Life Cycle Analysis of processes for resource recovery from Waste-to-Energy bottom ash

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Executive Summary

Combustion with energy recovery of post-recycling municipal solid waste (MSW) plays an important role in sustainable waste management worldwide. The main by-product of MSW combustion is the ash discharged at the end of the moving grate, which has significant resource potential, since it mainly consists of ferrous, non-ferrous metals and mineral aggregates. This potential has led to increasing attention on advanced separation and treatment techniques of waste-to-energy bottom ash (WTE-BA), Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) are carried out in this research, to identify the burdens and environmental benefits from WTE-BA processing and recovery methods, and the related expenditures and revenue to WTE facility. Four scenarios are selected with the data corresponding to four WTE-BA treatment facilities in the United States and Europe:

a) *Wet ash discharge with dry treatment system (U.S.A.)*
b) *Wet ash discharge and wet treatment system (Denmark)*
c) *Wet ash discharge followed by dry treatment system with ballistic system (Netherlands)*
d) *Dry ash discharge followed by dry treatment (no ballistic system) (Switzerland)*

The results showed that:

(i) the dry ash, dry processing system is the most cost-effective system, with the highest metal recovery rate and raw material resource saving;

(ii) the Advanced Dry Treatment (ADR) system effectively recovers non-ferrous metal, as compared to conventional dry treatment and wet treatment;

(iii) civil engineering applications of aggregate minerals derived from WTE-BA, after metal separation, reduce the environmental impacts and cost of landfilling ash, and can result in significant additional profit to WTE operations.

Acknowledgements

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1. Introduction

Municipal solid waste (MSW) typically consists of residential and commercial waste. Waste-to-Energy (WTE) is the only proven alternative for the management of post-recycled MSW and has the ability to reduce the volume of MSW by 90%, associated with the high temperature of combustion of 700 – 900 °C [3]. There are over 1,000 WTE plants in the world combusting more than 200 million tons of MSW per year [1]. In 2014 in the US, about 30 million tons of MSW were thermally processed in77 WTE facilities and produced14 millions MWh of electricity [2].

There are two types of WTE residues, the WTE bottom ash (WTE-BA) and the fly ash (WTE-FA). WTE-BA is the main by-product of MSW combustion and represents about 20-25 wt.% as compared to the as-received MSW. WTE-BA is a fine gray material and consists of rocks, ceramic, glass, metal and mineral aggregates [4]. Silicon, calcium, iron and aluminum are the main components and have the highest mass percentage in WTE-BA [4]. WTE-FA is the by-product of the Air Pollution Control (APC) systems [5], associated with the volatile metals, dioxins, and other pollutants of environmental concern contained in the WTE-FA [5].

Increasing pressure on natural resources led to rising attention on separation and recovery methods of metals and mineral aggregates from WTE-BA [6, 7]. According to data from EPA (Figure 1), the total ferrous metals contained in MSW in 2013 were 17 million tons, and 6 million tons were recovered, while the rest were landfilled. The same year, 6 million tons of non-ferrous metals were contained in MSW and only 2 million tons were recovered. WTE-BA contains high amounts of valuable metals; however, only 48% of ferrous and 9% of non-ferrous are recovered at WTE facilities (Figure 2). The aim of this research is to characterize different options for metal recovery and recycling of mineral aggregates, by considering the environmental and economic aspects of the treatment techniques with the use of Life Cycle Analysis.

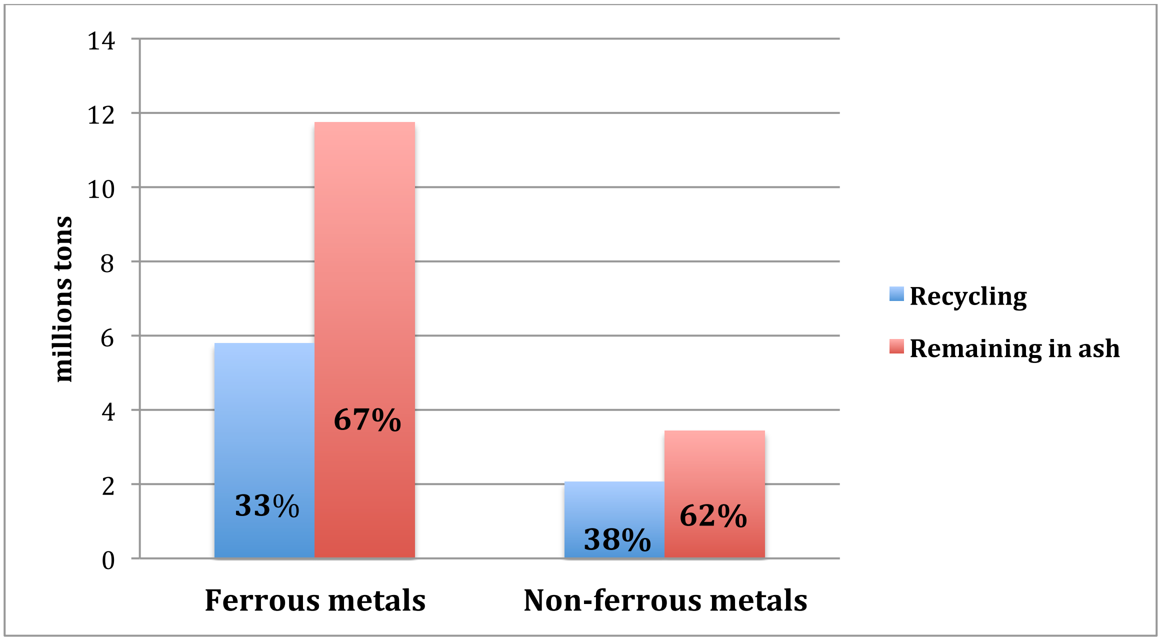


Figure 1. Recycling fraction of ferrous and non-ferrous metal from MSW [8]

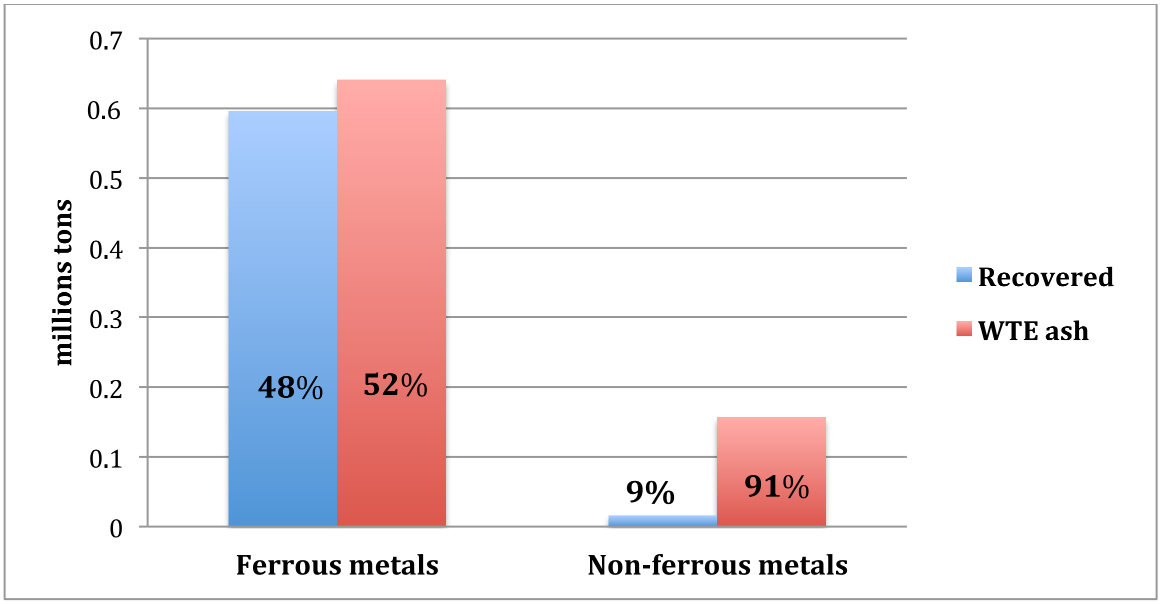


Figure 2. Average metal recovery fraction at Waste-to Energy facilities in the United States in 2006 [9]

2. The Ash Discharge System

WTE plants operate with either wet or dry discharge systems. Dry discharge system is the newest developed system that indicates improved metal recovery [1, 3, 6].

2.1 Wet Discharge System

The most common discharge system both in the United States and Europe is wet discharge system. WTE-BA drops from the moving grate into a water tank below the furnace [3]. The discharger is filled with water and a constant amount of wet WTE-BA up to the level of air sealing wall, in order to prevent flue gas and thermal pollution and false air ingress into the boiler [3]. The drive shaft, which is typically a pressure piston, forces quenched WTE-BA out of the discharger, while water is extracted by the compressing action of discharge ram before the drop-off edge [3]. Therefore, quenched WTE-BA is moist rather than wet after discharged [3]. The drive shaft is regulated by a timer or by the height of the quenched WTE-BA. The discharge rate of wet discharge systems range within 4.5 to 12.0 m^3/h [3]. The energy requirement of the wet discharge systems is 2 MWh/ 1,000 tons WTE-BA and the water used is 50,000 liters / 1,000 tonnes WTE-BA discharged [3].

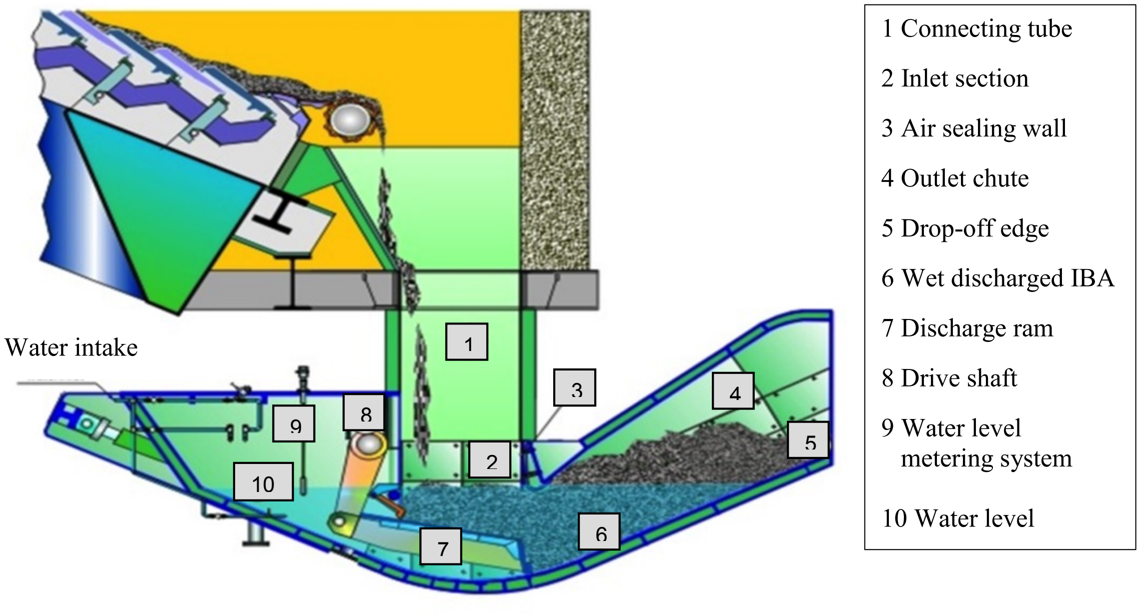


Figure 3. Schematic of combustion chamber and wet discharge system. Scenario 1, 2 and 3 is wet discharged ash.

