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OPTIMAL RECYCLING COMBINATION OF ASH IN SOUTH-EAST FINLAND

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ABSTRACT

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ARVI – Material Value Chains

50 pages, 13 tables, 22 figures, 1 annex

Keywords: fly ash, bottom ash, boiler slag, life cycle assessment, cost-benefit analysis, systems analysis

The present world energy production is heavily relying on the combustion of solid fuels like coals, peat, biomass, municipal solid waste, whereas the share of renewable fuels is anticipated to increase in the future to mitigate climate change. In Finland, peat and wood are widely used for energy production. In any case, the combustion of solid fuels results in generation of several types of thermal conversion residues, such as bottom ash, fly ash, and boiler slag. The predominant residue type is determined by the incineration technology applied, while its composition is primarily relevant to the composition of fuels combusted.

An extensive research has been conducted on technical suitability of ash for multiple recycling methods. Most of attention was drawn to the recycling of the coal combustion residues, as coal is the primary solid fuel consumed globally. The recycling methods of coal residues include utilization in a cement industry, in concrete manufacturing, and mine backfilling, to name few. Biomass combustion residues were also studied to some extent with forest fertilization, road construction, and road stabilization being the predominant utilization options. Lastly, residues form municipal solid waste incineration attracted more attention recently following the growing number of waste incineration plants globally. The recycling methods of waste incineration residues are the most limited due to its hazardous nature and varying composition, and include, among others, landfill construction, road construction, mine backfilling.

In the study, environmental and economic aspects of multiple recycling options of thermal conversion residues generated within a case-study area were studied. The case-study area was South-East Finland. The environmental analysis was performed using an internationally recognized methodology — life cycle assessment. Economic assessment was conducted applying a widely used methodology — cost-benefit analysis. Finally, the results of the analyses were combined to enable easier comparison of the recycling methods. The recycling methods included the use of ash in forest fertilization, road construction, road stabilization, and landfill construction. Ash landfilling was set as a baseline scenario.

Quantitative data about the amounts of ash generated and its composition was obtained from companies, their environmental reports, technical reports and other previously published literature. Overall, the amount of ash in the case-study area was 101 700 t. However, the data about 58 400 t of fly ash and 35 100 t of bottom ash and boiler slag were included in the study due to lack of data about leaching of heavy metals in some cases. The recycling methods were modelled according to the scientific studies published previously.

Overall, the results of the study indicated that ash utilization for fertilization and neutralization of 17 600 ha of forest was the most economically beneficial method, which resulted in the net present value increase by 58% compared to ash landfilling. Regarding the environmental impact, the use of ash in the construction of 11 km of roads was the most attractive method with decreased environmental impact of 13% compared to ash landfilling. The least preferred method was the use of ash for landfill construction since it only enabled 11% increase of net present value, while inducing additional 1% of negative impact on the environment.

Therefore, a following recycling route was proposed in the study. Where possible and legally acceptable, recycle fly and bottom ash for forest fertilization, which has strictest requirements out of all studied methods. If the quality of fly ash is not suitable for forest fertilization, then it should be utilized, first, in paved road construction, second, in road stabilization. Bottom ash not suitable for forest fertilization, as well as boiler slag, should be used in landfill construction. Landfilling should only be practiced when recycling by either of the methods is not possible due to legal requirements or there is not enough demand on the market.

Current demand on ash and possible changes in the future were assessed in the study. Currently, the area of forest fertilized in the case-study are is only 451 ha, whereas about 17 600 ha of forest could be fertilized with ash generated in the region. Provided that the average forest fertilizing values in Finland are higher and the area treated with fellings is about 40 000 ha, the amount of ash utilized in forest fertilization could be increased. Regarding road construction, no new projects launched by the Centre of Economic Development, Transport and the Environment in the case-study area were identified. A potential application can be found in the construction of private roads. However, no centralized data about such projects is available. The use of ash in stabilization of forest roads is not expected to increased in the future with a current downwards trend in the length of forest roads built. Finally, the use of ash in landfill construction is not a promising option due to the reducing number of landfills in operation in Finland.

FOREWORD

This report and the work related to it was conducted within the ARVI (Material Value chains) research program, which was managed by CLIC Innovation Ltd. The funding for the program was received from Tekes (the Finnish Funding Agency for Innovation), industrial partners, and research institutes. The aim of the ARVI program is to create understanding of business opportunities related to recycling of materials, required knowhow, and abilities for utilization. This is achieved by creating knowledge, methods and concepts related to the management of material flows and exploring the global demands.

This report is based on research related to the Work Package 3: “Systematic resource efficiency – concept modelling and optimization.” The current report presents the work done within the Task 3.4 concerning optimal feasibility and sustainability of ash and recovery in a regional scale. Valuable information on ash amounts and composition was received from the energy and pulp & paper industries. The authors would wish to thank for their contribution to the report.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

AP	Acidification Potential
ARVI	Material Value Chains
CBA	Cost-Benefit Analysis
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
DHP	District Heating Plant
DMC	Dry Matter Content
DOC	Dissolved Organic Carbon
EC	Electric Conductivity
ESP	Electrostatic Precipitator
ETP	Ecotoxicity Potential
FBB	Fluidized Bed Boiler
FEP	Freshwater Eutrophication Potential
GF	Grate Furnace
GWP	Global Warming Potential
HTP_c	Carcinogenic Human Toxicity Potential
HTP_{non-c}	Non-Carcinogenic Human Toxicity Potential
IC	Impact Category
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ISO	International Organization For Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LOI	Loss Of Ignition
MEP	Marine Eutrophication Potential
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
MTT	Agrifood Research Finland
NPV	Net Present Value
NV	Neutralizing Value
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorobiphenyl
POFP	Photochemical Ozone Formation Potential
RDP	Resource Depletion Potential
RV	Reactivity Value
TEP	Terrestrial Eutrophication Potential
TOC	Total Organic Carbon
VOC	Volatile Organic Compounds

1. INTRODUCTION

World energy consumption constantly grows following the increase of world population and expansion of industrial production (Enerdata, 2014). Still, fossil fuels dominate the niche of world's total primary energy supply accounting for 82% of total energy supply in 2012 (International Energy Agengy, 2014). Furthermore, solid fuels, such as hard coal, biomass, and waste, account for about 40% of the total energy supply. In Finland, 22% of electricity is generated by combusting hard coal, woody biomass, and peat (Official Statistics of Finland, 2012).

While consuming solid fuels for energy production, fly ash, bottom ash, and boiler slag of different nature, collectively called ash in this study, are generated and their amounts are directly linked to the energy demand. Ash can be classified and defined based on the place of origin of the residue, the fuels consumed, and the type of incinerator used. The residues are dominantly generated in power plants operated by energy, and pulp and paper industries.

Following the principles of the waste management hierarchy developed for the Member states of the European Union (The EU Parliament and the Council of the EU, 2008), disposal of waste in general and ash or slag in particular should only be practiced when no other management option is available for that waste. That principle is implemented in a Finnish Waste Tax Act (Valtiovarainministeriö, 2014).

Recycling of ash has been studied widely. The studies focused primarily on the technical side of material recovery, namely on physical applicability of ash in different utilization options. Coal fly ash, which was studied more than other types of residues, found wide application in a cement industry, concrete manufacturing, filling engineered structures, and land reclamation (Ahmaruzzaman, 2010; American Coal Ash Association, 2014; Yao et al., 2015). Biomass ash could be used for forest fertilization, road construction, and soil stabilization (James et al., 2012; KEMA, 2012; Pels and Sarabèr, 2011). Ash from waste incineration could be utilized in landfill construction, road construction, and mine backfilling (Crillesen and Skaarup, 2006; KEMA, 2012).

