State-of-the-art Waste-to-Energy plants are reducing the volume of municipal and commercial waste as well as generating electric power and district heating. This survey concentrates on bottom ash treatment and utilization from a wet discharge process all Bavarian Waste-to-Energy – WtE – plants have in common. Minimum treatment of the bottom ash focusses on removing ferrous and non-ferrous metals as well producing materials mainly for roadbuilding purposes. The non-organic tailings from this process are usually landfilled whereas the organic residues are fed back into the incineration process. Due to the limited landfill volumes available and rising costs the feasibility of an improved ash treatment was studied for 8 Bavarian WtE plants with respect to costs, possible co-operations, available landfill volume and material markets.

The bottom ash treatment in Bavaria follows different concepts partly operating on-site treatment facilities, partly assigning specialized subcontractors. Therefore the quality of the secondary materials generated, may vary significantly.

The main focus of current research, development and optimization work is to improve the yields and qualities of the metal fractions which comprise about 12 to 15 percent
of the total weight of the bottom ashes. The main part, about 85 percent of the bottom ash, is mineral and has to be deposited or is – after further processing – used as base layer for landfill or road constructions. Additionally it is used as backfilling material in mines, but this application is hardly feasible in Bavaria and requires a transport to other federal states like Baden-Württemberg.

Forthcoming legislation like the substitute material ordinance may add further restrictions to both the utilization of bottom ashes and mineral building and construction waste, so that bigger efforts and better treatment might be required in the future. In this study the feasibility of the implementation of advanced ash treatment technologies without significant modifications of the existing discharge systems of the WtE plants is prioritized for a better cost efficiency expected.

1. Approach

The study started with the development of a questionnaire that was send to the involved 8 WtE plants to prepare an overview about the current situation at the plants, ash volume, storage, treatment and further utilization.

New developments in bottom ash treatment were reviewed in a desk research study. The possibilities to use the treated ashes as filler materials, base layer applications, landfilling or even in other utilizations were included.

Additionally, the current state of stakeholder discussions on forthcoming legislation was examined for its potential impacts on treatment requirements, on bottom ash utilization, disposal and costs. The prevailing legal environment in Germany is expected to change because of

a) the revision of the European Waste Catalogue, which have to be implemented and

b) forthcoming new requirements for the use of substitute construction materials.

The results are used to elaborate recommendations for an optimized medium to long term development strategy for the WtE plants in Bavaria.

2. Survey of current ash treatment solutions

2.1. Bottom ash quantities and specifications

Almost all of the municipal solid waste generated in Bavaria is treated in the 15 WtE plants operated by members of the Association of Waste-to-Energy Plant Operators in Bavaria, ATAB. Including the amount of waste from other origins, being treated in those plants the bottom ashes in 2013 added up to 613.000 tons.

From the bottom ashes approximately 10 percent is recovered in total as iron (ferrous) scrap (Fe) and non-ferrous metal (NF) [21]. Most of the treated bottom ashes is used
as a secondary building material on landfill sites or as a back-filler in mines. Only a small part is used as construction aggregate. About 11 percent of the bottom ashes generated in Bavaria are landfilled.

In total, German WtE plants generate almost 5,000 kt per year of bottom ash from which 400 kt per year of metals are recovered. [16]

MSWI bottom ash mainly consists of aggregates containing a mixture of inert materials – stone, glass, ceramics –, mineral phases formed in the combustion process, salts and metals. The composition can vary between different MSWI plants because of input variations and differences in operating conditions. A comprehensive survey on Swiss bottom ash composition [8] concluded that the average composition has not changed much in the past decade. They found significant changes in the glass and metals content only, both decreasing due to changes in municipal solid waste composition.

Fresh bottom ash contains approximately 8 percent of particles below 0.063 mm grain size – silt and sludge. This fraction is known for leaching, because leachable compounds of heavy metals such as lead, copper and zinc are enriched in this fraction [17]. The fractions 0.063 to 2 mm, 2 to 6 mm and 6 to 20 mm have similar shares of 25 to 28 percent of the total composition. Particles with grain sizes exceeding 20 mm occur less frequently, summing up to 10 percent of the bottom ash weight (Figure 1). In a wet treatment of bottom ashes, the < 0.063 mm fraction will probably require additional stabilization or it has to be landfilled due to a lack of application and its hazardous potential. In the most frequently used wet discharging and subsequent dry processing of bottom ash the silt and sludge fraction is found adhering to the larger particles of the other fractions. During ageing of the ashes chemical reactions, setting and agglomeration take place and the small particles become part of larger aggregates. However, the contaminants in this fraction will be dispersed onto the sand and granulate fractions, impairing their leaching quality.