2.2 Dry Discharge System

An innovative technique for the discharge of WTE-BA is dry discharge system, which was developed by Martin GmbH and applied in the WTE plant in Monthey, Switzerland. In the dry discharge system, WTE-BA drops from the moving grate and passes through an ash drum, and then it falls onto a baffle plate to comminute further [3]. Ash is discharged on a vibrating conveyor, which is designed to withstand temperature up to 400°C, and then air-cooled by injecting air with the aid of fans [3]. A 2-way diverter camera is installed to monitor the discharge process and an electrical-driven hood removes any oversized items that are not combusted. The water sprinkler helps to extinguish the still burning material when necessary. A set of flaps reduces the flow of air through the system. Very fine dust (<500 μm) is passed through a cyclone and is returned to the combustion furnace [3]. In this case, lower amount of fine fraction (<2mm) is produced from dry discharged system (10-12 wt.%) compared to wet discharged system (30 to 40 wt.%) [3]. The Monthey dry discharge system separate WTE-BA fractions into coarse fraction (>9mm) and fine fraction (<9mm). The discharge system increases the recycling of metals by 50% - 90% compared to the wet discharge systems [3].

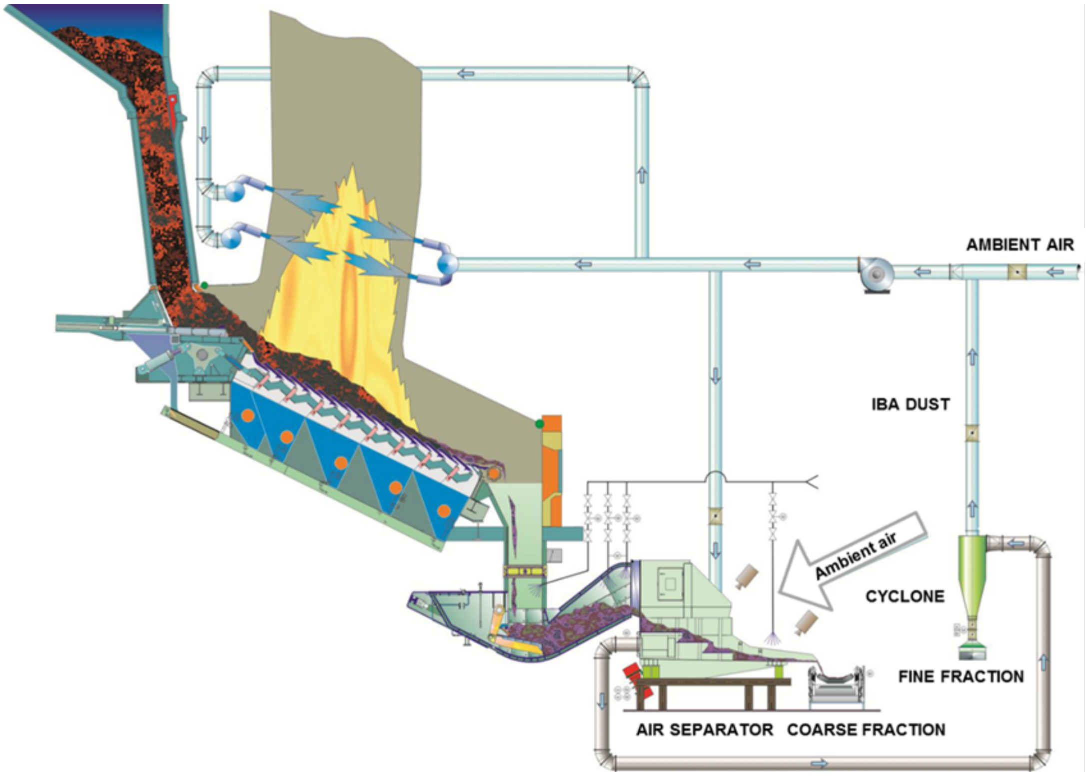


Figure 4. Schematic of Combustion Chamber and Dry Discharge System. Scenario 4 is dry discharged.

3. Metal Recovery

After WTE-BA is discharged, metals are separated from the stream. The amount of metallic items that can be separated from bottom ash is associated with the separation techniques and the composition of waste input. According to existing literature, ferrous and non-ferrous metals contained in WTE-BA range between 7-15% and 1-2% respectively [7]. Ferrous and non-ferrous metals can be distinguished by their magnetic properties. Ferrous scrap metals including iron and steel are usually separated by magnets, while non-ferrous metals including aluminum, heavy metals and steel are separated by eddy current or other sorting systems, i.e. induction/X-ray sorting system. The technology of recovering non-ferrous metals has undergone remarkable development because of the rapid increasing of metal price in recent years [4]. Removal of metals helps to save more than 95% of the energy in primary metal production in environmental aspect [20].

3.1 Conventional Dry Treatment

Bottom ash is commonly separated by dry physical treatment (screening, sieving, magnetic separation and eddy current). These methods play significant roles in separating and recycling metals from MSW.

3.1.1 Screening and sieving

The most important step in metal removal is an efficient fractioning system to WTE-BA [1]. Especially in the case to improve non-ferrous metals recovery quality, sieving plays significant role to have a precise fractioning of WTE-BA [4]. Water percentage of WTE-BA is also important in screening and sieving. If the water percentage is too high, WTE-BA has a problem of agglomerations and is difficult to be separated in different size fraction. If the water percentage were lower than 10%, dust emission of dusty material would also be a problem [3]. It is vital to control the water percentage of WTE-BA to have accurate and effective fractioning of WTE-BA.

3.1.2 Magnetic separation

Magnetic separation is typically used in separating ferrous metals from the WTE-BA stream. However, stainless steel, which is also ferrous metal but not having magnetic property, cannot be separated in magnetic separation system. Examples of magnetic separation are magnetic drum and overhead suspension magnets [4].

3.1.3 Eddy Current Separation

Eddy current is the most common system to separate non-ferrous metal out of the waste stream. It consists of a conveyor, and a non-magnetic drum equipped with an internal rotating set of magnets [4]. The magnets inside of the drum create magnetic deflecting and repulsive forces, pushes non-ferrous metals away from the drum. Because of the conductivity property, metals will have a more flat ballistic curve than non- metallic minerals [4]. Multiple Eddy Currents can increase non-ferrous metal recovery rate.

3.1.4 X-ray sorting

XRF is one of the spectrographic techniques that the spectral ratios of scrap materials are determined according to their major alloying element. Each relevant source hits the metal, and then the metal produces different emission (spectra). Varying types of detectors read these spectra, and a computer signal can separate the piece of scrap to appropriate bin using a pulse of compressed air [9]. This technology is one of the advanced but high cost metal separation technologies.

3.2 Wet Separation Metal Treatment

Wet separation metal treatment (Figure 5) is an innovative wet process that screens WTE-BA into several fraction streams (0-2 mm, 2-6 mm, 6-20 mm and 20-40 mm) and classifies 0-2 mm in a cyclone to take out the sludge (0-45 micron) or treated in Advanced Dry Treatment [10]. This wet technology can recover high proportion of metals larger than 0.3mm and remove organic material and fine aggregates from residues [11]. The wet process system recovers ferrous metals up to 80 – 85% of ferrous and 65% of non-ferrous metals [12]. Using a wet process system, clean sand grit is separated and used in producing sand-lime bricks and concrete [13]. The combination of screening and washing improve the quality of metal, aggregates recovery and residues in the terms of leaching of elements in ash [11].

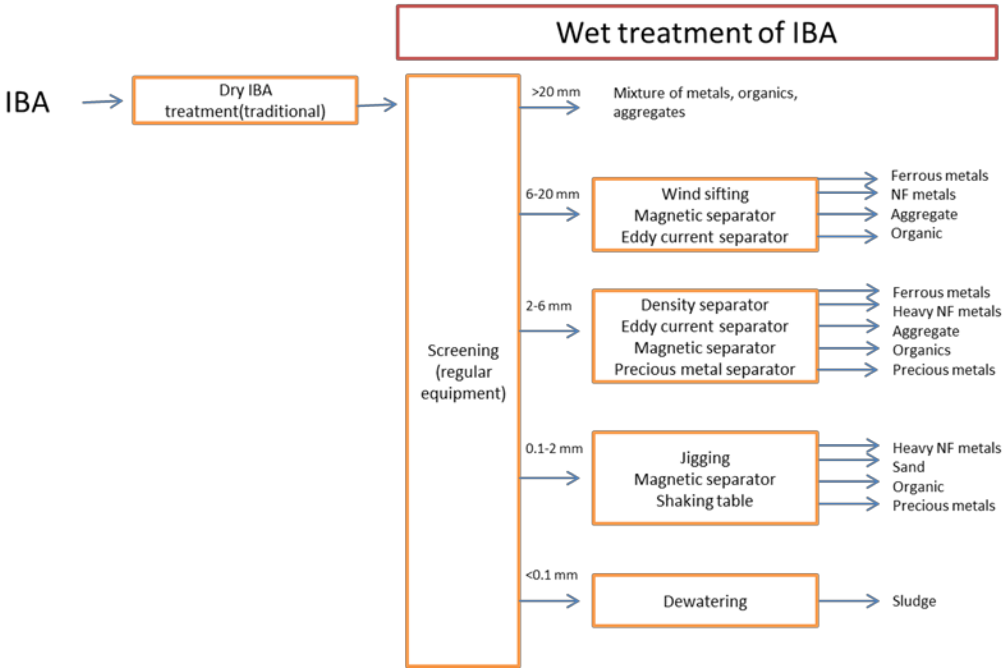


Figure 5. The wet process treatment diagram for the recovery of valuable materials from WTE-BA. Scenario 3 is assumed to use this wet treatment technique.

3.3 Advanced Dry Treatment - ballistic system

Inashco collaborated with Delft University of Technology (TU Delft) to develop an Advanced Dry Recovery (ADR) system and have industrialized new bottom ash dry treatment plants since 2008 [14]. The most common problem associated with moist bottom ash is in the 0-2mm grains, which small particle size metals are difficult to be recovered from. The ADR system not only can extract more metals from the challenging fine fraction (<2mm), but also enhance the recovery of almost all metals and glass in some case from the upstream (>2mm) wet bottom ash. Inashco concentrator can treat bottom ash with moisture content up to 20% [13]. This system highly increases metal recovery efficiency.

The moist bottom ash is sized and screened in different fraction. The coarse fraction (+12mm) of bottom ash will be recovered in traditional treatment, and the remainder is sent to Inashco concentrator. Figure 6 shows the schematic diagram of Inashco dry separation technology. WTE-BA falls on a rotating bladed drum, and then different components have different ballistic paths according to their gravity. Light components such as mineral fraction will fall down on the first conveyer, and heavy components like metals and rock would have a more flat curve and land on the second conveyer [13]. The downward blowing air jets help to increase purity of separated streams. This Advanced Dry Treatment concentrator helps to separate fine and light components and coarse and heavy components, and increase the recovery of non-ferrous metals in 0-12mm fraction from bottom ash. When the fine fraction are separated from coarse section, recovery rate of latter conventional metal recovery system will be higher. This system has smaller amount of heavy non-ferrous because it cannot blow > 0.5 mm copper because copper has four times higher density than sand [10]. This technology allows classification of moist bottom ash down to 2mm without drying or the additional of water. This system can be installed as a stand-alone or add on system on conventional technology (eddy current, magnetic and sieving system) [13].

