Developing material recovery projects: Lessons learned from processing municipal solid waste incineration residues

Sandra R. Mueller a,1, Ulrich Kral b, Patrick A. Wäger c

a School of Life Sciences, University of Applied Sciences and Arts Northwestern Switzerland, 4132, Muttenz, Switzerland
b International Centre for Environmental Science, Faculty of Engineering & the Environment, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
c Institute for Water Quality and Resource Management, Technische Universität Wien, Karlsplatz 13/226, 1040, Vienna, Austria

KEYWORDS: Resource assessment, Secondary raw materials, Circular economy, United Nations framework classification for resources, Material flow analysis, Bottom-ash

ABSTRACT

This research explores the material recovery from bottom-ash, which is a residue from municipal solid waste incineration. The investigations aimed to characterize, evaluate, categorize and classify the development status of the recovery projects in the Canton of Zürich, including two technology pathways, i.e. dry and wet bottom-ash recovery. The temporal scale commenced with the exploration phase in 2003 and concluded with two technological pathways, both operating commercial projects in 2017. A retrospective view allowed the identification of enablers and barriers that affected the development status of the recovery projects. Further, the recovery perspective allowed the results to be communicated to the United Nations Framework Classification for Resources (UNFC). The investigation showed two main trends. Firstly, the development status of the recovery projects from exploration to commercial project phase was mainly driven by the knowledge increase regarding sampling and metal characterization in bottom-ash, the readiness and effectiveness of the recovery technologies and the changes of the legal and financial environment. Secondly, the amount of recovered material (dry matter content) increased from about 6,900 tons in 2003 to 16,500 tons in 2017, which is congruent with an increase in the recovery rate from 5 to 14 percent per weight. In particular, the amount of elements recoverable with an economic and environmental benefit, such as copper, gold and silver, increased. Correspondingly, the residual particular metal content in the disposable bottom-ash (fraction 2–16 mm) decreased to < 1 percent per weight dry matter and therefore reduced the risk for environmental at the sanitary landfills. The findings provide ‘lessons learned’ for companies, authorities and investors who intend to develop material recovery projects. Even though the recovery potentials depend on site-specific conditions, the UNFC allows comparing individual recovery projects under different boundary conditions.

© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Since the industrial revolution, the ore grades in geogenic deposits steadily declined, while simultaneously annual production increased (Arndt and Ganino, 2012). This increasing difference...

http://dx.doi.org/10.1016/j.jclepro.2020.120490
0959-6526/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
2009 by the United Nations with the aim of developing a single uniform classification system. The UNFC is a principle-based system to classify physical resources based on the maturity of recovery projects. This system classifies resources according to three criteria: socio-economic viability, project feasibility and geological knowledge (see Fig. 1, UNECE, 2013). The recovery projects are classified according to maturity levels into: commercial projects, potentially commercial projects, non-commercial projects, and exploration projects. Each level of classification can hold quantities identified as past production, future sales production, future non-sales production, and additional quantities in place. The next UNFC update will likely include a more general nomenclature, make UNFC applicable to a broader and more generic resource field to address all kinds of resources; renaming the G-, E-, and F- axis; and recommending updates to the principles of the UNFC (UNECE, 2017). The further development of environmental and social consideration includes inter alia the adaption of the name ‘economic viability’ to ‘commercial viability’ and adding a new subclass on classifying environmental and social issues that have to be resolved, namely E2.2 (UNECE, 2017). It further defines the terms environmental, social, and political contingencies2 and the social license to operate (UNECE, 2017). This classification is an easy communication tool for stakeholders.

The long tradition in applying classification systems indicates that the quantification of raw material availability is valuable for decision-makers. In contrast to primary raw materials, internationally accepted standards for communicating the future production quantities of secondary raw materials are not currently institutionalised and there is limited knowledge on anthropogenic3 resource deposits (e.g. Brunner and Rechberger, 2015). This prevents a common comparison of the future production of primary and secondary raw material quantities, and therefore integrative material sourcing strategies.

In 2008, Hashimoto et al. (2008) suggested a concept for resource classification, namely ‘potential waste and secondary resources’. Since 2014, several case studies, relying on McKelvey and the UNFC have been published (see Table 1). Winternetter et al., 2015b, 2015a tested the application of the UNFC to anthropogenic resources and presented the results at the 6th Session of the UNECE Expert Group of Resource Classification (EGRC). In 2016 at the 7th Session of the EGRC, the pan-European expert Network ‘Mining the European Anthroposphere’ suggested expansion upon previous case study findings and to extend the scope of the UNFC through integrating anthropogenic resources (Kral et al., 2016). Subsequently, the Specifications to apply the UNFC to Anthropogenic Resources have been developed and endorsed by the UNECE Committee on Sustainable Energy (Kral et al., 2018; UNECE, 2018).

The review of case studies in Table 1 revealed that both the McKelvey and UNFC classification were applied on different spatial scales, namely project level, regional, national and continental. The ‘lessons learned regarding classifications’ of case studies demonstrate successful applications of resource classifications. These enable the comparison of different perspectives, namely geological and anthropogenic resources, as well as a private investor’s micro view and a public entity’s macro view. The various case studies are unique regarding their wide range of applications. These include aluminium, copper and zinc resources, chromium from slag of stainless steel production, infrastructure, landfill, incineration fly ashes, and various end-of-life products.

