to mineral extraction, waste management, land use planning and environmental protection, and practices are not harmonized. For example, it is not always clear whether any resource recovery would be regarded as mineral extraction, waste management or remediation, all of which have different regulatory regimes in place. Therefore, it is rarely clear which stakeholders would need to be consulted to examine the potential of resource recovery, and many different regulations could apply, making the permit process less transparent and potentially much more costly and protracted.

Economic feasibility

There is not much data available on the economics of mining/metallurgical residue recycling. Two models are generally accepted. One assumes that residue deposits constitute no danger to the environment and that they do not need to be remediated in the future. This type of economic feasibility model usually includes calculations of OPEX and CAPEX costs as compared to revenues. Experience from different projects around the world show that in such cases the economic profitability is marginal or lacking entirely. This is mostly due to the fact that mining/metallurgical residue

Residues from extractive industries

deposits may be very heterogeneous, and a lot of unwanted substances are generally present, requiring the material to be pre-processed, sorted and/or homogenized. Mining residues also compete with other industrial wastes (i.e., slags from steel plants, ashes from the energy and paper industry, red muds from alumina processing, etc.) which are usually more homogeneous in composition, making the whole raw material recovery process more economically and technically sound.

On the other hand, the economic viability of material/mineral recovery from mining/metallurgical residues can be improved if the deposit has not been properly rehabilitated and if it poses no dangers of negative impacts to the environment in its current state. In this case, costs for re-cultivation can be deducted from OPEX and CAPEX costs, thus improving the project's economic viability.

Socio-political acceptance

Public acceptance of mining is nowadays acknowledged as important and addressed by means of the Social License to Operate, the acquisition of which remains a challenge in many EU regions. The STRADE project (Strategic Dialogue on Sustainable Raw Materials for Europe) has examined successful concepts to address the 'not-in-my-backyard' mentality. To facilitate this process, STRADE recommends that the EU create awareness campaigns for its citizens and Members of European Parliament, with a particular focus on the high EU standards and directives under which domestic mining takes place [53].

These considerations have previously been expressed for primary raw materials production and are valid for secondary raw materials. Although mining/metallurgical residues are already negatively perceived by the population, recovery projects must carefully address local environmental impact and facilitate communication with local communities to highlight the positive effects of such interventions on the environment in order to prevent "NIMBY" (Not In My Backyard) or "BANANA" (Build Absolutely Nothing Anywhere Near Anything) syndromes.

Market acceptance

Today, almost every naturally-occurring element in the periodic table is needed in order to produce all types of goods used by society [54]. This means that many elements needed to produce new technologies, electronic devices, green technologies, etc., were completely disregarded even 50-60 years ago and were deposited as mining waste (Fig. 1). Prime examples are semiconductors (e.g. Ge and Ga), Rare Earth Elements (e.g. Ce, Nd, Eu, Er, Lu) or so-called energy elements, needed for batteries (Co, Li) [55].

Market acceptance mostly depends on the quality of the product, which must be considered when assessing the economic feasibility.

Another important aspect of market acceptance involves a mentality shift. Current "cultural resistance" of the market means that the price of recycled products must be approx. 20% lower than the price of materials produced from natural sources in order to successfully compete on the market. This is the case, for example, for aggregates [56]. It has been stated that a public perception shift must occur from the origin (source) of the materials towards its technical characteristics, and green public procurement might provide a required boost towards higher social acceptance [57].

Residues from extractive industries

TABLE 3
Knowledge for evaluating
resources in extractive industries.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> • Knowledge available in technical and research reports. • Information regarding policies and regulations are accessible (Although sometimes conflicting). • Residue deposit ownership available. 	<ul style="list-style-type: none"> • Databases and maps (e. g. transport, energy and water supply) in remote areas. • Partial or missing information (mainly with regard to the socio-political acceptance, but also in terms of environmental impact, market acceptance, technical recoverability, infrastructure, legal compliance, legal accessibility to the source and economic feasibility). 	<ul style="list-style-type: none"> • Harmonization of policies and regulations at National and EU level.

2.1.4 Classification

Current knowledge

Specifications for mining/metallurgical residue classification already exist as many of the reporting standards already consider dumps and tailings as “mineral resources”. For instance, the Pan-European Resource and Reserve Reporting Committee Public Reporting Standard (PERC) applies to the reporting of mineralized fill, remnants, pillars, low grade mineralization, stockpiles, dumps and tailings (remnant materials) where there are reasonable prospects for eventual economic extraction in the case of “Mineral Resources”, and where extraction is reasonably justifiable in the case of “Mineral Reserves”.

While CRIRSCO standards (such as PERC) aim at providing reliable, transparent information for investors and potential investors (each standard providing specifications for the Stock Exchange of reference), the purpose of the UNFC is to create a reliable mineral inventory which can be used to underpin mineral policies (especially cross border, e.g. Europe) and be made available to exploration and mining companies wishing to attract inward investment and exploration activity.

All standards address the same users (Mining Companies, Financial Institutions, Stock Exchange Regulators, Governments, Shareholders) and provide specifications to quantify, qualify and categorize mineral assets (Exploration results, Mineral Resources or Mineral Reserves) on the basis of data, models and criteria.

Thanks to the common terminology agreed upon by CRIRSCO and UN, a project’s classification may be easily mapped from one standard to another (CRIRSCO to UNFC, and vice versa). Nonetheless, CRIRSCO reporting does not consider (while UNFC does) “non-sales production” (production which is unused or consumed in operations, as defined by UNFC), and thus does not address the needs of resource managers and policy makers.

UNFC provides a method for governments and NGOs to incorporate published industry data (using the CRIRSCO classification) into databases, mineral inventories, etc.

In September 2018, with the contribution of MINEA WG 4, the UNECE Sustainable Energy Committee endorsed the “Specifications for the application of the United Nations Framework Classification for Resources to Anthropogenic Resources” [23], which notes that:

Residues from extractive industries

- non-technical and external factors are of key importance for classifying Anthropogenic Resources. For instance, the quantities of Anthropogenic Material Products are limited by social, legislative and environmental factors that go beyond economic ones;
- current market conditions and realistic assumptions regarding future market conditions should include favorable and adverse policy support mechanisms for anthropogenic material sourcing Projects, but should not assume that such mechanisms will become more beneficial in the future unless already specified in the regulation;
- in the case of Anthropogenic Resources, the G-axis (labelled “Geological knowledge”) is “the level of confidence in the potential recoverability of the quantities”. It expresses the level of confidence in the understanding of the Anthropogenic Material characteristics and potential for exploitation of the quantities.

Resource characterization through investigation (remote sensing, geophysics, drilling, sampling, etc.), which is mandatory for any Public Reporting Standard at any project development stage, is the starting point for scoping, pre-feasibility or feasibility studies concerning the mineability of mining and metallurgical residues.

As long as the characterization of residues is weak or missing, these will be classified as undiscovered, unrecoverable or uneconomic.

Knowledge gaps

Although mineral resources classification and reporting standards exist and can be used for mining/metallurgical residues, the lack of information for characterization and evaluation makes classification unfeasible from an “inventory creation perspective”.

Moreover, existing standards (apart from UNFC) do not take all relevant evaluation factors appropriately into account. Social aspects are neglected or poorly addressed and compliance with existing regulations must be fulfilled (although not explicitly reported).

In April 2018, the “Task Force on Environmental and Social Considerations”, established by the “UNECE Expert Group on Resource Classification” to redefine the E - axis label (socio-economic viability), provided guidance on accommodating economic, environmental and social considerations in UNFC [58]. In 2020, the Expert Group of Resource Management released a draft UNFC 2019 update. In this update, the E-Axis is now called “environmental-socio-economic viability” [5]

Needs

There’s no or little evidence of mining/metallurgical residue resources/reserves estimates according to PERC or UNFC, meaning that specific policies and strategies must be implemented to foster the creation of a comprehensive inventory of the available secondary raw materials resources in the EU.

CRIRSCO should include reporting of “non-sales production” quantities to allow a comprehensive mapping and bridging to UNFC.

Although UNFC includes the “non-sales production” quantities, the products should also be specified in order to create a comprehensive inventory that allows long-term resource management under varying boundary conditions to be improved.

Residues from extractive industries

TABLE 4
Classification knowledge
for residues from extractive
industries.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> Specifications (reporting standards) for mining/metallurgical residue classification as a potential source of raw materials already exist, providing reliable and transparent information for potential investors. 	<ul style="list-style-type: none"> Reporting on non-sales production and non-technical and external factors, such as social, legislative and environmental factors (needed for resource managers and policy makers). Lack of information on resource characterization and evaluation. 	<ul style="list-style-type: none"> Reliable mineral inventory to underpin mineral policies. Incorporation of data from governments, NGOs as well as industry into databases and mineral inventories.

2.2 Residues in landfills

There are many factors that could influence the recoverability of materials and energy resources in landfills, [TABLE 4](#). The characterization of such potential resource reservoirs therefore needs to go beyond the content and physical structures of the specific landfill(s) in question and also address various conditions occurring on the surrounding local and regional levels. Apart from this, such contextual settings directly influence the costs and feasibility of resource recovery (e.g. available transport, energy and waste management and recycling infrastructure, and the need for landfill aftercare and remediation). They could also constitute the main drivers for mining landfills (e.g. the need and possibility to create new landfill void space or reclaim land for more productive and sustainable purposes). Here, knowledge about other specific reasons for managing landfills due to malfunctionality, protection of sensitive environments or risks for flooding, for example, are also of relevance because such plans or initiatives could in the end offer an opportunity for resource recovery.

2.2.1 Characterization

From a resource recovery perspective, knowledge about the content of a landfill in terms of its material composition and characteristics is fundamental [59]. So far, however, such detailed investigations on the grade and quality of deposited materials have only been conducted for a few landfills in Europe [60-62]. Most early stage prospecting initiatives therefore have to rely on less precise data sources for estimating the materiality of landfills such as logbooks including information about the amounts and types of deposited waste or extrapolations from data of historical waste streams. When it comes to other site-specific data and local settings that could influence the recoverability of such resources, relevant information is also often available on the regional level through existing local and regional plan documents, surveys of landfills and contaminated sites, water and climate maps, land use and GIS registers, and so on [63, 64]. However, given that all these databases and sources have been developed for different purposes and by different actors, the available information is somewhat scattered and inconsistent. It is therefore often a cumbersome task to collect all relevant data about the landfill and its local surroundings and to interpret its relevance and potential implications for landfill mining. In addition, the quality and recency of available information can sometimes be questioned, especially when it comes to old deposits where current regulations on monitoring and documentation of landfills and landfilling practices were simply not in place [64].

A key topic for facilitating the characterization and prospection of landfills for mining is therefore to develop generic procedures for how to deal with and utilize such scattered and imperfect data [65]. Fortunately, there are some past as well as ongoing attempts (e.g. the EU funded RAWFILL project) to develop coherent databases [66] and step-by-step prospecting frameworks [66, 67] for landfill mining but their usefulness and validity have yet to be further improved and validated. One key challenge here is that the available information about landfills and their local context can vary widely among different countries and regions. Another is that the existing knowledge about exactly which sites and local conditions and settings constitute landfills suitable for mining is still limited [68-70]. While most of the pros-



Residues in landfills

pecting frameworks target a first selection of “high-potential” landfills for mining in a region, there is also a need to develop more systematic and trustworthy methods for detailed investigations of particular deposits [71-73]. This is especially so when it comes to procedures for the material characterization of such largely heterogenic stocks. Here, the development of conceptual models of landfills that distinguish between their different compartments could be one way forward to facilitate more strategic and representative sampling schemes.

2.2.2 Evaluation

Although recent research shows that landfill mining could potentially offer a sustainable management option for some landfills by combining remediation with recovery of dormant materials, energy carriers and land resources [74-77], there has been up till now a lack of real-life projects validating the feasibility of such an approach [60]. In order to support the further development of landfill mining, there is thus a need for more in-depth knowledge on how such projects could be realised in a cost-efficient manner and with positive environmental and societal consequences.

TABLE 5
Knowledge for characterizing
resources in landfills.

Current knowledge	Gaps	Needs
<p>Site-specifics:</p> <ul style="list-style-type: none"> Information about landfill geometry, size, installed landfill technology, time of operation, content of main waste types, etc. is often available on the regional level in different databases and records (e.g. landfill surveys). For specific sites, logbooks and the like could give valuable information about the material content. There are also on-going initiatives to develop regional and temporal archetypes for landfills in this respect. Detailed characterization of the material composition and occurrence of hazardous waste only exists for a few, specific sites in Europe. <p>Local/regional context:</p> <ul style="list-style-type: none"> Information about land use plans, aftercare and remediation needs, climate conditions (e.g. precipitation), vulnerability and risks of surrounding environment (e.g. flooding, sensitive areas), landfill void capacities and needs, existing transport as well as energy and waste infrastructures is typically available but in a range of different databases and records. 	<ul style="list-style-type: none"> A lack of knowledge about the detailed material composition of landfills (concentration of different materials, levels of degradation, geometry, heterogeneity in terms of waste types and hazards). Lack of documentation and knowledge about the occurrence of illegal dumping. Lack of consistent data and information about landfills and their local and regional context. 	<ul style="list-style-type: none"> Development of coherent databases for facilitating a step-by-step prospecting procedure for LFM, where high potential sites, both in terms of their site-specifics and local context, can be identified. Development of reliable methods for sampling and characterization of the material content in heterogenic landfills. Conceptual models for landfills that distinguish between their different compartments could facilitate the sampling and characterization of such sites. What site-specific information and data is actually available for “new” landfills governed under the Landfill Directive?

Residues in landfills

TABLE 6
Knowledge for evaluating
resources in landfills.

Factors	Current knowledge	Gaps	Needs
Technical recoverability	<ul style="list-style-type: none"> The LFM process chains studied typically involve mature technologies but their performance in processing previously landfilled waste is often unknown. There have been a few pilot tests on the processing of landfilled waste involving standard material processing units For advanced technologies, only laboratory results are available. 	<ul style="list-style-type: none"> Which materials could be recovered from landfills and at what quality levels? How could efficient and effective excavation and material processing schemes be developed? How could landfills be optimally prepared for mining? 	<ul style="list-style-type: none"> Well planned and large-scale pilot projects involving testing, monitoring and comparisons of the performance of different processing lines. Development of models for different processing lines in terms of material transfer coefficients and resource quality estimates. Establishment of platforms for facilitating knowledge sharing and networking among LFM practitioners. Dissemination of good practices for landfill mining.
Economic recoverability	<ul style="list-style-type: none"> Principle understanding of which site-, project- and system conditions and interactions influence the economic outcome in different situations and settings. System conditions should guide selection of landfill sites for mining and the corresponding project set-ups. Resource recovery alone cannot justify such projects financially. The local and regional setting is of higher relevance for the selection of landfills than their material content. 	<ul style="list-style-type: none"> A lack of in-depth knowledge about what makes specific projects economically viable. Influence and potential of different financing mechanisms (bankability, loan and investment risks) & business models (timing and distribution of costs & benefits among actors). Influence and potential of internalizing socio-economic impacts into the project economy (e.g. future carbon tax systems). 	<ul style="list-style-type: none"> Development of certified and specialized actors in LFM technology and know-how to enable accumulation of knowledge and gradual improvements in cost-efficiency. More in-depth reviews of previous projects displaying economic profitability. Development of methods to assess socio-economic impacts and social consequences of LFM.
Environmental impact	<ul style="list-style-type: none"> Principle understanding of which site-, project- and system conditions and interactions influence the climate impact in different situations and settings. The most important factors pertaining to climate impact occur on the site level and are related to methane generation and management. At present, local vulnerability & pollution risks typically drive the environmental motivation for landfill rehabilitation projects 	<ul style="list-style-type: none"> What about all other types of positive and negative environmental & health impacts of LFM projects occurring on the global, regional and local levels? What are the long-term and short-term impacts of LFM when it comes to ecotoxicity & other hazards and risks? A need for improved communication of results from conducted assessments of LFM 	<ul style="list-style-type: none"> Testing & monitoring of what actually happens in real-life projects in terms of emissions and the fate and transport of various pollutants. There is also a need to develop a better understanding about the long-term environmental impacts of landfills.
Market acceptance	<ul style="list-style-type: none"> Current regulatory and gate requirements for metals, RDF and various aggregates extracted from landfills are difficult to fulfil. Metals are typically salable but in terms of low-quality categories. 	<ul style="list-style-type: none"> Is there any market demand and need for material and energy carriers extracted from landfills? 	<ul style="list-style-type: none"> Reviews of current market structures and commodities of different industrial sectors to better understand supply and demand dynamics and contracts, resource competition and price-settings for secondary resources. Applied research on upgrading of materials from landfills (producer) & technical and organizational measures to facilitate utilization (user).
Socio-political acceptance	<ul style="list-style-type: none"> When re-opened, old issues related to the operation of landfills and NIMBY seem to re-occur. Geo-political changes causing supply risks or higher resource prices could increase political acceptance. However, a LFM project needs to result in an improved local environment. 	<ul style="list-style-type: none"> Trade-offs between global, regional and local impacts and the effects of LFM. Low awareness of what LFM is and its potential benefits make it difficult to convince politicians and the public. What is the role of landfills and LFM in a circular economy and in relation to the new waste framework? What should we use previously deposited materials 	<ul style="list-style-type: none"> Demonstration projects validating feasibility and assessing and communicating environmental and societal impacts. Potential and feasibility of policy interventions, targeting resource circulation, sustainable landfill management and related hazards and risks.

(continuation of table 6 see following page)

Residues in landfills

Continuation of **TABLE 6**
Knowledge for evaluating
resources in landfills.

Factors	Current knowledge	Gaps	Needs
Legal compliance	<ul style="list-style-type: none"> • Landfill legislation only applicable for deposits from 1990s. • The fact that current legislation advocates final closure and aftercare of landfills causes several barriers for LFM. • Ownership and accessibility issues related to landfills influence the potential of LFM. 	<ul style="list-style-type: none"> • How does current legislation apply to LFM? • Is LFM to be regulated under the legislative framework for remediation or recycling? • Such uncertainties make it difficult for actors to foresee the outcome of investments in such projects (e.g. mining tax, landfill tax, availability of public funding, requirements as regards safety and work environment, etc.). 	<ul style="list-style-type: none"> • Training authorities and convincing politicians that LFM could be a viable alternative for managing waste deposits. • Specific LFM regulations for permitting, operation and project closure. • Acquisition of knowledge on how to bookkeep materials recycled in LFM projects in waste statistics and proper reporting on the fulfilment of recycling targets.