![Figure 1: Fractions of bottom ash – wet sieving, compilation of different sources](image-url)
The bottom ash grain size distribution is important for the use as aggregates. Ideally, the grain size has a smooth distribution, e.g. covering a range from 0.1 to 20 mm according to (EN 13242:2008). High shares of very fine particles (< 0.063 mm), however, not only increase the heavy metal and salt concentration but also reduce the frost resistance.

The mean share of fines, 0 to 2 mm, is approximately 40 percent as can be seen in Figure 1. In this fraction several metals including precious metals can be found. Therefore a large interest can be observed to gain the economic recovery of these metals (see chapter 2.3 below).

2.2. Potential applications of bottom ashes

As a mineral product, bottom ash might be used to substitute natural aggregates in various applications:

**Road construction or foundation material**

After metals extraction and adjusting maximum grain size, wet extracted bottom ash has a grain size distribution that meets the specifications of construction aggregates. The ashes can be compacted to achieve sufficient supporting power serving as base layers for buildings or roads. To minimize potential pollution from leaching the usage is restricted to aged bottom ash – lower leaching – covered by a non-permeable layer. The leaching criteria are usually measured according to [20] and according to the German Bundesbodenschutzverordnung [1].

**Aggregate for concrete production**

A utilisation in concrete may be limited to non-armoured concrete for the (corrosive) salt content of bottom ashes. In addition bottom ashes may still contain some metallic aluminium even after NF-removal. Upon long term storage the aluminium will oxidize under volume expansion and the corrosion products will induce stress in the concrete and cracking can occur. Therefore a prerequisite for the use in concrete is a sufficient elimination of aluminium metal and ageing of the ash to have residual aluminium oxidized. If both prerequisites are fulfilled – removal of salt and aluminium – bottom ash can be successfully blended in concrete materials [6].

Legal restrictions may be present as well. According to [20] in Germany substitute materials and recycled materials must not contaminate the environment.

**Aggregate or filler in asphalt**

For the same reasons as above (application in concrete), bottom ash usually is not used as an aggregate or as filler in asphalt in Germany.

**Cement production**

Although according to [27] and [13] bottom ash in Italy is used for cement production, bottom ash is regarded not to be suited for that purpose because of e.g. the high chlorine content in Germany [25]. Additionally, the threshold concentrations of heavy metals might be exceeded.
2.3. Metal separation and use of reclaimed metals

After leaving the wet discharger a carbonation process of the bottom ash is initiated and the forming of stable aggregates and mineral phases can be supported by ageing of the ash for several weeks (e.g. up to 3 months) to reduce the hazardous potential prior to further treatment [17].

Ageing processes on the other hand can reduce the metal yield in conventional refining processes and additional efforts for proper separation of metals will be required like crushing, sifting, sensor sorting etc.

Wet processing – washing – can remove leachates like sulfates and chlorides. Subsequent wet sieving allows the removal of metals and fines in good quality. Such bottom ash treatment might be financed by the revenues for the metals recovered.

The metal content has a significant value if it can be extracted efficiently. Basing on prices for medium quality scrap and assuming a composition of the non-ferrous metals fraction being similar to other WtE plants [2, 23] the metal content of the Bavarian bottom ashes has a theoretical cumulated value of 48 million EUR (Figure 2), corresponding to 79 EUR/t of bottom ash. However, yield losses and refining costs of the metals have to be taken into account, so that the economic optimum in most cases is well below the theoretical maximum of the total metal extraction. Bunge [5] showed that the economic optimum of metal extraction depends on the metal prices. At 1 SFR/kg of reclaimed NF metals, the optimum is in the range of 30 to 50 percent recovery yield of the NF-metals, whereas at 1.5 SFR/kg, 60 percent NF-recovery or even more might be economically feasible.

![Figure 2: Amount and potential value of metals in Bavarian bottom ash](image)

Sources: bifa results

Metal recovery from MSWI bottom ashes is included in the BREF document on waste incineration [9]. According to the BREF document, both the separation of iron scrap and the separation of non-ferrous metals are part of the best available technique for the bottom ash fraction >11 mm.
New technologies allow an efficient extraction of valuable materials from aged bottom ash in the fine fractions 0 to 11 mm and 0 to 2 mm down to a metal particle size of about 1 mm [32]. Modern sensor based sorting with magnetic separators, eddy current separators, optical sorting, density sorting and x-ray fluorescence separators (XRF) can be used to optimize yields [33].

