

# Reduction of Natural Resource Use by Improving Resource Efficiency

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**Abstract** In 2011, the German Association of Engineers (VDI) started working on a set of guidelines dealing with the improvement of resource efficiency. These guidelines represent a framework that defines resource efficiency and outlines proposals for the producing industry. A special guideline for small and medium-sized enterprises (SMEs) is included as well as guidelines on methodologies for evaluating resource use indicators, such as the cumulative raw material demand of products and production systems. The work on resource use indicators is still in progress. The evaluation of raw materials expenditure will include water, soil and land use. The model will include the availability of raw materials (criticality). Improving resource efficiency at the end-of-life stage is illustrated in this paper by the example of materials recovery from waste, here from residues out of municipal solid waste incineration (MSWI). With mechanical treatment valuable materials like ferrous and non-ferrous metals and secondary construction material can be extracted from MSWI bottom ash. The potential contribution on the resource efficiency is discussed.

**Keywords** Resource Efficiency, Raw Material Equivalent, Mechanical Treatment, Bottom Ash, Waste Incineration, Secondary Raw Materials, Product Life Cycle

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## 1. Introduction

Resource protection and the efficient use of natural resources are some of the biggest challenges of the 21st century. Reasons for this include the production and consumption behaviours displayed by the world's developed countries, as well as the ongoing growth of the world population. Together with the price increases experienced in the energy and natural resource markets, this development is predicted to have a detrimental effect on the world's ecologies, economies, and societies. From an ecological perspective, the extent and methods of global resource exploitation are causing harmful emissions and waste products, a loss of biodiversity, and other issues. This is

accompanied by strongly fluctuating, mostly rising prices for raw materials, conflicts caused by supply uncertainty, and resource scarcity for selected raw materials. Therefore, there is significant pressure on society and the economy to increase the efficiency of using natural resources.

Resource efficiency is defined here as the ratio of specific quantifiable use to natural resource consumption. It can be evaluated by defining a function which expresses the specific use and quantifies the resource requirements through a set of indicators such as the use of raw materials, energy, water, land and ecosystem services including sinks. The respective results depend on system boundary parameters and allocation rules for by-products and waste treatment options. Minimising resource use is possible at all stages of a product's or production system's life cycle chain (raw material extraction, production and manufacturing, use and consumption, and the end-of-life stage).

In science, resource efficiency and resource conservation has been a major topic since the 1990s. In the European Union, increased resource efficiency is also a well-established political goal [1]. Germany addressed the topic of natural resource efficiency and conservation in its 2020 sustainability strategy [2]. More than 20 indicators and quantifiable goals were defined for the strategy's different areas. These are the economic indicators for resource conservation: "Doubling of Energy Productivity Between 1990 and 2020" and "Doubling of Natural Resource Productivity Between 1994 and 2020". The progress made in attaining these goals is regularly surveyed and documented [3].

In the processing industries, which also carry very high material costs, the potential savings associated with natural resource efficiency are estimated at around 7 percent [4]. In order to help SMEs identify and achieve these savings opportunities, the Federal German Ministry for Economic Affairs and Labour launched a support programme for consultation services in 2004 [5]. According to an analysis conducted as part of the federal programme, the potential savings associated with resource efficiency were 2.4 percent on average in relation to company turnover (in relation to material costs, the average increases correspondingly).

Nevertheless, the path towards improved resource efficiency in the private sector is frequently not followed as consistently as it could be [6].