Following the intention of the UNFC, all UNFC related case studies estimate the future recoverability of anthropogenic resources. In contrast to these studies, we use the UNFC for a retrospective assessment. The aim of this research paper is to characterize, evaluate, categorize and classify the material recovery projects during their successful development, i.e. the exploration to the production stage; and then use the UNFC for communication
In section 2 of this paper, we introduce the materials and methods for assessing and classifying the anthropogenic resource bottom-ash. In section 3, we present the results from assessing and classifying the case study. The resource assessment includes the definition of the recovery projects, the characterization of material flows and production data, and the evaluation of factors influencing the material recovery project. The resource classification includes the categorization and classification of category-levels that impact the viability of the recovery project. The recovery projects are classified based on project maturity at project milestones and communicate the results with the UNFC. Finally, in section 4, we conclude with 'lessons learned' as well as reflect on the application of the UNFC in the context of anthropogenic resources assessment.

### 2. Materials and methods

For this research, we adopted the methodology from Lederer et al. (2014), who assessed phosphorus stocks in Austrian landfills, and present the concept in Fig. 2. We assigned an alternate framework for the first three steps in resource assessment and then a separate fourth step as resource classification. In resource assessment, we applied an alternative methodology for the 'evaluation' step, which goes beyond the economic perspective and integrates additional socio-economic factors that affect the recoverability of materials. For resource classification that includes the 'categorization/classification' step, we applied the UNFC instead of two-dimensional concepts.

In this framework, the status of project development and the associated material quantities are assessed and classified based on three fundamental criteria, namely level of confidence in the potential recoverability of the quantities (G), economic and social viability (E), and field project status and feasibility (F), while using a numerical coding system (UNEC, 2013).

---

**Table 1**

Case studies for anthropogenic resource assessment including spatial scope, classification system and reference.

| Scope | Spatial scope | Classification system | Lessons learned regarding classification | Uniqueness | Reference |
|-------|---------------|------------------------|-----------------------------------------|------------|-----------|
| Phosphorus recovery from Austrian landfills | National | McKelvey | A consistent method for evaluating anthropogenic resources can provide a basis for the utilization of anthropogenic resources. | To our knowledge, the first study to apply the McKelvey to phosphorus. | Lederer et al. (2014) |
| A landfill mining case study | Project level | UNFC | Systematic classification based on the operative procedure steps: prospection, exploration, evaluation and classification. | To our knowledge, the first study on landfills and applying UNFC E, F, and G-axis to anthropogenic resources. | Winterstetter et al. (2015b) |
| Zinc recovery from MSWI incineration residues | Europe | McKelvey | Classification was possible and a small share was classified as demonstrated resources. | The first McKelvey application to Zinc recovery from municipal solid waste incineration residues. | (Fellner et al., 2015) |
| A geological reconnaissance of electronic and electrical waste as a source for rare earth metals | National | UNFC | Anthropogenic resources in Switzerland, as a deposit, assessed based on UNFC G-axis. | Systematically characterising Switzerland as a deposit and then evaluating the geological knowledge according to the UNFC. | Mueller et al. (2015) |
| Material recovery from old landfills, obsolete computers and laptops, and wind turbines. | Project level | UNFC | Classification was possible. The economic results depend on the defined recovery project. | Comparison of the recovery of three different types of anthropogenic material types. | Winterstetter (2016) |
| Material recovery from old landfills in Flanders | Project level | UNFC | A tool to systematically characterize and judge a current and future portfolio of historic landfills. | Assessing three former landfill sites and potential landfill mining project. | Winterstetter (2017); Winterstetter et al. (2018) |
| Material recovery from Vienna’s Subway Network | Regional | McKelvey | Classification was possible. A small share was classified as resources. | First classification application to subway building stocks. | Lederer et al. (2016) |
| Secondary aluminium, copper and zinc reserves on national level | National | McKelvey | Applying the classification as a means to enable a management approach for both primary and secondary resource. | Applying the classification to both primary and secondary resources in six major countries. | Maung et al. (2017a,b); Maung et al. (2019); Huber and Fellner (2018) |
| Metal and salt recovery from MSWI fly-ash | Project level | UNFC | One assessment approach for describing both the private investor’s micro and public entity’s macro view. | Classifying the incineration fly ash. | Winterstetter (2018) |
| Chromium recovery from steel slags | Project level | UNFC | Evaluation (E), Classification (CL) of Anthropogenic Resources (AR) ECLAR. Tentatively applying of the UNFC is possible. | Classifying for the first time chromium rich slags from stainless steel production. | Wäger et al. (2018) |
| Recovery of scarce/critical metals from electrical and electronic devices in passenger vehicles | Project level | UNFC | | | |

---

4 A significant stage or event in the development of the recovery projects, which can consist of an action, publication or report (Oxford Dictionaries, 2019).
Resource assessment and classification

1. **Recovery project definitions**: In alignment with the UNFC and UNFC specifications for anthropogenic resources, a recovery project is a ‘defined development status or sourcing operation, which provides the basis for socio-economic and environmental evaluation and decision-making’ (UNECE, 2018, UNECE, 2010). It is the starting point to assess the recovery potential and comprises key project cornerstones such as the target material, the project area, the material source, and the reference point. It further includes a description of the material flow system and chronicling the timeline of the status of project development.