One part of establishing such know-how is to address the essential question of which materials and energy carriers can be extracted from landfills and at what quality levels [62]. Despite the fact that several studies have dealt with this topic, our knowledge about the efficiency of different technologies for processing deposited waste is still limited to small-scale trials and laboratory studies. There is therefore a need for additional pilot projects in which the separation efficiencies and material flows of different technologies and processing lines are monitored and gradually improved on a scale comparable to full-scale projects [69]. Such process development would benefit from being clearly goal-oriented, involving specific targets on what materials and energy resources to produce and which resource quality levels to aim for. Among other things, this means that developers of technologies need to account for how the performance of their processing units interrelate with and are influenced by both upstream (e.g. variations in the composition and characteristics of deposited waste) and downstream (e.g. gate and regulatory requirements for separated materials and energy carriers) conditions and processes. The establishment of common platforms to discuss and share experiences of excavation and processing of landfilled waste would also benefit learning processes and contribute to common knowledge acquisition within the discipline.

When it comes to understanding different the impacts and consequences of landfill mining, quite a few assessments are available in terms of both case-studies [e.g. 14, 78, 79] and more generic modelling approaches analysing the outcome of a wide range of different scenarios [68, 80]. Together, this body of literature offers a principle understanding of how different site, project and system conditions and interrelations influence the economics and climate impact of landfill mining in different situations and settings. On an overarching level, it can be concluded that such projects are indeed challenging from a business perspective and that their climate impact could vary widely among different cases, from large savings to significant net contributions to global warming. System conditions as well as determining landfill aftercare and waste disposal costs constitute the most critical factors influencing the economic performance of landfill mining. Specific regulatory and market settings should therefore guide the selection of suitable sites for mining and aid in determining how the projects are set-up technically and organizationally [68]. In addition, resource recovery alone cannot justify such projects financially. Other values need to be taken into account as well such as avoidance of significant landfill aftercare costs, reclamation of valuable land or creation of new landfill void space [74, 81]. For one thing, this means that the local and regional context of such sites are often of higher relevance than their material content for the selection of suitable landfills for mining. However, with respect to the climate impact of landfill mining projects, the material content and the landfill gas management system implemented at the specific site in question are indeed crucial and constitute the most critical factors concerning the net contribution to global warming [70].

It should, however, be stressed that our current knowledge about the different impacts and consequences of landfill mining is still largely limited [82]. When it comes to economics, more in-depth assessments are needed with regard to what produces the net outcome in specific projects and how that is influenced by different financing mechanisms and

Residues in landfills



business models [60]. In such studies, plausible effects of different policy and market interventions could also be assessed [14, 75]. Given that any real-life landfill mining project would generate several positive and negative socio-economic and social impacts, a broader scope is also needed that goes beyond business economics by developing and applying methods for assessing such potential societal impacts [77, 82]. The same could be said about the environmental impacts of landfill mining, where our current knowledge is more or less constrained by global warming [76]. In order to support policymaking and public acceptance of such projects, a better understanding is needed about the different types of environmental and health impacts that occur on the local, regional and global levels [82, 83]. A key issue here is ecotoxicity and various health risks related to different kinds of hazardous substances contained in the landfilled waste [69]. In order to be able to include such issues in environmental assessment, there is, however, first a need for field studies to monitor what happens during the processing and recovery of landfilled waste in terms of emissions and the fate and transport of different pollutants.

It is also worth noting here as well that the trustworthiness of the ex-ante assessments conducted till now is somewhat questionable due to some overall assumptions about how the different processes of the landfill mining value chain will work [60]. As previously mentioned, we know very little about the technical feasibility of extracting various materials from landfills. This lack of practice and records of accomplishment means that most assessments have to rely on data and experiences from the processing of other waste (e.g. fresh municipal solid waste) to estimate the separation efficiency of different commodities from landfills. Another critical assumption occurs at the very end of the landfill mining chain and concerns the quality and marketability of the resources extracted [84]. Here, most assessments simply assume that different separated materials and energy carriers will be readily accepted by the market [69]. If this is not true, as indicated by some studies contrasting the properties of landfilled materials with corresponding legislative and end-user requirements [84], it will have a large impact on both the economic and environmental motives for such projects. The issues of resource quality and marketability of various resources extracted from landfills therefore need to be much more strongly emphasized in future research.

Apart from this, landfill mining actors often experience a hard time financially when exposed to current market conditions. Moreover, there are several other types of institutional barriers that need to be overcome as well to enable implementation [85]. For instance, there are at present large uncertainties as to how current environmental and waste legislations will apply to such projects. As shown by previous studies, authorities are therefore somewhat ambivalent in terms of how landfill mining projects should be permitted and handled in relation to existing regulatory frameworks [86]. Given that different legislation (e.g. for remediation and recycling) involve significantly different requirements for the realization of the project, this situation also makes it difficult for landfill mining practitioners to foresee the outcome of such initiatives – something that constrains their will to engage in such projects. In order to address this inertia and create foreseeable playing rules, landfill mining needs to be institutionalised and provided with clear regulatory framing. In fact, several national and EU-wide initiatives have already been conducted to initiate such a process but so far without any success [87].

Facilitating implementation of landfill mining is also related to several socio-political aspects. For instance, the previous failures to institutionalise and develop political support for landfill mining within the EU could to some extent be explained by such factors as policymakers and authorities simply not being convinced that such a practice is a good idea [88]. This lack of credibility may well be justified, given its early stage of development, lack of real-life projects and large deficits in knowledge regarding its societal benefits and costs. Regarding specific projects, locals are also often sceptical about landfill mining since historical precedents and local pollution and health concerns related to the landfill in question are often revived in contexts of renewed discussion of the landfill [89]. Being able to convince such actors that landfill mining is a societally motivated activity and, above all, will lead to an improved local environment

Residues in landfills

is therefore key to facilitating implementation [90]. Demonstration projects, where the feasibility of landfill mining can be illustrated and the trade-offs between different global, regional and local societal effects assessed and clearly communicated, would be particularly useful at this stage. Adding a resource recovery element to already planned landfill remediation projects could be one strategy to facilitate the realization of such demonstrations. Perhaps such a development could also be further stimulated by framing landfill mining in terms of on-going trends and activities related to circular economy and material autonomy.

2.2.3 Classification

Previous studies have demonstrated that it is possible to classify landfilled resources according to the UNFC framework, but individual approaches have been used to grade the different axes and several challenges therefore remain to be addressed. One such challenge is to determine in which of the axes different factors and aspects related to the feasibility of landfill mining should be accounted for to facilitate consistent procedures for classification. Another partly related challenge is to establish where other values that are not part of the UNFC framework (e.g. avoided environmental impacts or other drivers that are not possible to quantify economically), but that could be of high relevance for the feasibility and motives for landfill mining, should be included. Beyond this, there are several elements of ambiguity when it comes to the interpretation of the grading scales and how to systematically handle the relative importance of different factors and aspects within each axis.

TABLE 7
Knowledge for classifying resources in landfills.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> • Previous studies demonstrate that it is possible to classify landfilled resources. within the UNFC framework, but selective approaches were used to grade the different axes. • This raises concerns about issues related to simplification and ambiguity. 	<ul style="list-style-type: none"> • In which axes (F&E) should different aspects and parameters currently be accounted for? • Where to put drivers for LFM beyond what is possible to quantify economically using NPV? • How to handle the relative importance of different aspects & parameters within each axis. • There is at present an ambiguity regarding the interpretation of the grading scales for the different axes. • If there are factors beyond the business economics, the question is how to deal with multiple factors on the E-Axis. 	<ul style="list-style-type: none"> • UNFC should develop best practices for the F and E axes through case studies. • Assess the feasibility of inserting an intermediate weighing step making the perceived importance of different aspects for the grading of the different axes explicit. Such weighing should be done from the user and decision-maker perspective. • Development of detailed grading scales, specifically tailored for landfills and LFM projects (e.g. conceptual model for degree of confidence – G axis, acknowledge lack of practical experience in F-axis, internalize different societal values in the E-axis).

Based on case studies, best practices for using UNFC should be developed to show which aspects and factors in the F and E axes should be considered when classifying secondary resource flows and stocks. Such work might also involve extending the scope of the E-axis beyond net present values (NPV) to also include selected environmental or socio-economic consequences. The current ambiguity when it comes to the grading of the different axes could partly be addressed by introducing an intermediate weighing step, making the perceived importance of different factors, and thus their relative contribution to the final grade, explicit. Furthermore, the development of more detailed grading scales that are specifically tailored for landfill mining projects could contribute to more consistent and systematic procedures for the classification of such deposited resources. Such a tailored approach would, for instance, make it easier to account for the extraordinarily large uncertainties that are related to most feasibility assessments of landfill mining due to the current lack of practical knowledge and experience.

Residues in landfills

2.3 Residues from municipal solid waste incineration

2.3.1 Characterization

When it comes to knowledge of the recovery of secondary raw materials from municipal solid waste incineration (MSWI) ashes, a reasonably good data base should be available on the quantities of wastes incinerated as they have to be well documented (for legal reasons due to their environmental impact). Furthermore, some of this data is centrally collected by national (or regional) governments and statistics departments. As these report to EU institutions (EUROSTAT-AT), at least when part of the EU, these data are even published at European level [91]. In addition, non-governmental bodies like the International Solid Waste Association (ISWA) and the Confederation of the European Waste-to-Energy Plants (CEWEP) frequently publish reports with such data [92, 93]. However, the same cannot be said for the types of waste which are incinerated, and where. For instance, the EUROSTAT data for quantities of waste incinerated include waste of different types (including non-MSW) as well as waste co-incinerated in industrial plants such as those for cement production [94]. The ISWA and CEWEP reports do make these distinctions [93].

With respect to the composition of waste incinerated, data compilation at national and EU level is much less frequently practiced. For this reason, researchers and practitioners that want to make use of that data have to look for case studies in the literature or from bodies like ISWA or CEWEP [92, 93].

TABLE 8
Knowledge for evaluating resources in MSWI residues.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> Quantities of waste incinerated. Waste incineration and APC technology. Quantities of bottom-ash for most MSWI plants in Europe. Rough composition and other parameters of bottom ashes and APC residues including fly ash. 	<ul style="list-style-type: none"> Specification of wastes incinerated. Differentiation between industrial co-combustion and MSWI. Clear distinction between different types of MSWI technology (the latter including APC technology – detailed description). Systematic collection and management of composition-related and other parameters data as most of the data presently comes from selected literature sources. 	<ul style="list-style-type: none"> Enabling national authorities or other stakeholders to systematically collect and manage the most important data on waste incineration and the residues produced from it.

When the composition of waste (and type), the MSWI technology (grate incineration, fluidized bed incineration), operation details (temperature), the consumables and the APC (and probably the bottom ash discharge) technology is known, the quantity and composition of residues (APC residues, bottom ashes) can be calculated based on the literature [8]. Data like these have been compiled, for instance, by ISWA [93]. However, the data has to be updated frequently as the number of MSWI plants and waste incinerated as well as waste composition is changing quite fast.

In addition, the quantities and qualities (e.g. composition, ph value) of ashes from MSWI would be helpful. However, these data are not at all frequently collected (if monitored at all) and published. For this reason, case studies from the literature on these data have to be retrieved [95-98].

For all the data mentioned and currently collected, stakeholders have to evaluate whether it makes sense to collect and manage them. If this evaluation is positive, authorities or other stakeholders that collect and manage data should be enabled to do so (i.e. financially and capacity wise and, hence, with well-trained staff). For instance, Fellner et al. [8] showed that recoverable Zn in MSWI residues is 2% of the Zn demand in Europe. Whether this justifies the central collection of Zn contents in waste and MSWI residues at National or even European levels is as political-economic decision. If this decision is favored, then naturally more data monitoring, sampling and research is required.



Residues from Municipal Solid Waste Incineration

2.3.2 Evaluation

In the following, we list and describe factors that affect the viability of resource recovery:

For **technical recoverability**, a larger number of studies describe different processing and thus recovery technologies for MSWI ash [95, 96, 99, 100]. Within a resource classification framework applied to the anthropogenic resource of MSWI ash, however, knowledge of certain technologies has been elaborated in few case studies [8, 101]. Gaps also exist when it comes to recovering more than just one material. This is important as MSWI residues contain more or less the whole periodic table of elements. To give an example, from bottom ashes, metals, minerals and glass can all be extracted. However, if the maximum amount of metal is supposed to be recovered, the mineral fraction containing some of the metals in their aggregates (i.e. if aggregates are formed during incineration, and metal kernels are embedded) must be crushed into a small grain size. This, however, reduces the applicability of the mineral fraction as recycling aggregate in concrete or in road construction as large grain sizes of aggregates are required there [100]. Contrary to that, the recovery of salts, metals, and minerals (for cement production) from MSWI fly ash can be complementary [12]. Furthermore, and unlike for phosphorus recovery from sewage sludge incineration ash [102], the different technologies for the upconcentration of valuable materials requires much more research. Some examples, however, are already available, which is also the case concerning the question of the energy demand of the different recovery technologies, such as for the evaporation of water for deicing salt production from MSWI fly ash [99].

In the following, we list and describe factors that affect the viability of resource recovery:

For **economic recoverability**, important are the price that can be achieved for the commodity produced as well as the costs for production. For the first, data is available, at least for primary raw materials. The same is true, in part, for the production costs, as the example of Fellner et al. [8] and Huber et al. [12] show. However, detailed prices for secondary raw materials are often not available. Furthermore, alternative disposal prices at landfilling and some other factors (e.g. land price, incineration price) are of relevance [8]. With the emergence of new applications and transparency, this state of affairs should improve.

Environmental impacts are another important factor, and they have been considered in the evaluation of metal, salt, and minerals recovery by Huber et al. [12]. In general, there is a great deal of literature on that available [103]. However, the long-term emissions from landfills pose a challenge [95, 96, 103, 104], particularly if ashes are used as construction material by, for instance, leaching of heavy metals. Thus, more long-term impact assessment studies are required.

Market and socio-political acceptance very much has to do with different aspects already described or described later. For many recovery options from MSWI ash, no large-scale applications have been done, thus no experience has been gained from that. An exception is the use of MSWI bottom ash in road construction in Northern Europe, particularly the so-called Green-deal in the Netherlands [92].

With respect to **legal compliance** across different countries in Europa, large steps have been made by Kahle *et al.* [92], Dou *et al.* [105], and more recently by Blasenbauer et al. [106] concerning utilization practices and the related legal situation (including determination of environmental parameters) for the use of MSWI bottom ash in road construction. However, the elaboration of compliance using the more detailed study of Blasenbauer et al. [106] was quite time consuming and only possible with the help of a large number of experts from each country in the EU 28 + Norway and Switzerland. This expertise was very important, not only for language questions (which was sometimes also the case), but also to acquire the local information required to read between the lines of legal documents. This was an example of the so-called expert network that has to be built up when dealing with questions like these [94]. For other forms

Residues from
Municipal Solid Waste Incineration

of utilization, however, many more networking activities are required to compile similar information. This is the case, for instance, for the utilization of MSWI ash in cement where, for instance, Austria and Switzerland have some clear regulations [99]. For deicing salts, however, there is a similar lack of clarity; not much is there for salts from hazardous wastes like MSWI fly ash.

TABLE 9
Overview of current knowledge levels, gaps and needs for evaluating resources in residues from extractive industries.

Factors	Current knowledge	Gaps	Needs
Technical recoverability	<ul style="list-style-type: none"> • Influence of waste composition. • Influence of waste incineration technology. • Influence of APC system. • Influence of bottom ash discharge system. 	<ul style="list-style-type: none"> • Selected recovery of a large number of different elements. • Recovery of metals from bottom ash while, at the same time, not destroying the mineral fraction completely (to make better use of the latter). • Technology for the upconcentration of metals (chemical, thermal, biochemical, a combination). • Energy consumption (e.g. for salt recovery). 	<ul style="list-style-type: none"> • Enabling more research and technological development, including large-scale testing of technologies at different technological readiness levels.
Economic recoverability	<ul style="list-style-type: none"> • General prices for raw materials. • Some general and rough costing positions (e.g. price for energy, consumables like CaOH, etc.). 	<ul style="list-style-type: none"> • Detailed prices of commodities depending on the quality of the raw material produced and the market (i.e. country – relevant for locally and nationally traded goods like most bulk mineral construction materials). • Alternative disposal prices, i.e. for landfilling. • Incineration costs. • Land costs. 	<ul style="list-style-type: none"> • Enabling authorities and other stakeholders to provide the information if required.
Environmental impact	<ul style="list-style-type: none"> • Environmental impacts of different technologies (in general). 	<ul style="list-style-type: none"> • Long-term emissions from MSWI fly ash and bottom ash, i.e. from landfills and, if applied, in construction. 	<ul style="list-style-type: none"> • More research on long-term emissions, e.g. continuous monitoring of leaching of pollutants from incineration bottom ash in roads or in concretes/cement.
Market acceptance	–	–	–
Socio-political acceptance			–
Legal compliance	<ul style="list-style-type: none"> • Legal situation concerning the use of bottom ash in road construction in most European countries, including testing procedures for environmental compliance. • Partly, some technical compliance is present as well. 	<ul style="list-style-type: none"> • Overview of the legal situation concerning the utilization of incineration bottom and fly ash in concretes, cements or salts from these ashes as deicing agents. • A lot of the information is not openly published, and very often only in the national language. However, this should not be a problem if national experts from that country are always be involved in resource classification. 	<ul style="list-style-type: none"> • Countries that may want to encourage industry to recover more incineration ash in construction materials or as salts should develop guidelines based on an informed decision (which again requires research and large-scale long-term experiments).

**Residues from
Municipal Solid Waste Incineration**

2.3.3 Classification

If classification is based on characterization and evaluation, most details required for these points have already been dealt with in the preceding subsections. The only issue remaining is, then, the number of case studies required in order to compare and gain an impression of whether a result of an evaluation is favourable or less so. The good news is that there are a few case studies on MSWI residues and related fields [7, 8, 99, 101]. The bad news is that many more of them are needed to compare many more secondary raw materials. Thus, there should be a focus on that in future, namely, to apply UNFC (or other classification codes) as desired in this COST Action.

TABLE 10
Knowledge for classifying resources in MSWI residues.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> A few case studies are available on some recovery options. 	<ul style="list-style-type: none"> On many recovery options and secondary raw materials, there are no applications of McKelvey, UNFC, or other standards, making it difficult to compare between different ores and raw material recovery options. 	<ul style="list-style-type: none"> More case studies should be done on different MSWI ash streams with different raw materials recovered and technologies applied.