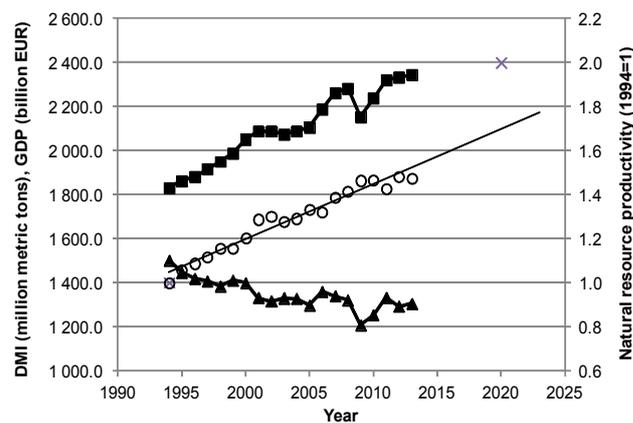
With more than 152,000 members, VDI (the German Association of Engineers) is Europe's biggest science and technology association, and, next to the German Institute for Standardization (DIN), the most important source of regulations in Germany. Given its wide-ranging base of technical expertise, VDI decided in 2009 to embrace resource efficiency as a cross-sectional topic. The objective was to close terminological and definitional gaps by streamlining both the terminology and the basic methods of calculating and evaluating the resource efficiency of products, processes and services. The goal of this is to work out consistent sets of rules. To VDI, "resource efficiency" means that all natural resources such as raw materials, energy, air, water and land (soils) are exploited as responsibly and efficiently as possible, and that environmental impact is reduced to a minimum. Any evaluation of resource efficiency can therefore only take place if the deployment of all natural resources is quantified (raw materials, energy, air, water, soils, ecosystem performance) and viewed in context. Quantification is based on a set of indicators, each of which represents a resource group. The indicators are modular; when combined, they form a basis for evaluating the deployment of natural resources.

VDI 4800 Part 1 Resource Efficiency – Methodical Principles and Strategies defines general terms pertaining to resource efficiency. It also provides descriptions of the resource groups, general assessment principles and rules, and recommendations on how to conduct resource efficiency analyses and evaluations. The final version of this VDI standard was released in February 2016 [7]. Currently, VDI 4800 Part 2 Resource Efficiency – Evaluation of Raw Materials Expenditure is being compiled for the "Raw Materials" resource group. This standard will describe an assessment model for raw materials including water and soils. Air is not included as a raw material in the model, as its ubiquitous global availability makes it largely irrelevant in this context. Another model is provided for assessing the availability of raw materials – their so-called criticality. This enables criticality evaluations for abiotic materials (metallic and non-metallic), fossil energy materials and biotic materials. VDI 4800 Part 2 furthermore describes important evaluation methods for the exploitation of land and soils.

## 2. Quantifying Resource Productivity

An assessment of the objectives of the German government to date reveals that domestic extraction and importing of natural resources has indeed declined. Viewed in combination with the increased gross domestic product, this indicates increased natural resource productivity (see Table 1).

In examining the domestic extraction and importing of natural resources and goods, the Federal German Statistical Office only assessed abiotic raw materials. With biotic raw materials included, the values are slightly different (2011 – domestically extracted and utilised raw materials: 1,110.4 million metric tons (mmt); imports: 613.0 mmt; natural resource productivity (-): 1.31). According to current data, the target value for 2020 will most likely not be reached (see Figure 1). However, the goal of absolute decoupling was achieved. Detailed analyses of the reasons behind the decline in natural resource consumption have already taken place [8], as have discussions of the influence of raw materials that were extracted but not utilised (unused extraction) [9].



**Figure 1.** Development of natural resource consumption (utilised domestic extraction and imports, abiotic raw materials only) (symbol: triangles), gross domestic product (adjusted for price) (symbol: squares) and the ratio between the two (natural resource productivity in 1994 normalized to 1). The target value of 2 for the normalized natural resource productivity in the year 2020 is marked by an 'X'. (Graph compiled by author)

The resource consumption as displayed in Table 1 is expressed in terms of mass regardless of what type of resource is considered. The consumption of 1 ton of copper has therefore the same impact as the consumption of 1 ton of sand. This is different in the concept of Total Material Requirement (TMR) [10]. TMR of sand and gravel is 1.18 tons/ton, TMR of copper 300 tons/ton [11]. At least for the imports the different stages of processing (i.e. metal ores, metal concentrates, raw, semi-finished or finished products) lead to an asymmetry. Domestic extraction is a gross value whereas imports are measured in weight of goods crossing the boundary independent of how far the imported products have been processed. This effect can be adjusted when imports are expressed as raw material equivalents (RME). The RME of a product indicates how much extraction of material was necessary over the whole production chain for manufacturing a specific product, irrespective of whether those raw materials were extracted from the domestic or the rest of the world [12]. For copper a value of 99.5 tons RME/ton traded weight is given (data for year 2010). The RME time series shows an increase starting at 76.5 tons/ton in the year 2000 indicating lowering of ore quality in producing countries [13].