2. **Characterization**: The recovery projects were characterized regarding material quantity and quality. The quantity included an investigation of the material flow system that comprises the material source, processes that transfer or transform the material and material flows that link the processes. We applied the tool ‘material flow analysis’ according to Brunner and Rechberger (2003) who carried out the following three steps. Firstly, relevant processes and flows are selected. Secondly, quantification of the material flow system is carried out by collecting data from public reports, expert interviews, literature and agencies. For an independent and balanced investigation, we focus on knowledge that is available from all recovery and agencies. For an independent and balanced investigation, we focus on knowledge that is available from all recovery and agencies.

3. **Evaluation**: The recovery projects are evaluated regarding the development status of the projects. This evaluation step includes two parts. Firstly, a literature review was conducted. This included recent and relevant literature (Elliott, 2016; Feiz and Ammenberg, 2017; Mueller et al., 2017; UNECE, 2017, UNECE, 2017; Winterstetter, 2016) with a comprehensive list of factors. Secondly, an expert workshop was carried out in the frame of the MiNEA project on the 14th December 2017 in Vienna (Mueller, 2017) to confirm the most relevant factors from the literature review as an outcome (Table 2). Thirdly, between November 2017 and July 2018 expert interviews were carried out with regional experts (Hitachi Zosen Inova AG, 2018; Morf, 2017; ZAV Recycling AG, 2018; DHZ AG, 2018). This made it possible to narrow down the factors to focus upon relevant factors for recovery projects. These relevant factors and determinations are described in Table 5. Fourthly, the factors were determined with quantitative or qualitative methods at key project milestones.

4. **Categorization and classification**: Categorizing and classifying the development of the recovery project through the application of the United Nations Framework Classification for Resources (UNFC). It is noted that the characterization and evaluation steps are dependent upon one another. For instance, the amount of recoverable materials depends on the economic and technological conditions of the recovery project.

The selected factors should be generically applicable to allow comparability. However, the factors were developed based on a specific case study and recovery projects in other regions might be driven by alternative factors and assessments.

For future applications, the list of factors could be complemented by a factor addressing environmental impacts such as Mehr et al. (2019). Transparency in factor selection and assessment is central to ensure reliable and reproducible assessment results.

3. **Results and discussions**

In this section the results and discussion are presented from the approach on resource assessment and classification (see Fig. 2). We assessed and classified two main material recovery projects and one minor material recovery project.

3.1. **Recovery project definitions**

The project cornerstones are presented in section 3.1.1. The subsequent material flow system is presented in section 3.1.2. To describe the recovery project further, the timeline with project milestones is presented in section 0.

3.1.1. **Project cornerstones**

In the Canton of Zurich’s material recovery has been in place for the last two decades (hereby named project 0) and recently two additional material recovery projects have been developed (hereby named project wet-bottom-ash (WBA) and project dry-bottom-ash (DBA)). An overview of this development status is provided in the following bullet-point list. In Table 3, we provide an overview of all project characteristics.

- Recovery project 0: Metal separation from wet bottom-ash with metal content >1 wt percent in dry matter was the single
technological pathway between 2003 and 2015. From 2016 to 2017 the minor part of wet-bottom was recovered in project 0.

- Recovery project WBA: The development status of new recovery technologies, sourcing materials from wet-bottom-ash (WBA) began in 2009. The application on an industrial scale commissioned in 2012.
- Recovery project DBA: The development status of new recovery technologies, sourcing materials from dry bottom-ash (DBA) began in 2003. Application on an industrial scale was commissioned in 2014.

### 3.1.2. Material flow system

The project definition determines the recovery system including the relevant processes and material flows, as shown in the generic Fig. 3 and described in Table 4. The recovery projects receive bottom-ash from mainly 5 MSWI in the Canton of Zurich (see SL2). The DBA and WBA technology pathway is used to evaluate the recovery projects from 2003 to 2017. Processes associated with the recovery project but not characterized in this study include the ‘processing and utilization of recovered materials’ and the ‘land disposal for non-recyclable residues’.

#### 3.1.3. Timeline

The development status of both recovery projects WBA and DBA passed 21 key milestones (see Fig. 4). The development phase from 2003 to 2016 included evidence-based knowledge generation on recovery potential and overcoming socio-economic barriers. The development status of the recovery projects was based partly on a private-public partnership, where academics and scholars provided...
the knowledge to assess the resource potential, industry provided the capability to implement the recovery technology, and public authorities set the legal framework conditions. Both recovery projects have been in full production since 2017.

3.2. Characterization

Results of the material quantity investigations are presented in sections 3.2.1 and 3.1.2. At present, the results showed no consistent reported data on material quality is available. Consequently, this could not be reported.