2.4 Residues (C&D waste) from the built environment

2.4.1 Introduction

Buildings and infrastructure play multiple roles in our socio-economic metabolism: they serve as the backbone of modern societies and human well-being, drive the material cycles throughout the economy, and entail temporal and spatial lock-ins on energy use and emissions. More importantly, the extensive use of materials in building and infrastructure stocks contributes to the scarcity of natural resources and represents an extensive reservoir of secondary materials (see the types of buildings and infrastructure in [FIGURE 4](#)).

In recent years, increased demand for many materials and concerns for the effects of waste have stimulated interest in urban mining from various perspectives, environmental and economic. As concentrations of elements in anthropogenic stocks are often comparable or even higher than natural stocks, recovering resources from the anthroposphere is an attractive alternative to depleting natural ones, incurring high costs for extraction and transport from primary sources or becoming dependent on those who control the primary sources. The promise of anthropogenic stocks seems substantial and is widely accepted, not only with respect to household waste and end-of-life products like vehicles or electrical and equipment waste (WEEE), but also buildings and infrastructure since construction is both a major user of materials and a primary producer of waste [107, 108]. For example, with the worldwide popularity of reinforced concrete as building material and the increasing quantities of wiring and piping in buildings, it is not surprising that buildings contain 50% or possibly more of all metals in use [109].

However, the lifespan of building and infrastructure components is not only significantly longer than that of electronic equipment but is also quite varied, depending on material, subsystem (e.g. road, metro, water pipes, for heating of buildings, plumbing, electrical or loadbearing), use intensity and weathering. Some analysts suggest that as little as 3% of materials may be extractable from buildings and infrastructure and then only after a protracted lifespan.

Even though there has been a large amount of research investigating the quantity of built-in materials in buildings in selected urban areas from a resource perspective [e.g. 110, 111-113], infrastructure networks have only recently been investigated for their anthropogenic stocks. The residues from buildings and infrastructure have been studied from various angles, such as examining waste management practices in major economies like Canada [114], Germany [115], the United States [116], the United Kingdom [117], China [118], Australia [119] and Malaysia [120]. The performance of waste management has been evaluated from the perspective of sustainability, feasibility, viability [121], and waste

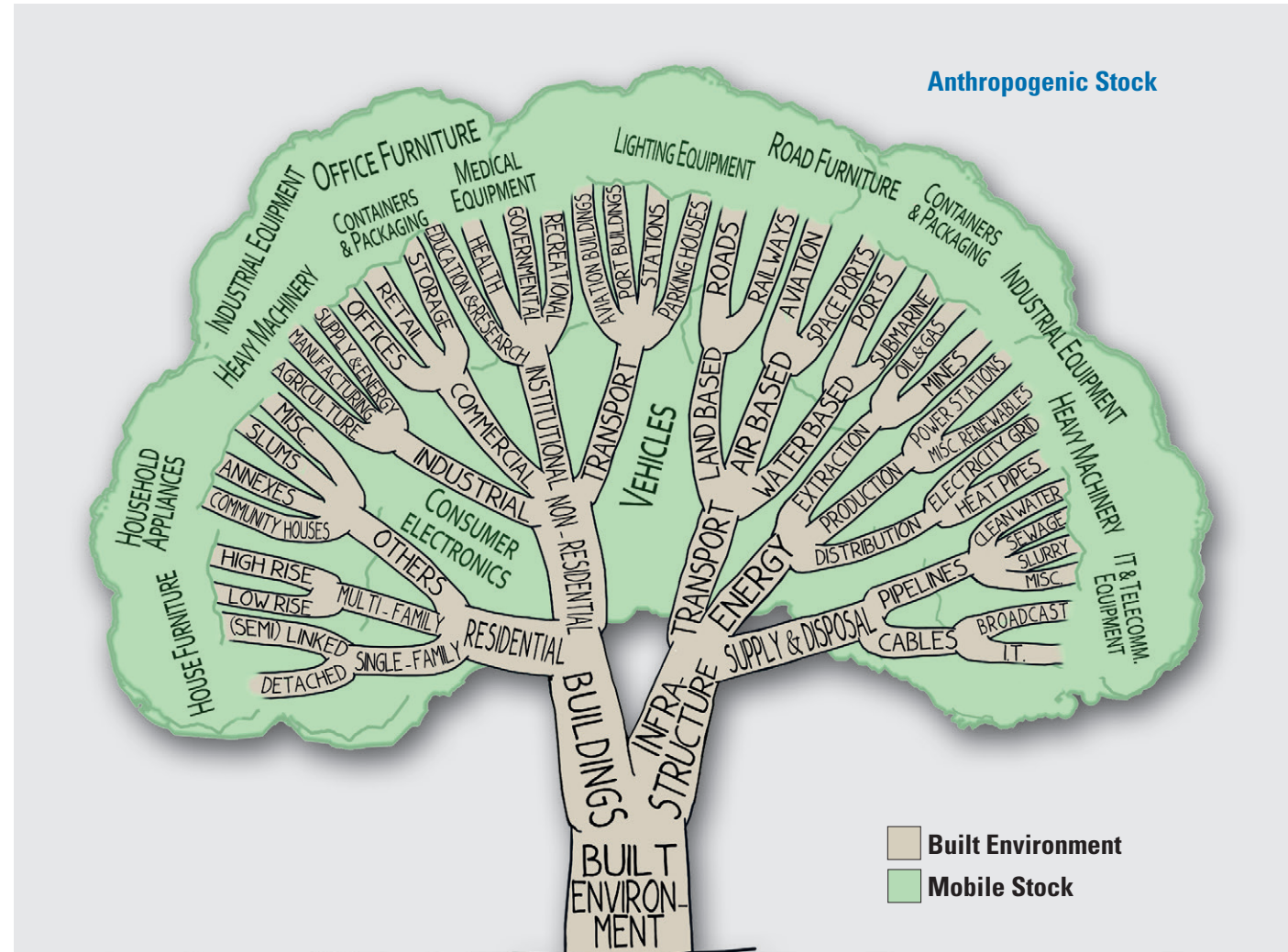


Residues from Buildings & Infrastructure

management efficiency [122, 123]. The physical and ecological impacts of residues from buildings and infrastructure have been investigated by assessing and handling heavy metals and organic compositions that are leached out from the waste [124] as well as by testing and improving the physical performance such as the strength and durability of recycled products [125, 126].

In this report, we compile existing literature regarding the characterization of material stocks in the built environment and regarding the recoverability of resources from C&D waste. The review on the recoverability built only on a few cases and the classification was only found in one of Vienna's subway network studies [9].

FIGURE 4 >
The types of buildings and infrastructure in a "tree" structure.
(Source: Lanau et al. [127])



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2.4.2 Characterization

In the following, we describe the current knowledge, gaps and needs:

Current knowledge

Estimation approaches to resource stocks in buildings and infrastructure are generally categorized into top-down approaches, bottom-up approaches, and their combination and extension. The top-down approach builds on the mass-balance principle that a change in stock is the result of the difference between inflows and outflows of a material over time, usually over a year [128]. The bottom-up approach (also called coefficient-based approach) quantifies the amount of stock “piece by piece”, by counting all items containing a specific material and multiplying the number of each specific product by its material intensity [129]. A bottom-up approach for stock estimation is therefore highly data and labor intensive. Integrating Geographical Information System (GIS) tools and data in bottom-up studies allows for higher spatial resolution and improved understanding of the physical system and composition of built environment stock. The use of remote sensing technologies has been on the rise in recent years in material stock research, inspired by findings indicating that the radiance of nighttime lights (NTL) correlate well with human activity and socio-economic parameters such as population, energy consumption, gross domestic product (GDP) and CO2 emissions [130].

Waste generation has been a hot topic in (construction and demolition) C&D waste research over the period. Those studies can be generally divided into three categories, i.e., surveying C&D waste generation in a specific region, investigating waste generation rates, and estimating C&D waste generation through various models. A considerable number of studies have been conducted to survey waste generation in specific countries/regions, such as the USA [131], Norway [111, 132], Malaysia

[133], Spain [134], Portugal [135] and China [136, 137]. Data for estimating waste generation are mainly through methods of site interview, questionnaire, site visits and observation.

Given that there are various types of construction projects inducing waste, the waste generation rate is regarded as a critical indicator of C&D waste generation. The rationale for developing this indicator is that the average amount of waste generated in the same type of projects is normally of small variation [138-140]. As for the estimation of C&D waste via models, Kern et al. (2015) proposed a model to estimate C&D waste in high-rise buildings following a multiple regression approach. Won *et al.* [141] proposed an approach to estimate the amount of C&D waste avoided through Building Information Modelling (BIM) oriented design. Wu *et al.* [136] developed a method to predict the amount of demolition waste at the city level with the aid of the Geographic Information System (GIS). Although traditional methods (e.g., site interview, questionnaire, site visits, and observation) are primarily used, it is observed that new approaches have been developed in recent years.

We identified three methods for estimating the generation of C&D waste flows:

(1) Site visit (SV) method

This methodology requires investigators to visit the construction or demolition sites in order to conduct a realistic survey. Direct or indirect approaches can be utilized to collect C&D waste generation data.

Direct measurement requires weighing the waste produced or to measuring its volume on site. Before implementing direct measurement, some assumptions have to be made. For instance, in the research conducted by Lau *et al.* [133], four assumptions were made, depending on how C&D waste was stockpiled, gathered, scattered or stacked.

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As direct measurement requires a substantial amount of time and labor, indirect measurement is more frequently used for practical estimation. For example, Poon et al. [142] employed truck load records to estimate the volume of C&D waste generated on site. The investigators recorded the number of trucks for waste collecting, together with the container's volume of each. Based on this information, the total waste volume at a project level was derived.

(2) Generation rate calculation (GRC) method

The literature review revealed that GRC is the most popular methodology for estimating C&D waste amounts. It can be implemented for construction, renovation and demolition activities at both regional and project levels. The principle of this methodology is to obtain the waste generation rate for a particular activity unit (such as kg/m², and m³/m²). With this principle, several methods were introduced by using alternative parameters in previous studies, such as per capita multiplier, financial value extrapolation and area-based calculation.

(3) Lifetime analysis (LA) method

Lifetime analysis is mainly implemented when quantifying demolition waste. The primary principle involved in this method is material mass balance. It is assumed that constructed buildings will eventually be demolished and become demolition waste. Consequently, the amount of demolition waste must equal the mass of the constructed structure and can be projected by assuming reasonable lifetimes of buildings/materials. Building lifetime analysis and material lifetime analysis are the two branches of this method.

- **Lack of quantification of infrastructure.** From the literature review, it can be concluded that quantification activities are focused much more on residential or commercial buildings than on civil engineering works or infrastructures. Some possible reasons are the following: (1) residential and commercial buildings are often smaller than public construction works and thus are easier and cheaper to study; (2) the construction durations and the lifetimes of these buildings are much shorter than those of public civil engineering works, which makes it applicable for demolition waste estimation; (3) as residential and commercial buildings are generally of similar construction, the waste generation information collected from different projects are comparable and can be generalized.
- **Lack of current data.** Current data are very important for an accurate quantification. However, these days reliable data for C&D waste estimation are missing, with only a few exceptions in some developed countries. To achieve relatively accurate estimation, researchers must draw support from assumptions. For example, as the annual total area of construction (m²) in Florida is not directly available, Cochran *et al.* [131] estimated it by dividing the total value of construction activity (\$/year) by the average cost per area of construction activity (\$/m²). Poon (1997) assumed a constant waste generation rate (m³/m²), a general demolition waste density (kg/m³), and the most likely scenario for demolition area (m²) to investigate the demolition waste. Though the assumptions are reasonable, it is suggested that more effort should be made to record current data for more accurate estimation.
- **Lack of verification.** Though many quantification methodologies have been proposed and case studies have been implemented in the literature, there has been little verification to prove whether a methodology is appropriate or how far its estimation is from the truth. The only evidence of verification in the literature is when employing an SV quantification method. After the waste generation rate was collected, the investigators adjusted their estimation with the help of experienced on-site professionals through interviews. This verification can make their estimation more practical. However, at a regional level, there is little chance for the researchers to conduct verification because the local government has no record of C&D generation.
- **Lack of knowledge** on the source of residues. Residues from buildings and infrastructure are generally categorized according to cause: new construction, renovation and demolition. The activity "demolition" provides up to 70% of the total residues quantities and the remaining 30% cannot be related to any specific activity.

Residues from
Buildings & Infrastructure

Needs

Buildings and infrastructure material stocks represent an extensive reservoir of secondary raw materials, and therefore a deepened knowledge of the amount, quality, location, and time availability of these material stocks can support urban mining, smart demolition, and waste management strategies for a variety of stakeholders (e.g., waste and recycling companies, architects, developers and planners). This would lead to a decrease in the final amount of waste disposed of, thus fostering the circular economy and limiting both the excess production of building material and the lack of waste disposal capacity.

TABLE 11
Knowledge for characterizing resources in buildings & infrastructure and C&D waste, respectively.

Current knowledge	Gaps	Needs
<ul style="list-style-type: none"> Quantities of residues generated from buildings. Different waste quantification method. Main waste composition from buildings and infrastructure. 	<ul style="list-style-type: none"> Lack of quantification on infrastructure. Lack of current data. Lack of verification. Lack of residues from new construction and renovation stages. 	<ul style="list-style-type: none"> Deepened knowledge of the amount, quality, location, and time availability of residues from buildings and infrastructure. More studies should be done across all stages of residue generation (new construction, renovation and demolition).

2.4.3 Evaluation

In the following, we list and describe factors that affect the viability of resource recovery:

Technical recoverability: A larger number of studies describe the processes and recovery technologies from building and infrastructure residues. **TABLE 12** shows the recyclable building and infrastructure residues, recycled products, and the use of recycled products identified from previous studies.

TABLE 12
Building and infrastructure residues, recycled products, and use of recycled products.

Building and infrastructure residues	Recycled products	Use of recycled products	Typical studies
Concrete	Recycled aggregate	Pavement Base/Subbase	[143-145]
Concrete	Recycled aggregate	Hot mix asphalt (the hot mix asphalt is normally made with recycled concrete aggregates coated with bitumen emulsion)	[146-149]
Mortar	Recycled sand	Mortars	[150-152]
Brick	Crushed brick aggregates	Pavement base/Subbase	[153]
Glass	Recycled glass blends	Pavement Base/Subbase (adding glass blends into mortar and concrete to improve the physico-mechanical performance)	[154-156]
–	Mixed composite powder materials	Cementitious materials in small-scale prefabricated concrete	[157]
–	Mixed recycled components (e.g. recycled mixed fine aggregate)	Fillers	[158, 159]

Residues from Buildings & Infrastructure

The residues such as concrete, mortar, brick, and glass have attracted the most attention. Concrete and bricks are usually crushed to make recycled aggregate [143, 144, 153, 160]. Mortars are usually crushed to make recycled sand [150, 161]. Cement mortar adhering to the surface of aggregate is viewed as undesirable and thus needs to be removed from recycled aggregate [162]. As another critical C&D waste material, glass has been considered to have great potential to be recycled [154-156]. Compared to other waste materials (e.g. glass, timber, and plastics), this kind of waste is technically more accessible for recycling and economically feasible due to the scale effect. As a result, the treatment of remaining waste fractions has been overlooked. This may cause severe impacts on human health and the natural environment because some unclassified materials contain hazardous components (e.g., asbestos) [163]. Recycled C&D waste products (e.g., recycled aggregate, recycled sand, crushed brick aggregate, and recycled glass blends) can be used in different contexts. For instance, recycled aggregate is frequently used in concrete, large volumes in pavement base or subbase [160, 164-166], while recycled aggregate of sound quality is also used to produce precast and structural concrete [167]. Although various applications of recycled C&D waste products have been developed, they are mainly based on recycled aggregate related products due to the technique's feasibility. Other materials can also be used in some applications. For instance, mixed recycled components have been used as filler [158, 159]. Timber can be used for land rehabilitation, soil improvement and urban development. These applications have been used in practice for years but have not been documented in prior studies, as is also the case with metals with higher economic value, which might limit the growth of recycled C&D waste applications.

Economic recoverability: Several studies have been conducted to examine the economic feasibility of recycling residues from buildings and infrastructure given that a primary drive for stakeholders to implement waste recycling lies in the economic benefits of residue recycling [121, 168-170]. Their findings showed that recycling is economically feasible and plays an important role in the improvement of environmental management [168]. However, prioritizing reductions in incineration and landfilling associated with recycling does not increase the quality of recycling but rather the quantity of recycled waste, which leads to investments in lower value applications (low quality aggregates) and supersaturation on the low-quality aggregates market. Recycling costs are significantly influenced by the transport distance, the construction site conditions, and the amount of waste to be recycled [121]. Moreover, the C&D waste materials cannot always be treated on time (high payback time), the recycled products cannot always be traded at the targeted prices, and the cost of selective demolition influences the outcome of evaluating the economic feasibility. With respect to disposal costs, 24 EU Member States have a landfill tax (AT, BE, BG, CZ, DK, EE, EL*, ES, FI, FR, HU, IE, IT, LT, LU**, LV, NL, PL, PT, RO, SE, SL, SK, UK), as well as Norway and Switzerland. 4 EU Member States do not have a landfill tax (CY, DE, HR, MT).

Environmental impact: The most common environmental concerns related to residues from buildings and infrastructure are the pollution of overland water [171], groundwater [172], and soils [173, 174]. These have received extensive attention from scholars with environmental science and environmental engineering backgrounds. These studies attempt to examine the environmental impacts through testing the pollutant compositions of the waste and analyzing the influence of pollutants in C&D waste on the total environment.

Identification of pollutant composition from C&D waste plays an essential role in understanding the environmental concerns of C&D waste. Pollutant composition of residues from buildings and infrastructure may vary, such as with heavy metals (e.g., copper and chromium), organic matter (e.g., polycyclic aromatic hydrocarbons (PAH), carbon, methane, sulfuret and hydrogen sulfide [175, 176]. Overall, the research work in this area is relatively robust as many results are based on experimental studies in the laboratories of leading universities and institutes. However, since the sample selection was limited to residential/commercial project sites and landfills, some toxicity pollutants have been overlooked. Recently, some toxic organic matter components such as polycyclic aromatic hydrocrack and hydrogen sulfide have

Residues from Buildings & Infrastructure

been found in mixed C&D waste derived from the demolition of industrial buildings, such as a pesticide factory [177]. The composition and properties of mixed C&D waste are very complex. As a result, the environmental and health risks associated with industrial C&D wastes have attracted wide concern [178, 179].