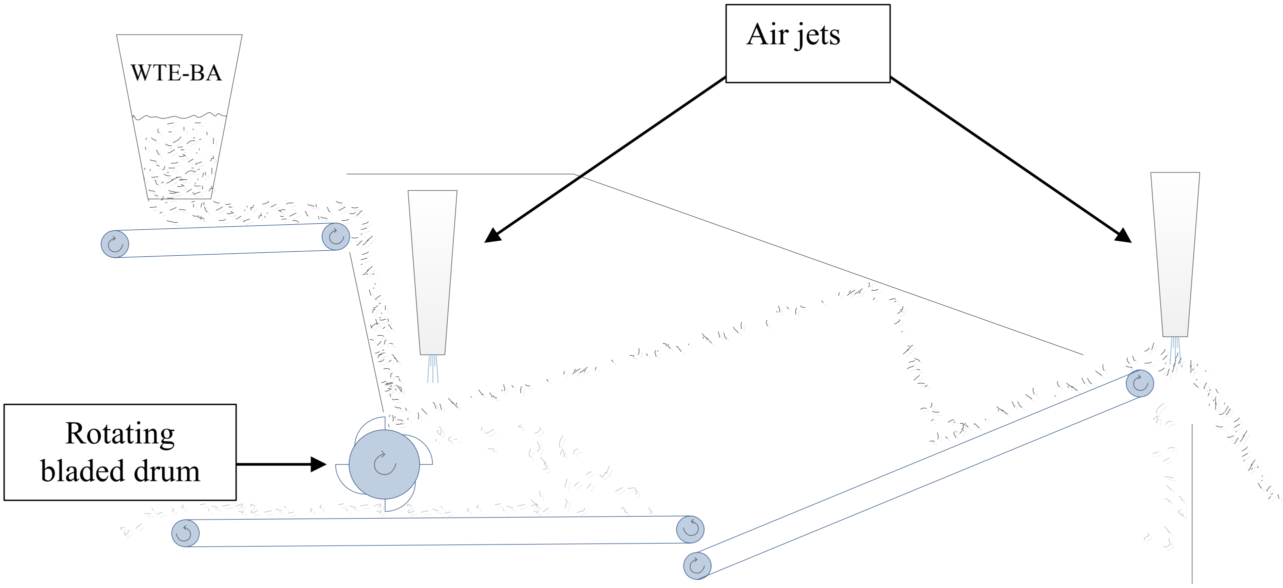


Figure 6. Schematic diagram of the Advanced Dry Treatment separation technique. Scenario 4 is assumed to use this technique.

3.4 Metal Recovery Rates

The recovery of metals from bottom ash plays a significant role in metal recycling at WTE facility. Different metal treatment methods lead to different metal recovery rate (Figure 7). Figure 7 is made according to Dr. Ralf Koralewska, Martin Gmbh's presentation at NAWTEC 2016 in West Palm Beach, Florida. It is noteworthy that conventional technologies typically have the 80% and 20% rate for ferrous and non-ferrous recovery, but innovative technology, which treating the fine fraction metal as well, achieved up to 90% and 98% of ferrous and non-ferrous recovery rate according to ZAR company and excluding the startup plant ZAV recycling.

Inashco and Afval Energie Bedrijf (AEB) Amsterdam also has comparative high efficiency of metal recovery especially in non-ferrous. The recovery of metals can be significant higher in the future, as it has potential to be moving forward with our efforts. The primary purpose of this research is to provide useful information about performance and cost analysis regarding techniques that are used to recover metals, and to enhance improvement of metal recycling in WTE facility.

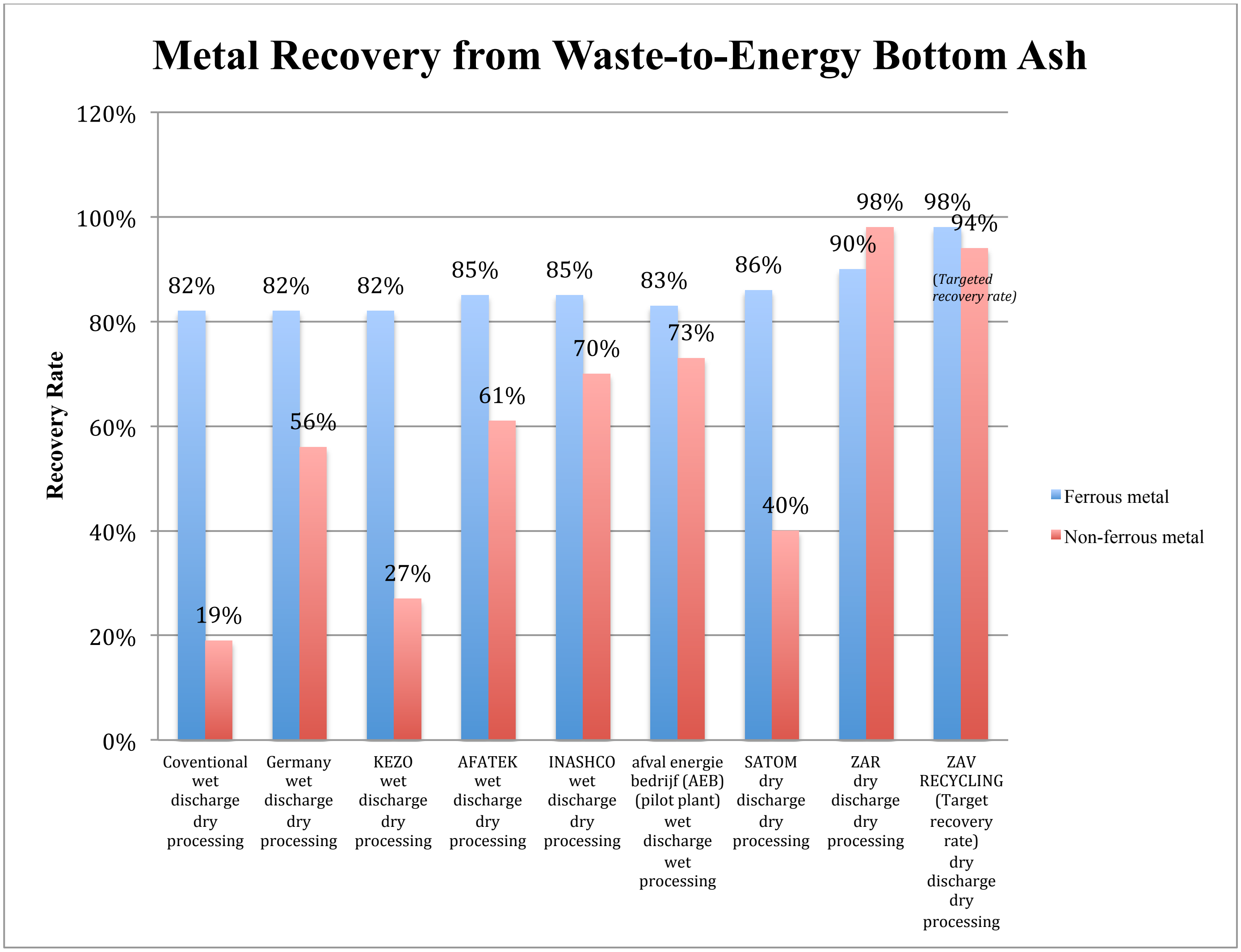


Figure 7. Metal recovery from processing Waste-to-Energy Bottom Ash in Europe (reproduced from Dr. Ralf Koralewska, Martin Gmbh's presentation at NAWTEC 2016) [12]

3.5 Weathering

Weathering or aging is a simple treatment to wet bottom ash or wet screening ash before or after metal recovery in Europe. It is a reaction of wet bottom ash with CO_2 uptake from atmosphere [4]. Proper weathering can be achieved by making ash with good access to air.

Appropriate weathering helps to lower the pH of metals, from 11-12 to 8-10, and the leaching of dissolved salts in ash. Weathering changes the chemical reaction with water from strongly alkaline to neutral [4]. It improves the chemical and mechanical properties of bottom ash. It takes 6-20 weeks of weathering before ash can be processed to further metal treatment, or for suitable utilization and landfilling.

4. Treatment of bottom ash after metal recovery

While the metal recovery from bottom ash is important due to its market value, mineral aggregates also plays an important role in urban application and environmental consideration. In the United States, bottom ash after metal recovery is mixed with fly ash and landfilled. Denmark, France, Germany and the Netherlands in Europe are examples that use weathered bottom ash as a sub-base material for road construction, substituting virgin gravel and sand material [4]. Certain specification and testing can refer to standardization EN 13285 and EN 13242 [4].

Denmark has many years of experience to use bottom ash in road construction. Studies from Denmark claim that their gravel and sand are more anti-abrasive comparing with bottom ash [4]. However, other studies also indicate that bottom ash is more compression resistance to support heavier load. The reason is because the non-uniform structure of bottom ash allows the normal forces from loading to dissipate and distribute into multiple directions, and increase the road's loading capacity [4]. With the same realization as Denmark, Danish also uses bottom ash in road construction without load restriction. In Switzerland, bottom ash is landfilled, but the fine fraction (<2mm) is allowed to be used in fly ash stabilization to create solid chemical inert concrete block [4]. Mixing of fine fraction of bottom ash with fly ash can reduce the demand of virgin produced cement that add to the mixture to solidify and stabilize fly ash [4]. Besides these, bottom ash is used for concrete products with low tensile strength, highway embankments and noise barriers in Europe [4].

However, the premise of maximum utilization of bottom ash is the proper metal recovery prior to recycling bottom ash. Removal of metal in bottom ash helps to create bottom ash with strong mechanical properties, and ensure the stony fraction has high value for urban application [4]. The utilization/ disposal of the bottom and fly ashes is associated with the leaching of heavy metals and other environmental hazards contained in these materials. The leaching standard is Toxicity Characteristic Leaching Procedure (TCLP) from EPA in the United States and Leaching Assessment Framework (LEAF) in Europe [3].

Metal recovery in WTE-BA recycling is a significant key for energy and raw materials saving both in environmental and business aspect. This study models different options for WTE-BA treatment, including recyclability of key metals and minerals and the impact of upcycling WTE-BA metals and minerals, and analysis environmental and economic impacts of these activities using scientific methods, by making reference to four WTE-BA processing facilities.

5. Method of LCA and LCCA Comparison

In order to compare the performance of different alternatives, Life Cycle Analysis and Life Cycle Cost Analysis are conducted in this research to identify the environmental resource and cost efficiencies of WTE-BA, which includes process of metals and aggregates recovery, achieved from four treatment methods of both wet and dry discharged WTE-BA. This study is cradle-to-grave and considers the whole life cycle of WTE-BA. The system boundary includes the WTE-BA output from combustion chamber, and the subsequent use and disposal stages of the upcycled WTE-BA co-products. The functional unit is defined as “management of 1,000 tonnes of wet or dry discharged WTE-BA”. The feedstock of MSW combusted affects the quality of resources in WTE-BA but it is assumed to be similar for all the scenarios examined.

The aim of this analysis is to obtain initial indication of the differences in energy resources and environmental impact arising from processing wet or dry discharged WTE-BA, and to determine the most cost-effective option among different competing WTE-BA processing methods.

5.1 Life Cycle Analysis

Life Cycle Analysis (LCA) is used in this study to qualify the environmental impact of resource recovery from the bottom ash. The process is carried out of the guideline of CML (Center of Environmental Science of Leiden University) [19]. Three indicators are selected to investigate environmental impact scores on four scenarios: Global Warming Potential 100 years (GWP100), Human Toxicity (HT), and Fresh-water Aquatic Eco-toxicity (FAET). GWP 100 is developed by the Intergovernmental Panel on Climate Change (IPCC), and factors are expressed in kg carbon dioxide/kg emission. HT factor is expressed as 1,4-dichlorobenzene equivalents/ kg emission, and referring to effects of toxic substances on human environment and health [19]. FAET describes emissions of toxic substances to air, water and soil, and also expressed as 1,4-dichlorobenzene equivalents/kg emission.

WTE-BA recycling plant	S1 Conventional treatment, U.S.A	S2 Advanced wet treatment, DK	S3 Advanced dry treatment, NL	S4 Advanced dry recovery, Monthey, CH	Units
Amount	1,000	1,000	1,000	1,000	tonnes
Discharge system	Wet	Wet	Wet	Dry	

Table 1. Function unit and discharge systems in Scenario 1 to Scenario 4. Function unit set up as 1,000 tonnes of wet or dry discharged WTE-BA. WTE-BA is wet discharged in Scenario 1, 2 and 3, and is dry discharged in Scenario 4.