3.2.1. Material flow analysis

The generic material flow system, as given in Fig. 3, has been quantified for 2003 and 2017. We used various data sources, including annual reports and personal communications (AWEL, 2005, 2004; ZAV, 2009, 2011, 2014, 2017; ZAV Recycling AG, 2018; DHZ AG, 2018). Details on the model quantification are provided in section SI.3. Traditionally, material flow analysis (MFA) deals with datasets from various sources and heterogeneity and quality of data (Laner et al., 2016, 2014). As this material flow system is based on historical data with reliable measures of quantities, we did not include uncertainty modelling. Nevertheless, the mass balance applies for each process, therefore, we quantified each flow except the ‘off-gas’, which is calculated due to mass balancing. Sankey diagrams visualize the results of the characterization step (see Fig. 5).

3.2.2. Material production data

The flows at the reference points (see Figs. 3–5) have been labelled as ‘recovered material quantities’ and ‘landfilled material quantities’ and the sums of the flow rates are given in Fig. 6. The presented data values in this section are rounded to two significant digits, because of the involved data uncertainty. The raw data can be obtained from SI.3.

In 2017, the recovered material quantities peak at 11,100 tons ferrous, 4400 tons non-ferrous metals as dry matter content. Additionally, the recovered non-ferrous fractions contain large amounts of valuable material such as copper, gold, silver and other precious metals (Morf et al., 2013; ZAV Recycling AG, 2018; Böni and Morf, 2018). Between 2003 and 2017, the amount of recovered materials ranged between 6900 and 16,000 tons per year as dry matter content. The variance results from (i) the annual generation of bottom-ash and (ii) the fluctuating metal content in bottom-ash.

The recovery rate is the result from the division of the recovered quantities and the total quantities (¼ sum of recovered and landfilled quantities). The material recovery rate increased from 5% in 2003 to 14% in 2017 (see Fig. 7). This increased material recovery ratio indicates that a technological development took place in the Canton of Zurich and the metal content might have changed in bottom-ash, as WBA and DBA demonstrate. The many technological advancements for higher recovery rates demonstrate that a key factor for high material recovery is the technology readiness level.

Fig. 4. Milestones of project WBA for wet bottom-ash treatment in the Canton of Zurich (DHZ, 2018, DHZ AG, 2017; Morf, 2017; Stadt Stadt Winterthur, 2012; ZAV Recycling AG, 2018; DHZ AG, 2018) and Project DBA for dry bottom-ash treatment in the Canton of Zurich (Morf, 2017; Morf et al., 2013; Stadt Winterthur, 2012; ZAR, 2017, ZAR, 2015; ZAV Recycling AG, 2018).
Table 2
Identification of factors that influence the development of the recovery projects.

4. Categorization and classification: We use the UNFC and the UNFC specifications for anthropogenic resources (UNEP, 2018) to categorize the factors at specific project milestones and to classify the recovery projects based on its maturity level. We carried out four steps. Firstly, relating the ‘factors’ to one of the three axes of the UNFC cube. Secondly, assigning a ‘category’ from the affected axis to each ‘factor’ at each project milestone. This decision making was reflected in an expert workshop (Mueller, 2017) and profited from alternative case study procedures (UNEP, 2017). The assignment considers the category definitions as given in SI.1. Thirdly, as there are multiple factors, we aggregate the categories on each axis by selecting the lowest category as the final categories for the E-, F-, and G-axis. This approach is recommended by UNEP, 2017. Fourthly, the combination of the three categories (one from each axis) determines the ‘class’ of the recovery project in alignment with the ‘Specifications to apply the UNFC specifications to anthropogenic resources’ (UNEP, 2018).

| UNFC axis | Factor | Identification [X] in literature review and expert workshop | Inclusion [x]/exclusion [-] in evaluation after expert interviews |
|-----------|--------|-------------------------------------------------------------|---------------------------------------------------------------|
| Level of confidence in the potential recoverability of the quantities (G-axis) | Knowledge of material regarding quantity and quality | X | X |
| Socio-economic viability (E-axis) | Legislation | X | X |
| | Policy implementation | X | X |
| | Awareness of raw material criticality | X | X |
| | Political willingness | X | X |
| | Governmental requirement/visions | X | – Since this is covered by legislation and policy implementation. |
| | Stakeholder interest | X | Inclusion |
| | Social license | X | Inclusion |
| | Environmental impacts | X | – Since there is a strong legislation, policy implementation, knowledge of material regarding quantity and quality describes the hazardousness, and, moreover, this is not a direct driver for the recovery of municipal solid waste as investigated in this case study. |
| | Financial capability | X | X |
| | Profitability | X | X |
| | Cost | X | – Since this is covered by profitability and capability. |
| | Price | X | – Since this is covered by profitability. |
| | Price volatility | X | – Since this is covered by profitability. |
| | Market process for secondary products | X | – Since this is covered by profitability. |
| | Economics of scale | X | – Since this is out of scope of this research paper. |
| Field status and feasibility (F-axis) | Infrastructure | X | X |
| | Technology readiness level (TRL) | X | X |
| | Operating license | X | X |

Table 3
Characteristics of the material recovery projects for this case study.