Recycling of technologically suitable residues might result in multiple economic benefits. First, recycling of residues eliminates levying waste tax, which is constantly increasing. Second, recycled ash substitute conventionally consumed raw materials, therefore, preventing the costs associated with their acquisition and production. Additional costs associated with residues recycling can arise from their transportation to a utilization place, which can be located more remotely than a landfill. In addition, possible need for residues pretreatment and the process of their incorporation into a final product would induce additional costs.

Technically suitable and economically feasible, recycling of residues should reduce negative effect on the environment compared to landfilling. The major risks for the environment are associated with leaching of toxic substances into soil and, possibly, ground water, when ash is used for forest fertilization, in road construction, or by other methods implying placement of ash in the ground. Other sources of negative environmental impact arise from possible pretreatment and transportation of ash. On contrary, avoided production of materials substituted with ash will lead to reduced environmental impact. Therefore, environmental impact of recycling activities should be quantitatively assessed in order to reveal whether a certain recycling option would reduce or induce impact on the environment.

Several studies about environmental impact of ash recycling by different methods, e.g. (Birgisdóttir et al., 2007; Carpenter et al., 2007; Fruergaard et al., 2010; Margallo et al., 2014; Mroueh et al., 2001; Olsson et al., 2006; Schwab et al., 2014; Toller et al., 2009) were published previously. However, none of the studies focused on systematic assessment of ash utilization on a regional level including multiple types of residues and several utilization possibilities.

Nevertheless, practical experience shows that the same residues can oftentimes be utilized by several alternative utilization methods and the choice of a specific utilization method to apply is commonly driven by economic factors, environmental impact, local demand on the residue, and legislative aspects. Therefore, the objectives of the study were:

- to overview types of ash and their properties;
- identify places of ash generation within the case-study area, amounts and properties of residues generated therein;
- describe the recycling methods assessed;
- overview legal requirements on residues being recycled;
- estimate demand on ash in the case-study area;
- conduct life cycle assessment of the recycling methods;
- conduct cost-benefit analysis of the recycling methods;
- make recommendations.

2. CHARACTERIZATION OF ASH

Ash is inorganic by-products of combustion of solid fuels, such as coal, biomass, or waste. The amount of ash generated is proportional to the amount of fuels consumed and their properties, whereas its composition depends on a number of factors. Knowledge of properties of residues is needed for studying the technical applicability of the residues, and further environmental and economic analyses.

2.1. Classification

To start with, ash is classified into several categories (Figure 1) depending on the place of its origin, a fuel consumed, and a type of combustion technology applied. Residues collected from below the flame or the boiler grate are generally called bottom ash. When incineration temperature is sufficient to enable ash melting, the residues after being cooled are called boiler slag. Residues of smaller size are entrained with exhaust fumes from a combustion zone to a flue gas treatment system where the residues are captured. Such residues are called fly ash. Fly ash captured in cyclones is called coarse fly ash, whereas fly ash captured in baghouse filters or electrostatic precipitators is called fine fly ash. In addition, fly ash deposited in heat exchangers can be distinguished. However, this type of fly ash is rarely collected separately and is collected together with coarse fly ash. Additionally, air pollution control residues, such as lime and activated coal, could be present in fly ash if a dry or semi-dry system is applied (Astrup, 2008).

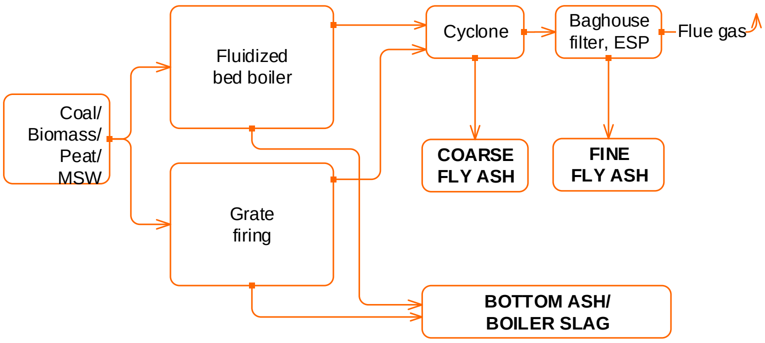


Figure 1: Classification of ash with respect to the type of fuel consumed, incineration technology applied, and place of origin.

Regarding the type of a fuel consumed, ash from incineration of coal, biomass, peat, municipal solid waste, or their mixture can be distinguished. The type of fuel significantly affects properties and composition of the residues. As regards the combustion technologies, fly ash is the largest thermal residue stream (80–100% of total ash) generated in fluidized bed boilers, whereas boiler slag or bottom ash dominate the mass of ash during grate firing accounting for 60-90% of total residues. Taking into account increasing number of FBBs in energy industry compared to grate boilers, larger amount of fly ash generated could be anticipated in the future.

2.2. Properties

A vital step to be undertaken in order to identify utilization possibilities for ash is to determine their composition and properties. A list of properties is presented in Table 1.

Table 1: Properties of ash often determined during technical assessment of residues applicability for recycling methods and compliance with legislative requirements.

Parameter	Unit	Possible determination method/standard
pH	-	SFS-EN 12880
Dry matter content (DMC)	%	SFS-EN 12880
Loss of ignition (LOI)	%	SFS-EN 12879
Electric conductivity (EC)	mS cm^{-1}	SFS-EN 13037
Dissolved organic carbon (DOC)	%	SFS-EN 1484
Total organic carbon (TOC)	%	SFS-EN 13137
Neutralizing value (NV)	% Ca	SFS-EN 12945
Reactivity value (RV)	% Ca	SFS-EN 13971
Bulk density	kg m^3	Volumetric and gravimetric
Particle size distribution	-	Sieving
Mineralogical composition (e.g. $CaCO_3$, Ca(SiO_2, Fe_2O_3, Al_2O_3, MgO)	%	X-day diffractometry
Soluble nutrients (K, Ca, P, etc.)	%	Manual by MTT
Total heavy metal contents	%	Acid digestion and ICP-MS
Leachable content of heavy metals and salts	%	CEN/TS 14405

The properties could be divided into two categories: environmental and technological. The former group defines applicability of residues from environmental point of view to enable least possible hazard. Total and leachable heavy metals contents are the major environmental parameters. The rest parameters describe technical properties of ash to be used e.g. for forest fertilization (content of nutrients, neutralizing value, pH, etc.), or in civil engineering (content of heavy metals, content of CaO, particle size distribution, etc.).

Composition and properties of ash, which are expected to vary significantly, especially in case of biomass and waste combustion, should be determined. However, average values are known and presented in Tables 2-5 for ash from wood and peat combustion. Table 2 contains data about basic ash properties like pH, LOI, DMC, as well as the content of macro elements in ash presented either as total or soluble amounts. Table 3 presents data on particle size distribution of the residues. Table 4 presents data on distribution of certain chemical elements in different size fractions of bottom ash. Table 5 shows the content of micro elements in ash. Table 6 presents leachable contents of substances contained in ash.

Table 2: Basic properties and content of macro elements of several ash types.