**Table 1.** Calculation of natural resource productivity from the ratio of gross domestic product (GDP) to the sum of domestically extracted and utilised raw materials and imports (table compiled by author)

Year	Utilised domestic extraction <sup>1</sup>	Imports <sup>1</sup>	GDP <sup>2</sup>	Natural resource productivity <sup>3</sup>
1994	1,107.9	392.5	1.830.3	1.00
1995	1,051.1	393.3	1.863.2	1.06
1996	1,013.5	405.2	1.880.0	1.09
1997	993.9	411.8	1.915.7	1.12
1998	953.3	430.3	1.950.2	1.16
1999	997.1	412.3	1.987.3	1.16
2000	959.7	439.9	2.050.9	1.20
2001	902.9	426.6	2.087.8	1.29
2002	882.8	431.5	2.087.8	1.30
2003	875.7	453.5	2.073.2	1.28
2004	854.8	470.9	2.087.7	1.29
2005	827.6	468.9	2.106.5	1.33
2006	861.1	497.5	2.188.6	1.32
2007	841.4	496.5	2.263.0	1.39
2008	821.5	498.4	2.281.1	1.42
2009	773.3	432.5	2.153.4	1.46
2010	772.1	478.8	2.237.4	1.47
2011	833.5	498.7	2.320.1	1.43
2012	803.8	487.0	2.334.1	1.48
2013	798.0	506.3	2.343.4	1.47

<sup>1</sup> Abiotic raw materials in millions of metric tons

<sup>2</sup> Billions of euros, adjusted for price, base year: 1994

<sup>3</sup> Normalized values, Natural resource productivity in 1994 = 1.0

The assessment of the cumulative energy demand (CED) of products and services is more straightforward. The cumulative energy demand represents the overall expenditure of primary energy (in energy units) arising from, or attributable to, the production, use or disposal of a product or service. CED of copper (primary production) is 44,214 MJ/ton, CED of sand 44 MJ/ton [14].

The consumption of natural resources in Germany would be higher by a factor of 2.4 if the raw material equivalents were used instead of the simple mass unit in the traditional approach [9]. The resource consumption is dominated by sand and gravel. E.g. the material flow of construction materials is higher by a factor of about 250 compared to that of non-ferrous metals [15] so that high specific values of RME like for copper (see above) and other metals lead to a moderate increase under the line only. The impact of metals could even be lowered if the recycling rates were higher [16]. Utilization of resources derived from waste could help to increase recycling rates.

### 3. Materials and Methods

An example for a waste material which could help to

increase metal recycling rates is bottom ash (BA) from municipal solid waste incineration (MSWI). MSWI BA amounts to 20-25% by weight and 10% by volume of the initial MSW. It consists of solid phases already contained in MSW such as pieces of glass, ceramics, cinder and metals (iron and non-ferrous metals) as well as new phases formed during the incineration process [17]. The 5 major elements in MSWI BA are silicon, calcium, iron, aluminium and sodium. Whereas silicon and calcium are only bound as oxides and silicates, aluminum and iron occur in their elemental form as well. Sodium is additionally present as chloride [18].

BA is an extremely inhomogeneous material and its exact composition strongly depends on the type of combusted waste and on the conditions of incineration and further treatment [17, 19, 20]. A typical composition is

- 10 % unburnt material (organic (1%), glass cullet, ceramics etc. (9%)),
- 10% metals (ferrous (8%) and non-ferrous (2%), especially aluminum and copper),
- 40% ash and
- 40% melting products.

In contact with water BA leads to alkaline pH values of 12 and above due to the formation of  $\text{Ca}(\text{OH})_2$ . Aluminum is partly oxidized under alkaline conditions reacting to  $\text{Al}(\text{OH})_3$  and hydrogen. Subsequent storage of BA results in carbonization of the ash and a decrease of pH values [21]. Therefore, the wet ash discharge and the ageing (both common practice in Germany) results in mineral coatings and coagulation of all different types and sizes of particles [22]. These reactions are accompanied by hardening and hydraulic cementation of the BA.