| Item | Characteristic |
|------|----------------|
| Target materials | Ferrous, non-ferrous metals, stainless (VA-) steel, glass. The target materials between recovery project WBA and DBA are different. For simplification in this study, these materials were consolidated. For detailed information on the DBA project see ZAV Recycling AG (2018b) and for the WBA project see DZH (2018). |
| Processing and recovery technology | Municipal solid waste incineration (MSWI) and wet and dry bottom-ash treatment |
| Material source | Bottom-ash from MSWI |
| Spatial scope | Canton of Zurich, Switzerland |
| Temporal scope | 2003–2017 (the 2003 was selected, since then the well-founded monitoring of metals in bottom-ash commenced (Morf, 2006) |
| Reference point | Located at the output side of bottom-ash treatment plants (see Fig. 3) |

* It is expected that the quantity and quality of the municipal solid waste remains constant within the project lifetime.

3.3. Evaluation

In this study material recovery is evaluated in a retrospective manner. The detailed description and explanation on the establishment of the selected factors is provided in section 2, which includes an inclusion or exclusion of factors during the expert interviews is provided in Table 2. A compilation of factors, including descriptions and assessment methods, is provided in Table 5. Each individual factor is assessed at the milestones of the three recovery projects 0, WBA and DBA. The assessment is fully documented in SI.4.

3.4. Categorization and classification

Results of the categorization are presented in section 3.4.1 and the subsequent result of classifying the recovery project to different maturity levels is presented in section 3.4.2.

3.4.1. Categories on the E-, F-, and G-axes

This section presents the change of the scores in UNFC categories over time, based on the underlying factors. The categorization steps are described in section 2 with the relevant factors in
Table 5 and categorised as shown in Table 7. A detailed compilation for each factor of the UNFC categories, the overall category and the final combination of the minimum categories is described in the SI.5. An overview of the results is presented in Table 6, which includes from left to right the UNFC axes, the UNFC categories, the UNFC sub-categories, and the UNFC classes. In the UNFC classes the change of the category is shown, which bases on the assignment of specific factors.

For projects WBA and DBA all contingencies were met in the different UNFC classes, over the projects development period. The changes of UNFC category were mostly based on the same factors. Consequently, the following text applies for both recovery projects. For readability the name of the axes and the factors are highlighted in bold.

Regarding the UNFC–axis ‘level of confidence in the potential recoverability of the quantities (G-axis)’, two category changes were distinctly related to the factors ‘knowledge of raw material regarding quantity and quality’ and ‘supply continuity’. The ‘knowledge of raw material regarding quantity and quality’ was relevant for the category change, because after the identification of valuable material in bottom-ash, development began in 2003. The ‘supply continuity’ was relevant for the category change, because amongst others the highest G-axis levels could only be assigned after supply continuity was demonstrated in practice. Similarly, the supply continuity of production was also considered important for the case studies of the UNFC specifications of geothermal energies (UNECE, 2017).

Regarding the UNFC–axis ‘socio-economic viability (E-axis)’,

---

### Table 4

| Process name | Process description |
|--------------|---------------------|
| Incineration | The MSW is treated by MSWI plants (see details in SI, section SI.1). Each MSWI plant has a discharger for bottom-ash, either based on dry or wet discharger technology. |
| Treatment of wet-bottom-ash (project WBA) | In 2012, in project WBA, the commissioning of the wet bottom-ash separation began. Since 2013, this plant has been in operation. Since 2015, the owner of project WBA has been operating the fine wet bottom-ash refining plant. Both of these plants have a maximum capacity of 160,000 t per year with a one-shift operation (DHE AG, 2018). Details on the development status are chronicled in Fig. 4. |
| Treatment of dry-bottom-ash (project DBA) | In 2014, project DBA commissioned the start of large-scale dry bottom-ash separation. Since 2016, the ZAV Recycling AG has been fully operating the plant. The current capacity is 100,000 t per year, extended to 200,000 t by 2025 (ZAV Recycling AG, 2018). Details on the development status are chronicled in Fig. 4. |
| Treatment of wet-bottom-ash (project 0) | Metal separation from wet bottom-ash was the sole technological pathway until 2015. From 2016 to 2017 minor quantities were recovered from wet-bottom-ash in project 0. For completeness of the bottom-ash flow in the Canton of Zurich, this project was included for material balance but not included for chronicling, categorizing, and classifying the development status of the material recovery. |

---

**Fig. 5.** Material flows system for the years 2003 (a) and 2017 (b). Numbers are given as dry matter content and rounded to two significant digits. Abbreviation APC residues = Air pollution control residues. The imports and exports to and from the Canton of Zurich are not considered.
the highest category (E1) was assigned to the factors 'legislation', 'policy implementation' and 'political willingness' at the beginning of the recovery project. This indicates a favourable environment for the development of recovery projects. During project development three category changes for the WBA project and four for the DBA project were distinctly related to the factor 'profitability'. The same is true for 'stakeholder interest' and 'social license' between 2011 and 2014. The factor 'profitability' was relevant for each category change. For instance, the highest category (E1) could only be assigned after demonstration of successful operation of one year from the large-scale plants. This also included the fulfillment of all contingencies. The influence of the factor 'stakeholder interest' was relevant for the category change. The collaboration of different stakeholders enabled the creation of the technically and financially supportive stakeholder association 'ZAR foundation'. Stakeholders included the Canton of Zurich together with the VBSA (Association of Swiss Waste Treatment Plant Operators), and an innovative plant operator (KEZO Hinwil). The factor 'social license', was relevant to the category change, since local municipalities overcame objections (DHZ AG, 2018; ZAV Recycling AG, 2018). In 2011, 350 similar mining projects were delayed due to public opposition in the USA (Elliott, 2016). The 'social license' is currently integrated into the UNFC (UNECE, 2017).