5.1.1 Life Cycle Inventory and Material Flow Analysis Methodology

Life Cycle Inventory includes data collection of material and energy consumption and outputs in four scenarios. Data are collected from literature review and official reports of WTE-BA recycling plants from the United States and Europe [1, 3, 4, 10, 11, 12, 14]. In order to calculate the metal recovery in each plant, we assumed that ferrous metals account for 7-15% of the bottom weight, and non-ferrous metals account for 1-2% [4]. On the basis of this assumption and reported metal recovery rate from each plant, calculated data are presented as recovery rate of ferrous and non-ferrous metal and aggregates minerals from 1,000 tonnes of WTE-BA. Another source of material and emissions data is the Ecoinvent v2.2 database and the Simapro software. Data of electricity in Simapro is estimated to be grid in the United States and electricity reused in MSW incineration only, as we prospect all activities take place in the United States. Water data is assumed as decarbonized industry water. The effects of production from nature resource (e.g.

primary iron ore or primary aluminum ore) are subtracted from related scenarios' scores, as a result of treated WTE-BA replacing natural resources.

Material Flow Analysis (MFA) is also used to quantify flows and stocks of materials or substances in the system examined. Data were aggregated, elaborated and entered into the software package STAN 2.5 [6]. The following section discusses the four scenario compared and the countries where they are being applied.

Scenario 1: Wet ash discharge with dry treatment system (U.S.A.)

WTE-BA is wet discharged and processed in conventional dry treatment (magnet and eddy current). 66.1±3 tonnes of ferrous and 6.7±3 tonnes of non-ferrous metals/ 1,000 tonnes wet discharged WTE-BA are recovered. 822 tonnes of WTE-BA after metal recovery (coarse, medium, and fine fractions) are mixed with fly ash and cement and disposed in monofill. Water and energy consumption of scenario 1 are 50,000 liters and 14 MWh/1,000 tonnes WTE-BA treated, respectively [1,3].

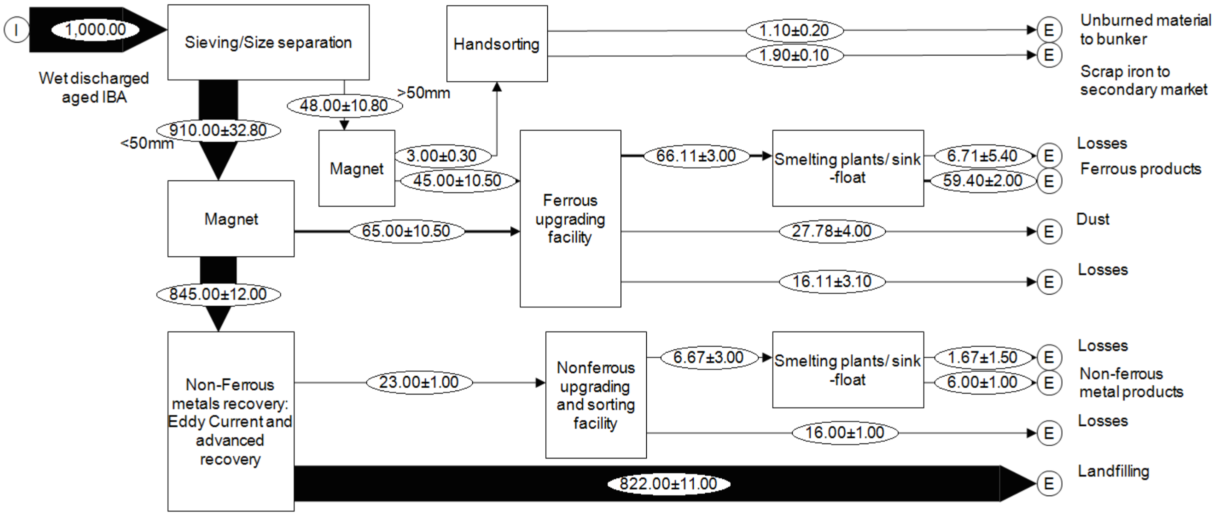


Figure 8. Sankey diagrams of Scenario 1 examined for wet discharge system

Scenario 2 Wet ash discharge and wet treatment system (Denmark)

WTE-BA is wet discharged and processed in wet treatment (Figure 5) in this scenario. Water is used to screen WTE-BA into 0-1.6 mm, 1.6-6 mm, 6-20 mm and 20-40 mm factions. In 1,000 tonnes of WTE-BA treated, 93.5±4 tonnes of ferrous and 9.2±2 tons of non-ferrous metals are recovered. Wet screening method can recover 85% of ferrous and 61% of non-ferrous metal from metals in bottom ash. 581.4 tonnes of coarse fraction (1.6mm-50mm) are treated in urban application such as road construction [4], and the fine fractions (<1.6mm) are landfilled. By allocating to functional unit of 1,000 tonnes of wet discharged bottom ash, this scenario consumes 50,020 litters of water (50,000 liters from wet discharge system and 20 litters from wet screening system), and 22 MWh of energy [1,3].

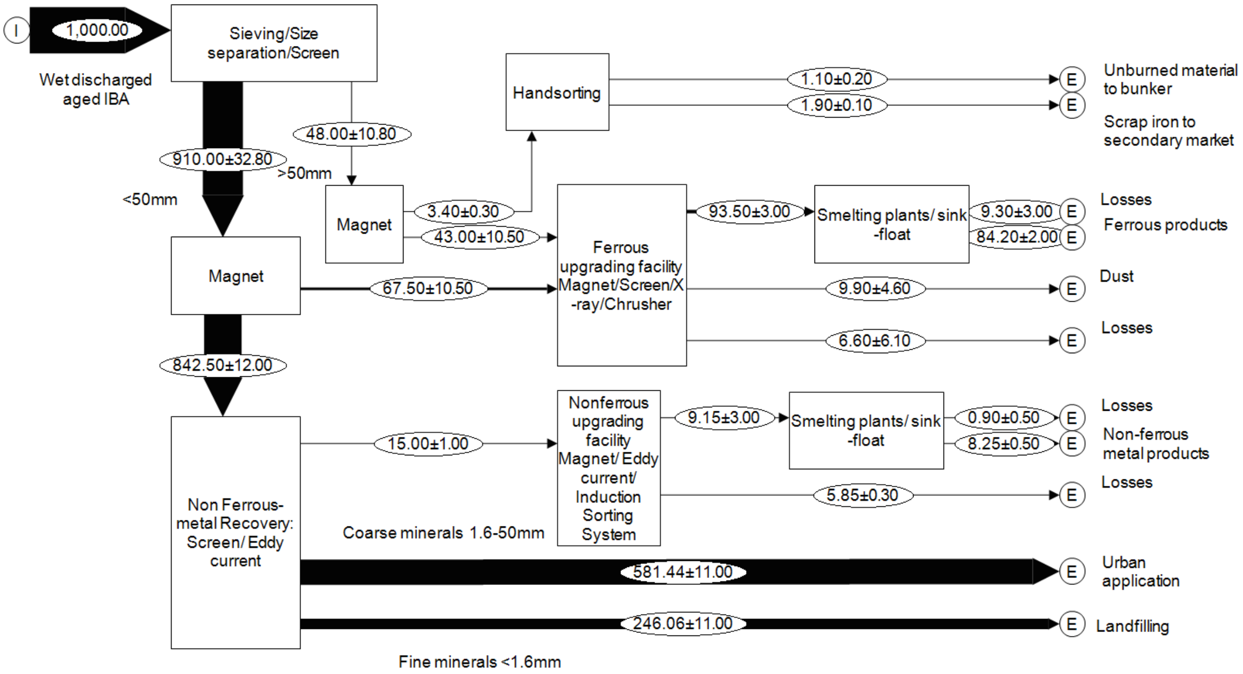


Figure 9. Sankey diagrams of Scenario 2 examined for wet discharge system

<u>Scenario 3 Wet ash discharge followed by advanced dry processing system with ballistic system (Netherlands)</u>

Scenario 3 is a schematic diagram of the Advanced Dry Recovery (ADR) system developed in the Netherlands (Figure 6) that increases metal recovery rate from the ash fraction below 12 mm. The reported recovery rate of ferrous metal is 85% and of non-ferrous metal 70%. For the functional unit of 1,000 tonnes of WTE-BA treated, Scenario 3 results in the recovery of 93.5±3 ferrous and 10.5±2 tons non-ferrous metals. Also, an estimated 266±20 tonnes of WTE-BA coarse fraction (>12mm) are used as secondary aggregates in construction, 292±20 tonnes of medium fraction (2-12mm) are used as asphalt admixture, and 306±20 tonnes fine fraction (<2mm) are landfilled. The energy consumption of ADR is 17 MWh of electricity and 5,000 liters of water per 1,000 WTE-BA treated [1,3].

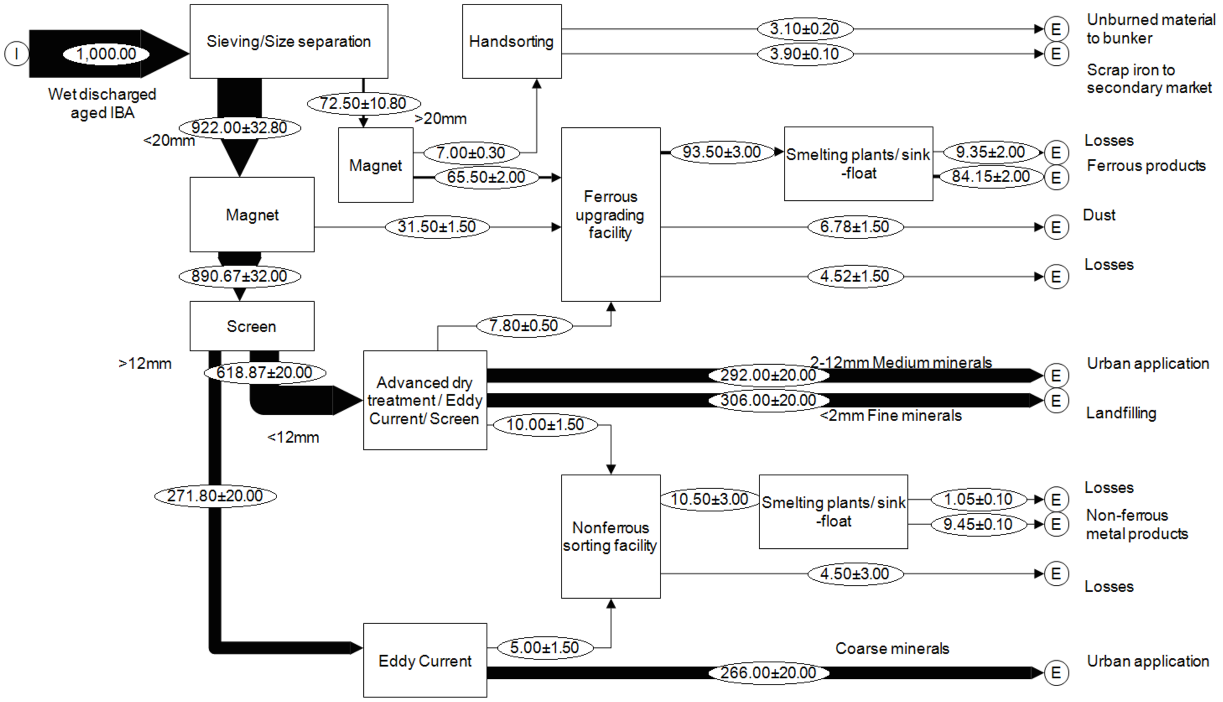


Figure 10. Sankey diagrams of Scenario 3 examined for wet discharge system

Scenario 4 Dry ash discharge followed by dry treatment (no ballistic system) (Switzerland)

Scenario 4 (Figure 4) refers to dry discharge system followed by the conventional dry treatment method. The metal recovery is 99 tonnes of ferrous and 14.7 tonnes of non-ferrous metal; also, 741 tonnes of coarse fraction (>1mm) and 100 tonnes of fine fractions (<1mm) are landfilled. The energy consumption is 12.2 MWh per 1,000 tonnes of WTE-BA treated [1,3].