Parameter	Unit										
		Ash type:	Bottom ash	Fly ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash
		Place of orig for fly ash:		ESP (first zone)	ESP (second zone)		Cyclone		ESP		ESP
		Boiler type:	FBB	FBB	FBB	GF	GF	FBB	FBB	FBB	FBB
		Operating temperature:	850 ºC	850 ºC	850 ºC	800-1100 ºC	800-1100 ºC	810-830 ºC	810-830 ºC	800 ºC	800 ºC
		Fuels consumed:	50% wood 50% peat	50% wood 50% peat	50% wood 50% peat	100% wood	100% wood	50% wood 50% peat	50% wood 50% peat	97% wood 3% sludge	97% wood 3% sludge
		Reference:	(Dahl et al., 2010)			(Pöykiö et al., 2009)		(Dahl et al., 2009)		(Nurmesniemi et al., 2012)	
pH			11.9	12.6	12.6	12.0	12.3	12.1	12.5	11.9	12.8
EC	mS cm^{-1}		*3.1*	18.0	25.4	3.7	**42.3**	*3.2*	13.9	—	—
LOI	%		<0.5	<0.5	<0.5	**6.8**	2.1	<0.5	<0.5	—	—
TOC	g kg^{-1}		<2.0	2.1	2.2	n.d.	**16**	<1	4	—	—
DMC	%		99.9	99.9	99.9	*69.3*	99.8	99.7	99.9	99.5	99.5
NV	% Ca		8.7	15.8	20.4	30.6	**31.1**	*6.2*	28.5	8.7	26.1
RV	% Ca		*3.4*	8.0	11.9	19.0	29.2	*2.9*	18.2	—	—
Macro elements		Type:	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Soluble	Total	Total
Ca	g kg^{-1}		*22.2*	62.3	90.1	84.2	138	*19.2*	140	60	**205**
Mg	g kg^{-1}		*2.3*	2.9	3.8	12.4	19.4	*2.1*	17	6	**26**
Na	g kg^{-1}		0.43	1.6	**3.3**	2.3	**3.3**	*0.1*	1.4	—	—
K	g kg^{-1}		0.36	4.3	8.7	22.1	**65.0**	*0.09*	9.7	26	39
P	g kg^{-1}		*0.41*	2.4	2.8	2.3	**24.1**	*0.4*	0.6	3	15
S	g kg^{-1}		0.43	4.7	7.4	1.2	3.4	*0.2*	**17.3**	—	—
Cu	mg kg^{-1}		*4.6*	12	20	47.5	**100**	*3.7*	22.0	18	**100**
Zn	mg kg^{-1}		130	150	250	762	3500	*41*	370	720	**3360**
Mn	mg kg^{-1}		200	520	740	—	—	*180*	**1510**	—	—

Table 3: Particle size distribution of several ash types.

Parameter						
	Ash type:	Bottom ash	Fly ash	Fly ash	Bottom ash	Fly ash
	Place of orig for fly ash:		ESP (first zone)	ESP (second zone)		ESP
	Boiler type:	FBB	FBB	FBB	FBB	FBB
	Operating temperature:	850 ºC			810-830 ºC	
	Fuels consumed:	50% wood 50% peat			50% wood 50% peat	
	Reference:	(Dahl et al., 2010)			(Dahl et al., 2009)	
Particle size, mm		Share, %				
16.0…31.5		0	0	0	3.7	0
8.0…16.0		0	0	0	0.6	0
4.0...8.0		0	0	0	0.8	0
2.0...4.0		0	0	0	0.7	0
1.0...2.0		0.4	0	0	**42.0**	0
0.5...1.0		**19.0**	0.1	0.1	**45.7**	0
0.25...0.5		**65.9**	10.2	0.7	6.3	0
0.125...0.25		11.0	19.3	5.4	0.2	2.4
0.075...0.125		1.6	13.0	9.9	0	6.6
…<0.075		2.1	**57.4**	**83.9**	0	**91.0**

Table 4: Distribution of several elements in different fractions of bottom ash (Dahl et al., 2009).

Element	Size fraction, mm							
	0.125...0.25	0.25...0.5	**0.5...1.0**	**1.0...2.0**	2.0...4.0	4.0...8.0	8.0…16.0	16.0…31.5
As	0.2	6.3	**45.7**	**42.0**	0.7	0.8	0.6	3.7
Ba	0.2	8.6	**53.4**	**34.5**	0.3	0.1	0.8	2.1
Cd	0.2	6.3	**45.7**	**42.0**	0.7	0.8	0.6	3.7
Co	0.2	6.1	**48.1**	**40.9**	1.4	0.4	0.2	2.7
Cr	0.3	7.3	**46.5**	**37.1**	1.3	0.5	0.2	6.8
Ni	0.2	7.5	**522**	**37.1**	0.8	0.2	0.1	1.9
V	0.2	**10.2**	**54.3**	**34.5**	0.2	0.1	(0.02)	0.5
Zn	0.3	5.8	**47.9**	**44.0**	0.7	0.1	0.1	1.1

As can be seen, only pH and DMC of different types of ash are similar in most cases (Table 2). The rest properties vary significantly from case to case even among the same type of residue, fuel, or boiler type. Oftentimes, fly ash has higher concentrations of heavy metals compared to bottom ash (Tables 5 and 6). Moreover, heavy metals are accumulated mainly in fine fraction of fly ash (Table 6). Most of elements contained in bottom ash are presented in ash fraction 0.5–2 mm (Table 2).

With regard to the content of elements in different leaching extractions from ash, the amount of elements leached when dissolved in water is generally insignificant compared to the amount of metals leached with acid (Figure 2). The most soluble elements in water are Cd, Mo, and S.

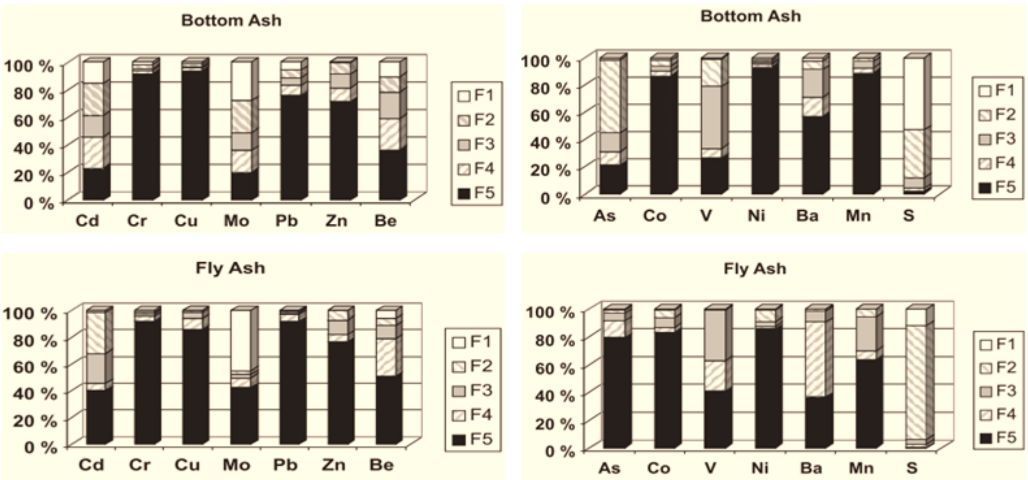


Figure 2: Content of several elements in F1 — water-soluble fraction (H_2O, pH=4), F2 — exchangeable fraction (CH_3COOH), F3 — easily reduced fraction (NH_2OH-HCl), F4 — oxidizable fraction (H_2O_2 + CH_3COONH_4), and F5 — residual fraction (HF + HNO_3 + HCl) (Nurmesniemi et al., 2008).