Regarding the UNFC – axis 'field status and feasibility (F-axis), five category changes for the WBA project and five for the DBA project were distinctly related to the factors 'operating license' and 'technology readiness level'. The factor 'operating license' was relevant for each category change. During research and development, the planning permit was approved for both plants after legally compliant operation was demonstrated. Both plants operate with licences that are valid for five years. Without these valid licenses, the operation would be stopped. In a similar way, an 'operating license' was also important for other mining resources, such as geothermal, which also required demonstration of operation (UNECE, 2017). The factor 'technology readiness level' was relevant for the last two category changes before operating the recovery during building and operation of the large-scale plants.

It should be noted that a statement about the UNFC G-axis would become more robust if more than two factors would be used to describe these axes.

![Diagram](image-url)
3.4.2. Project maturity levels

The UNFC communicates the maturity level of recovery projects by defining ‘classes’ along the UNFC value chain. The ‘classes’ include ‘Exploration projects’, ‘Non-commercial projects’, ‘Potentially commercial projects’ and ‘Commercial projects’ (see Fig. 8). A challenge in this case study was to distinguish between potentially commercial and non-commercial project status, since the definitions in the F-axis and their sub-categories were similar.

- Project 0: This project always produced secondary raw materials and that is why the UNFC class is classified as ‘Commercial projects’.
- Project WBA: The project was in ‘exploration’ status between 2003 and 2009. From then there was a 4-year period of ‘non-commerciality’, mainly because the recovery technology was in the research and development phase. From 2011 to 2012 the project was in a potentially commercial phase. In 2012, the first large scale metal recovery operation commenced on an industrial scale. In 2013, the planning for the extension plant, i.e. fine fraction, commenced. From 2012 to 2014, when the building of the first large scale metal recovery operation began, the project reached commercial status.
- Project DBA: The project began as an exploration project. From 2007, there was a 6-year period where it was classed as ‘non-commercial’, mainly because the plant was still in the research and development phase, and upscaling to a full industrial operation was not confirmed. Additionally, the profitability of the metal production was unclear. Then in 2013, the metal recovery potential was estimated at a detailed level (Morf et al., 2013) and from 2012 to 2014 a large scale plant was developed. From 2013 to 2014 the project was in a potentially commercial
phase. From 2014 to 2016, when the building of the large-scale plant began, the project reached commercial status.

4. Conclusions

In this paper, we aimed to assess and classify the development status, respective of maturity, of projects that are recovering materials from MSWI bottom-ash in the Canton of Zurich based on the United Nations Framework Classification for Resources. We conclude with ‘lessons learned’ for developing material recovery projects and identify challenges for applying the UNFC in the context of anthropogenic resource assessment.

4.1. Lessons learned

Based on the case study findings in the Canton Zurich, we provide lessons learned for stakeholders involved in developments of recovery projects in other regions.

(1) The development of recovery projects in the Canton Zurich was driven by a continuous knowledge increase with respect to analytical characterization of metal contents in bottom-ash (including adequate correct sampling methods and substance flow analysis approach), the understanding of the importance of these measures regarding social and ecological influence in waste management, and the effectiveness of recovery technology, as well as by the changes in the legal and financial environments. Sound cooperation between researchers, the project developers and the authorities push the development for two different recovery technologies, which both fulfill the VVEA requirements well.

(2) We identified distinctive factors, which can easily both enable and obstruct project progression. For the G-axis, we identified all factors ‘knowledge of material regarding quantity and quality’ and ‘supply continuity’, as central, since without knowledge and MSW supply there would be no recovery options. The factor regarding ‘knowledge of material regarding quantity and quality’ includes knowledge on the impact to the environment. For the E-axis, we identified the factors ‘profitability’, ‘stakeholder interest’ and ‘social license’ that were central for assigning the material recovery project to the next category, i.e. from E3 to E2 and E2 to E1. For the F-axis, we identified the factor ‘operating license’ as a central factor.