#### 3.1. Treatment Methods

Treatment options for the reduction of potential environmental impacts from BA reuse or disposal can be grouped in three categories [23]: separation processes with physical or chemical methods, solidification processes and thermal processes. Thermal processes comprise sintering (treatment below smelting point) [24] and smelting processes. Due to high energy consumption especially smelting processes are not suitable to the complete BA. It was suggested to smelt only the fine fraction [25]. However, smelting processes did not win recognition in technical scale. Wet treatment is applied as physical process to remove very fine particles and inorganic constituents such as chloride and sulphate [26] if high-grad quality of the mineral fraction is required for utilization. Extension of washing processes with chemical process steps (e.g. precipitation) is not common. BA treatment is dominated by non-thermal, dry processes. Some basic mechanical treatment methods are common and are implemented in nearly all plants. These methods are sieving, crushing, magnetic separation, eddy current separation, manual separation and air separation.

Sensor based separation techniques are also applied, but are not as common because the mineral coatings limit the

usage of available sensors. Electromagnetic or possibly X-ray (fluorescence or transmission) sensors are in principle suitable, optical sensors is not as long as the material is not washed or separated adequately. However, wet treatment is rarely used in Germany currently. New approaches for material specific separation (as e.g. electrodynamic fragmentation) are still in the stage of development [27]. The applicability of sensor based separators is also limited to larger grain sizes (approx. > 8 mm) due to the required size of the blast pipes and the gap between, respectively.

#### 3.1.1. Sieving

Bar sieves are usually used for retention of oversized particles (> 40 - 80 mm). These are sometimes already placed at the outlet of the incinerator. Drum sieves are occasionally used for the removal of mineral coatings and agglomerations of the oversized particles by friction.

In the processing of BA sieving is not only a grading step. It also serves for agitation and friction as well as for gapping and singularizing of the particles, which are released to the different conveyor belts. Vibrating flip-flow screens are widely applied to obtain different size fractions down to 1 mm in order to optimize following treatment steps.

#### 3.1.2. Crushing

As aforementioned BA is a very complex, agglomerated and cemented material and breaking up seems to be desirable for further treatment steps. On the other hand crushing is a very intensive process with high energy consumption, high degree of wearout and rather unspecific impact. The higher the impact the more the metals can be uncovered from the mineral coatings. Separation methods applied in the following could be more efficient, but in correspondence the mineral residues have smaller grain size distributions. The additional fine particles may hinder the applicability as construction material for instance due to less gas and water permeability.

Crushing is used in various manners in the treatment of BA and is applied to the whole BA as well as for selected particular fractions (e.g. for refining of pre-separated metals). Most common are impact, hammer and jaw crushers. A few treatment plants operate entirely without crushing at least in the standard procedure.

#### 3.1.3. Magnetic Separation

Magnetic separation has a long tradition in mechanical treatment of BA. Ferrous metals were separated from the BA already in early stages of the waste incineration methodology either by manual separation or even by magnets. In most cases the magnets are placed above a conveyor belt to lift the magnetic particles out of the mass flow. A separate conveyor belt transports the lifted particles across or beyond the mass flow to a separate chamber. Another widely used configuration for stronger magnetic forces is a magnetic roll placed at the end of a conveyor belt to pull magnetic particles around the edge. At the end of the magnetic roll they are then

released to a separate chamber located beneath the conveyor belt.

For a long period, magnetic separation was only applied for coarse grain sizes. Nowadays it is implemented at different stages of BA treatment and is also used for small grain size distributions, for instance to improve the eddy current separation or to recover more ferrous metals after crushing. Moreover, special blends of oxidized metals can be extracted using extra strong magnets.