When optimizing the iron scrap recovery yield using magnetic separators, additional weak magnetic material – magnetic iron oxides and stainless steel scrap – may be caught and cumulated. Some stainless steel in the magnetic ferrous metal fraction can be enriched via inductive sorting systems [14].

The iron scrap recovered usually contains mineral matter attached as impurity. The oxides and the mineral matter attached to the scrap will cause additional slag formation in electric arc furnaces of the steel industry where oxides are not reduced during the treatment. To account for these slags price deductions are made according to the impurity concentration [19] or the copper content from electric motor windings – meat balls – caught by magnetic separators. Therefore iron scrap recovered from bottom ash should be refined at specialized plants before being fed to the steel works to achieve better revenues.

The non-ferrous metals fraction mainly consists of a light ((partly oxidized) aluminium) and a heavy fraction (copper, zinc and alloys, tin, stainless steel, lead, silver, gold etc.) [23]. Depending on the original bottom ash grain size fraction from which it was separated, it can contain up to 30 percent of bottom ash. Further separation from the bottom ash residues can be achieved by eddy current separators. The heavy fraction can be separated from the light aluminium one, e.g. by ballistic separators or by sensor sorting devices. This should be done at the NF scrap processing plants for economic reasons. The separation of the metals in the heavy fraction may be carried out at the smelter works.

Transport costs contribute significantly to the total processing costs and should be minimized. For this reason advanced metal recovery technologies could be implemented at the WtE plants, at the bottom ash recovery plants, and the smelters. Only selected and enriched ash fractions may be processed in another centralized treatment plant for economic reasons.

3. New developments

The Dutch Ministerie van Infrastructuur en Milieu and the Association of MSWI plant operators in the Netherlands agreed on a Green Deal obliging them to find applications for 50 percent of the bottom ash until 2017 and 100 percent until 2020 [24]. Only the silt and sludge fraction of bottom ashes will be allowed to be landfilled in future. A little earlier, the Swiss government changed the waste landfill directive urging MSWI plant operators to maximize metal recovery from bottom ashes before landfilling [4]. Thus driven by the need to recover a maximum of metals in Switzerland and to optimize
leaching quality in the Netherlands, several new developments were initiated. At the same time in Germany concurrent developments to improve metal recovery and to generate a mineral product that can be used in additional applications were started.

The development of new techniques can be classified into three groups (Figure 3):

**Advanced metals separation**

a) Advanced metals separation with conventional techniques: The bottom ash to be treated is separated into 3 or more grain size fractions and passing eddy current separators (ECS) separately. This has been realized at several plants [23]. The additional yield on NF metals is 1 to 1.5 percent of the bottom ash weight. According to the economy of scale large bottom ash treatment plants can profit from this development.

b) Use of sensor sorting technology: This allows removing residual metal particles from the bottom ash treated by magnet separator and ECS. The concentrate can contain significant amounts of the bottom ash and has to be further refined before it can be used in a smelter. Non-magnetic stainless steel can be separated into an own fraction via this process.

**Disintegration of agglomerates**

a) Non-specific comminution (crushing): All metal particles are liberated; however, the mineral fraction is crushed to sand and has to be disposed of if no other specific applications could be identified. In this case the mineral phase cannot be used as construction material any more without further processing. Up to 2 percent additional NF metals can be recovered.

b) Selective disintegration (mechanical): Metal particles are more ductile than the mineral matrix. Therefore the grains predominantly brake along the metal/mineral interface. The TAR processor developed by Tartech is a special type of a vertical impact crusher optimized for a good liberation of the metal parts without crushing the mineral phase too much. The additional NF metal yield is estimated to be approximately 1 percent [15].

c) Specific disintegration by electric shock waves (electrodynamic fragmentation): Electric pulse discharges follow conductive paths in an agglomerate in a water bath. This effect can be used for specific disintegration of bottom ash agglomerates [29]. Due to the wet process the mineral phase residues are washed so that it may be suitable for an application according to Dutch criteria. The process water has to be treated and can be reused after removal of the fine bottom ash sludge to be deposited. An additional yield of iron scrap of 3 percent can be obtained. The NF metals are separated by sensor sorting; the additional yield is expected to be 2 percent after upgrading.
### Classification on bottom ash treatment approaches