| UNFC axis          | Factor                          | Description                                                                                     | Quantitative or qualitative determination                                                                 |
|--------------------|---------------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Level of confidence in the potential recoverability of the quantities (G-axis) | Knowledge of material regarding quantity and quality (adapted Mueller et al., 2017). | Description about the material type, quantity and if possible quality (adapted from UNECE, 2013). This includes a review on reports such as annual supplied and processed quantities, impacts to the environment and metal sampling, sample preparation and analysis (Skutan et al., 2014). |
|                    | Supply continuity                | Confidence in the estimates of the material source and recovery production over a period of time (adapted from Oxford Dictionaries, 2018c). | Description of the likelihood of consistent recovery production and annual production quantity over a specific period in time and spatial location (adapted from UNECE, 2011). |
| Socio-economic viability (E-axis) | Legislation | A law or set of laws that is being created (Cambridge English Dictionary, 2018). The quality of policy formulation and implementation. | Description of key aspects in existing regulatory system in the relevant spatial location. |
|                    | Policy implementation            | Conclusiveness and knowledge about the criticality of situation regarding raw material shortages. | Description of potential on material shortages in the area of interest. |
|                    | Awareness of raw material criticality | A preparedness or readiness on how a community, company or other political unit manages raw materials. | Description of intentions and implementations of measures from a political unit in the relevant spatial location. |
|                    | Political willingness            | The interest of a group of people that influences the intended mining project’s progress with regard to market conditions. | Description of the stakeholders’ interests and intentions. |
|                    | Stakeholder interest             | The recovery sector’s efforts on reaching out to global and local stakeholders (Owen and Kemp, 2013). | Status description of legal local requirement and activities to societal and community situation regarding access to land, water and other financial and human resources (Owen and Kemp, 2013). |
|                    | Social license                   | The degree to which a business or activity yields profit or financial gain (Oxford Dictionaries, 2018a). | Description of management and investment capabilities. |
| Field status and feasibility (F-axis) | Infrastructure | The basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise (Oxford Dictionaries, 2018b). | Description of existing infrastructure network such as road and railway, electricity infrastructure, and waste management (adapted from Pohl, 2011). |
|                    | Technology readiness level (TRL) | A systematic process to evaluate the development status of technological advances into a system (NASA, 2007). | Description and status of technological advances with the following TRL: - 1—4: from 1) basic principles observed to 4) experimental and validation in laboratory environment, i.e. in research 5—7: component and later system validation in relevant environment, i.e. scale up - 8, 9: actual system completed through testing and demonstration; and actual system proven through operation, i.e. large scale production (NASA, 2007). |
|                    | Operating License                | A permit from an authority to operate a recovery process. | Description and date with the duration of the existence of an operating license from an authority. A license could include a permit related to hazardous waste handling or atomic energy licensing board (adapted from Mueller, 2018). |
We identified three key milestones in the development of the recovery projects WBA and DBA. These were, firstly, establishment of the ZAR foundation, which unites donors and technical expertise, secondly, technological readiness, in particular the recovery of larger quantities of raw material, and thirdly, the launch of full operation, which allows more correct, respectively unbiased sampling and the optimisation of recovery efficiency in future.

We identified social and environmental considerations as important. In 1986 the foundation was laid on a national level through the objectives and principles of the Guidelines for Waste Management stating the disposal quality of bottom-ash should resemble the properties of rocks or ores and their geochemical behaviour as in the Earth’s crust. Since 2016 even stricter VVEA requirements for the disposal of bottom-ash have been defined (VBSA, 2016). On Cantonal level, the Waste and Resource Management Action Plans 2011–2014 (AWEL, 2011), and 2015–2018 (AWEL, 2014) and 2019–2022 (AWEL, 2019) include the objective of recovering as much material as possible.

4.2. Applying the UNFC in the context of anthropogenic resource assessment

The UNFC is a generic, principle-based system to classify physical resources based on the maturity of recovery projects. Based on the findings of this case study, we came up with suggestions for...
applying the UNFC in the context of anthropogenic resource assessments. We are fully aware that more challenges can be addressed, and we encourage the scientific community to support the UNECE Expert Group on Resource Management in developing the UNFC further.

(1) The UNFC standardises terminology and principles for communicating the development status of physical resource projects for markets, but it does not give any guidance on how to characterize physical resources or how to evaluate the socio-economic viability of recovery projects in practice. This is because the UN classification is designed as a framework that allows for the comparison of results from resource assessment, which are currently standardized by multiple countries and industries differently. The current lack of standardisation in methodologies for characterisation and evaluation of the physical resources in general and anthropogenic resources gives maximum flexibility in the selection of assessment tools and data. This flexibility, however, stands in contradiction to reproducible assessment results. For instance, different evaluators might have results with different outcomes concerning project development status. To pave the way towards reliable, evidence-based expert results, our suggestions are threefold. Firstly, the development of guidelines and recommendations about how to characterize and evaluate specific waste flows such as MSWI bottom-ash flows across all countries and industries. Secondly, the communication of the UNFC results only in combination with a complete documentation of the resource assessment. This effort for transparency enables verifiable results, independent and anonymous reviews, and contributes to the standardization of characterization and evaluation methods in the long-term. Thirdly, there is need for a competent person with specific qualifications, i.e. evaluator qualifications, as implemented for primary raw materials (UNECE, 2013). This could be implemented by certifying institutions.

(2) The linkage between the evaluation results and the categorization under UNFC is given by fulfilling the functional requirements of the category definitions. Assessment results would be more comparable, if the linkage went beyond qualitative justification towards a quantitative concept. For instance, the net present value justifies the categories E1, E2 or E3. Additionally, further standardisation of the process of assigning categories and classes while applying UNFC guidelines is essential.