Other properties could also be studied depending on the recycling method assessed and requirements of a particular legislative act.

Table 5: Mass content of micro elements of several ash types.

Parameter	Unit	Ash type:	Bottom ash	Fly ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash	Fly ash	Fly ash	Bottom ash	Bottom ash	Fly ash	Fly ash
		Place of orig for fly ash:		ESP (first zone)	ESP (second zone)		Cyclone		ESP		ESP						
		Boiler type:	FBB	FBB	FBB	GF	GF	FBB	FBB	FBB	FBB	—	—	FBB	GF	FBB	GF
		Operating temperature:	850 °C			800-1100 °C		810-830 °C		800 °C		—	—	—	—	—	—
		Fuels consumed:	50% wood 50% peat			100% wood		50% wood 50% peat		97% wood 3% sludge		Peat	Wood	Wood	Wood	Wood	Wood
		Reference:	(Dahl et al., 2010)			(Pöykiö et al., 2009)		(Dahl et al., 2009)		(Nurmesniemi et al., 2012)		(Lahtinen, 2001)		(Swedish University of Agricultural Science, 2015)			
Micro elements		Type:	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total	Total[a]	Total[b]	Total[c]	Total[d]
As	mg kg^{-1}		4	**21**	**40**	14	4.0	<3	16	<3.0	<3.0	2-284	<26	16.6±13	5.78±1.18	57.0±20.6	19.3±4.9
Ba	mg kg^{-1}		—	—	—	2210	**4260**	330	**3000**	—	—	55-790	115-1340	900±62	1727±105	2005±274	2341±800
Cd	mg kg^{-1}		0.4	3.6	6.5	5.7	**25**	<0.3	3	0.3	**12**	0.5-19	0.8-11	0.11±0.06	1.41±0.3	9.5±2.1	30.8±3.6
Co	mg kg^{-1}		—	—	—	**11**	**13**	2.5	8	—	—	13-33	7-23	6.5±3.7	9.69±0.6	16.7±2.3	12.2±1.2
Cr	mg kg^{-1}		39	89	120	**318**	**290**	15	24	39	69	37-212	40-85	44.5±12	82.5±8.6	121±27.9	60.3±6.5
Cu	mg kg^{-1}		28	94	130	**196**	**200**	<10	60	-	-	55-180	58-230	64.7±13	77.6±8.8	147±28.3	146±9.6
Hg	mg kg^{-1}		<0.04	0.2	0.6	n.d.	**1.7**	<0.03	0.3	<0.1	<0.1	0.01-0.6	0.2	0.05±0.00	0.08±0.02	0.63±0.13	1.75±1.95
Mn	mg kg^{-1}		—	—	—	15600	20000	—	—	—	—	—	—	2.63±0.55	7.25±2.9	10.8±2.6	10.9±2.0
Mo	mg kg^{-1}		—	—	—	—	—	<1	2	—	—	0.9-19	<5-14	2.79±0.11	5.17±0.6	6.8±1.1	12.4±3.8
Ni	mg kg^{-1}		20	**60**	**83**	46	47	19	**67**	16	38	32-700	32-68	8.78±4.5	34.2±3.9	46.6±5.9	49.5±13.5
Pb	mg kg^{-1}		7	47	**78**	29	**76**	<3	**49**	<3.0	33	16-970	20-103	13.04±2.3	32.1±7.5	233±68.7	165±23
Sb	mg kg^{-1}		—	—	—	—	—	<4	<4	—	—	<20	2-15	—	1.56±0.7	—	2.31±.0.7
Ti	mg kg^{-1}		—	—	—	1240	250	—	—	—	—	—	—	0.96±0.21	1.19±0.2	3.96±0.85	0.93±0.44
V	mg kg^{-1}		—	—	—	41	39	95	**140**	—	—	68-356	32-100	14.3±4.6	28.7±2.3	51.8±6.4	29.3±6.8
Zn	mg kg^{-1}		620	750	**1120**	950	**3630**	160	480	—	—	<20-900	300-1900	1116±175	401±31	2307±558	5886±872

[a] – number of data sets varied between 4–11;
[b] – number of data sets varied between 8–78;
[c] – number of data sets varied between 25–32;
[d] – number of data sets varied between 9–67.
n.d. – not determined.

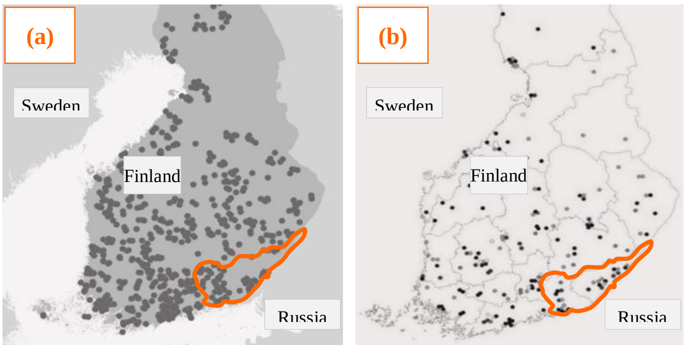
Table 6: Leachable content of several ash types.