The life cycle thinking provides a more comprehensive understanding of the impacts of waste management, particularly the methods for addressing the waste (i.e., reuse, recycling, energy recovery, and landfilling). However, the development of a life cycle database for C&D waste still is still lacking, even in developed countries, which would limit the adoption of LCA in C&D waste.

To control and mitigate the pollution from residues from buildings and infrastructure, studies have been conducted on the mechanisms of sorption, adsorption, release, immobilization, incineration, and pyrolysis [180-182].

Market acceptance: The quality of recycled products from buildings and infrastructure residues has been the primary influence on market acceptance. And the market for recycled metals such as steel or aluminum is fast growing because of their high economic value. Increasing prices of metals encourage contractors to separate reinforcement bars from crushed concrete on construction sites as much as possible. However, the recycled aggregates of low-quality are super-saturated on the market. And barriers exist with respect to the standardization of products, cost effectiveness (higher cost of recycled materials), and the inelastic supply of recycled material.

Future needs might be shifting the awareness of people from cost to opportunity, promoting environmental advantages (LCA in regulation), certification, improving government subsidies and designing more efficient.

Social political acceptance: the designers, constructors and residents don't know the quality of reused materials, which requires experts to certify reused materials and a change in people's perception of recycled products. And the policy of prioritizing the reduction in incineration & landfilling C&D waste does not imply an increase in the quality of recycling, but rather an increase in the quantity of recycled waste, which leads to many more investments in more low value applications. The combination of LCA and LCC can provide useful information to policy makers in carrying out environmentally caused & avoided impacts analysis and economic cost and benefits analysis.

Future needs include:

- (1) Maintaining a high landfill tax.
- (2) Tax on natural aggregates mining.
- (3) Public procurements for recycled aggregates (certification system).

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TABLE 13
Knowledge for evaluating resources in residues from buildings & infrastructure.

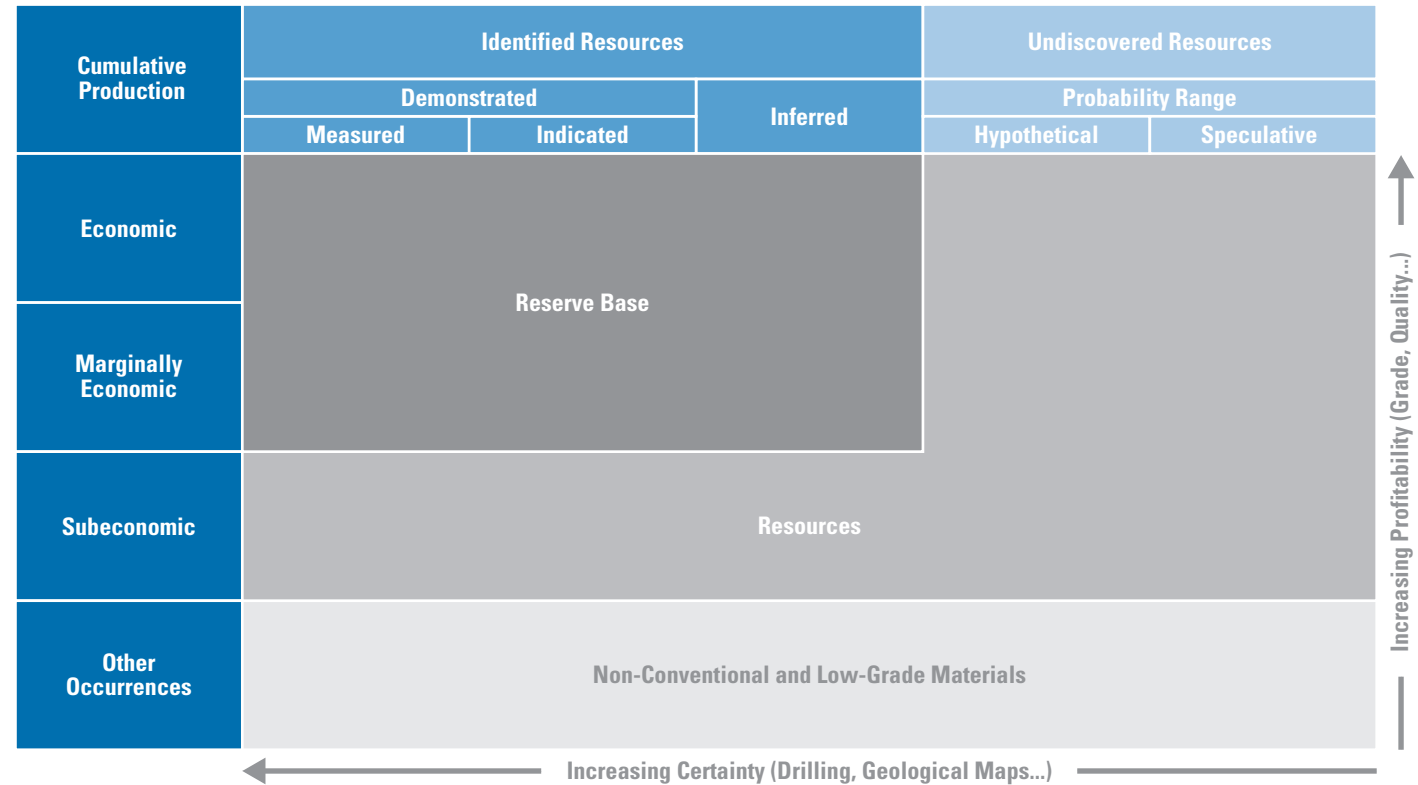
Factors	Current knowledge	Gaps	Needs
Technical recoverability	<ul style="list-style-type: none"> The technical recoverability of residues like concrete, mortar, brick and glass are mature. For advanced technologies, only laboratory results are available. 	<ul style="list-style-type: none"> The technical recoverability of wood and metal are less well studied. Lack of quality standards. Promote the practice of technical recoverability. 	<ul style="list-style-type: none"> The technical extraction of metals in building and infrastructure residues. Enabling more technological development, including advanced cleaning after crushing, advance sorting during demolition and construction activities and large-scale testing of technologies.
Economic recoverability	<ul style="list-style-type: none"> A primary driver for stakeholders to implement waste recycling lies in the economic benefits of residue recycling. Recycling is economically feasible and plays an important role in the improvement of environmental management 24 EU Member States have a landfill tax, as well as Norway and Switzerland. 4 EU Member States do not have a landfill tax (CY, DE, HR, MT). 	<ul style="list-style-type: none"> Investments in lower values application (low quality aggregates). The recycling costs would be significantly influenced by the transport distance, the construction site conditions, and the amount of waste to be recycled. The C&D waste materials cannot always be treated on time (high payback time), the recycled products cannot always be traded at the targeted prices, and the comparable high cost of selective demolition. 	<ul style="list-style-type: none"> Implement landfill tax and gate fee in all EU countries. Stable price of recycled residues. Optimized transportation to site.
Environmental impact	<ul style="list-style-type: none"> The most common environmental concerns of overland water, groundwater and soils are studied. Pollutant compositions of residues from buildings and infrastructure may vary, such as with heavy metals, organic matter, carbon, methane, sulfuret and hydrogen sulfide. The environmental and health risks associated with industrial C&D wastes have attracted wide concern. The life cycle thinking research provides a more comprehensive understanding of the impacts of waste management. Studies have been conducted on the mechanism of sorption, adsorption, release, immobilization, incineration, and pyrolysis to control and mitigate the pollution from residues from buildings and infrastructure. 	<ul style="list-style-type: none"> Some toxicity pollutants have been overlooked because the sample selection was limited to residential/commercial projects. Lack of life cycle database for C&D waste. 	<ul style="list-style-type: none"> The analysis of environmental impacts of residues from industry buildings and infrastructure. LCA Database for C&D waste.
Market acceptance	<ul style="list-style-type: none"> The quality of products was the primary influence on market acceptance. The market for recycled metals such as steel or aluminum is rapidly growing. The recycled aggregates of low-quality are supersaturated in market. 	<ul style="list-style-type: none"> Supersaturation of low-quality aggregates market. No standardization of products. Higher price of recycled materials Inelastic supply of recycled material. 	<ul style="list-style-type: none"> Shifting the awareness of people from cost to opportunity. Promoting environmental advantages (LCA in regulation). Certification. Improving government subsidies. Designing more efficiently.
Socio-political acceptance	<ul style="list-style-type: none"> Priority to reduce incineration & landfilling increases the quantity of recycled waste, but not quality. The combination of LCA and LCC can provide useful information to policy makers. 	<ul style="list-style-type: none"> Designers, constructors and residents don't know the quality of reused materials. 	<ul style="list-style-type: none"> Maintaining a high landfill tax. Tax on natural aggregates mining. Public procurements for recycled products (certification system). More LCA and LCC studies.

Residues from Buildings & Infrastructure

2.4.4 Classification

FIGURE 5
McKelvey diagram illustrating resource and reserve terminology derived from USGS [183].

Current knowledge



For the classification of natural stock resources, the so-called McKelvey diagram is used by the U.S. Geological Survey (USGS) to distinguish between resources, reserves, and other occurrences [183, 184] (see [FIGURE 5](#)). From this approach, resources are defined as the concentration of materials that meet certain minimal physical and chemical criteria that allow an extraction of raw materials from this resource. Reserves are defined as the part of the resources that are currently economically extractable. Other occurrences are defined as nonconventional and low-grade materials for which the feasibility of extracting these materials for future use is very low.

The resource classification scheme that has been developed by McKelvey [184] was applied to the subway network in Vienna to properly classify the materials [9]. The anthropogenic resource classification simply distinguishes between resources and other occurrences (not extractable). Resources were further classified depending on their age and appearance, which is a function of the life span of the building elements and associated materials. Other occurrences (not extractable) were found in those parts of the subway system where future demolition is highly unlikely. In practice, this accounts for the permanent structures with assumed life spans of far more than 100 years. This applies mainly to concrete and steel in load-carrying structures (bridges, tunnels) and bricks in cultural heritage buildings. Results were generated for the material quantities in the stock as well as for their economic secondary raw material value.

Residues from Buildings & Infrastructure

Knowledge Gaps

Although the classification of residues from buildings and infrastructure exists and can be used for other residues, the lack of studies for characterization and evaluation makes classification unfeasible from an “inventory perspective”.

Moreover, Lederer et al. [9] found that only a small portion (3%) of the total built-in material quantities will be potentially available as secondary raw materials in an appropriate time span and can thus be designated as a resource. However, the bulk of the materials have to be classified as other occurrences.

And the gaps also existed in:

- (1) conducting the economic evaluation of the extractability for different materials;
- (2) estimating the time of building and infrastructure elements containing the materials classified as resources reach their end of life; and
- (3) defining the materials that could be classified as valuable resource and other occurrences.

Needs

There’s no evidence of mining residues from buildings and infrastructure by using UNFC, meaning that specific policies and strategies must be implemented to foster the creation of a classification framework for the residues from buildings and infrastructure in the EU.

TABLE 14
Knowledge for classifying resources in C&D waste.

Current knowledge	Gaps	Future needs
<ul style="list-style-type: none"> Few studies are available on the classification of residues from buildings and infrastructure, except for the one using a simple resource/other occurrence classification from McKelvey for Vienna’s Subway networks. 	<ul style="list-style-type: none"> What are the economic values for different materials? When do the building and infrastructure elements containing the materials classified as resources reach their end of life? Which materials could be classified as valuable resource materials and what should be done with other residues? 	<ul style="list-style-type: none"> More case studies should be done on the classification of different residues from buildings and infrastructure. There should be a focus on materials like metal that are going to become relevant secondary raw materials. Future investigations should go into more detail by accessing the internal documents of the buildings and infrastructure by means of interviews with experts and site investigations.

Residues from Buildings & Infrastructure

3 CASE STUDIES

This section includes case studies for anthropogenic resource assessment. The selection of case studies follows two criteria:

- The resource assessment includes, apart from the characterization and evaluation steps, also a classification step. The classification either uses an established standard such as PERC and JORC or adopts existing classifications such as McKelvey and UNFC to anthropogenic resources.
- The case study includes material sources that are addressed by one of the MINEA WGs. In detail, the material source is either a residue from the extractive industry (WG2.1), a landfill (WG2.2), a residue from municipal solid waste incineration (WG3), or C&D waste from buildings and infrastructure (WG1).

3.1 Residues from extractive industries

In order to provide an overview of the current knowledge and missing information (gaps), MINEA WG 2.1 made a comprehensive collection of case studies (66 at the end of March 2020, [TABLE 15](#)) related to projects using mining and metallurgical residues as a source of minerals or materials.

The information available for the case studies analysis came from different document types. When the source is a technical or financial document (CRIRSCO/UNFC compliant Public Report, research paper, project, etc.) the information is usually more complete than the ones coming from media release documents, collections of case studies, presentations and so on.

It is worth noting that less than 1 in 4 of the case studies collected fall within Europe (24%). Briefly, from an analysis of the case studies, it can be noted that ([FIGURE 6](#), [FIGURE 7](#)):

- the most frequently addressed raw materials source is tailings (80,3%);
- the target material is usually only a previously mined mineral (71,2%). Nonetheless, due to the increasing demand for critical raw materials, there are many case studies targeting new minerals (28,8%) and an increasing number of projects dealing with the production of new materials using mining/metallurgical residues as an ingredient (6%);
- project development is mainly at prospection phase (75,8%), followed by research projects and operating plants (12,1% each);
- financing bodies are Mining Companies (71,2%), followed by Public Agencies (13,6%) and the EU (7,6%);
- most of the projects analysed deal with mineral recovery (80,3%), followed by a relevant number of case studies (7,6%), mostly from Spain and dating back to the end of '90s, dealing with Land recovery and Environmental Remediation;
- as might be expected, the most targeted audience (80,3%) is the Market (Investors, Mining Companies, Industry, etc.).

The information related to the assessment process (characterization, evaluation, classification) have been analysed according to the general framework defined by MINEA participants. The results are summarised in [TABLE 15](#).



FIGURE 6
Results of case studies analysis.
Sources, target materials and
project maturity level.

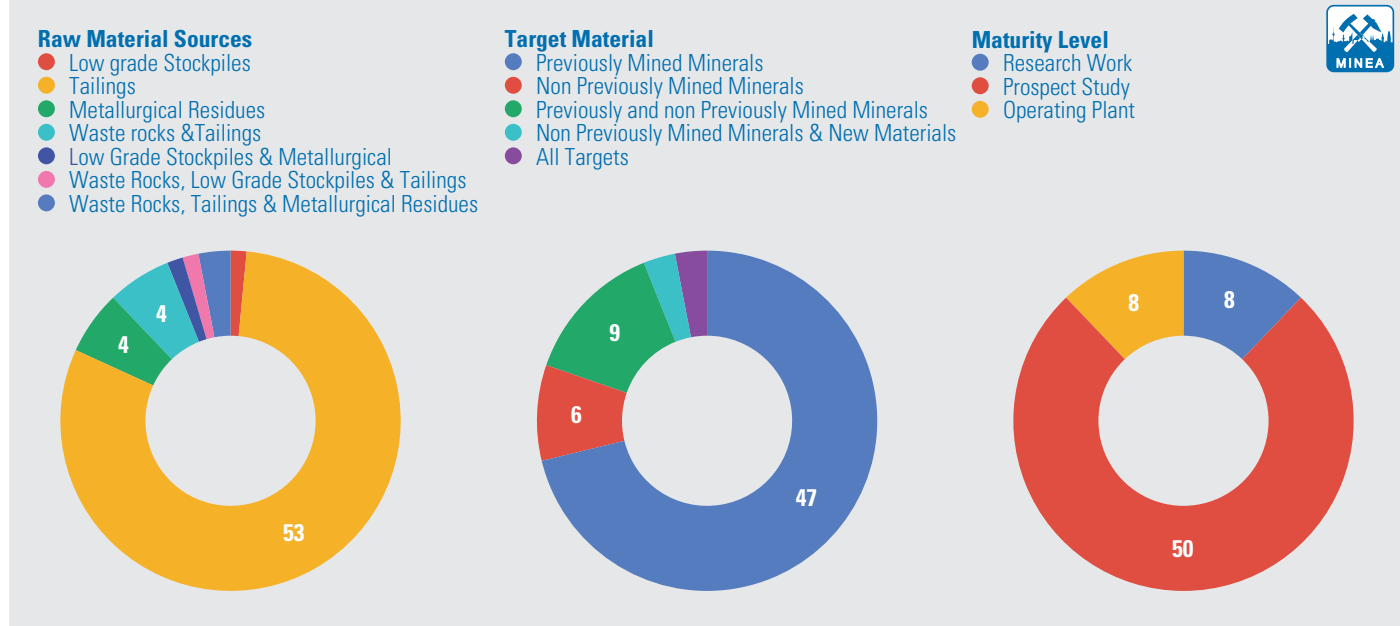
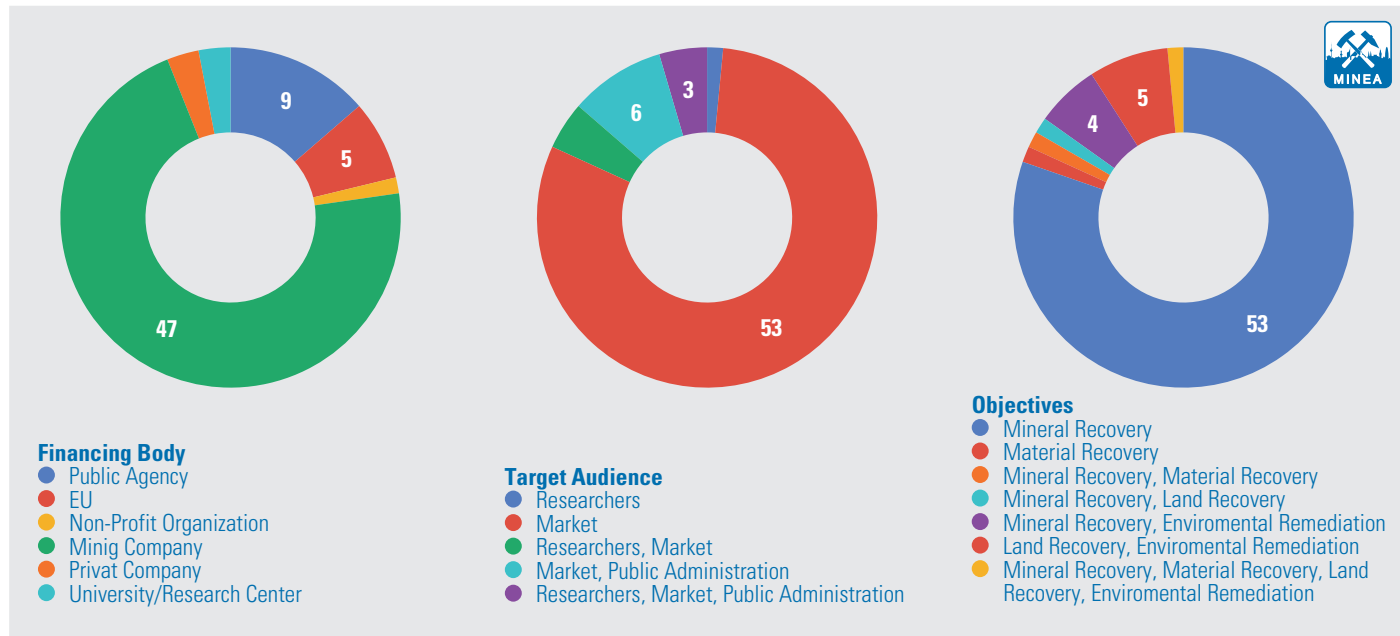


FIGURE 7
Results of case studies analysis.
Financing body, objectives and
target audience.