#### 3.1.4. Eddy Current Separation

Eddy current separation is used for the recovery of non-ferrous metals especially aluminum, copper, zinc and alloys like brass. Eddy current separators induce magnetic fields in electric conductive particles, which are contrary to the alternately arranged permanent magnets located in a rotating magnet wheel. While nonconductive particles fall from the conveyor belt in correspondence to the forces of gravity and velocity, conductive particles are extracted by the repulsive forces. Amongst others, the trajectory of particles depends on their size. Therefore, in most treatment plants several grain size distributions are processed separately in order to improve the metal recovery. The trajectory can also be influenced by the speed of the conveyor belt and the setting of the magnetic wheel (type, position, rotational speed). An adjustable baffle is installed to adapt the separation cut. Since ferrous metals weaken the magnetic fields, they should be separated previously. Moisture disturbs the procedure as well. In addition the grain density, shape and the position of the grains on the conveyor belt are important for the separation process.

Regarding these numerous influencing factors the procedure can be optimized either to obtain a high yield or to generate a high purity of the valuable metals. In the latter case a second treatment with the same or an additional eddy current separator may be worthwhile. In contrast to sensor based separators there is in principle no technical limit to treat fine particles by eddy current separation.

## 4. Performance of Resource Recovery

The above described treatment steps are combined to a treatment train which represents an entire sequence of selected processing techniques in order to optimize the desired product characteristics. A separation of oversized particles with bar sizers is generally the first step of BA treatment. A drum sieve can be used for uncovering the metals by friction and to screen out fine particles. The oversized fraction is then automatically processed with magnetic separators only. Afterwards selected groups of material as organic residues, metallic hollowware, electric coils and non-ferrous metals, especially stainless steel, are separated manually. While unburnt organic material is returned to the feed of the incinerator, all other fractions will be recycled.

Various procedures composed of already established

processing methods exist for further treatment of the sieved fraction (< 40 – 80 mm). In either case a magnetic separation and the fractionation to desired grain size distributions is conducted before specifically optimized eddy current separation. Crushing can be used for the whole BA to increase the efficiency of following sorting processes as well as to refine metal fractions. Air separation is placed in numerous positions for the removal of organic residues or lightweight fractions. Usually a fraction of fine particles (average mesh size 2 mm) is screened out and not treated further. In order to achieve high metal recovery rates multiple magnetic separators and separate eddy current separators for different grain size fractions (coarse, medium, fine) come into operation. Recovered mass percentages of ferrous metals and non-ferrous metals are in average 7.6 % and 1.7 %, respectively. Mineral residues are negligible in the fraction of ferrous metals but range between 15 and 60 % for the non-ferrous fractions [28].

Further, processed mineral material from BA can be applied in civil engineering. Legislative issues in this respect are challenging. The composition of the residual products of waste incineration strongly depends on the input material. As MSW is a very complex material these input contents vary in a wide range. For the environmental impact assessment posed by the application of BA on soil in Germany column percolation tests are preferred to simulate and evaluate the leaching behavior of solid materials [29]. Here the status of the ageing process is highly relevant [21]. The pH value decreases in the course of the ageing process, as mentioned above, and influences the leaching behavior of the BA. In particular critical elements like lead may be substantially immobilized [30, 31]. For this reason the ageing procedure has to be specified in detail and stipulated in regulations when the mineral fraction of BA is utilized.

## 5. Conclusions

The recovery of elemental metals from MSWI BA is technically feasible and helps to increase recycling rates of metals. Increased application of secondary metals recovered from waste help to lower natural resource consumption in terms of raw material equivalents (RME). The benefits of metals recovery are also supported by exergetic considerations [32]. Elemental Al and Fe account for more than 80 % of the total exergy of BA. Comparison of cumulative energy demand for copper and sand and gravel points in the same direction (see chapter 2.). However, 90 % of BA is non-metallic mineral material. Here an application in civil engineering is in principle feasible as a substitute for natural sand and gravel although there are alternative secondary building materials such as processed construction and demolition waste (C&D waste). The quantities of C&D waste are much higher than those of MSWI BA and the pollutant content is assumed to be lower [33].