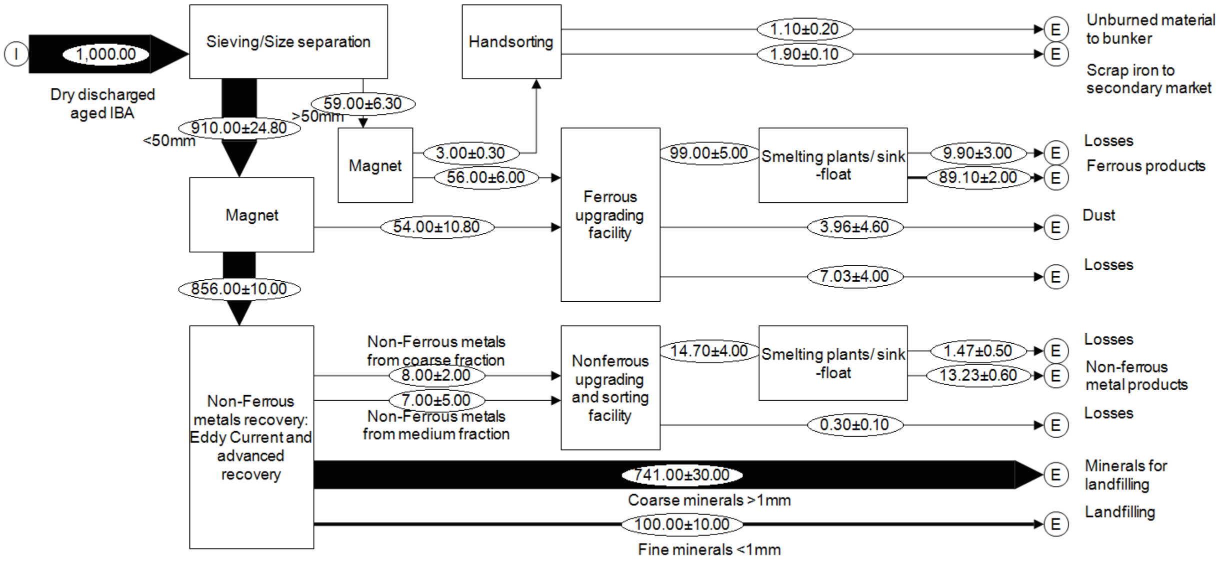
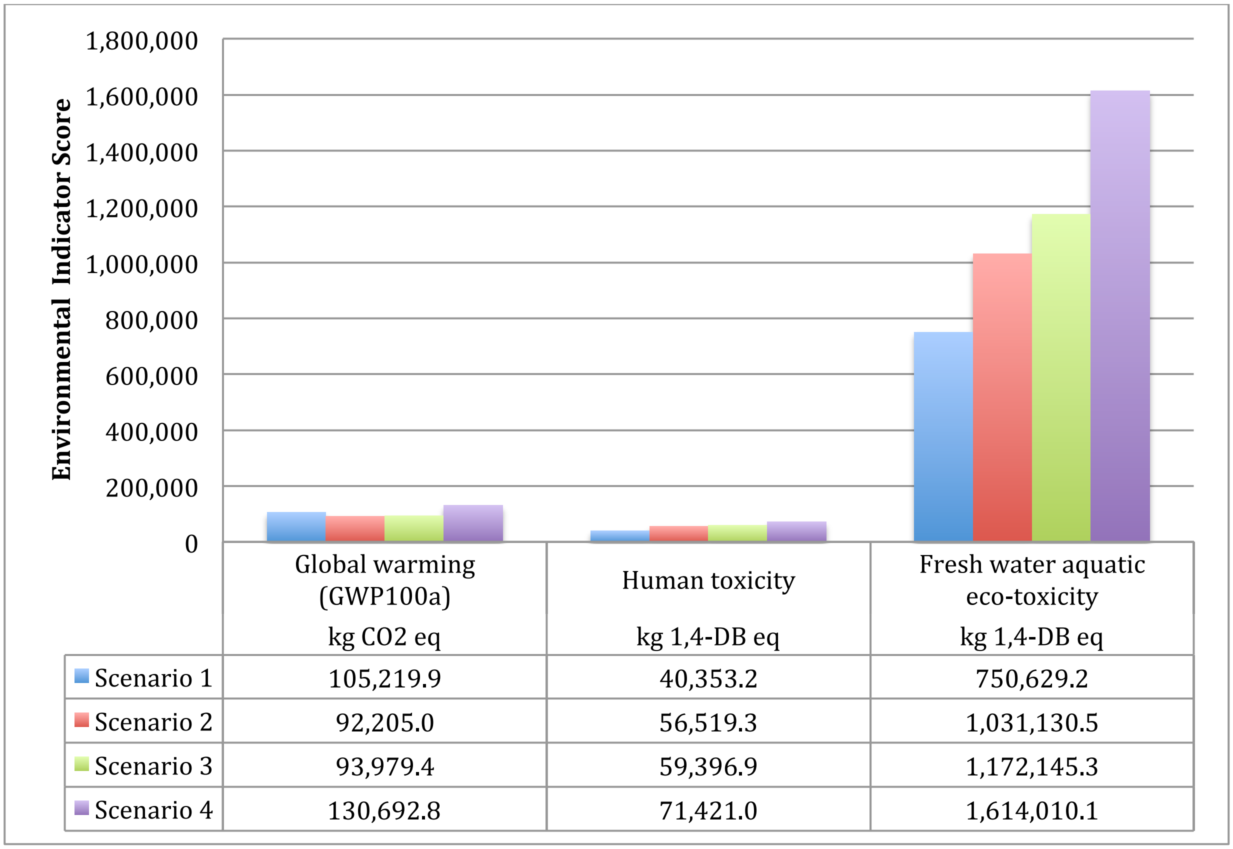


Figure 11. Sankey diagrams of Scenario 4 examined for dry discharge system

5.1.2 LCA Results & Discussion

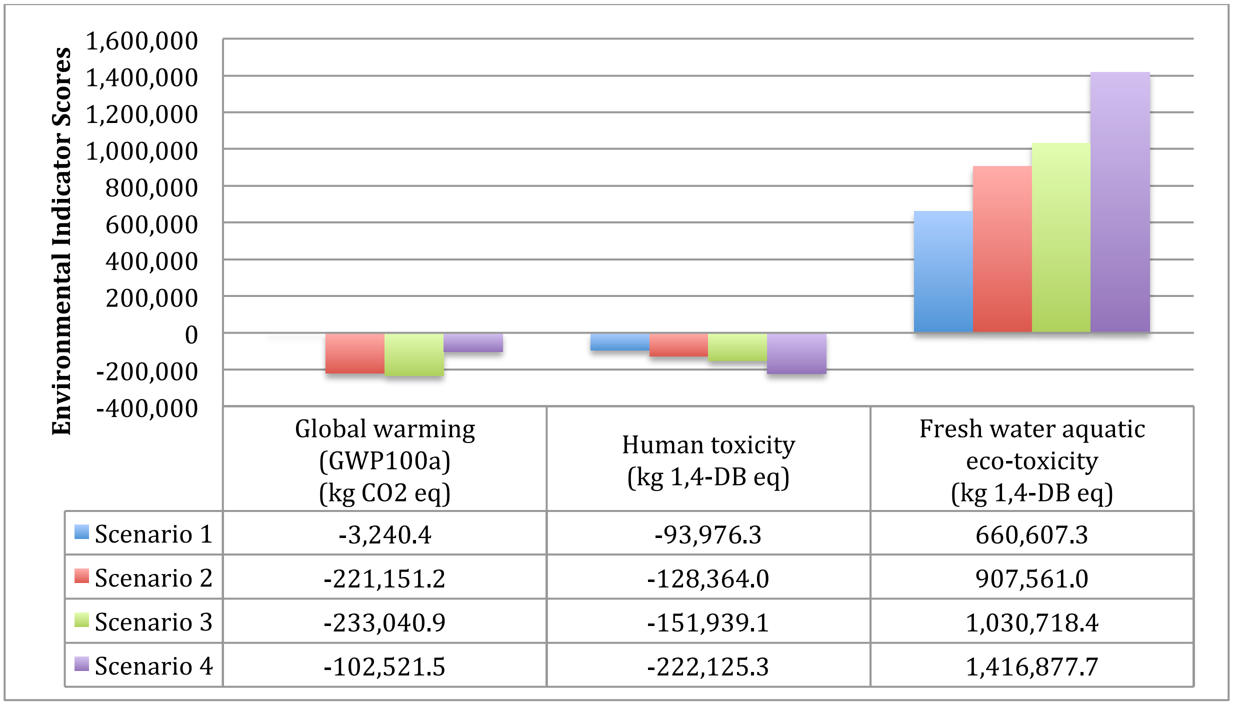
Three indicators GWP100, HT and FAET in Figure 12 show the environmental impacts of energy use and water consumption in three processes of WTE-BA which are discharge system, metal recovery and sorting, and secondary scrap metal or aggregate production or landfilling. Scenario 4 has the highest scores in four indicators, associated with its large volume of recovered scrap metals and high amounts of energy for secondary metal production. In order to show the beneficial overview of metal recovery in energy and water saving, substitution of energy in primary production from metal recovery and aggregates applications are count in LCA and the results are represented in Figure 13 and Figure 14.



	Global warming (GWP100a) kg CO2 eq	Human toxicity kg 1,4-DB eq	Fresh water aquatic eco-toxicity kg 1,4-DB eq
🟦 Scenario 1	105,219.9	40,353.2	750,629.2
🟥 Scenario 2	92,205.0	56,519.3	1,031,130.5
🟩 Scenario 3	93,979.4	59,396.9	1,172,145.3
🟪 Scenario 4	130,692.8	71,421.0	1,614,010.1

Figure 12. Global Warming Potential 100 years (GWP100), Human Toxicity (HT), Fresh-water Aquatic Eco-toxicity (FAET) of WTE-BA discharge, metals and minerals extraction systems examined.

Figure 13 shows the result of resource efficiency in four scenarios after counting the energy saving from primary metal and concrete production. Both GWP100 and HT show negative scores exhibited the energy and material saving from application in four scenarios excessed the energy consumed in WTE-BA discharge and recovery processes. Figure 14 coverts the environmental impact scores to percentage between four scenarios for clearer and concise comparison. It is presented in percentages that each scenarios' environmental score divided by the one having the highest score. Primary metal and concrete production has less demand of water, so four scenarios have smaller change on score of FAET. Scenario 2 has high GWP100 score because of its consumption of water in discharge and recovery process. Scenario 3 and 4 are observed to be the most beneficial treatment to environment because of their high rate of metal recovery.



	Global warming (GWP100a) (kg CO2 eq)	Human toxicity (kg 1,4-DB eq)	Fresh water aquatic eco-toxicity (kg 1,4-DB eq)
🟦 Scenario 1	-3,240.4	-93,976.3	660,607.3
🟥 Scenario 2	-221,151.2	-128,364.0	907,561.0
🟩 Scenario 3	-233,040.9	-151,939.1	1,030,718.4
🟪 Scenario 4	-102,521.5	-222,125.3	1,416,877.7

Figure 13. Global Warming Potential 100 years (GWP100), Human Toxicity (HT), Fresh-water Aquatic Eco-toxicity (FAET) of WTE-BA discharge, and metals and minerals extraction systems examined. Substitution of energy to primary production from metal recovery and aggregates applications are count.