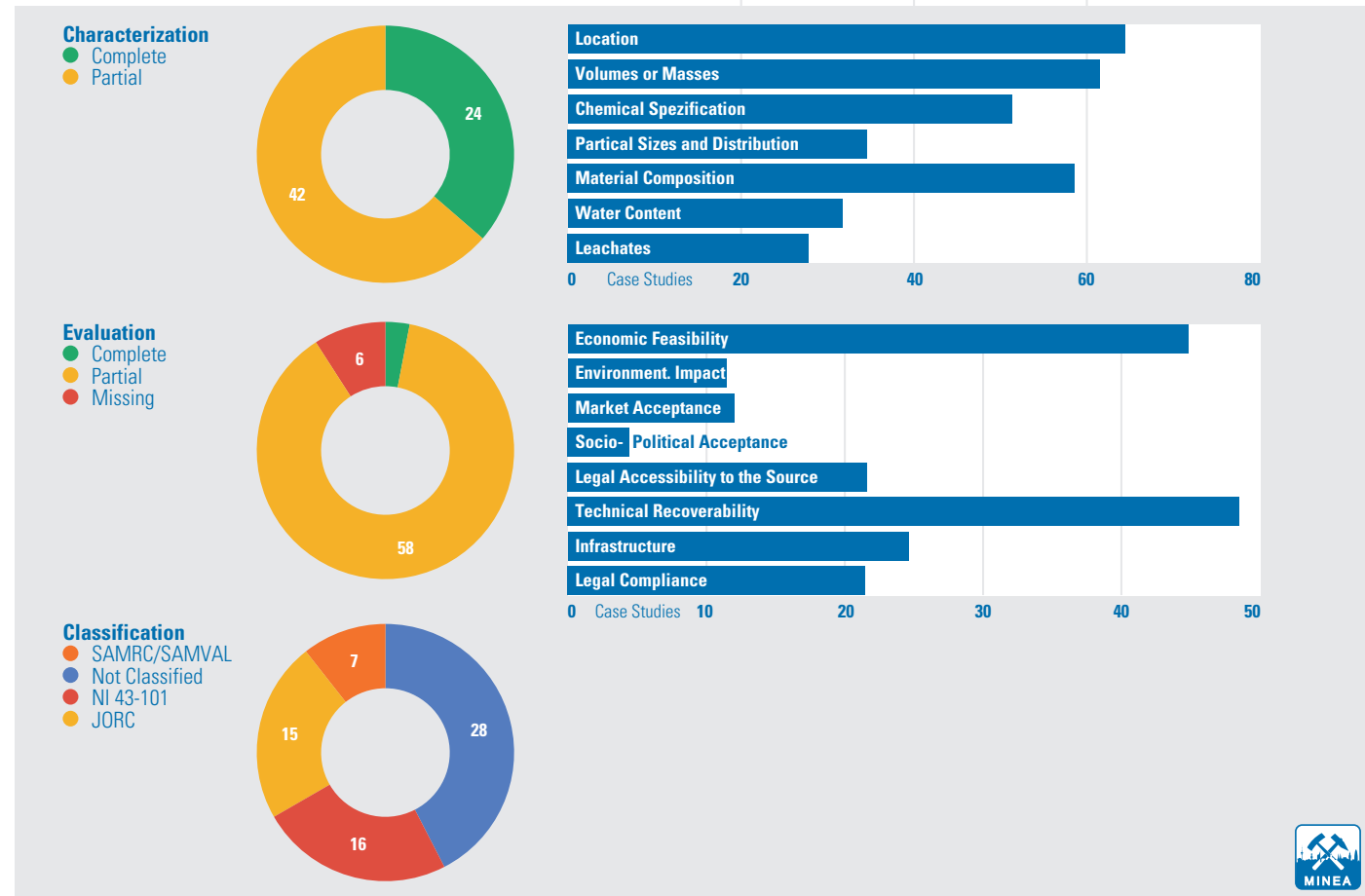


Case Studies
Residues from extractive industries

Briefly, from analysis of the case studies analysis it can be noted that (FIGURE 8):

- 2 of 3 case studies (63,6%) have a complete characterization. Missing information is mostly related to particle size and distribution, water content and leachates composition (taking into account that for some case studies information about water content and leachates were not missing but unnecessary);
- Only 2 case studies (3%) have a complete evaluation, which is completely missing for 6 case studies (9,1%, largely due to them being research works mostly focused on characterisation). Environmental impact, market acceptance and socio-political acceptance are mostly missing (information available, respectively, for 6,3%, 6,8% and 2,6% of case studies);
- Classification is never performed for almost half of the case studies considered (42,4%), and when available case studies are located outside Europe, except for one in the Czech Republic. There's no classification available according to PERC or UNFC standards.

FIGURE 8
Results of case studies analysis. Assessment stages and knowledge factors according to MINEA framework.



Case Studies
Residues from extractive industries

3.2 Residues from landfills

3.2.1 Case studies 1 to 4

The United Nations Framework Classification for Resources (UNFC) has been applied to four different landfill mining case studies in total, published by Winterstetter *et al.* [14] and by Winterstetter *et al.* [74]. To make the UNFC (which was originally designed for primary raw materials) applicable to historic landfills, the authors developed the methodology ECLAR for the evaluation (E) and classification (CL) of anthropogenic resources (AR) in line with the UNFC. Considering each landfill's specific characteristics, this methodology helps to decide whether a landfill site is to be mined or not, and under which boundary conditions. Relevant material and energy flows are first quantified in a Material Flow Analysis. Then a Discounted Cash Flow analysis is performed to evaluate the economic viability of mining the former landfills. Finally, the individual projects, where clean land and / or resources are recovered, are mapped onto the three UNFC axes "knowledge on composition and recoverable material / land share" (G-axis), "technical feasibility and project status" (F-axis) and "socioeconomic viability" (E-axis).

Based on the analysis, we present the results as follows:

- Landfill 1: For the Bornem landfill, focusing on both land and resource recovery, the evaluation from a public perspective yields a negative Net Present Value (NPV) of -17 Mio € (-44 €/ t of excavated waste), i.e., the project is currently not economically viable. A combination of increasing land prices and simultaneously decreasing sorting costs can realistically be reached to make the project economically viable in the near future.
- Landfill 2: The Turnhout case, performed as a land development project by a private investor without any resource recovery, turns out to be economically viable with a NPV of 392,000 € (8 €/ t of excavated waste).
- Landfill 3: The Zuienkerke remediation project is at too early a stage, i.e. key data and information are missing to determine its socio-economic viability.
- Landfill 4: For the REMO landfill-mining project in Belgium, the focus of the evaluation was set on technological options and economics, including an uncertainty and sensitivity analysis by using Monte Carlo simulations. 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.

To conclude, 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. Potential future price increases for non-ferrous metals or electricity might make the project economically viable. All four landfills result in different final classification results under UNFC.

3.2.2 Case study 5



This case study, done by Lederer *et al.* [7], classified the phosphorus quantities in Austria. The authors used the standard procedure for resource and reserve identification, evaluation, and classification of the U.S. Geological Survey for natural stock resources [184] to develop a framework for the evaluation of anthropogenic resources. Phosphorus (P) stocks in Austria were examined by screening the potential sources' landfills, steel and iron slags, building materials, water bodies, households and infrastructure and soils. The total P stock is about 1 Mio tons. About 10% of the 1 Mio. tons are extractable at sub-economic levels, with production costs 5–10 times above the market price for P fertilizer. 70% of P stocks are not technically extractable and 20% of such a low grade that recovery is not practically feasible. The researchers recommend complementing the screening by adding flow resources as well as more evaluation criteria such as technological, legal, environmental and societal aspects. Further, it is recommended that comprehensive extraction scenarios with the recovery of P and other potential valuable materials from one source be considered.

3.3 Residues from municipal solid waste incineration

3.3.1 Case study 1

According to our knowledge, researchers applied natural resources classification to anthropogenic resources in three case studies. Two studies focus on MSWI fly ash and one on MSWI bottom ash.

Fellner *et al.* [8] evaluated and classified the recovery of Zn (and other metals) from MSWI fly ash using the FLUREC Technology of leaching these metals with acidic washing water. Therefore, they first calculated the amount of MSW incinerated, determined the amounts of MSWI residues produced, retrieved data on their composition, and then performed an economic evaluation. These data are used then for the classification according to the McKelvey Box. Results show that some residues perform quite well and are marginally economically viable. These are MSWI filter ash separately collected from boiler ash in MSWI incineration with grate furnace and a wet-flue gas treatment. All other MSWI ash was far from being marginally economically viable. The evaluation was done for Europe.

3.3.2 Case study 2

Huber *et al.* [12] used the UNFC, which also includes the important point project feasibility. Other authors elaborated quite well what project feasibility means, namely that the recovery of minerals from MSWI fly ash is not legally allowed in Switzerland, thus an investigation of this technology and classification with UNFC would yield here 0 points, namely a very low rank as it is simply not possible [99]. In Austria, it is possible (in theory) [99], and this is also considered by Huber *et al.* [12]. Unlike Fellner *et al.* [8], Huber *et al.* [12] also included environmental impacts by LCA, making use of an earlier investigation on that topic [104]. Thus, this latter example is much more elaborated than the first and should thus be used as a guideline for future works on resource classification.

3.3.3 Case study 3



The third application, done by Mueller *et al.* [18], investigated the production of secondary raw materials from material recovery projects. The development of material recovery projects is a complex task. The retrospective view from 2003 to 2017 allows challenges to be identified and enablers to recover materials from municipal solid waste incineration (MSWI) bottom-ash in the Canton of Zürich. The authors focused on the recovery of wet and dry bottom ash and used the UNFC to communicate the different phases of recovery project development, including the phases exploration, non-commercial, potentially commercial and commercial. The findings of this research disclose the complex interactions during recovery project development. Researchers, industry stakeholders, legislators and policy makers are joining forces to identify the recovery potential as well as to implement recovery projects in reality. The recovery projects underwent a continuous change from the early stage of exploration to the final stage of production. The authors conclude with lessons learned for the development of future recovery projects beyond the Canton of Zurich and provide suggestions for applying the UNFC in the future.

3.4 Residues (C&D waste) from buildings and infrastructure

3.4.1 Case study 1



Lederer *et al.* [9] studied the recoverability of materials installed in Vienna's subway network. They quantified the built-in materials. The main part consists of minerals (12,000,000 t concrete, 300,000t gravel, and 250,000 t bricks); the metallic fraction consists of iron and steel (600,000t), copper (10,000 t) and aluminium (6,000 t). About 3 % of the materials have to be replaced within the next 100 years, and therefore have the potential to be extractable from those that have to remain in the subway. The authors used the McKelvey principles [185] to classify the resources in the Viennese subway network. With respect to the total material stock of about 13 Mio tons, about 3% per mass are classified as "resource" and 97% are classified as "other occurrences. The authors recommend further investigations to get more details on the composition of the resources, on the extraction of resources during maintenance and renewal works, and on the identification of hibernating material stocks.

3.4.2 Case study 2

The second application was by Mueller *et al.* [186]. These authors develop a framework that allows the establishment of analogies between geological and anthropogenic processes. These analogies were applied to three selected products (electric car, fluorescent lamp, fibre optic cable) containing rare earth elements (REE) to identify the most concentrated deposits in the anthropogenic cycle. The three anthropogenic deposits identified were characterised according to criteria such as “host rock”, “REE mineralisation” and “age of mineralisation”, i.e. regarding their “geological” setting. The results of this characterisation demonstrated that anthropogenic deposits have both a higher concentration of REE and a longer mine life than the evaluated geogenic deposit (Mount Weld, Australia). The results were further evaluated by comparison with the United Nations Framework Classification for Resources (UNFC), axis G, to determine the degree of confidence in the deposit quantities. The application of our approach to the three selected cases show a potential for recovery of REE in anthropogenic deposits.

3.4.3 Case study 3

Winterstetter *et al.* [187] used UNFC to classify recovery projects for permanent magnets in wind turbines.

In this case study two different options for 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). For simplicity reasons, NdFeB permanent magnets from wind turbines in Austria are assumed to be mined under current conditions within one year. 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 Net Present Values (NPV), with Scenario 1 (re-use) resulting in 6.2 million € and Scenario 2 (hydrometallurgy) in 5.3 million €. 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 re-use Scenario 1 are obviously the prices of permanent magnets (40 € /kg, [188]), and in Scenario 2 the prices of Nd, Pr and Dy, for which average prices between 2008 and 2015 were assumed.

In terms of “knowledge about 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 about 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 Stiesdal [189]. Siemens initiated a research project on the re-use of NdFeB magnets from hybrid cars and e-vehicles [190]. Therefore, the re-use of permanent magnets from wind turbines relates to 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” [191]. The REE extraction via hydrometallurgical methods (Scenario 2) refers to F4.2 as the technology necessary to recover some or all of these quantities is currently being researched [e.g. 192, 193], but no successful pilot studies have yet been completed” [191] 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.

More details can be found in Winterstetter *et al.* [187] and Winterstetter [13].

Case Studies

Residues from Buildings & Infrastructure

3.4.4 Case study 4

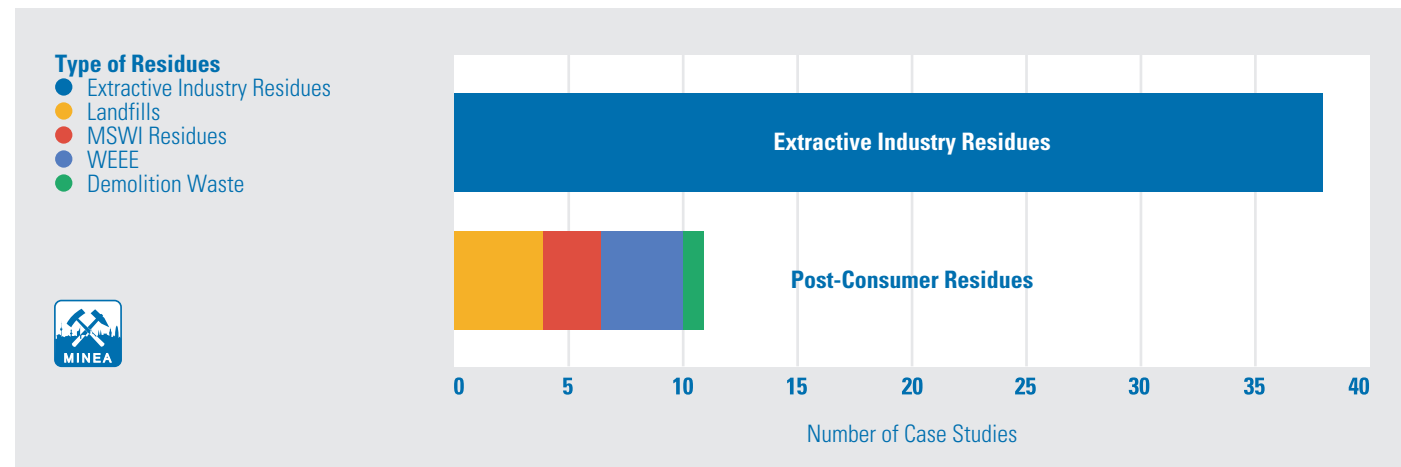
The fourth application was done by Mueller *et al.* [16]. These authors developed a consistent framework for evaluating raw material supply from both anthropogenic and geological sources. A method for concept extraction was applied to evaluate systematically the use of fundamental terms in the evaluation of raw material supply. The results have shown that 'availability' is commonly used in raw material supply evaluations, whilst other researchers suggest that raw material supply should be evaluated based on 'accessibility'. It was revealed that 'accessibility' actually comprises two aspects: 'availability' and 'approachability'. Raw material 'approachability' has not previously been explicitly addressed at a system level. A novel, consistent framework for evaluating raw material 'accessibility' was therefore developed. To demonstrate the application of the established framework, the authors evaluated the raw material supply of four rare earth element case studies. Three case studies are End-of-Life products (the anthroposphere) from Switzerland: (i) phosphors in fluorescent lamps, (ii) permanent magnets in the drive motors of electric cars and (iii) fibre optic cable. The fourth case study source is the Earth's crust (the geosphere): Mount Weld deposit in Australia. The framework comprises a comprehensive evaluation of six components relating to raw material mining and processing: their geological knowledge, eligibility, technology, economic, societal and environmental impacts. This framework is partly based on the United Nations Framework Classification for Resources (UNFC). The results show that metals are not considered to be fully accessible in any of the case studies due to a lack of necessary technologies and potential societal and environmental impacts. The framework presented here can serve as a starting point for the development of an evaluation framework.

3.5 Case studies - Synthesis

3.5.1 Review (details)

With respect to previous sections 3.1 to 3.4, we identified 49 case studies with resource assessments in combination with resource classification. Of these case studies, 76% cover extractive industry residues and 24% post-consumer residues (FIGURE 9).

FIGURE 9
Type of residues in case studies that estimate and communicate the viability of anthropogenic resource recovery.