Leachable content	Unit	Ash type:	Fly ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash	Fly ash	Fly ash	Fly ash	Fly ash	Fly ash	Fly ash	Fly ash
		Place of origin for fly ash:	Cyclone	ESP		ESP		ESP		ESP	Bag filter	ESP	ESP (coarse fraction)	ESP (fine fraction)	ESP	ESP (coarse fraction)	ESP (fine fraction)
		Boiler type:	GF	FBB	FBB	FBB	FBB	FBB	FBB	—	—	—	—	—	—	—	—
		Operating temperature:	800-1100 °C	800-900 °C		800-900 °C		800-900 °C		—	—	—	—	—	—	—	—
		Fuels consumed:	100% wood	100% wood		75% wood 25% peat		25% wood 75% wood		60% wood 20% peat 20% REF		53% wood 47% peat			31% wood 69% peat		
		Reference:	(Pöykiö et al., 2009)	(Pekkala, 2012)						(Korpijärvi et al., 2009)							
Element		L/S ratio	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10	L/S=10
Al	mg kg^{-1}		<0.2	<0.015	<0.015	<0.015	<0.015	<0.15	<0.15	—	—	<0.11	<0.83	<0.17	<1.0	**106**	<4.6
As	mg kg^{-1}		—	—	—	—	—	—	—	<0.02	**0.04**	<0.02	<0.01	<0.02	<0.01	<0.01	<0.01
Ba	mg kg^{-1}		2.7	2.6	0.3	2.6	2	1	0.15	2.0	2.4	2.5	5.2	2.2	**64**	9.9	**290**
Cd	mg kg^{-1}		<0.02	<0.02	<0.02	<0.02	<0.02	<0.015	<0.015	<0.01	<0.01	0.01	0.003	0.02	<0.01	<0.01	0.011
Cl^-	mg kg^{-1}		**7220**	1200	1.9	1500	1200	880	6.6	2800	**7900**	1750	300	**3090**	653	169	1320
Co	mg kg^{-1}		—	—	—	—	—	—	—	—	—	<0.006	<0.001	<0.0067	<0.002	<0.0003	<0.005
Cr	mg kg^{-1}		**38**	0.95	<0.11	0.87	1.2	1.5	<0.15	6.2	3.6	3.7	0.76	4.1	0.36	0.13	0.16
Cu	mg kg^{-1}		<0.1	<0.05	<0.05	<0.05	<0.05	<0.1	<0.1	0.10	**0.53**	<0.02	<0.03	<0.02	0.02	0.03	<0.02
DOC	mg kg^{-1}		**29**	14	9.6	18	15	8.9	5.3	**27.8**	**26.3**	<5.5	7.5	<6.2	15	<8.1	9.0
F^-	mg kg^{-1}		**28**	<2	<2	<2	<2	<5	<5	**27**	**31**	16	7.6	16	18	6.7	18
Fe	mg kg^{-1}		—	—	—	—	—	—	—	—	—	<0.41	0.66	<0.30	<0.5	<0.60	<0.39
Hg	mg kg^{-1}		<0.005	<0.002	<0.002	<0.002	<0.002	<0.005	<0.005	<0.001	<0.001	<0.001	<0.0002	<0.0002	<0.001	<0.0005	<0.0002
Mn	mg kg^{-1}		—	—	—	—	—	—	—	—	—	**<0.09**	0.01	**<0.09**	0.03	0.01	<0.07
Mo	mg kg^{-1}		**5.4**	1.2	<0.071	1.6	2.4	2.5	<0.1	3.0	1.9	**6.0**	1.7	**9.0**	4.3	1.4	**6.1**
Ni	mg kg^{-1}		**<0.1**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.03	<0.03	**0.09**	0.02	**0.10**	<0.01	0.01	0.03
Pb	mg kg^{-1}		**2.1**	<0.015	<0.015	<0.015	<0.015	<0.15	<0.15	1.4	**19**	2.1	1.7	1.5	0.33	0.07	0.44
Sb	mg kg^{-1}		<0.05	<0.034	**0.058**	<0.032	<0.031	<0.05	<0.05	0.01	0.01	<0.02	<0.001	<0.003	<0.03	<0.01	<0.004
Se	mg kg^{-1}		**1.5**	0.17	0.065	0.16	0.18	0.073	<0.02	0.25	<0.1	0.54	<0.07	**0.95**	0.22	0.06	0.43
SO_4^{2-}	mg kg^{-1}		**50000**	4400	28	6000	11000	2330	20.3	13900	14700	12630	3840	**17900**	3418	1850	2990
V	mg kg^{-1}		—	0.26	1.1	0.25	0.31	0.27	**0.75**	0.05	0.01	<0.01	0.04	<0.01	<0.01	0.06	<0.01
Zn	mg kg^{-1}		**51**	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.1	2.4	0.92	0.79	0.77	0.17	0.09	0.23

3. CASE-STUDY AREA DESCRIPTION

Out of 15 centers for economic development, transport and the environment, i.e. regions, existing in Finland (Ely-keskus, 2013), a region of Southeast Finland (Kaakkois-Suomi) was chosen as a case-study area. The location of the area is shown in Figure 3. Moreover, power and district heating plants, as well as forest industry production plants, potential ash generating units, are depicted in the figure.

Figure 3: Locations of power and district heating plants (a) (Energiateollisuus,



2014), as well as the forest industry production plants (b) in Finland (Finnish Forest Industries, 2013). The area encircled with the black line is Southeast Finland.

The case-study area consists of two regions: South Karelia and Kymenlaakso. The regions, in turn, comprise 16 municipalities. In 2013, there were about 210 000 inhabitants in the case-study area what accounts for nearly 4% of the entire population of Finland. The case-study area occupies approximately 12 500 km^2 what is nearly 4% of the total Finnish territory.

To reveal ash generating units, official statistics of energy, and pulp and paper industries were reviewed.

3.1 Energy industry

Data about combined heat and power (CHP) plants and district heating plants (DHPs) are included in the register of power plants published by the Finnish Energy Authority (Energiavirasto, 2014), as well as in the report prepared by the Finnish Energy Industries (Energiateollisuus, 2014). Only industrial and domestic CHP plants excluding nuclear, hydro and wind power plants were considered. The plants consuming natural gas or light fuel oil as a prime fuel are listed in the study, but were not assessed during the environmental and economic analyses, since no or negligible amounts of ash are generated therein.

Major electricity and heat supply companies revealed in the case-study area are: – KSS Lämpö Oy, – Kotkan Energia Oy, – Haminan Energia Oy, – Lappeenrannan Energia Oy, and – Imatran Lämpö Oy.

3.1.1 KSS Lämpö Oy

KSS Lämpö is a company distributing district heat in Kouvola region. The company does not own CHP plants, but owns 15 DHPs which consume either natural gas or light fuel oil for energy production. In addition, the company imports heat from several companies. The structure of the company is presented in Figure 4.

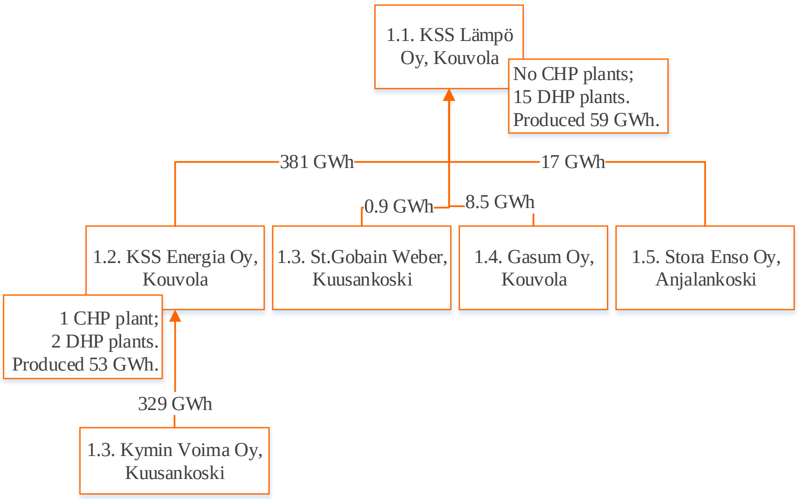


Figure 4: Structure of KSS Lämpö and the amount of district heat imported from other companies.

KSS Energia Oy owns a CHP plant and 2 DHPs, which use natural gas for electricity and district heat production. Additionally, the company imports district heating from a CHP plant of *Kymin Voima Oy* which owns two CHP plants that use multiple fuels including milled peat, natural gas, forest fuels, industrial wood residues and other biomass.

St.Gobain Weber produces lightweight aggregates and does not generate ash during its production process. Heat exported is heat from industrial exothermic reaction. *Gasum Oy* does not generate ash during energy production, since only natural gas is consumed.

Stora Enso mill in Anjalankoski utilizes several types of solid fuels including bark, industrial wood residues, sludge, as well as natural gas (Itä-Suomen Ymparistölupavirasto, 2006).

3.1.2 Kotkan Energia Oy

Kotkan Energia Oy owns 2 CHP plants and 3 DHPs which together generate 393 GWh of district heat. In addition, Kotkan Energia Oy imports heat from Kotkamills Oy. The structure of the company is presented in Figure 5.

Both CHP plants utilize solid fuels for electricity and heat production. A CHP plant in Hovinsaari utilizes mainly peat, natural gas, forest fuels, and industrial forest residues, while another one named Hyötyvoimala is a waste incineration plant. One out of three DHPs, Karhulan biobased heat plant, consumes forest fuels, while other two plants consume light fuel oil.