(3) The UNFC allows for categorization of entire quantities at the source. They are subdivided into ‘sales quantities’, ‘non-sales quantities’ and ‘additional quantities in place’. As our case study is dealing with material flows, only sales and non-sales are of relevance. For non-sales, we reported the landfilled materials and excluded the emissions from the recovery process and landfills. For future assessment studies, we recommend all non-sales quantities be included to obtain a more complete understanding of the environmental impact.

(4) The UNFC provides the following results: a) the positioning of the recovery project on the UNFC value chain, b) the estimation of sales and non-sales quantities and c) the identification of possible barriers and enablers that affect the recovery project development. The UNFC results can be communicated to relevant stakeholders, such as policymakers, industries and governance to discuss actions to produce of secondary raw materials.

Acknowledgements

We express our gratitude to Leo Morf from the Office of Waste, Water, Energy and Air in the Canton of Zurich for expert discussion, René Müller from ZAV Recycling AG for expert discussion and data provision, Alfred Sigg from Hitachi Zosen Innova AG, Adrian Aebersold and Ueli Christen from Zürcher Abfallverwertungs AG for expert discussion, Benjamin Blumer and Ivan Züst from DHZ for expert discussion and data provision, Robert Schnyder from the Canton of Luzern for expert discussion, and the three anonymous reviewers for their many constructive inputs. We are grateful for the figure layout drawn by Ingeborg Hengl. This article is based upon work from COST Action Mining the European Anthroposphere (CA15115), supported by COST (European Cooperation in Science and Technology).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120490.

Abbreviations

SI Supplementary information
UNFC United Nations Framework Classification
UNECE United Nations Economic Commission for Europe
MSW Municipal solid waste
WBA Wet-bottom-ash
DBA Dry bottom-ash
MFA Material flow analysis
TLR Technology readiness level

References

Arndt, N.T., Canino, C., 2012. Metals and Society: an Introduction to Economic Geology. Springer, Berlin, New York.
AWEL, 2004. Kehrichtverbrennungsanlagen im Kanton Zürich Jahresbericht 2003 [Incineration plants in the Canton of Zurich annual report 2003]. Amt für Abfall, Wasser, Energie und Luft (AWEL), Zürich, Schweiz.
AWEL, 2005. Kehrichtverbrennungsanlagen im Kanton Zürich Jahresbericht 2004 [Incineration plants in the Canton of Zurich annual report 2004]. Amt für Abfall, Wasser, Energie und Luft (AWEL), Zürich, Schweiz.
AWEL, 2011. Massnahmenplan der Abbfall- und Ressourcenwirtschaft 2011 - 2014 [Action plan for waste and resource management 2011–2014]. Amt für Abfall, Wasser, Energie und Luft (AWEL), Zürich, Schweiz.
AWEL, 2014. Massnahmenplan der Abbfall- und Ressourcenwirtschaft 2015 - 2018 [Action plan for waste and resource management 2015–2018]. Amt für Abfall, Wasser, Energie und Luft (AWEL), Zürich, Schweiz.
AWEL, 2019. Massnahmenplan der Abbfall- und Ressourcenwirtschaft 2019 - 2022 [Action plan for waste and resource management 2019–2022]. Amt für Abfall, Wasser, Energie und Luft (AWEL), Zürich, Schweiz.
Boesch, M.E., Vadenbo, C., Saner, D., Huter, C., Hellweg, S., 2014. An LCA model for waste incineration enhanced with new technologies for metal recovery and application to the case of Switzerland. Waste Manag. 34, 378–389. https://doi.org/10.1016/j.wasman.2013.10.019.
Boni, D., Morf, L.S., 2018. Thermo-Recycling – efficient recovery of valuable materials from dry bottom ash in Removal. In: Holm, O., Thöne-Kozmiensky, E. (Eds.), Treatment and Utilisation of Waste Incineration Bottom Ash. Thöne-Kozmiensky Verlag GmbH, Germany.
Brüner, P.H., Rechberger, H., 2003. Practical Handbook for Material Flow Analysis. CRC, Boca Raton, Florida, London.
Brüner, P.H., Rechberger, H., 2015. Waste to energy – key element for sustainable waste management. Waste Manag. 37, 3–12. https://doi.org/10.1016/j.wasman.2014.02.003.
Cambridge English Dictionary. Legislation definition. https://dictionary.cambridge.org/us/dictionary/english/legislation accessed 25.05.19.
CIRRSO, 2008. International Standards for Reporting of Minerial Resources and Reserves – Status, Outlook and Important Issues. Committee for Mineral Resources International Reporting Standards, Australia.
DHZ AG, 2017. Supersort Technology - Resources from Waste - Detailed. Luzingen, Schweiz. https://www.supersort.ch/data/docs/en/2551/DHZ-Brosch%C3%84re-April-17-ES.pdf?v¼1.8, accessed 28.02.2020.
DHZ, 2018a. 5 Jahre Supersort Technologie [5 years supersort technology]. URL https://www.supersort.ch/de/, accessed 04.02.19.