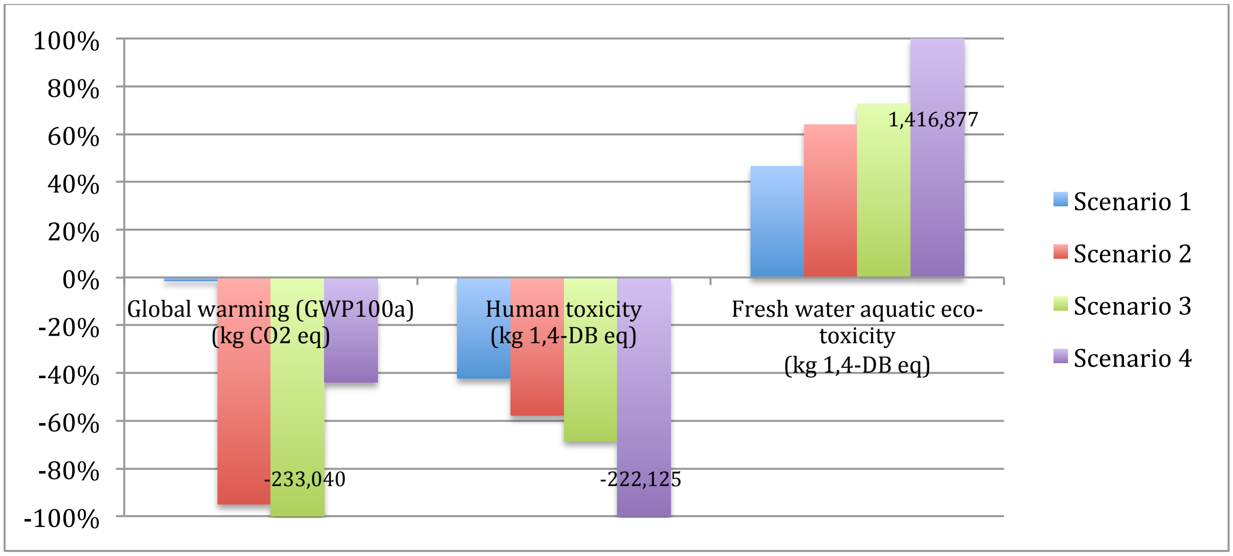


Figure 14. Global Warming Potential 100 years (GWP100), Human Toxicity (HT), Fresh-water Aquatic Eco-toxicity (FAET) calculated in percentage of WTE-BA discharge, and metals and minerals extraction systems examined (the highest scores is reported). Substitution of energy to primary production from metal recovery and aggregates applications are count.

Discharge system

Conventional wet discharge system (S1, S2, S3) and dry discharge system (S4) are compared in this study. Figure 15 presents the results of the comparison between two discharge systems in three environmental impact indicators (figure is presented in percentages that each scenarios' environmental score divided by the one having the highest score). Wet discharge system shows extremely high environmental impacts comparing to dry discharge system. The factors of the high score are the energy and water consumption of wet discharge system. Wet discharge system (2 MWh/1000 tonnes of WTE-BA) demands 10 times of energy comparing to dry discharge system (0.2 MWh/1000 tonnes of WTE-BA). Also, wet discharge needs 50,000 liters to quenched 1,000 tonnes of bottom ash.

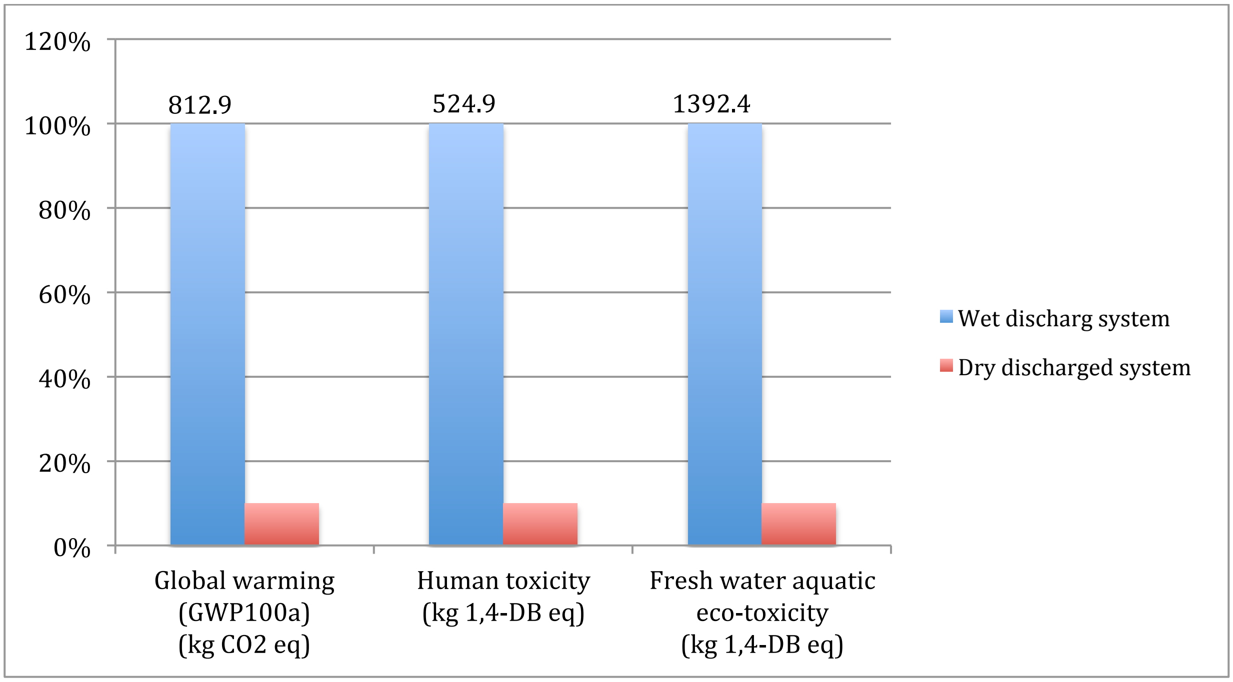


Figure 15. Global Warming Potential 100 years (GWP100), Human Toxicity (HT), Fresh-water Aquatic Eco-toxicity (FAET) calculated in percentage of wet and dry discharge system examined (the highest scores is reported).

Ferrous Metal

Figure 16 shows the environmental impacts of scenarios of wet or discharged WTE-BA in four ferrous metal recovery systems (figure is presented in percentages that each scenarios' environmental score divided by the one having the highest score). Scenario 2 exhibits the highest score of three indicators as it involves water treatment in metal recovery and discharge system.

Scenario 1 has the lowest score because of its low recovery efficiencies and energy resource of metal treatment method. Scenario 2 has recovered least ferrous metal (93.5 tonnes) beside Scenario 1, but it still has the highest indicators' scores; Scenario 4 recovered the most amount (99 tonnes) of ferrous metals from 1,000 bottom ash, but it has the lowest environmental impacts. The reason is because of the different quantity of electricity and energy use between dry and wet discharge systems (according to data analysis in Simapro). In other words, the raw material saving, and the energy and resource consumption in Scenario 4 achieved in highest energy efficiencies and lowest environmental impacts.

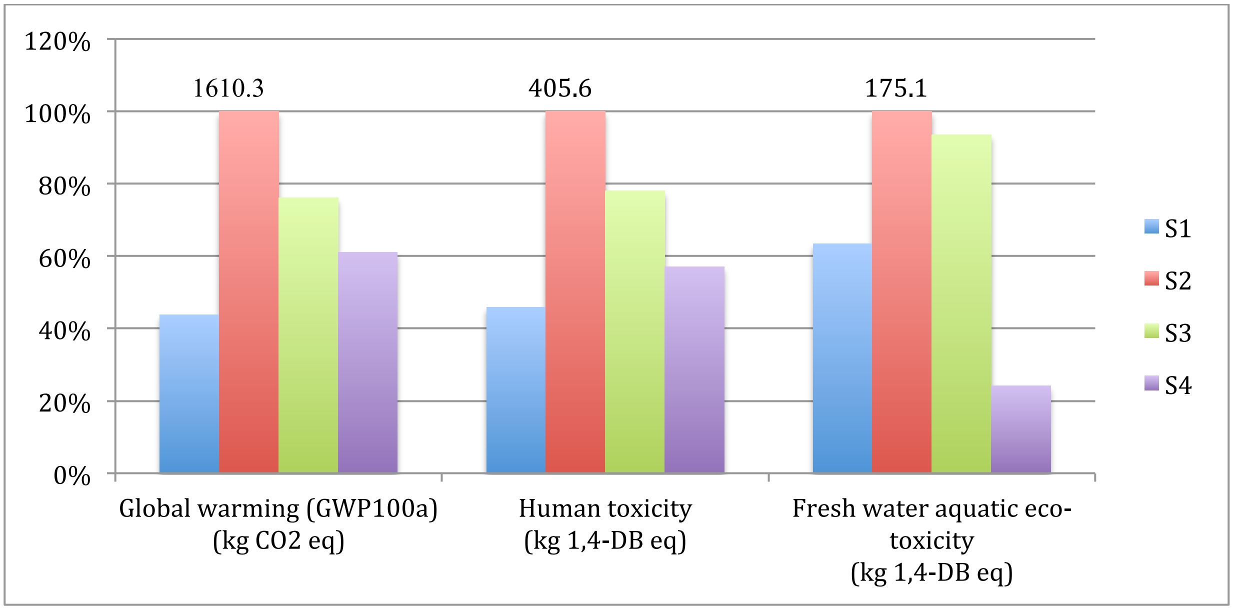


Figure 16. Global Warming Potential 100 years (GWP100), Human Toxicity (HT) and Fresh-water Aquatic Eco-toxicity (FAET) calculated in percentage of ferrous metal treatment examined (the highest scores is reported).

Non-Ferrous Metal

High amount of resource and volume of material used in wet discharge system continue affects the environmental scores of Scenario 1, 2 and 3 in Figure 17 (figure is presented in percentage that each scenarios' environmental score divided by the one having the highest score). Scenario 2 and Scenario 3 have the highest GWP100, HT and FAET scores. Scenario 4 has the higher environment score in non-ferrous metal, as it recovers more than two times of non-ferrous metal comparing to other scenarios. Higher recovery rate of non-ferrous metals leads to high demand of resource and energy in metal recovery and secondary production even with substitution of energy used in primary production.