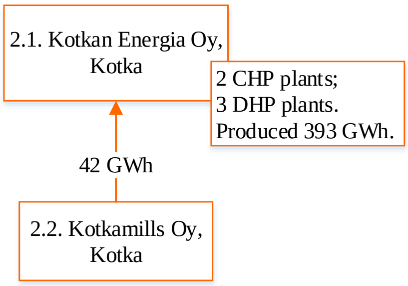


Figure 5: Structure of Kotkan Energia Oy and the amount of district heat imported from other companies.

Kotkamills Oy is a pulp and paper mill which generates wood residues during its production process. However, the residues are sent to Kotkan Energia CHP plant for energy production.

3.1.3 Haminan Energia Oy

Haminan Energia owns five DHPs and does not import heat from other companies. The structure of the company is presented in Figure 6. Each DHP consumes natural gas.

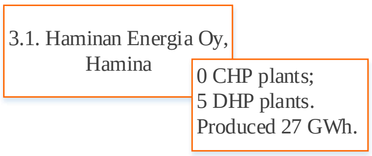


Figure 6. Structure of Haminan Energia Oy.

3.1.4 Lappeenrannan Energia Oy

Lappeenrannan Energia Oy does not own CHP plants or DHPs. The company imports heat from several companies and its structure is presented in Figure 7.

Nordkalk Oyj is a mining company manufacturing calcium carbonate and other mineral products. The company does not generate ash during its production process. Heat exported is heat from industrial exothermic reaction.

Finnsementti Oy produces cement and does not generate ash during its production process. Heat exported is heat from industrial exothermic reaction. *FC Power Oy* incinerates hydrogen and light fuel oil only.

Lappeenrannan Lämpövoima owns one CHP plant and 12 DHPs which together produce 116 GWh of district heating. The CHP plant and DHPs utilize natural gas and light fuel oil for district heat production.

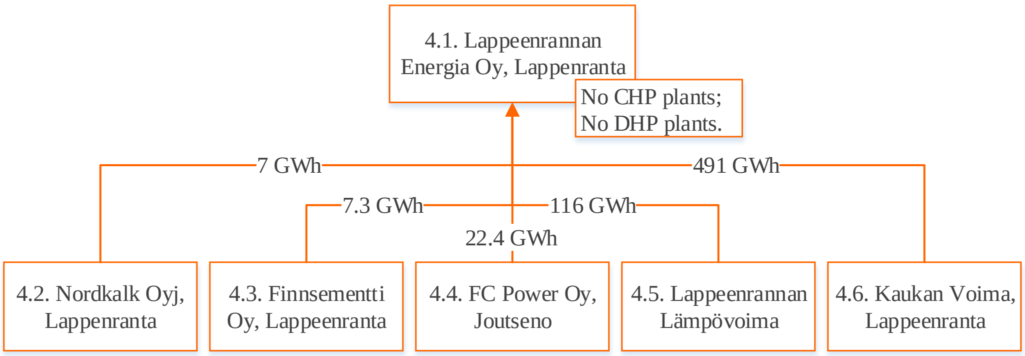


Figure 7: Structure of Lappeenrannan Energia Oy and the amount of district heat imported from other companies.

Kaukaan Voima is located on premises of UPM-Kymmene Oy. Fuels consumed at Kaukaan Voima are mainly peat, natural gas, forest fuels, and industrial wood residues.

3.1.5 Imatran Lämpö Oy

Imatran Lämpö does not own CHP plants, but 11 DHPs which together produce 77 GWh of district heat. Also, the company imports heat from Imatran Energia Oy. The structure of the company is presented in Figure 8. Each DHP consumes natural gas and light fuel oil for energy production.

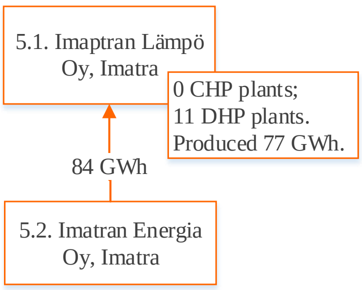


Figure 8. Structure of Imatran Lämpö and the amount of district heat imported from other companies.

Imatran Energia Oy consumed natural gas for electricity and heat production.

3.2 Pulp and paper industry plants

Forest industry includes plants manufacturing pulp, paper, cardboard, converted products, wood-based panels, sawn and further processed goods, service industry and suppliers of the industry. The companies were identified using the data available on the Finnish Forest Industries' website (Finnish Forest Industries, 2014a).

Table 7: Finnish forest industry plants located in the case-study area.

Region	Company	Generates ash
Kouvola	Shaefer Kalk	No
	UPM-Kymmene Oyj (Kymin Voima)	Yes
Kotka	Kotkamills	No
	Sonoco-Alcore	No
	Stora Enso Anjalankoski mill	Yes
Lappeenranta	UPM-Kymmene Oyj (Kaukaan voima)	Yes
	Metsä Joutseno mills	Yes
Imatra	Coresnso	No
	Efora	No
	Omya	No
	Tornator Oyj	No
	Stora Enso Imatra mills	Yes
	Metsä Simpele mills	Yes

3.3 Thermal residue generating units included in the study

Having analyzed all potential thermal residue generating units in the case-study area, a list of units, which will be assessed further in the study, was created and is shown in Table 8. Companies were asked to fill the questionnaire presented in Annex I. Average annual amount of ash and slag generated in the case-study area is 101 700 t according to cumulative data gathered from companies under the study. However, only 58 400 t of fly ash and 35 100 t of bottom ash and boiler slag were included in the study due to lack of data about leaching content of heavy metals for in some of the ashes.

Table 8: Thermal residue generating units located in the case-study area.

Name	Region	Main types of solid fuels utilized
Hovinsaari CHP	Kymenlaakso	Peat, wood, bark
Hyötyvoimala CHP	Kymenlaakso	Municipal solid waste
Karhula heating plant	Kymenlaakso	Wood
Kaukaan Voima	South Karelia	Peat, wood, bark
Kymin Voima	Kymenlaakso	Peat, wood, bark
Metsä Simpele mill	South Karelia	Peat, wood
Stora Enso Anjalankoski mills	Kymenlaakso	Bark, sewage sludge, packaging
Stora Enso Imatra mills	South Karelia	Bark, sewage sludge

4. ASH UTILIZATION POSSIBILITIES

Once data about ash generating companies were gathered, the study focused only on fly ash and bottom ash from wood mono-incineration and wood-peat co-combustion, and slag from municipal solid waste incineration since these residues are primarily generated in the area. Therefore, utilization methods of coal residues were excluded from the scope of the study.

Technical applicability of a particular type of thermal residue is determined by its properties and requirements set on the residue. Recycling of ash is attractive due to content of valuable materials, e.g. nutrients for forest fertilization, or CaO for civil engineering. However, such factors as market perception, possible risk for the environment, health and safety issues, sales price and market volume should also be acknowledged when analyzing utilization methods (KEMA, 2012).

The overview of utilization possibilities is presented in Table 9. The utilization possibilities were divided into two categories: already applied methods, and possible methods. None of the utilization methods listed could be considered as a universal method suitable for all ash generated in the case-study area due to large variation of properties and composition of ash.

Table 9: Overview of utilization possibilities for biomass and MSWI ashes.