We clustered the information⁴ from the case studies according to (1) the aim of the authors in performing the cases study, (2) the relation of case study to a stage in the resource development chain, (3) the scope of the study, (4) the procedure to estimate and communicate the viability of anthropogenic resource recovery, and the methods to (5) estimate and (6) communicate the viability of anthropogenic resource recovery:

(1) Aim and motivations: All case studies aim in common to communicate recoverable quantities in analogy to the mining sectors. In detail, the aim and motivations differ as follows:

a) Identifying future recovery potentials on regional levels [e.g. 7, 8, 9]. These studies define target materials (e.g. phosphorus, building materials), select potential sources (e.g. landfills, APC residues from MSW, subway systems), and estimate resource availability on regional levels (e.g. national, European). These studies do not consider site-specific factors of individual material recovery projects. The studies use the McKelvey box to classify the anthropogenic resources.

b) Developing site-specific material recovery projects and portfolios, respectively [e.g. 12, 74, 187]. These studies make a site-specific assessment of individual recovery projects.

- The landfill mining case studies have been developed to demonstrate the applicability of resource classification. Based on these studies, a web-based tool for screening numerous landfills have been developed [195], which helps authorities to assess resource availability of landfilled materials. The landfill mining case studies use the UNFC to categorize the quantities and classify the recovery projects, as well as McKelvey to screen recoverable quantities on a national level.
- The extractive industry case studies are used to report the resource availability to potential future investors. The MINEA WG2.1 identified 66 studies, of which about 60% used classifications such as JORC, SAMREC/SAMVAL or NI 43-101 to communicate resource availability.

c) Contrasting the resource availability from natural and anthropogenic sources, respectively [e.g. 7, 16].

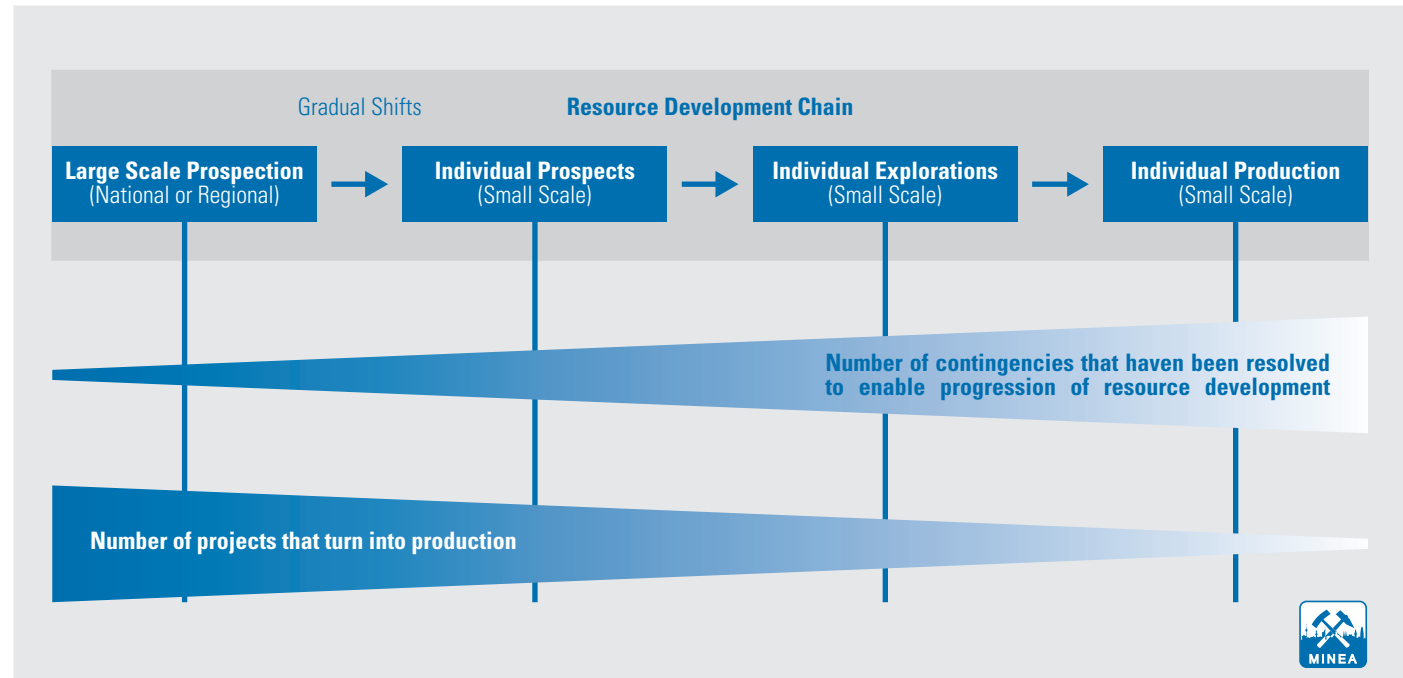
d) Providing lessons learned for the development of future recovery projects [18]. One study monitors the historic development of material recovery projects. The authors give a retrospective view on challenges and enablers during a real recovery project's development. The study concludes with lessons learned, which facilitates the development of recovery projects in other regions. The study used UNFC to communicate resource availability.

(2) Relating the case studies to stages in the resource development chain: We have defined, in analogy to the mining sector, 5 different stages in the resource development chain ([FIGURE 10](#)). The case studies review showed that each study can be related to one or more stages. In detail, the studies with the motivations (1) refer to stage 1 in [FIGURE 8](#). For instance, Fellner *et al.* [8] and Lederer *et al.* [7] use the findings to give recommendations on future individual prospects. The studies with motivation (2) start at a small-scale level either at the stage of prospection or exploration. These studies have been performed to either test methodologies for estimating and communicating the viability of resource recovery, or to inform recovery project developers on the recovery potential. These studies are not the consequence of large-scale prospection results (stage 1) and are not intended to identify recovery potentials in a region. The case study with motivation (4) is an untypical but interesting application of resource classification. In a retrospect, Mueller *et al.* [18] analysed the past stages of the site-specific recovery projects and thus reflects on the development from stages 2 to 5.

⁴Kral, Heuss-Aßbichler and Winterstetter (2020). Future availability of anthropogenic resources. Manuscript in preparation.

FIGURE 10

The resource development chain covers four stages. At each stage, resource assessment and classification can be applied to estimate recoverable material quantities from anthropogenic sources.



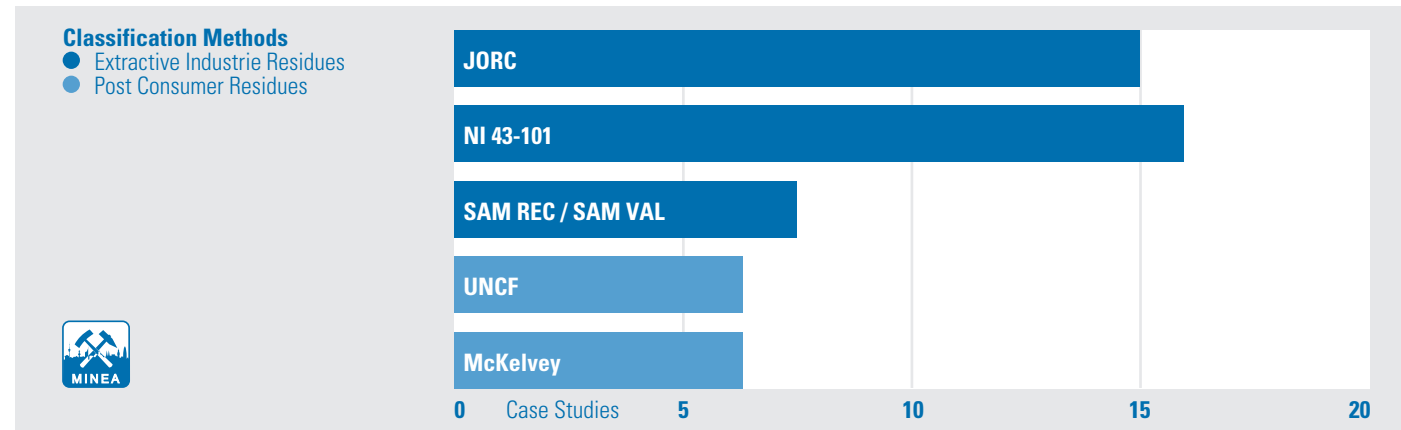
(3) Scope: In a spatial perspective, the case studies present estimates on site-specific, national and European levels. In a temporal perspective, the case studies estimate the accumulated production over the entire recovery project lifetime. Consequently, the estimated quantities refer to different time spans and cannot be aggregated. Up to now, there is no methodology in place to allow for aggregation. One option would be to estimate the quantities on a yearly basis and to sum up the annual quantities from different recovery projects.

(4) Procedure: The individual steps for estimating the viability of anthropogenic resource recovery vary among the case studies. For instance, Lederer *et al.* [7] used the steps “prospection”, “exploration”, “evaluation” and “classification”; Winterstetter *et al.* [74] prefixed to the Lederer *et al.* approach the step “pre-prospection”; Mueller *et al.* [18] used the steps “recovery project definition”, “characterization”, “evaluation”, “categorization and classification”; Maung *et al.* [10] presented a Sankey diagram for copper before using a “classification of secondary resources” step. In summary, a generic procedure is currently not established. To enable a harmonized approach in future case studies, we propose developing and using a generic procedure (see [24, section 3.1.2 and 3.2]).

(5) Methods to estimate the viability of anthropogenic resource recovery: In general, the estimations are based on two steps: characterization of the materials at the source (quantity, quality, location) and evaluation of the viability of material recovery. The viability of recovery is influenced by various factors such as economics, technological readiness or market access. We found that the individual case studies considered a limited number of factors, and some studies recommend including more factors in future studies.

(6) Methods to communicate the viability of anthropogenic resource recovery: The studies use different concepts, terms and principles to classify the anthropogenic resources (FIGURE 11). The case studies from the extractive industries use common standards such as JORC, SAMREC/SAMVAL and NI 43-101. Based on our knowledge, there is up to now no case study that converts these resource/reserve data into UNFC numbers. The case studies for landfill mining and MSWI residues used the UNFC and McKelvey, respectively. There are also studies that developed their own classification, inspired by McKelvey.

FIGURE 11
Classification methods used
in 49 case studies.



3.5.2 Review (summary)

The findings are summarized as followed:

- The case studies on **extractive industry residues** are driven by the need to gain investments to develop site-specific recovery projects. The *characterization* methods originate from those in the mining sector and provide information on the location, volumes or masses, chemical specification, particle size and distribution, material composition, water content and leachates (FIGURE 8). To *evaluate* the mineability, most studies consider economic and technical factors, some consider infrastructural and legal aspects, and comparably few studies consider environmental impacts, market acceptance and socio-political acceptance (FIGURE 8). To *classify* the resources, the studies used JORC, NI 43-101 and SAMREC/VAL.
- The case studies on **post-consumer residues** are motivated by communicating recoverable quantities in analogy to the mining sector, but not to gain investments. The case studies have been developed to inform stakeholders on recoverable quantities on project level, but also to compare the recoverability between natural and anthropogenic resources and to provide lessons learned from the historic development of recovery projects. The *characterization* methods are specified in dependence on the type of residue and can be retrieved from the individual case studies. They *evaluate* the recoverability, and most case studies considered economics and recovery technologies, while some also considered environmental impacts. Most case studies assumed that market and socio-political acceptance is guaranteed, and did not provide site-specific or regional circumstances on this matter. Nevertheless, several authors recommended moving towards a comprehensive understanding of recoverable quantities by considering additional recoverability factors such as environmental impacts, market acceptance and others. To *classify* the resources, the studies used McKelvey for regional assessments and UNFC to assess site-specific recovery projects.

Generally, the individual case studies generated resource classification data, but these data are hardly **comparable** and **summable**. We identified the following barriers:

- The intentions of the case studies vary. The intention determines the relation of the study along the resource development chain (e.g. prospective studies on regional level versus detailed explorative studies on site-specific level), and the backward- or forward-looking perspective.
- Different resource classifications (McKelvey, UNFC, JORC, NI 43-101, and SAMREC/SAMVAL) have been used. Each resource classification uses its own terms and principles. If it comes to specific resource classifications, the methods to classify the anthropogenic resource based on the assessment results vary.
- The recoverable quantities, a key outcome of classification, stand for the accumulated production quantities over the assumed lifetime of the recovery operation. As the lifetimes vary among the case studies, the recoverable quantities refer to different time spans.
- The recoverability is evaluated based on economic assessments and, in some cases, other factors such as environmental impacts. The case studies differ in terms of selecting factors and their assessment methods.

4 CONCLUSIONS AND OUTLOOK

Raw materials are fundamental for industrial production, the prosperity of nations and modern living standards. Raw material extraction from natural and anthropogenic sources is the starting point for establishing an integrative raw material value chain. Stakeholders all along the raw material value chains need reliable, consistent and transparent estimates on the future availability of resources. The future availability of natural resources and extractive industry residues is communicated based on resource classifications, compliant with JORC, NI 43-101, PERC and others. 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. This report traces the recent developments in anthropogenic resource classification and the necessary resource assessments. Resource assessments are future statements on recoverable material quantities from potential anthropogenic sources. The potential sources, highlighted in this report, are: extractive industry residues, landfills, municipal solid waste incineration residues, and construction and demolition waste. These four types of residues have been selected to map current knowledge levels, gaps and future needs in order to optimally assess the viability of anthropogenic resource recovery.

Resource availability is fundamental for industrial production, prosperity of nations and modern living standards.

Estimates on resource availability require a knowledge base. We mapped current knowledge levels, gaps and needs for 4 different residues.

Due to distinctive differences among the four types of residues and associated recoverability conditions, a comparative analysis is hardly possible at a high level of detail. But in common, the assessments combine information on the quantity, quality and location of resources (characterization step) and on resource recoverability depending

on technical and economic feasibility, environmental impacts, social and market acceptance, legal requirements and political willingness (evaluation step). Next, the characterization and evaluation results are linked to finally classify the anthropogenic resources. With respect to **current knowledge levels, gaps and needs**, the general findings and recommendations are:

- **Characterization:** Public statistics on waste generation and processing have insufficient levels of information to characterize resources in view of recoverability. Sufficient levels of information are generated and provided by plant operators, research institutions and networks. A research driven bottom-up approach enables **data collection of resources** in terms of material quality, quantity and location **and relevant social- and environmental-oriented parameters**. To bridge the gap between the research domain and public statistics, we suggest that an international research panel specify a set of relevant parameters for **continuous data monitoring** for each type of residue (as listed in the European waste catalogue). Such specifications profit from the current knowledge, gaps and needs in [TABLE 2](#), [TABLE 5](#), [TABLE 8](#), and [TABLE 11](#) as well as from other EU funded projects like ORAMA, Mintel4EU, Raw-FILL, and COCOON. Based on the specifications, EUROSTAT or an alternative institution could commission industrial umbrella organizations (e.g. CEWEP) and national authorities (e.g. environmental agencies, geological surveys) to **manage bottom-up data generation and reporting to the EU**. These data can be used to show the amount of resources potentially available for recovery and for harmonizing legislation on the recovery and utilization of raw materials from anthropogenic sources.
- **Evaluation:** Estimates of recoverable resources depends on site-specific factors and sectoral/national boundary conditions. The MINEA WGs identified the following factors as relevant: technical feasibility, economic viability, environmental impact, market acceptance, socio-political acceptance, and legal compliance. With respect to the factors, the current knowledge levels, gaps and needs are compiled in [TABLE 3](#), [TABLE 6](#), [TABLE 9](#), and [TABLE 13](#).

The case study review (section 3.5) shows that several authors recommend striving beyond economic and technical assessments to add more recoverability criteria such as environmental impacts, socio-political acceptance, and market acceptance. The call for more case studies is also motivated by methodological challenges that should be addressed in the future. Next, a large-scale pilot project should be developed to test in practice process chains for material recovery and measure environmental impacts. A screening of the legal situation for bottom-ash utilization in European countries has been performed. Analogous screenings are needed for other types of residues too. Such knowledge facilitates the harmonization of legislation across Europe and helps industry to optimize resource recovery.

We feel the need to identify methods and concepts to assess the parameters of certain anthropogenic resources in a uniform and thus comparable manner. These objectives can be pursued in pan-European research and capacity building projects.

- **Classification:** The characterization and evaluation results are used to classify the anthropogenic resources. With respect to extractive industry residues, the MINEA WG recommends systematically collecting data from industry, governments and NGOs and pooling them in public databases and mineral inventories (TABLE 4). With respect to post-consumer residues, the MINEA WGs recommend developing more resource-specific case studies (TABLE 7, TABLE 10, TABLE 14). First, to communicate the effects of different recovery technologies on the estimated recoverable quantities and, second, to develop a clear guidance for the multi-criteria assessment at the UNFC E-, F-, and G-Axes. Despite these resource-specific recommendations on classification, we feel, in a broader context, the need for the strategic development of new case studies.

Case studies on extractive industry residues will be carried out as long as there is a future potential for economic benefits to those instrumental in recovering resources and decreasing environmental impacts. We found 66 studies, but it is likely that many more are out there and will be developed in the future. The studies fulfill quality assurance standards and, to a wide extent, should attract investors from the financial market. In contrast, the development of case studies on post-consumer residues started in the academic domain in 2014. The intention at the beginning was to test the generation of classification data in analogy to the mining sector. We have collected 10 studies, all published in peer-reviewed journals, and reviewed them. They all reflect a cautious approach towards a comprehensive assessment and classification of anthropogenic resources, but also indicate the need for more case studies. We recommend developing new case studies in the following areas⁵:

Case studies demonstrate the generation of classification data. However, more case studies are needed.

- **To map and bridge to UNFC.** The case studies on extractive industry residues, at a rate of 60%, are compliant with JORC, SAMREC/VAL or NI 43-101. As the results from different classification are not aggregable and comparable, we suggest mapping and bridging the individual results to UNFC.
- **To develop new pioneering case studies.** Case studies are needed to address methodological challenges. For example, (1) how to apply the UNFC on a regional level (currently it is used on a site-specific project level only), (2) how to aggregate multiple environmental-socio-economic factors which affect the recoverability of resources into a single UNFC E-axis category, and to determine, for specific sources such as landfills or municipal solid waste incineration residues, the confidence of the estimates (UNFC G-Axis), and (3) how to integrate forecasting methods into resource assessments.

⁵More details on the development of new case studies are given in [MINEA Deliverable 3](#), section 3.1.