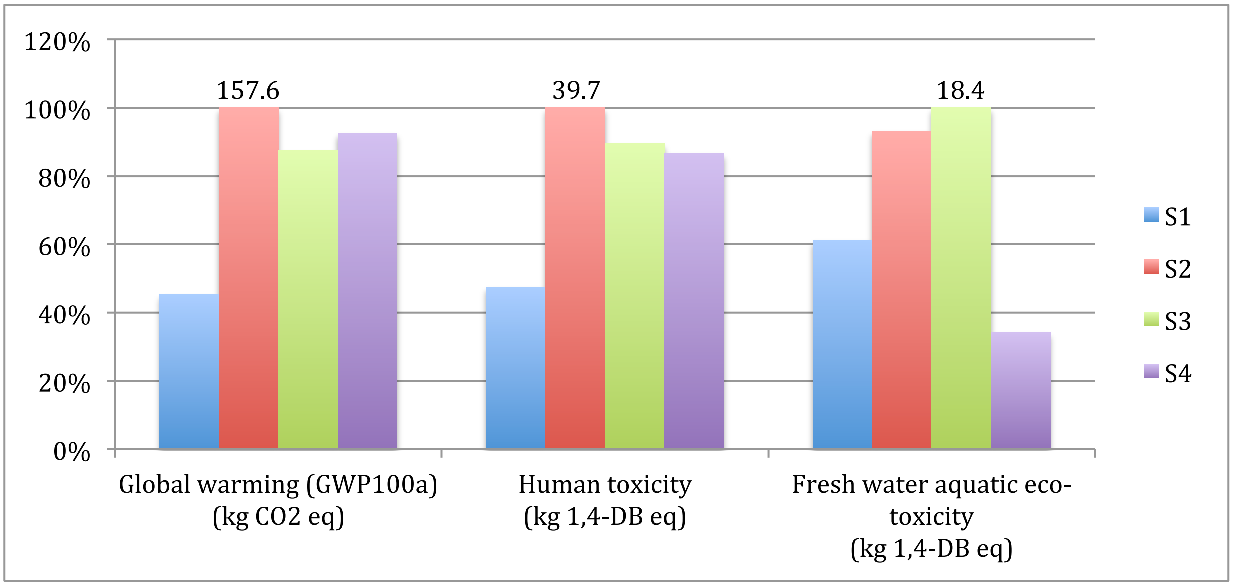


Figure 17. Global Warming Potential 100 years (GWP100), Human Toxicity (HT) and Fresh-water Aquatic Eco-toxicity (FAET) calculated in percentage of non-ferrous treatment examined (the highest scores is reported).

Minerals Aggregates Application or Landfilling

Figure 18 presents comparative analysis on environmental impacts between aggregates application and mineral landfilling (figure is presented in percentages that each scenarios' environmental score divided by the one having the highest score). Scenario 1 and Scenario 4 show high environmental impact score because of the lost of valuable resources in landfilling., Scenario 2 and 3 indicates the lowest environmental score even the reuse process of minerals is energy intensive. In other words, landfilling has 3 times more environment impacts than secondary asphalt and concrete production. Fresh water aquatic eco-toxicity is not affected by either landfilling or urban application.

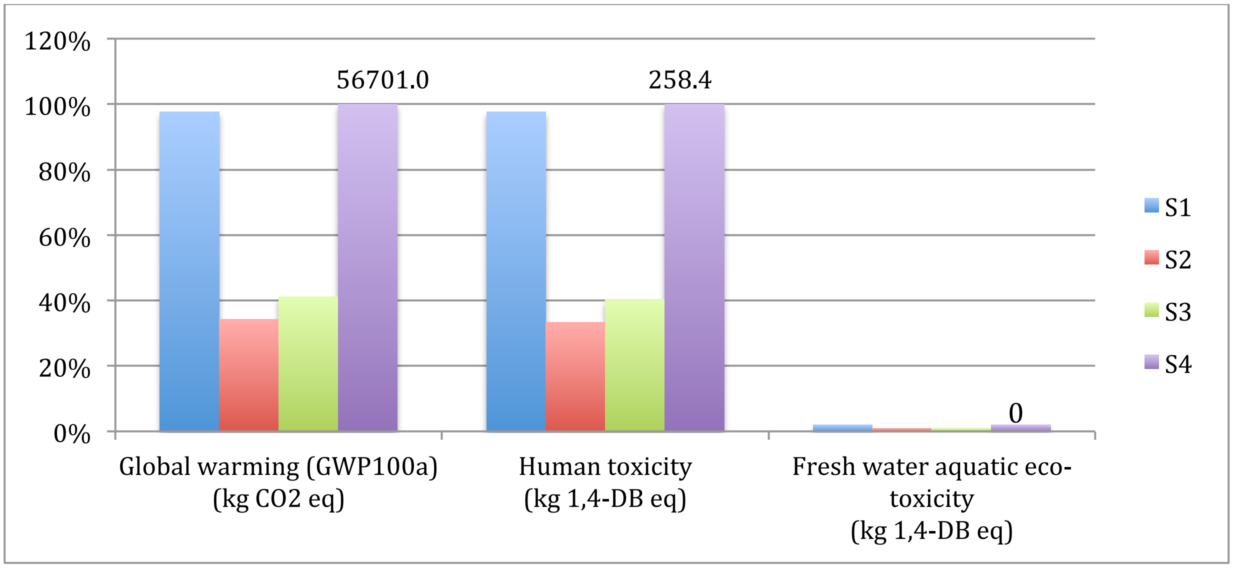


Figure 18. Global Warming Potential 100 years (GWP100), Human Toxicity (HT) and Fresh-water Aquatic Eco-toxicity (FAET) calculated in percentage of aggregates application and landfilling examined (the highest scores is reported).

Raw material saving

One of the purposes in this study is to find out the beneficial aspect of recovering WTE-BA to save raw material consumption and reduce environmental damage. Figure 19 to Figure 21 shows the comparison between primary and secondary metal production, and between concrete/asphalt and aggregates application, by conducting calculation of GWP100 scores. All three figures show a significant gap between primary and secondary production. The functional unit of the sub-process, the raw materials savings and the energy and water consumption for the use of recovered ferrous, non-ferrous and aggregates minerals involve huge benefits to lower environmental emissions and human health hazard.

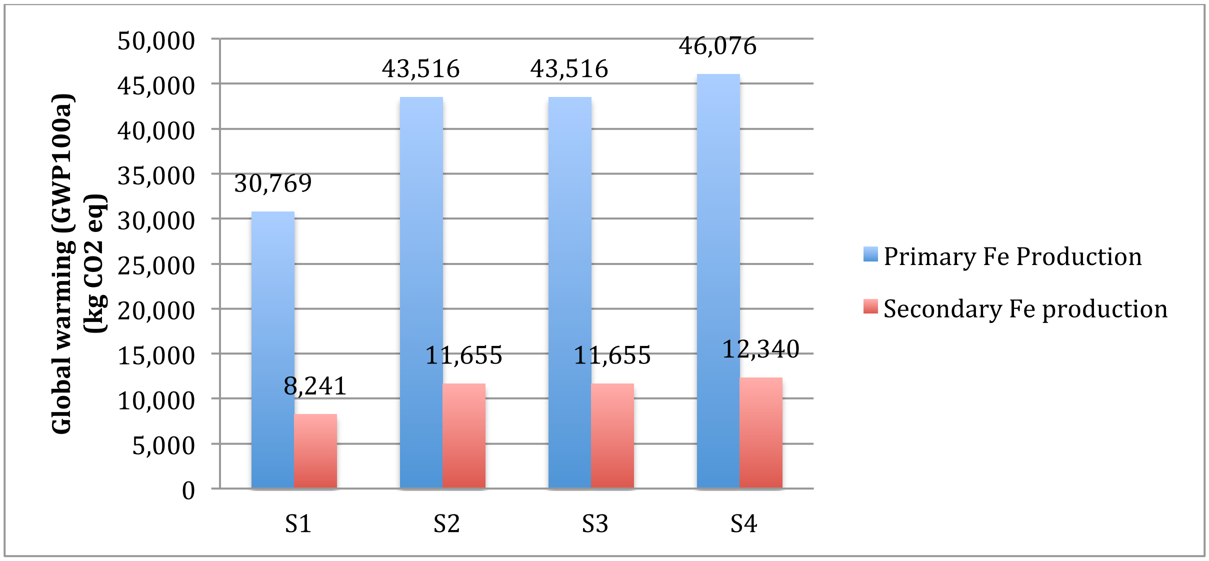


Figure 19. Global Warming Potential 100 years (GWP100) of primary and secondary ferrous production examined.

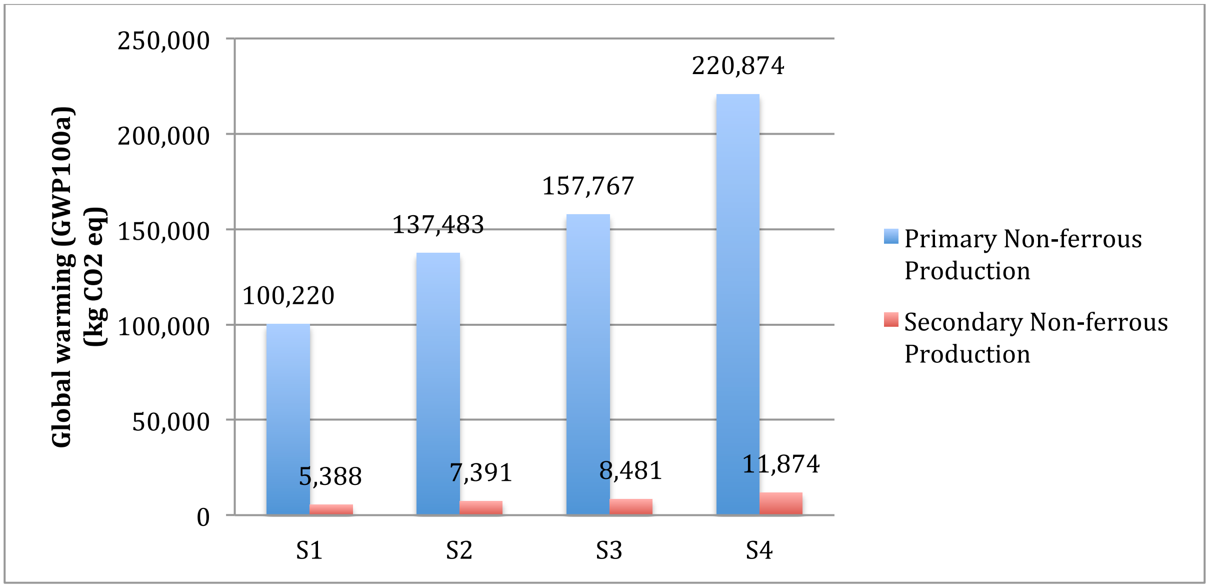


Figure 20. Global Warming Potential 100 years (GWP100) of primary and secondary non-ferrous production examined.

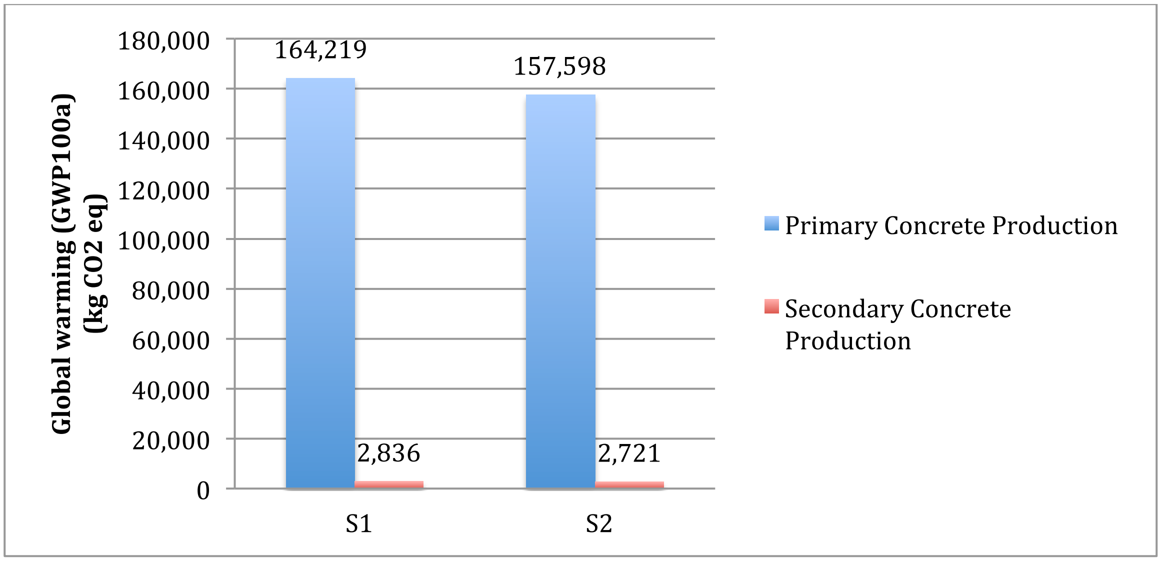


Figure 21. Global Warming Potential 100 years (GWP100) of primary and secondary concrete production examined (only Scenario 1 and 2).