Utilization methods	Ash from biomass/peat	Ash from MSW
Already applied		
Forest fertilizer	+[1,2,3)]	
Liming agent	+[1)]	
Additive for compost production	+[1)]	
Cement and brick industry	+[1)]	
Mine tailing cover	+[3)]	
Mine backfilling	+[1,2)]	+[1)]
Concrete filler	+[1,2)]	
Landfill construction	+[1,3)]	+[3,4)]
Soil stabilization	+[1,2)]	
Road construction	+[3)]	+[1,3,4)]
Possible		
Production of alternative binders (e.g. geopolymers)	?[1,2)]	
Production of synthetic aggregates by cold bonding or sintering	?[1,2)]	
Stabilizing dredged material	?[1,2)]	
Production of adsorbents (e.g. zeolites)	?[2)]	
Neutralization of waste acids	?[2)]	
Impermeable layer	?[2,3)]	
Vitrification	?[2)]	
Stone wool fibre production	?[2)]	
Metal recovery		?[1)]
Glass recovery		?[4)]
Phosphorus recovery	?[1)]	

+ – a method is used for utilization of a particular ash type;
? – a method might be suitable for utilization of a particular ash type;
[1)] – described in (KEMA, 2012; Supancic and Obernberger, 2009);
[2)] – described in (Pels and Sarabèr, 2011; Pels, 2012);
[3)] – described in (Ribbing, 2007);
[4)] – described in (Crillesen and Skaarup, 2006).

Multiple utilization possibilities have been applied and are under development for ash from biomass or peat combustion. Nutrients contained in the biomass/biomass-peat mixture residues allow its recycling as a forest fertilizer, whereas high neutralizing value facilitates its use as a liming agent. Biomass ash was seldom used in cement and bricks production with only experience in Austria and the Netherlands. The problems were partly due to high content of potassium and chlorine. Self-cementitious properties of ash determine its utilization in mine backfilling, concrete production, or in soil stabilization where ash acts as a binder. In other options related to civil engineering, bottom ash was used as an aggregate instead of gravel, sand, or crushed rock.

Apart from the utilization methods currently applied for utilization of wood and peat residues, a number of methods under development exists. The residues are seen as a suitable raw material for the production of alternative binders or synthetic aggregates. Residues could be used for stabilization of dredged materials. Alkaline pH of ash determines its possible application for neutralization of waste acids and acid waste. Possible content of unburned carbon could facilitate the use of the residue as an adsorbent, or for the production of zeolites. However, specific surface area of ash with low LOI is rather small as it was shown in the chapter related to ash properties. Vitrification is another method, which lowers leaching of heavy metals making residue more suitable for construction. Similarly, residues might be used in the production of stone wool. Where possible, the residue could be used for phosphorus recovery.

Ash from MSW incineration have a more limited range of utilization methods compared to biomass and peat residues. This is explained by contamination of MSW residues with heavy metals and toxic compounds, as well as its negative market perception. The only applications of MSW residues cited in literature were the use in roads, embankments, and landfills construction (Crillesen and Skaarup, 2006). Another use of MSW residues could be recovery of ferrous and non-ferrous metals. Still, the remaining amount of MSW residues would require proper utilization. Future prospects for MSW residues are more intensive recovery of metals (KEMA, 2012), as well as glass recovery (Crillesen and Skaarup, 2006).

4.1 Residues utilization in Finland

The mass of ash generated by the pulp and paper industry, which was utilized and landfilled in Finland between 2010-2013 is shown in Figure 9. As can be see, the most widespread applications were the use of ash in earth construction and for soil improvement as a fertilizer.

The recycling rate varied between 64-87% over the period shown. Starting from 2011, most of ash was utilized in earth construction. The share of landfilled ash significantly reduced in 2011, a year when a new waste act was introduced. According to the new waste act, all waste types that have environmentally and technically acceptable utilization possibilities are taxed when landfilled.

Under the Government Decree 591/2006 (Ministry of the Environment, 2006), four types of earth construction works are distinguished: 1) construction of public roads, streets, bicycle lanes, pavements and areas directly connected to these and required for road maintenance, excluding noise barriers; 2) parking areas; 3) sports grounds and routes in recreational and sports areas; 4) railways yards, as well as the storage fields and roads in industrial areas, waste processing areas and air traffic areas. Those construction types do not require an environmental permit, and only require notification of authorities. However, if waste do not meet the requirements of the Decree 591/2006, it still might be utilized, but an environmental permit would be required. The use of ash in roads stabilization, on contrary, is always a subject to the environmental permit application.

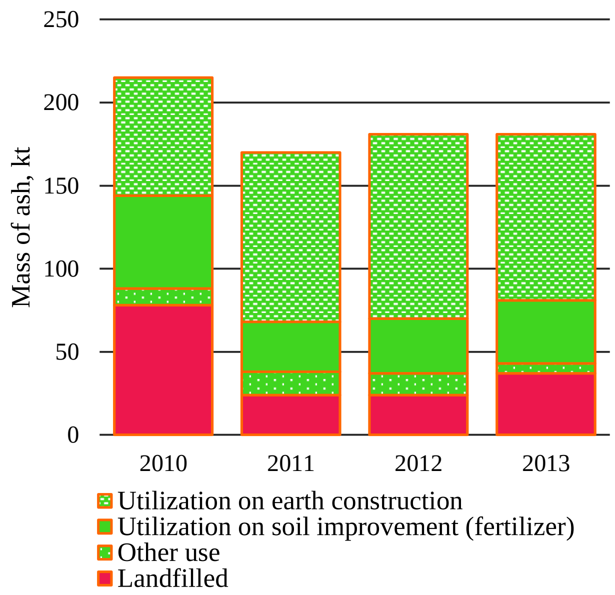


Figure 9: Mass of ash utilized and landfilled within Finnish pulp and paper industry (Finnish Forest Industries, 2014b).

Having regard to the world experience in ash utilization and the practice of Finnish industries, four utilization methods were chosen for further assessment:

1) Forest fertilization;
2) Road construction;
3) Road stabilization;
4) Landfill construction.

4.2 Forest fertilization

Recently, forest residues, such as crowns and branches, which contain most of plant's nutrients, found a greater potential for energy production in forest industry. However, such harvesting approach results in unprecedented export of nutrients from forests. Moreover, intensive forest exploitation causes depletion of acid-buffering substances what results in soil acidification, which in turn, can results in water acidification and increased leaching of heavy metals. Recycling of ash back to forests is especially required when harvesting forest residues with leaves. (Emilsson, 2006)

Ash should be applied on certain soil types in order to reach better forest growth. Wood ash should be recycled on nitrogen-rich soils to compensate absence of nitrogen in ash. Therefore, ash cannot be used as a source of nitrogen. The fertilizing effect of ash lasts for 40-50 years, what is two times longer compared to that of a commercial fertilizer – 15-25 years (Väätäinen et al., 2011). Acidic soils can also be successfully neutralized with ash due to its high neutralizing value (Emilsson, 2006; Karltun et al., 2008). Change of pH by 1.4-2 units for 10-19 years is anticipated when 5 t/ha ash is applied (Karltun et al., 2008).

There are certain amounts of nutrients that are recommended for forest fertilization. The amount of phosphorus, which should be applied on peat lands, is 40-50 kg/ha, whereas that of potassium is 80-100 kg/ha (Huotari, 2012). In general, 3–5 t/ha of wood ash or 4–8 t/ha of mixed ash should be applied to achieve the limits set (Emilsson, 2006). Regarding the use of commercial PK-fertilizer, e.g. Rauta-PK made by Yara, 500 kg/ha fertilizer is required.