- **To update existing case studies.** Resource assessments and classifications make statements on future recoverable quantities under specific boundary conditions. We propose re-assessing the recoverable quantities of existing case studies if new characterization results are available or if the boundary conditions that effect the recoverability criteria change.
- **To develop a broad set of new case studies.** More case studies are needed to consider different target materials and potential sources, to test the effect of different recovery technologies on recoverable quantities, to go beyond economic and recovery technology assessment by considering more factors such as social or environmental impacts, site-specific capabilities and market acceptance of raw materials.

To conclude, this report maps the current knowledge, gaps and needs, and compiles case studies to estimate and communicate the viability of anthropogenic resource recovery. To make the estimates more reliable, transparent and comparable requires their integration into a sustainable resource management framework. Such management goes beyond actual estimates. It provides an environment with information systems, quality assurance systems, and supporting networks and institutional structures. Further details are presented in the MINEA Roadmap for Sustainable Management of Anthropogenic Resources [24].

The generation of classification data needs to be part of sustainable resource management.

ANNEXES

Annex A: Case studies from extractive industries	56...
Annex B: Compilation of knowledge base across WGs	65...
Annex C: History of the report's development	73...



ANNEX A

Case studies from extractive industries

TABLE 15: Cases studies related to minerals/materials recovery from mining/metallurgical residues.

Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Pb-Ag mine Auvergne	T	PM	Auvergne France	P	Partial	Partial	Not classified	Public agency	Mineral recovery	Market	[196]
Pb-Zn Carnoulés	T	PM NP	Carnoulés France	P	Partial	Partial	Not classified	Public agency	Mineral recovery	Market	[196]
W BRGM	T	PM NP		P	Partial	Missing	Not classified	Public agency	Mineral recovery	Market	[196]
Kasese Uganda	T	NP	Uganda	O	Partial	Partial	Not classified	Mining company	Mineral recovery	Researchers, Market	[197]
Panasqueira Mine	T	PM NP	Portugal	R	Partial	Missing	Not classified	University/Research Center	Mineral recovery	Researchers	[198]
Minera Valle Aconcagua	T	PM	Tiltil, Santiago, Chile	O	Complete	Partial	Not classified	Public agency	Mineral recovery	Researchers, Market	[199]
Red mud processing - Almásfűzitő	M	NP NM	Almásfűzitő (Hungary)	P	Partial	Partial	Not classified	Private company	Mineral recovery, Land recovery	Market, Public Administration	[200]
Ni-Cu-Co-PGE Campello Monti mine (Smart Ground Project)	WR T	PM NP	Campello Monti (Western Alps, Italy)	R	Partial	Partial	Not classified	EU	Mineral recovery	Researchers, Market, Public Administration	[201]
Zn-Pb Gorno mining district (Smart Ground Project)	WR T	PM NP NM	Lombardy, Northern Italy	R	Complete	Partial	Not classified	EU	Mineral recovery	Researchers, Market, Public Administration	[29]
Fe-Mn mine, India (TECO project)	WR T	PM NP NM	Joda West, Orissa-India	R	Partial	Partial	Not classified	EU	Mineral recovery	Researchers, Market, Public Administration	[202]
Ag Esmeralda tailings	T	PM NP	Chihuahua State, Mexico	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[203]

WR = waste rocks	LgS = low grade stockpiles	T = tailings	M = metallurgical residues	PM = previously mined mineral
NP = non-previously mined mineral	NM = new material	R = Research work	P = Prospect study	O = operating plant

Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Cr Zandfontein tailings retreatment project	WR T M	PM NP	Brits, North West Province of South Africa	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[204]
El Oro - Tlalpujahua Mining District	T	PM	El Oro de Hidalgo and Tlalpujahua de Rayón, Mexico	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[205]
Mytilineos Bauxite Residue Landfill (COP-Piles project)	M	NP	St. Athanasios, Gulf of Corinth, Greece	R	Partial	Missing	Not classified	Non-profit Organization	Mineral recovery, Material recovery	Researchers, Market	[206]
Precious Metal Resources of the Hellyer Mine Tailings	T	PM	Mount Read Volcanic Arc, W Tasmania	P	Partial	Partial	JORC	Mining company	Mineral recovery	Market	[207, 208]
Zimbabwe Lithium Company. Kamativi Lithium Tailings Project.	T	NP	Kamativi Project, Kamativi, Matabeleland North Province, Zimbabwe	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[209]
Mineral Resource Estimate for Golden Meadows Tailings	T	PM	Golden Meadows Project, Stibnite-Yellow Pine Mining District, Valley County, Idaho	P	Partial	Missing	NI 43-101	Mining company	Mineral recovery	Market	[210]
Mineral Resource Estimation. Elsa Tailings Project	T	NP	Elsa Tailings, Keno Hill mining camp, Yukon, Canada	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[211]
Choghart iron mine stockpiles	LgS	PM	Region of Bagfh, Iran	O	Complete	Missing	Not classified	Mining company	Mineral recovery	Market	[212]

WR = waste rocks	LgS = low grade stockpiles	T = tailings	M = metallurgical residues	PM = previously mined mineral
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Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Kipushi Cobalt-Copper Tailings Project	T	PM	Kipushi, Lubumbashi, Democratic Republic of Congo	P	Partial	Partial	JORC	Mining company	Mineral recovery	Market	[217]
Avino Mine	T	PM	Durango, Mexico	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[218]
Parral Tailings Project	T	PM NP	Chihuahua, Mexico	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[219], [220]
Bom-Gorhon tungsten mine tailings	T	PM	Petrovsky-Trans-Baikal area of Chita, Russia	P	Complete	Partial	Not classified	University/Research Center	Mineral recovery	Market	[221]
St. Athanasios BR storage facilities, AoG (Mud2Metal project)	M	NP NM	St. Athanasios, Gulf of Corinth, Greece	R	Complete	Partial	Not classified	EU	Mineral recovery, Material recovery, Land recovery, Environmental remediation	Market	[213]
Century Tailings Deposit	T	PM	Darimah, Queensland, Australia	P	Partial	Partial	JORC	Mining company	Mineral recovery	Market	[214]
Coto Wagner	T	PM	Molinaseca, Bembibre, León Spain	P	Complete	Partial	Not classified	Public Agency	Land recovery, Environmental remediation	Market	[215, 216]
Vivaldi Mine	T	PM	Molinaseca, Bembibre, León Spain	P	Complete	Partial	Not classified	Public Agency	Land recovery, Environmental remediation	Market, Public Administration	[215, 216]
Respina Sources	T	PM	Puebla de Lillo, León, Spain	P	Complete	Partial	Not classified	Public Agency	Land recovery, Environmental remediation	Market, Public Administration	[215, 216]

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NP = non-previously mined mineral	NM = new material	R = Research work	P = Prospect study	O = operating plant

Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Coto Valley	T	PM	Pola de Gordón, León, Spain	P	Complete	Partial	Not classified	Public Agency	Land recovery, Environmental remediation	Market, Public Administration	[215, 216]
Oencia	T	PM	Oencia, León, Spain	P	Complete	Partial	Not classified	Public Agency	Land recovery, Environmental remediation	Market, Public Administration	[215, 216]
Kipushi Cobalt-Copper Tailings Project	T	PM	Kipushi, Lubumbashi, Democratic Republic of Congo	P	Partial	Partial	JORC	Mining company	Mineral recovery	Market	[217]
Avino Mine	T	PM	Durango, Mexico	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[218]
Parral Tailings Project	T	PM NP	Chihuahua, Mexico	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[219], [220]
Bom-Gorhon tungsten mine tailings	T	PM	Petrovsky-Trans-Baikal area of Chita, Russia	P	Complete	Partial	Not classified	University/Research Center	Mineral recovery	Market	[221]
Penouta Mine	WR T	PM NP	Galicia, Spain)	P	Partial	Partial	Not classified	Mining company	Mineral recovery	Market	[28]
Beltrame Steel slags	M	NP	Vicenza, Italy	R	Complete	Partial	Not classified	Private company	Material recovery	Market	[222]
REFRAM	WR T M	PM	Worldwide	R	Complete	Partial	Not classified	EU	Mineral recovery, Environmental remediation	Market, Public Administration	[30]
Cleveland-Luina	T	PM	Tasmania, Australia	P	Partial	Partial	JORC	Mining company	Mineral recovery, Environmental remediation	Market	[223, 224]

WR = waste rocks	LgS = low grade stockpiles	T = tailings	M = metallurgical residues	PM = previously mined mineral
NP = non-previously mined mineral	NM = new material	R = Research work	P = Prospect study	O = operating plant

Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Horseshoe Lights	LgS T	PM NP	Western Australia, Australia	P	Partial	Partial	JORC	Mining company	Mineral recovery, Environmental remediation	Market	[223, 225-229]
Renison Bell	T	PM	Tasmania, Australia	P	Partial	Partial	JORC	Mining company	Mineral recovery	Market	[223, 230-232]
Woodlawn	T	PM	New South Wales, Australia	O	Complete	Partial	JORC	Mining company	Mineral recovery	Market	[223, 233, 234]
Mount Washington	T	PM	British Columbia, Canada	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[235]
Phoenix (Tremblay-Twin Creek-Pit)	T	PM	British Columbia, Canada	P	Partial	Partial	Not classified	Mining company	Mineral recovery	Market	[223]
Kakanda	T	PM	Congo - DRC	P	Partial	Partial	Not classified	Mining company	Mineral recovery	Market	[223]
Kolwezi-Kingamyambo	T	PM	Congo - DRC	O	Complete	Partial J	ORC	Mining company	Mineral recovery	Market	[223]
Chashinskoye	T	PM	Kazakhstan	P	Complete	Partial	JORC	Mining company	Mineral recovery	Market	[236, 237]
Staroye	T	PM	Kazakhstan	P	Complete	Partial	JORC	Mining company	Mineral recovery	Market	[236, 238]
Tishinsky	T	PM	Kazakhstan	P	Complete	Partial	JORC	Mining company	Mineral recovery	Market	[236, 237]
Mamut	T	PM	Malaysia	P	Partial	Partial	Not classified	Mining company	Mineral recovery	Market	[223]
El Tecolote (Reyna del Cobre)	T	PM	Mexico	P	Partial	Partial	Not classified	Mining company	Mineral recovery	Market	[236, 239]
Kombat	T	PM	Namibia	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[223, 240]

WR = waste rocks	LgS = low grade stockpiles	T = tailings	M = metallurgical residues	PM = previously mined mineral
NP = non-previously mined mineral	NM = new material	R = Research work	P = Prospect study	O = operating plant

Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Tsumeb West	T	PM	Namibia	P	Partial	Partial	JORC	Mining company	Mineral recovery	Market	[223]
Dizon-Bayarong	T	PM	Philippines	P	Partial	Partial	Not classified	Mining company	Mineral recovery	Market	[223]
Grootboom	T	PM	South Africa	P	Partial	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[223, 241]
Impala (Pt only)	T	PM	South Africa	P	Partial	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[223, 242]
Marikana	T	PM	South Africa	P	Partial	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[223]
Phoenix Chrome-PGE	T	PM	South Africa	P	Partial	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[223]
Rustenburg-Union	T	PM	South Africa	P	Partial	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[223]
C.O.D.-Kingman	T	PM	USA	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[223, 243]
Mopani-Nkana	T	PM	Zambia	P	Complete	Partial	JORC	Mining company	Mineral recovery	Market	[223, 238]
Zeehan	M	PM	Tasmania, Australia	P	Complete	Partial	JORC	Mining company	Mineral recovery, Environmental remediation	Market	[244, 245]
La Solucion	T	PM	Bolivia	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[236, 246]
Sable Zinc Kabwe	T	PM	Congo-DRC	P	Partial	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[247, 248]
La Encantada	T	PM	Mexico	P	Complete	Partial	NI 43-101	Mining company	Mineral recovery	Market	[249-251]
Namib	T	PM	Namibia	P	Complete	Partial	JORC	Mining company	Mineral recovery	Market	[236, 252]

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NP = non-previously mined mineral	NM = new material	R = Research work	P = Prospect study	O = operating plant

Title	RM Source	Target materials	Geographical location	Maturity level	Characterization	Evaluation	Classification	Financing body	Objectives	Target audience	Reference
Santander	T	PM	Peru	P	Partial	Partial	NI 43-101	Mining company	Mineral recovery	Market	[247, 253]
Ruashi mine	T	PM	Congo - DRC	O	Complete	Partial	SAMREC/ SAMVAL	Mining company	Mineral recovery	Market	[247, 248]
Chvaletice Manganese Project	T	NP	Chvaletice, Czech Republic	P	Complete	Complete	NI 43-101	Mining company	Mineral recovery	Market	[254]
Paracatu mine	T	PM	Brazil	O	Complete	Complete	NI 43-101	Mining company	Mineral recovery	Market	[255]
Kalengwa Copper Project	T	PM	Zambia	P	Partial	Missing	Not classified	Mining company	Mineral recovery	Market	[256]

WR = waste rocks	LgS = low grade stockpiles	T = tailings	M = metallurgical residues	PM = previously mined mineral
NP = non-previously mined mineral	NM = new material	R = Research work	P = Prospect study	O = operating plant

ANNEX B

Compilation of knowledge base across WGs

TABLE 16: Characterization – overview of the four MINEA working groups' (WG) findings: residues from extractive industries (WG2.1), landfills (WG2.2) and municipal solid waste incineration (WG3), and construction & demolition waste (WG1).

WG	Factors	Current knowledge	Gaps	Needs
WG2.1	–	<ul style="list-style-type: none"> National mining waste inventories with environmental parameters (e.g., potentially toxic elements). 	<ul style="list-style-type: none"> Information in national mining waste inventories (e.g., critical elements occurrence and grade, contents in alkali ions, silicon, organic substances, etc.) useful to assess the potential for minerals and materials recovery. Harmonization of information in European countries. 	<ul style="list-style-type: none"> Access to organized and detailed reports with information needed for mineral and materials recovery. National inventory information in English.
WG2.2	<p>Site-specifics:</p> <ul style="list-style-type: none"> Information about landfill geometry, size, installed landfill technology, time of operation, content of main waste types, etc. is often available on the regional level in different databases and records (e.g. landfill surveys). For specific sites, logbooks and the like could give valuable information about the material content. There are also on-going initiatives to develop regional and temporal archetypes for landfills in this respect. Detailed characterization of the material composition and occurrence of hazardous waste only exists for a few, specific sites in Europe. <p>Local/regional context:</p> <ul style="list-style-type: none"> Information about land use plans, aftercare and remediation needs, climate conditions (e.g. precipitation), vulnerability and risks of surrounding environment (e.g. flooding, sensitive areas), landfill void capacities and needs, existing transport as well as energy and waste infrastructures is typically available but in a range of different databases and records. 	<ul style="list-style-type: none"> A lack of knowledge about the detailed material composition of landfills (concentration of different materials, levels of degradation, geometry, heterogeneity in terms of waste types and hazards). Lack of documentation and knowledge about the occurrence of illegal dumping. Lack of consistent data and information about landfills and their local and regional context. 	<ul style="list-style-type: none"> Development of coherent databases for facilitating a step-by-step prospecting procedure for LFM, where high potential sites, both in terms of their site-specifics and local context, can be identified. Development of reliable methods for sampling and characterization of the material content in heterogenic landfills. Conceptual models for landfills that distinguish between their different compartments could facilitate the sampling and characterization of such sites. What site-specific information and data is actually available for “new” landfills governed under the Landfill Directive? 	<p>Site-specifics:</p> <ul style="list-style-type: none"> Information about landfill geometry, size, installed landfill technology, time of operation, content of main waste types, etc. is often available on the regional level in different databases and records (e.g. landfill surveys). For specific sites, logbooks and the like could give valuable information about the material content. There are also on-going initiatives to develop regional and temporal archetypes for landfills in this respect. Detailed characterization of the material composition and occurrence of hazardous waste only exists for a few, specific sites in Europe. <p>Local/regional context:</p> <ul style="list-style-type: none"> Information about land use plans, aftercare and remediation needs, climate conditions (e.g. precipitation), vulnerability and risks of surrounding environment (e.g. flooding, sensitive areas), landfill void capacities and needs, existing transport as well as energy and waste infrastructures is typically available but in a range of different databases and records.

(continuation of table 16 see following page)

WG	Factors	Current knowledge	Gaps	Needs
WG3	<ul style="list-style-type: none"> Quantities of waste incinerated. Waste incineration and APC technology. Quantities of bottom-ash for most MSWI plants in Europe. Rough composition and other parameters of bottom ashes and APC residues including fly ash. 	<ul style="list-style-type: none"> Specification of wastes incinerated. Differentiation between industrial co-combustion and MSWI. Clear distinction between different types of MSWI technology (the latter including APC technology – detailed description). Systematic collection and management of composition-related and other parameters data as most of the data presently comes from selected literature sources. 	<ul style="list-style-type: none"> Enabling national authorities or other stakeholders to systematically collect and manage the most important data on waste incineration and the residues produced from it. 	<ul style="list-style-type: none"> Quantities of waste incinerated. Waste incineration and APC technology. Quantities of bottom-ash for most MSWI plants in Europe. Rough composition and other parameters of bottom ashes and APC residues including fly ash.
WG1		<ul style="list-style-type: none"> Quantities of residues generated from buildings. Different waste quantification method. Main waste composition from buildings and infrastructure. 	<ul style="list-style-type: none"> Lack of quantification on infrastructure. Lack of actual data. Lack of verification. Lack of residues from new construction and renovation stages 	<ul style="list-style-type: none"> Deepened knowledge about the amount, quality, location, and time availability of residues from buildings and infrastructure. More studies should be done across all stages of residues generation (new construction, renovation and demolition).

TABLE 17: Evaluation – overview of the four MINEA working groups' (WG) findings: residues from extractive industries (WG2.1), landfills (WG2.2) and municipal solid waste incineration (WG3), and construction & demolition waste (WG1).