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## REFERENCES

- [1] European Commission, Roadmap to a Resource Efficient Europe, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM (2011) 571 final. Commission of the European Communities, Belgium, 2011.
- [2] German Federal Government, Perspectives for Germany, Our Strategy for Sustainable Development, Berlin, 2002.
- [3] Statistisches Bundesamt, Nachhaltige Entwicklung in Deutschland, Indikatorenbericht 2012, Wiesbaden, Germany, 2012.
- [4] M. Schröter, C. Lerch and A. Jäger, Materialeffizienz in der Produktion: Einsparpotenziale und Verbreitung von Konzepten zur Materialeinsparung im Verarbeitenden Gewerbe, Endberichterstattung an das Bundesministerium für Wirtschaft und Technologie (BMWi). Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe, Germany, 2011.
- [5] F.G. Simon and K. Dosch, Verbesserung der Materialeffizienz von kleinen und mittleren Unternehmen, Wirtschaftsdienst, Zeitschrift für Wirtschaftspolitik 90(11) (2010) 754-759.
- [6] M. Schmidt and M. Schneider, Kosteneinsparungen durch Ressourceneffizienz in produzierenden Unternehmen, Umweltwirtschaftsforum 18(3-4) (2010) 153-164.
- [7] Verein Deutscher Ingenieure, Ressource efficiency, Methodological principles and strategies, VDI Guideline, VDI 4800, Part 1, 2016.
- [8] U. Lauber, Gesamtwirtschaftlicher Rohstoffeinsatz im Rahmen der Materialflussrechnungen, Wirtschaft und Statistik (3) (2005) 253-264.
- [9] S. Buyny and U. Lauber, Weiterentwicklung des Indikators "Rohstoffproduktivität" der nationalen Nachhaltigkeitsstrategie, Berechnung der Importe und Exporte in Rohstoffäquivalenten, Wirtschaft und Statistik (11) (2009) 1133-1145.
- [10] K. Halada, K. Ijima, N. Katagiri and T. Ohkura, An approximate estimation of total materials requirement of metals, Journal of the Japan Institute of Metals 65(7) (2001) 564-570.
- [11] F.G. Simon, A. Geburtig, V. Wachtendorf and P. Trubiroha, Materials and the environment, in: H. Czichos, T. Saito and L. Smith (Editors), Springer Handbook of Materials Measurement Methods, Springer Science and Business Media, Heidelberg, 2006, pp 789-803.