<table>
<thead>
<tr>
<th><strong>Approach</strong></th>
<th><strong>Characteristics</strong></th>
<th><strong>Provider or Reference Plant</strong></th>
<th><strong>Quality and Uses of Mineral Fraction</strong></th>
<th><strong>Metals Recovered</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Practice</td>
<td>Fe and nFe separation, treatment of max. 2 grain size fractions, ageing</td>
<td>Multiple plants</td>
<td>Fits for enclosed application: road filler or base layer, landfill site construction, landfilling</td>
<td>Fe: 5-10 % nFe: 0.5-1.5 % (of bottom ash weight)</td>
</tr>
<tr>
<td>Advanced Metals Separation</td>
<td>ECS treatment in additional grain size fractions, sensor sorting technologies (electromagnetic metal sensor, x-ray sensor)</td>
<td>Various plants, various providers</td>
<td>See above</td>
<td>nFe additional approx. 1 % - 1.5 % (of bottom ash weight) stainless steel sep., nFe addit. up to 1,5 - 2 %, nFe concentrate</td>
</tr>
<tr>
<td>Disintegration of Agglomerates</td>
<td>(impact) crusher, &quot;gentle&quot; impact crushing (&quot;TAR-Processor&quot;), electrodynamic fragmentation (implies wet processing)</td>
<td>E.g. Racco, Emmelcoord (NL); BiR Avfallsnings, Bergen (N.)</td>
<td>Crushed to sand → landfilling, other applications under research</td>
<td>nFe additional up to 2 % (estimated)</td>
</tr>
<tr>
<td>Dry Mach Treatment</td>
<td>Ballistic separator &lt; 2 mm (ADR unit), sieving at 2 mm, separate wet treatment of grain size fraction &lt; 2 mm</td>
<td>Inashco, Rotterdam (NL), e.g. HEROS, Slikskil</td>
<td>Moderate shift to fine grain size, landfill site construction, landfilling, after ageing other uses might be applicable</td>
<td>Additional Fe approx. 3 %, additional nFe 2 % after upgrading</td>
</tr>
<tr>
<td>Elimination of Fine Grain Fraction</td>
<td>Wet sieving with partial recycling of water, intense washing (e.g. washer barrel), wet sieving several size fractions</td>
<td>Martin GmbH, Munich, Bossals, Papendrecht (NL), Indaver, Doel (B), Evers &amp; Co, Helmond (D), Scherer + Kohl, Ludwigshafen (D)</td>
<td>In combination with high temperature combustion and recycle of the fines, consider-able amelioration of the bottom ash quality</td>
<td>No enhancement of metals recovery intended</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Free application according to Dutch and Flemish regulations. German LAGA guideline Z1.1 might be reached. Up to now, approx. 10 - 15 % of fine fraction has to be deposited.</td>
<td>nFe additional approx. 0.7 - &gt;1 % (without targeted treatment of fine fraction)</td>
</tr>
</tbody>
</table>

Figure 3: Classification on bottom ash treatment approaches
Elimination of a very fine grain fraction

a) Dry mechanical treatment, ballistic separator (ADR Processor): This approach is offered by Inashco [7]. The ADR-Processor breaks the adhering forces by acceleration of the particles with a cut-off size for minerals of 2 mm. Metal particles down to 0.5 mm are reported to be released, too. In combination with multiple grain size ECS separation, up to approximately 1 percent additional NF metals can be obtained. The mineral matter is split into a quite clean coarse fraction (> 2 mm, 70 percent) and a fine fraction (< 2 mm, 30 percent). The coarse fraction can be used as an aggregate in concrete applications. Additional research is still necessary to stabilize the fine fraction and to develop applications for it. The amount of fine fraction seems to be dependent on the waste incinerated, e.g., if sewage sludge is incinerated the amount of fine fraction usually rises.

b) Dry mechanical treatment, sieving at 2 mm: This technology has been developed by former Geodur, a Swiss ash treating company [12, 31]. The fine fraction is treated by wet processes on site to yield a metal concentrate which is treated at a central facility. Except of the additional sieving unit at the beginning of the ash treatment process, there is no difference to a conventional bottom ash treatment system. Therefore this approach should also work with existing treatment plants. It aims mainly at small particles of copper and other heavy metals not accessible to ECS in dry ash treatment systems.