5.2 Life Cycle Cost Analysis (LCCA)

Life Cycle Cost Analysis (LCCA) is also carried out in this study to identify cost, revenue and profit differences between the resource recovery methods of bottom ash. LCCA is an effective economic analysis used in selection of alternatives that affect both pending and future investments.

5.2.1 Life Cycle Cost Inventory

Besides collected Life Cycle Inventory (LCI) data in LCA, Life Cycle Cost Inventory (LCCI) also includes assumptions and related data in cost calculation. The calculated capital investment of dry and wet discharge and treatment systems is according to WTE guidebook [5] or confirmed by Dr.Athanasios, Bourtsalas' individual contacts. Lifetime of WTE facility is assumed to be 20 years [5]. Electricity cost is assumed to be recycled from WTE facility and count as a loss from electricity revenue. Water, employee cost, and landfilling cost is assumed according to United States average data [5]. Metal price and aggregates application prices are according to USGS data [15,16,17] and research conducted at Waste-to-Energy Research and Technology Council at Columbia University [18].

5.2.2 LCCA Results and Discussion

Figure 22 presents the result of LCCA in three components: capital investment, operational cost and revenue per 1,000 tons of WTE-BA, and Figure 23 shows the cost ratio (operation cost/revenue) of four processes. The combination of wet discharge system and conventional dry treatment (Scenario 1) has the lowest capital cost, but high operational cost and the lowest revenue because of its low energy efficiency and high WTE-BA landfilled cost. Wet discharge system and wet treatment (Scenario 2) has the highest cost in capital investment than other treatments due to its extra cost of water treatment and wet processing [10]. It requires additional wet process for the fine heavy non-ferrous metal recovery, such as jigging or a Humphrey spiral [10]. The other treatments Scenario 2 also has the second highest revenue and lower operation cost because of its revenue from mineral aggregates application and low amount of fine fraction landfilling cost. Wet discharge system and Advanced Dry Treatment (ADR) (Scenario 3) has low capital investment and operational cost as its non-ferrous recovery increase and fewer non-ferrous metal lost. Both Scenario 2 and 3 has the revenue from minerals aggregates for urban application, so Scenario 3 has the lowest cost ratio comparing to others. Dry discharge treatment and conventional dry treatment (Scenario 4) has high capital investment cost for discharge system but low cost for conventional dry treatment. It is noted that even Scenario 4 has high operational cost and lower revenue than Scenario 2 and 3, because of its high electricity and WTE-BA landfilling cost (as urban application of aggregates minerals is not included in Scenario 4), Scenario 4 still have comparative high amount of revenue (and therefore comparative low cost ratio). This is due to its 90% ferrous and 98% of non-ferrous metal recovery rate. There are now two different types but similar energy efficiencies of dry discharge system (Table 2). The more expensive one is applied in Monthey, Switzerland. Another advanced but cheaper dry discharge system is applied in in Zurich, Switzerland. Even the discharge system has high investment cost, high quality and quantity of ferrous and non-ferrous metal recovery has advantages of environmental benefit and earns biggest revenue for WTE facility.

	Scenario 1 *Wet discharge and conventional dry treatment*	**Scenario 2** *Wet discharge and wet treatment system*	**Scenario 3** *Wet discharge and advanced dry treatment system*	**Scenario 4** *Dry discharge and conventional dry treatment*
Discharge System investment /*unit in 20 years estimated life span*	$100,000	$100,000	$100,000	$1,200,000 (*Monthey, CH*) $ 500,000 (*Zurich, CH*)
Treatment investment/*unit in 20 years estimated life span*	$2.6 M - $5.2 M	$10.5 M - $21 M	$3.7 M - $7. 4 M	$2.6 M - $5.2 M

Table 2. Capital Investment of wet and dry discharge and treatment systems.

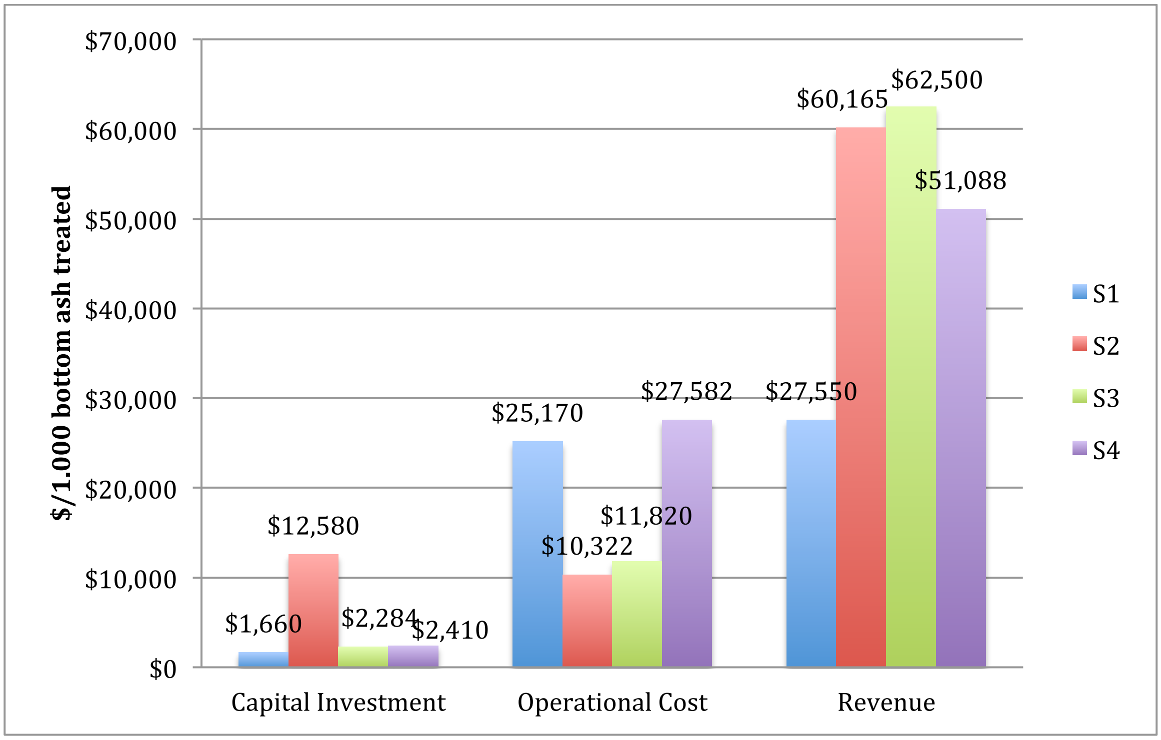


Figure 22. LCCA results of four dry and wet discharge and treatment processes

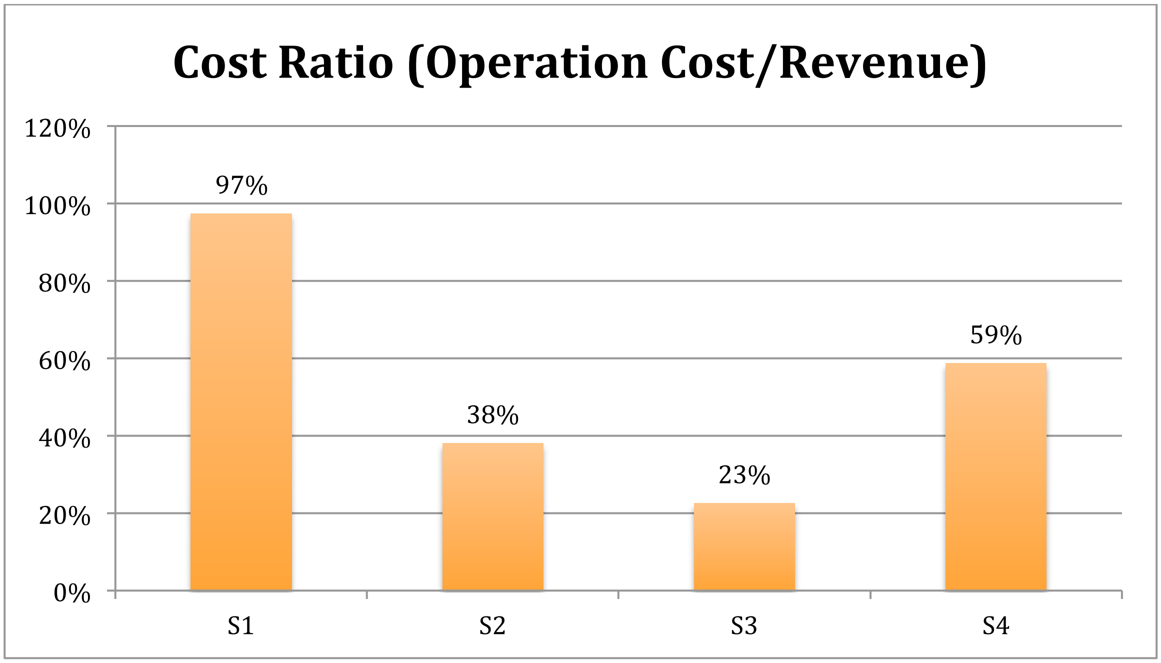


Figure 23. LCCA results (operation cost/revenue) of four dry and wet discharge and treatment processes

6. Conclusions

The environmental impacts and cost analysis of processing waste-to-energy bottom ash (WTE-BA) in dry or wet discharge systems were compared using the Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) methods. The functional unit is assumed to be the management of 1,000 metric tons of wet or dry discharged WTE-BA. The four systems considered were

a) *Wet ash discharge with dry treatment system (U.S.A.)*
b) *Wet ash discharge and wet treatment system (Denmark)*
c) *Wet ash discharge followed by dry treatment system with ballistic system (Netherlands)*
d) *Dry ash discharge followed by dry treatment (no ballistic system) (Switzerland)*

The results of the LCA and LCCA studies were presented in Figures 14 and 22. The overall conclusions regarding each sub-process are summarized in the following sections:

Discharge system

The dry discharge system was shown to be more energy and cost efficient than the wet discharge commonly used by the U.S. WTE industry. The very low moisture content in the dry discharge system reduces agglomerations problems, increases the metal recovery rate, decreases the weight of ash to monofills or landfills, and improves the profitability of the WTE plant which has raw material saving advantage and earns valuable profit to WTE plant. The disadvantage of higher dust emission has been overcome in European plants by means of fully enclosed systems.

Ferrous & non-ferrous metal recovery

The dry discharge system followed by conventional treatment (Scenario 4) was shown to have the highest ferrous and non-ferrous metal recovery, because it eliminates the strong water-particle bond of the fine fractions. The higher metal recovery is associated with higher energy consumption and higher environmental indicator scores in the LCA comparison without the substitution from primary production. After counting substitution from primary production, all treatment methods exhibit negative GWP 100 and human toxicity indicator scores. Higher ferrous metal recovery also results in increased revenues from secondary metal market. The wet discharge and wet treatment process (Scenario 2) has the highest cost of investment because of its extra cost of water and comparative lower amount of recovered ferrous and non-ferrous metals. The wet discharge system followed by the Advanced Dry Treatment (ADR) (Scenario 3) has lower cost and higher recovery rate of ferrous metals.

Use of minerals in ash as aggregates in construction

The mineral aggregates produced in Scenarios 2 and 3 are used for urban application in road construction. As would be expected, the LCA comparison showed that beneficial use of aggregates has lower environmental impacts than landfilling. The application of aggregates in road construction offers the advantage of material conservation and also the avoidance of landfilling the bottom ash. Therefore, it improves the economy of WTE plants considerably.

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