- [12] K. Schoer, J. Giegrich, J. Kovanda, C. Lauwigi, A. Liebich, S. Buyny and J. Matthias, Conversion of European product flows into raw material equivalents, Final report to project contract no. 50902.2010.001.-2010.612. ifeu - Institut für Energie- und Umweltforschung, Heidelberg, Germany, 2012.
- [13] G.M. Mudd, An analysis of historic production trends in Australian base metal mining, *Ore Geology Reviews* 32 (2007) 227-261.
- [14] Verein Deutscher Ingenieure, Cumulative energy demand (CED) - Terms, definitions, method of calculation, VDI Guideline, VDI 4600, 2012.
- [15] F.G. Simon, V. Wachtendorf, A. Geburtig and P. Trubiroha, Materials and the environment, *Environmental Impact of Materials*, in: H. Czichos, T. Saito and L. Smith (Editors), Springer Handbook of Metrology and Testing, Springer, Heidelberg, 2011, pp 845-860.
- [16] T.E. Graedel, J.M. Allwood, J.P. Birat, M. Buchert, C. Hagelüken, B.K. Reck, S.F. Sibley and G. Sonnemann, Recycling rates of metals, Report of the working group on global metal flows to the International Resource Panel. UNEP, 2011.
- [17] A.P. Bayuseno and W.W. Schmahl, Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash, *Waste Management* 30(8-9) (2010) 1509-1520.
- [18] A.J. Chandler, T.T. Eighmy, J. Hartlen, O. Hjelmar, D.S. Kosson, S.E. Sawell, H.A. van der Sloot and J. Vehlou, (Eds.) Municipal solid waste incineration residues: An international perspective on characterisation and management of residues from municipal solid waste Incineration. Included in series *Studies in Environmental Science (International Ash Working Group)*, Vol. 67, Elsevier, Amsterdam, 1997.
- [19] Y.M. Wei, T. Shimaoka, A. Saffarzadeh and F. Takahashi, Mineralogical characterization of municipal solid waste incineration bottom ash with an emphasis on heavy metal-bearing phases, *Journal of Hazardous Materials* 187(1-3) (2011) 534-543.
- [20] J. Hyks and T. Astrup, Influence of operational conditions, waste input and ageing on contaminant leaching from waste incinerator bottom ash: A full-scale study, *Chemosphere* 76(9) (2009) 1178-1184.
- [21] J.J. Dijkstra, J.C.L. Meeussen, H.A. Van der Sloot and R.N.J. Comans, A consistent geochemical modelling approach for the leaching and reactive transport of major and trace elements in MSWI bottom ash, *Applied Geochemistry* 23(6) (2008) 1544-1562.
- [22] C. Speiser, T. Baumann and R. Niessner, Morphological and chemical characterization of calcium hydrate phases formed in alteration processes of deposited municipal solid waste incinerator bottom ash, *Environmental Science & Technology* 34(23) (2000) 5030-5037.
- [23] T. Sabbas, A. Poletini, R. Pomi, T. Astrup, O. Hjelmar, P. Mostbauer, G. Cappai, G. Magel, S. Salhofer, C. Speiser, S. Heuss-Assbichler, R. Klein and P. Lechner, Management of municipal solid waste incineration residues, *Waste Management* 23(1) (2003) 61-88.
- [24] A.R. Boccaccini, I. Lancellotti and L. Barbieri, Sintering: An Alternative to Fusion for the Recycling of Silicate Waste?, *Glass Science and Technology (Glastechnische Berichte)* 73 (2000) 85-94.
- [25] D. Traber, U. Mäder, U. Eggenberger, F.-G. Simon and C. Wieckert, Phase Chemistry Study of Products from the Vitrification Processes AshArc and Deglor, *Glass Science and Technology (Glastechnische Berichte)* 72(3) (1999) 91-98.
- [26] A. Keulen, A. van Zomeren, P. Harpe, W. Aarnink, H.A.E. Simons and H.J.H. Brouwers, High performance of treated and washed MSWI bottom ash granulates as natural aggregate replacement within earth-moist concrete, *Waste Management* (2016) in press (<http://dx.doi.org/10.1016/j.wasman.2016.01.010>).
- [27] K.P. van der Wielen, R. Pascoe, A. Weh, F. Wall and G. Rollinson, The influence of equipment settings and rock properties on high voltage breakage, *Minerals Engineering* 46-47 (2013) 100-111.
- [28] K. Kuchta and V. Enzner, Ressourceneffizienz der Metallrückgewinnung vor und nach der Verbrennung, in: K.J. Thomé-Kozmiensky (Editor), *Mineralische Nebenprodukte und Abfälle 2*, TK Verlag, Neuruppin, 2015, pp 105-116.
- [29] BMU, Verordnung zur Festlegung von Anforderungen für das Einbringen und das Einleiten von Stoffen in das Grundwasser, an den Einbau von Ersatzbaustoffen und für die Verwendung von Boden und bodenähnlichem Material und der Bundes-Bodenschutz- und Altlastenverordnung, 2. Arbeitsentwurf (translation: Draft Mutual Release of the Ordinance on Groundwater Protection, Mineral Waste Utilization and Federal Soil Protection and Contaminated Sites) in German (2011)
- [30] S. Arickx, V. De Borger, T. Van Gerven and C. Vandecasteele, Effect of carbonation on the leaching of organic carbon and of copper from MSWI bottom ash, *Waste Management* 30(7) (2010) 1296-1302.
- [31] F. Takahashi and T. Shimaoka, The weathering of municipal solid waste incineration bottom ash evaluated by some weathering indices for natural rock, *Waste Management* 32(12) (2012) 2294-2305.
- [32] F.G. Simon and O. Holm, Exergetic Considerations on the Recovery of Metals from Waste, *International Journal of Exergy* 19(3) (2016) 352-363.
- [33] F.G. Simon and K. Keldenich, Abfallwirtschaft im Spannungsfeld zwischen thermischer Behandlung und Recycling (Waste Management between Thermal Treatment and Recycling), *Chemie Ingenieur Technik* 84(7) (2012) 985-990.