WG	Factors	Current knowledge	Gaps	Needs
WG2.1	–	<ul style="list-style-type: none"> • Knowledge available in technical and research reports. • Information regarding policies and regulations are accessible (Although sometimes conflicting). • Residue deposit ownership available. 	<ul style="list-style-type: none"> • Databases and maps (e. g. transport, energy and water supply) in remote areas. • Partial or missing information (mainly with regard to the socio-political acceptance, but also in terms of environmental impact, market acceptance, technical recoverability, infrastructure, legal compliance, legal accessibility to the source and economic feasibility). 	<ul style="list-style-type: none"> • Harmonization of policies and regulations at National and EU level.
WG2.2	Technical recoverability	<ul style="list-style-type: none"> • The LFM process chains studied typically involve mature technologies but their performance in processing previously landfilled waste is often unknown. • There have been a few pilot tests on the processing of landfilled waste involving standard material processing units. <p>For advanced technologies, only laboratory results are available.</p>	<ul style="list-style-type: none"> • Which materials could be recovered from landfills and at what quality levels? • How could efficient and effective excavation and material processing schemes be developed? <p>How could landfills be optimally prepared for mining?</p>	<ul style="list-style-type: none"> • Well planned and large-scale pilot projects involving testing, monitoring and comparisons of the performance of different processing lines. • Development of models for different processing lines in terms of material transfer coefficients and resource quality estimates. • Establishment of platforms for facilitating knowledge sharing and networking among LFM practitioners. <p>Dissemination of good practices for landfill mining</p>
	Economic recoverability	<ul style="list-style-type: none"> • Principle understanding of which site-, project- and system conditions and interactions influence the economic outcome in different situations and settings. • System conditions should guide selection of landfill sites for mining and the corresponding project set-ups. <p>Resource recovery alone cannot justify such projects financially. The local and regional setting is of higher relevance for the selection of landfills than their material content.</p>	<ul style="list-style-type: none"> • A lack of in-depth knowledge about what makes specific projects economically viable. • Influence and potential of different financing mechanisms (bankability, loan and investment risks) & business models (timing and distribution of costs & benefits among actors). <p>Influence and potential of internalizing socio-economic impacts into the project economy (e.g. future carbon tax systems).</p>	<ul style="list-style-type: none"> • Development of certified and specialized actors in LFM technology and know-how to enable accumulation of knowledge and gradual improvements in cost-efficiency. • More in-depth reviews of previous projects displaying economic profitability. • Development of methods to assess socio-economic impacts and social consequences of LFM.

(continuation of table 17 see following pages)

WG	Factors	Current knowledge	Gaps	Needs
	Environmental impact	<ul style="list-style-type: none"> Principle understanding of which site-, project- and system conditions and interactions influence the climate impact in different situations and settings. The most important factors pertaining to climate impact occur on the site level and are related to methane generation and management. At present, local vulnerability & pollution risks typically drive the environmental motivation for landfill rehabilitation projects. 	<ul style="list-style-type: none"> What about all other types of positive and negative environmental & health impacts of LFM projects occurring on the global, regional and local levels? What are the long-term and short-term impacts of LFM when it comes to ecotoxicity & other hazards and risks? A need for improved communication of results from conducted assessments of LFM. 	<ul style="list-style-type: none"> Testing & monitoring of what actually happens in real-life projects in terms of emissions and the fate and transport of various pollutants. There is also a need to develop a better understanding about the long-term environmental impacts of landfills.
	Market acceptance	<ul style="list-style-type: none"> Current regulatory and gate requirements for metals, RDF and various aggregates extracted from landfills are difficult to fulfil. Metals are typically salable but in terms of low-quality categories. 	<ul style="list-style-type: none"> Is there any market demand and need for material and energy carriers extracted from landfills? 	<ul style="list-style-type: none"> Reviews of current market structures and commodities of different industrial sectors to better understand supply and demand dynamics and contracts, resource competition and price-settings for secondary resources. Applied research on upgrading of materials from landfills (producer) & technical and organizational measures to facilitate utilization (user).
	Socio-political acceptance	<ul style="list-style-type: none"> When re-opened, old issues related to the operation of landfills and NIMBY seem to re-occur. Geo-political changes causing supply risks or higher resource prices could increase political acceptance. However, a LFM project needs to result in an improved local environment. 	<ul style="list-style-type: none"> Trade-offs between global, regional and local impacts and the effects of LFM. Low awareness of what LFM is and its potential benefits make it difficult to convince politicians and the public. What is the role of landfills and LFM in a circular economy and in relation to the new waste framework? What should we use previously deposited materials and energy resources for? 	<ul style="list-style-type: none"> Demonstration projects validating feasibility and assessing and communicating environmental and societal impacts. Potential and feasibility of policy interventions, targeting resource circulation, sustainable landfill management and related hazards and risks.

(continuation of table 17 see following pages)

WG	Factors	Current knowledge	Gaps	Needs
	Legal compliance	<ul style="list-style-type: none"> • Landfill legislation only applicable for deposits from 1990s. • The fact that current legislation advocates final closure and aftercare of landfills causes several barriers for LFM. • Ownership and accessibility issues related to landfills influence the potential of LFM. 	<ul style="list-style-type: none"> • How does current legislation apply to LFM? • Is LFM to be regulated under the legislative framework for remediation or recycling? • Such uncertainties make it difficult for actors to foresee the outcome of investments in such projects (e.g. mining tax, landfill tax, availability of public funding, requirements as regards safety and work environment, etc.). 	<ul style="list-style-type: none"> • Training authorities and convincing politicians that LFM could be a viable alternative for managing waste deposits. • Specific LFM regulations for permitting, operation and project closure. • Acquisition of knowledge on how to book-keep materials recycled in LFM projects in waste statistics and proper reporting on the fulfilment of recycling targets.
WG3	Technical recoverability	<ul style="list-style-type: none"> • Influence of waste composition. • Influence of waste incineration technology. • Influence of APC system. • Influence of bottom ash discharge system. 	<ul style="list-style-type: none"> • Selected recovery of a large number of different elements. • Recovery of metals from bottom ash while, at the same time, not destroying the mineral fraction completely (to make better use of the latter). • Technology for the upconcentration of metals (chemical, thermal, biochemical, a combination). • Energy consumption (e.g. for salt recovery). 	<ul style="list-style-type: none"> • Enabling more research and technological development, including large-scale testing of technologies at different technological readiness levels.
	Economic recoverability	<ul style="list-style-type: none"> • General prices for raw materials • Some general and rough costing positions (e.g. price for energy, consumables like CaOH, etc.). 	<ul style="list-style-type: none"> • Detailed prices of commodities depending on the quality of the raw material produced and the market (i.e. country – relevant for locally and nationally traded goods like most bulk mineral construction materials). • Alternative disposal prices, i.e. for landfilling. • Incineration costs. • Land costs. 	<ul style="list-style-type: none"> • Enabling authorities and other stakeholders to provide the information if required.
	Environmental impact	<ul style="list-style-type: none"> • Environmental impacts of different technologies (in general). 	<ul style="list-style-type: none"> • Long-term emissions from MSWI fly ash and bottom ash, i.e. from landfills and, if applied, in construction. 	<ul style="list-style-type: none"> • More research on long-term emissions, e.g. continuous monitoring of leaching of pollutants from incineration bottom ash in roads or in concretes/cement.
	Market acceptance	–	–	–
	Socio-political acceptance	–	–	–

(continuation of table 17 see following pages)

WG	Factors	Current knowledge	Gaps	Needs
	Legal compliance	<ul style="list-style-type: none"> • Legal situation concerning the use of bottom ash in road construction in most European countries, including testing procedures for environmental compliance. • Partly, some technical compliance is present as well. 	<ul style="list-style-type: none"> • Overview of the legal situation concerning the utilization of incineration bottom and fly ash in concretes, cements or salts from these ashes as deicing agents. • A lot of the information is not openly published, and very often only in the national language. However, this should not be a problem if national experts from that country are always be involved in resource classification. 	<ul style="list-style-type: none"> • Countries that may want to encourage industry to recover more incineration ash in construction materials or as salts should develop guidelines based on an informed decision (which again requires research and large-scale long-term experiments).
WG1	Technical recoverability	<ul style="list-style-type: none"> • The technical recoverability of residues like concrete, mortar, brick and glass are mature. • For advanced technologies, only laboratory results are available. 	<ul style="list-style-type: none"> • The technical recoverability of wood and metal are less well studied. • Lack of quality standards. • Promote the practice of technical recoverability. 	<ul style="list-style-type: none"> • The technical extraction of metals in building and infrastructure residues. • Enabling more technological development, including advanced cleaning after crushing, advance sorting during demolition and construction activities and large-scale testing of technologies.
	Economic recoverability	<ul style="list-style-type: none"> • A primary driver for stakeholders to implement waste recycling lies in the economic benefits of residue recycling. • Recycling is economically feasible and plays an important role in the improvement of environmental management. • 24 EU Member States have a landfill tax, as well as Norway and Switzerland. 4 EU Member States do not have a landfill tax (CY, DE, HR, MT). 	<ul style="list-style-type: none"> • Investments in lower values application (low quality aggregates). • The recycling costs would be significantly influenced by the transport distance, the construction site conditions, and the amount of waste to be recycled. • The C&D waste materials cannot always be treated on time (high payback time), the recycled products cannot always be traded at the targeted prices, and the comparable high cost of selective demolition. 	<ul style="list-style-type: none"> • Implement landfill tax and gate fee in all EU countries. • Stable price of recycled residues. • Optimized transportation to site.

(continuation of table 17 see following pages)

WG	Factors	Current knowledge	Gaps	Needs
	Environmental impact	<ul style="list-style-type: none"> The most common environmental concerns of overland water, groundwater and soils are studied. Pollutant compositions of residues from buildings and infrastructure may vary, such as with heavy metals, organic matter, carbon, methane, sulfuret and hydrogen sulfide. The environmental and health risks associated with industrial C&D wastes have attracted wide concern. The life cycle thinking research provides a more comprehensive understanding of the impacts of waste management. Studies have been conducted on the mechanism of sorption, adsorption, release, immobilization, incineration, and pyrolysis to control and mitigate the pollution from residues from buildings and infrastructure. 	<ul style="list-style-type: none"> Some toxicity pollutants have been overlooked because the sample selection was limited to residential/commercial projects. Lack of life cycle database for C&D waste. 	<ul style="list-style-type: none"> The analysis of environmental impacts of residues from industry buildings and infrastructure. LCA Database for C&D waste.
	Market acceptance	<ul style="list-style-type: none"> The quality of products was the primary influence on market acceptance. The market for recycled metals such as steel or aluminum is rapidly growing. The recycled aggregates of low-quality are supersaturated in market. 	<ul style="list-style-type: none"> Supersaturation of low-quality aggregates market. No standardization of products. Higher price of recycled materials. Inelastic supply of recycled material. 	<ul style="list-style-type: none"> Shifting the awareness of people from cost to opportunity. Promoting environmental advantages (LCA in regulation). Certification. Improving government subsidies. Designing more efficiently.
	Social political acceptance	<ul style="list-style-type: none"> Priority to reduce incineration & landfilling increases the quantity of recycled waste, but not quality. The combination of LCA and LCC can provide useful information to policy makers. 	<ul style="list-style-type: none"> Designers, constructors and residents don't know the quality of reused materials. 	<ul style="list-style-type: none"> Maintaining a high landfill tax. Tax on natural aggregates mining. Public procurements for recycled products (certification system). More LCA and LCC studies.

TABLE 18: Classification – overview of the four MINEA working groups' (WG) findings: residues from extractive industries (WG2.1), landfills (WG2.2) and municipal solid waste incineration (WG3), and construction & demolition waste (WG1).

WG	Current knowledge	Gaps	Needs
WG2.1	<ul style="list-style-type: none"> Specifications (reporting standards) for mining/metallurgical residue classification as a potential source of raw materials already exist, providing reliable and transparent information for potential investors. 	<ul style="list-style-type: none"> Reporting on non-sales production and non-technical and external factors, such as social, legislative and environmental factors (needed for resource managers and policy makers). Lack of information on resource characterization and evaluation. 	<ul style="list-style-type: none"> Reliable mineral inventory to underpin mineral policies. Incorporation of data from governments, NGOs as well as industry into databases and mineral inventories.
WG2.2	<ul style="list-style-type: none"> Previous studies demonstrate that it is possible to classify landfilled resources. within the UNFC framework, but selective approaches were used to grade the different axes. This raises concerns about issues related to simplification and ambiguity. 	<ul style="list-style-type: none"> In which axes (F&E) should different aspects and parameters currently be accounted for? Where to put drivers for LFM beyond what is possible to quantify economically using NPV? How to handle the relative importance of different aspects & parameters within each axis. There is at present an ambiguity regarding the interpretation of the grading scales for the different axes. If there are factors beyond the business economics, the question is how to deal with multiple factors on the E-Axis. 	<ul style="list-style-type: none"> UNFC should develop best practices for the F and E axes through case studies. Assess the feasibility of inserting an intermediate weighing step making the perceived importance of different aspects for the grading of the different axes explicit. Such weighing should be done from the user and decision-maker perspective. Development of detailed grading scales, specifically tailored for landfills and LFM projects (e.g. conceptual model for degree of confidence – G axis, acknowledge lack of practical experience in F-axis, internalize different societal values in the E-axis).
WG3	<ul style="list-style-type: none"> A few case studies are available on some recovery options. 	<ul style="list-style-type: none"> On many recovery options and secondary raw materials, there are no applications of McKelvey, UNFC, or other standards, making it difficult to compare between different ores and raw material recovery options. 	<ul style="list-style-type: none"> More case studies should be done on different MSWI ash streams with different raw materials recovered and technologies applied.
WG1	<ul style="list-style-type: none"> Few studies are available on the classification of residues from buildings and infrastructure, except for the one using a simple resource/other occurrence classification from McKelvey for Vienna's Subway networks. 	<ul style="list-style-type: none"> What are the economic values for different materials? When do the building and infrastructure elements containing the materials classified as resources reach their end of life? Which materials could be classified as valuable resource materials and what should be done with other residues? 	<ul style="list-style-type: none"> More case studies should be done on the classification of different residues from buildings and infrastructure. There should be a focus on materials like metal that are going to become relevant secondary raw materials. Future investigations should go into more detail by accessing the internal documents of the buildings and infrastructure by means of interviews with experts and site investigations.

ANNEX C

History of the report's development

This report has been developed in close cooperation among MINEA Working Group Members.

On 24-25 January 2019, the **kick-off event “Knowledge base for Anthropogenic material resources and reserves I”** was held in Prague. The Workshop basically covered two interactive sessions, one for discussing the mission of generating the knowledge base and one for getting an overview of the current knowledge of each WG. The following experts contributed to this workshop (in alphabetical order): Teresa Carvalho (Portugal), Carlo Cormio (Italy), Christina Ehlert (Luxembourg), Soraya Heuss-Aßbichler (Germany), Jan Hrdlička (Czech Republic), Florian Huber (Austria), Dagmar Juchelkova (Czech Republic), Ulrich Kral (Austria), Joakim Krook (Sweden), Marek Kucbel (Czech Republic), Mohamed Osmani (United Kingdom), Michal Šafář (Czech Republic), Barbora Švédová (Czech Republic), Michal Syc (Czech Republic), Katalin Szabo (Hungary), Paola Villoria Sáez (Spain), Eddy Wille (Belgium), Gürkan Yildirim (Turkey). The minutes of this workshop are available online [25]. Based on the minutes, the 1st version Initial Draft Report was developed, including title, draft structure, figures and expected content.

On 20 March 2019, the follow up **Workshop “Knowledge base for Anthropogenic material resources and reserves II”** was held in Brussels. The title, structure and expected content of the report was discussed. The following experts contributed to this workshop (in alphabetical order): Teresa Carvalho (Portugal), Carlo Cormio (Italy), Christina Ehlert (Luxembourg), Emilija Fidanchevski (Croatia), Soraya Heuss-Aßbichler (Germany), Ulrich Kral (Austria), Joakim Krook (Sweden), Sandra Mueller (Switzerland), Mohamed Osmani (United Kingdom), Danielle Sinnott (United Kingdom), Nemanja Stanisavljevic (Serbia), Julia Stegemann (United Kingdom), Katalin Szabo (Hungary), Patrick Wäger (Switzerland), Eddy Wille (Belgium), Andrea Winterstetter (Belgium), Gorazd Zibret (Slovenia). The minutes of this workshop are available online [26]. Based on the minutes, a **2nd version of the report** was generated.

On 1 May 2019, the 2nd version of the Initial Draft Report was **reviewed by MINEA WG4** Members (in alphabetical order): Sigurd Heiberg, Soraya Heuss-Aßbichler, Zoltan Horvath, Sandra Mueller, Julia Stegemann, Patrick Wäger and Andrea Winterstetter. Based on the minutes, a **3rd version of the report** was generated.

On 18 July 2019, the follow up Workshop **“Knowledge base for Anthropogenic material resources and reserves III”** and **“Framework for assessment of**

anthropogenic resources II” was held in Munich. The following experts contributed to this workshop (in alphabetical order): Teresa Carvalho (Portugal), Soraya Heuss-Aßbichler (Germany), Jakob Lederer (Austria), Sandra Mueller (Switzerland), Mohamed Osmani (United Kingdom), Julia Stegemann (United Kingdom), Patrick Wäger (Switzerland), Andrea Winterstetter (Belgium).

On 18-19 November 2019, at the **Workshop “Framework for assessment of anthropogenic resources III”** in London, the MINEA WG4 used preliminary inputs from WG1-3 to Deliverable 2 and discussed and revised the 3rd version of the report and, based on that, developed an initial concept for MINEA Deliverable 3. The following experts contributed to this workshop (in alphabetical order): Soraya Heuss-Aßbichler (Germany), Sandra Mueller (Switzerland), Mohamed Osmani (United Kingdom), Julia Stegemann (United Kingdom), Patrick Wäger (Switzerland), Andrea Winterstetter (Belgium). The **4th version of the report** was released.

By 31 December 2019, the **WG1-3** under the lead of Gang Liu (Denmark), Teresa Carvalho (Portugal), Joakim Krook (Sweden) and Jakob Lederer (Austria) **had undertaken substantial efforts to compile the findings during the MINEA lifetime and contributed a draft version for section 2**. The case studies in section 3 have been compiled by Jakob Lederer (Austria), Andrea Winterstetter (Belgium), Sandra Mueller (Switzerland) and Soraya Heuss-Aßbichler (Germany). The MINEA WG4, represented by Soraya Heuss-Aßbichler (Germany) and Ulrich Kral (Austria) compiled and concluded the findings (section 3.5, 4), which underwent final review by Julia Stegemann (United Kingdom) before release of the **5th version of the report** on 6th April 2020.

By 10 April 2020, the authors had finally reviewed and approved their contributions. We released the **6th version of the report** on 10th April 2020.

By 17 April 2020, Andrew Clarke had completed the proof-reading of the 6th version and Ulrich Kral had resolved the revisions and released the **7th version of the report** on 17 April 2020.

On 13 April 2020, the 6th version was sent to the MINEA Management Committee for approval. It is noted that the MC approved the **final report** on 17 April 2020.

By end of April 2020, the final report was published on the zenodo repository under a creative commons license (<http://dx.doi.org/10.5281/zenodo.3739164>) and submitted to the COST Association.

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