c) Wet sieving to eliminate the very fine ash fraction: This process has been tested by MARTIN GmbH [11, 18] on an incinerator operating with oxygen enriched air. The fine fraction was pelletized and fed back into the furnace (Syncom plus process). A considerable amelioration of the bottom ash quality was reached.

d) Intensive washing of the bottom ash [22, 26, 28]: Several bottom ash treatment plants have developed systems for washing the whole bottom ash or parts of it (e.g. the fine fraction). The quality improvement achieved on the coarse bottom ash fraction is excellent but the sand fraction (0.063 to 2 mm) reaches a lower quality and sludge is produced, making up approximately 10 percent of the bottom ash. The revenues of additional NF recovery may pay off for the extra expenses of the wet process. The sludge has to be landfilled.

4. Legal framework

The prevailing legal environment in Germany is expected to change in the future due to:

- revision of the European Waste Catalogue, which is expected to be implemented in 2016 and
- forthcoming new requirements for the use of substitute construction materials – substitute building materials ordinance –
The current state of draft versions and stakeholder discussions on forthcoming legislation was examined for its future potential impacts on treatment requirements, on bottom ash utilization, landfill disposal and costs. The German transposition of the revised European list of wastes passed the cabinet and is in the parliamentarian process now. The application of hazardous properties (HP) criteria according to the commission regulation (EU) No 1357/2014 of 18 December 2014 replacing Annex III to Directive 2008/98/EC of the European Parliament will be mandatory. The new hazardous class and category codes have to be used from (EC) No 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP regulation) – since 1 June 2015 – on a European level. The new hazardous category codes might cause some changes in the classification of wastes.

A new draft version of the substitute building materials ordinance was issued recently and the discussions will go on. Bigger obstacles can be expected in the use of recycled mineral building and construction materials and bigger amounts might have to be landfilled. The bottom ashes might hardly be usable as construction materials anymore and might have to compete with huge amounts of the constructions materials for affordable but limited landfill volumes.

5. Overview of Bavarian Waste-to-Energy plants

A questionnaire was sent to the operators of the Bavarian WtE plants to collect information about bottom ash output, quality, treatment and utilization. Most of the plants have their ashes treated and utilized externally by third party service providers, who may be quite efficient in the reclamation of metals. The mineral fraction is utilized as filler or base layer material at landfill sites or is even disposed of. The plants contacted cover about 75 percent of the total bottom ash amount produced. Therefore the answers are regarded as quite representative.

5.1. Metal recovery

Most of the WtE plants only recover coarse ferrous scrap on site and leave the rest to separate bottom ash processing plants separating NF-metals from various plants. The non-ferrous metal recovery is not always optimized, summing up to about 0.75 percent of the bottom ash produced. The amount of iron scrap is reported to be 8.7 percent.
5.2. Current use of the mineralic bottom ash fraction in Bavaria

Figure 4 gives an overview about the current use of WtE bottom ashes in Bavaria. The predominant share of landfill disposal or use as a landfill site construction material is due to abundant availability of cheap natural aggregates in Bavaria and to the quite low prices for landfilling of bottom ash. A substitution of natural aggregates in construction projects by refined bottom ash in Bavaria is currently not competitive.

Only two bottom ash processing plants have access to waterway transport allowing long distance transport at reasonable prices. Mine backfilling requires transport by train or truck to a bottom ash treatment facility close to a former salt mine in Baden-Württemberg.

6. Conclusions and recommendations

Bavarian bottom ashes are hardly used as construction materials apart from landfill construction today. Since all plants are currently using wet discharging processes the recommendations for future improvements on the recovery of metals and reduction of its hazardous potential were elaborated accounting for the special situation in Bavaria. New developments in ash treatment offer a good potential to improve yield and quality in metal recovery by better sifting processes in more fractions, in combination with moderate crushing to extract metals, remove contaminants and increase yield and quality of the products. The additional metal amounts to be extracted can be realized by a step by step upgrade of crushing, sifting and sensor based sorting machines partly at the WtE plants, the ash treatment companies and the smelters. A wet processing of selected, bottom ash fractions can further reduce a hazardous potential but should be introduced with a good eye to the resulting wastewater treatment facilities to be installed and the landfill costs for the sludge.

Forthcoming legislation like the substitute construction material ordinance might have a large impact on the future use of recycled building and demolition materials in competition to the current utilization of treated bottom ashes and may even have the potential change existing disposal paths.

7. References