Potassium and phosphorus have different leaching behavior in soil. Usually K present in ash is easily soluble and is rapidly released when contacting water (Karltun et al., 2008). Phosphorus, on contrary, is much less soluble and becomes fully available for plants within 20 years, what is not a problem for forest fertilization since a single rotation takes place in 20-60 years. (Karltun et al., 2008; Pels and Sarabèr, 2011).

The use of loose ash causes health risks to operators and possible hazard to the environment due to particle emissions. Moreover, unprepared ash cannot be distributed equally. Therefore, ash is pretreated by either of three basic techniques: self-hardening and crushing, compaction, and granulation (Emilsson, 2006). All techniques require ash mixing with water. Self- hardened ash has moisture content of around 30%, while it can range between 20-35% (Korpilahti, 2003). Pretreatment makes ash less reactive with water, thus, extending its fertilizing affect. Moreover, pretreated ash results in fewer amount of leached metals and particulate emissions (Karltun et al., 2008).

Considering actual ash spreading in forests, either of two main methods for ash spreading could be applied: ground spreading and aerial spreading. For ground spreading, a forest tractor or a forwarder equipped with a spreader can be used. A wheel loader is required to load ash into the spreader. A single forwarder can spread 40–80 t/d ash. For aerial spreading, a helicopter and a wheel loader are used. A helicopter can normally spread 500–1000 kg of ash at once with daily capacity of around 100 t. (Emilsson, 2006)

4.3 Road construction

The use of fly ash in road construction under Finnish conditions is described by Eskola et al. (1999), Laine-Ylijoki et al. (2000), and Mroueh et al. (2001) who studied the use of different waste materials in road cosntruiction using the MELI-model. The model was developed to compare and evalueate alternative road and earth consturction using LCA methodology. In the model, fly ash was used to build a sub-base layer of a road. The structures of a road built using ash and a conventionally built road are presented in Figure 10.

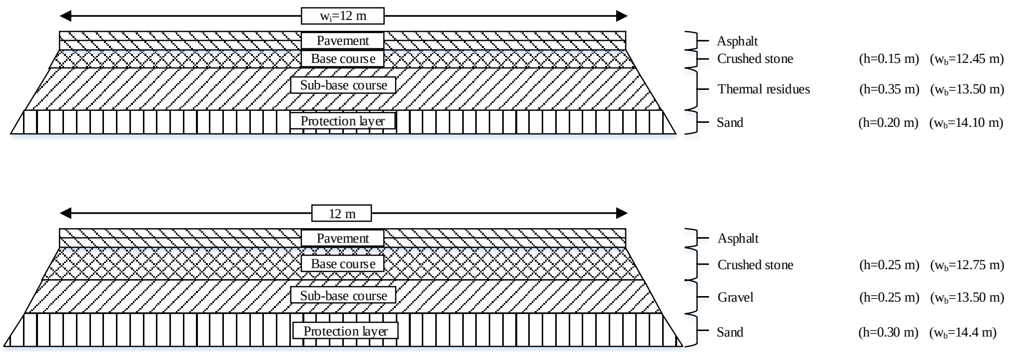


Figure 10: Structure of the road built from ash (top) and conventionally built road (bottom) (Eskola et al., 1999). Pavement is shown to give the initial width of the road, whereas it is not included in the study.

Wider range of earth coinstruction works was studied by Birgisdóttir (2005), who developed ROAD-RES model. The model assesses environmental impact from consturction and maintenance of several types of roads (motorway, primary road, seconadary road, urban road, and gravel road), parking areas, and embankents (noise barriers or fill beneafth a road). The types of constructions as shown in Figure 11.

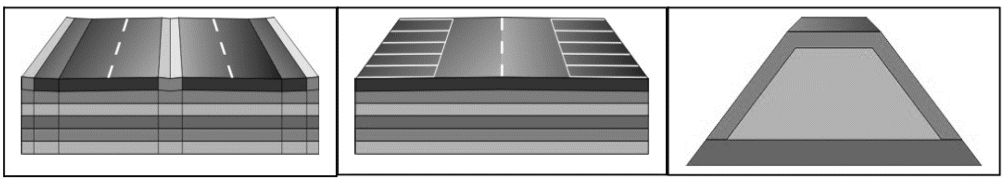


Figure 11: Types of earth works included in ROAD-RES model (Birgisdóttir, 2005).

The structure of a road included in the ROAD-RES model was similar to that of a road in the MELI-model. Moreover, the vertical structure of a parking area is similar to the structure of a road. In the ROAD-RES model, 4 400 t of MSW bottom ash was used for the construction of a sub-base layer of a one-kilometer-long secondary road with width of 17.2 m and thickness of 0.7 m. It was assumed in the model that the methods, workload and energy consumption for construction of a conventional road using natural gravel and a road using bottom ash are the same.

4.4 Road stabilization

The use of ash for stabilization of low-volume roads was studied by Lahtinen (2001). The study showed equal properties of fly ash from peat or wood incineration for road stabilization. Moreover, the use of fly ash results in longer road lifetime — around 30 years, compared to that of a conventional road built from crushed stone (6–8 years). The use of fly ash is possible due to its high calcium and silicate oxides content. Fly ash should be stored in a dry place to prevent its contact with water, what decreases its pozzolanic properties.

Vestin et al. (2012) described the use of fly ash for gravel road stabilization. The ash used in the research was obtained from a fluidized bed incinerator of a paper mill. The composition of ash was not stated, while the fuels burned were mainly bark and sludge. Density of fly ash was 1900 kg/m^3. The amount of fly ash used was 30% to the amount of road material. Depth of fly ash used in the upgrading was 12–20 cm depending on the milling depth which ranged 20–39 cm. Fly ash was covered with a 7 cm deep layer of gravel. The activities related to the road stabilization are presented in Figure 12.

Figure 12: Upgrade of a gravel road using fly ash (Vestin, 2012).

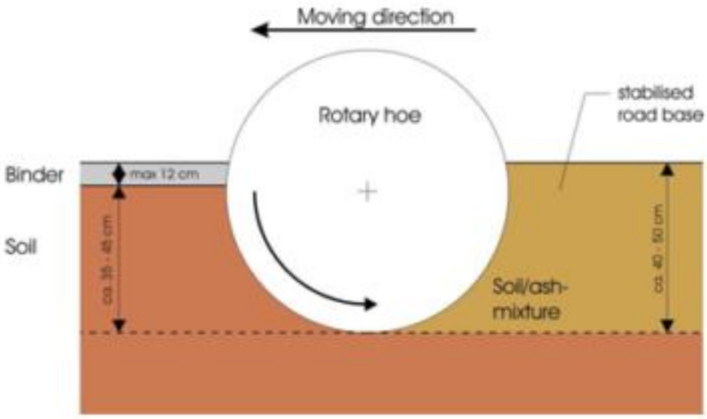


Figure 13: The use of a rotary hoe to mix the binders with soil. (Supancic and Obernberger, 2011)

The use of fly ash as a stabilizer was also studied by Supancic and Obernberger (2011). In the study, fly ash was used as a binder to substitute burned lime. Fly ash from fluidized bed boilers was applied by a spreader. Mixing of ash or burned lime with soil was performed using a rotary hoe mixer (Figure 13). Lastly, soil was compacted.

Finally, quantitative data about environmental inputs and outputs of a road stabilization process are included in the MELI-model, which was further used in the study for environmental assessment of the stabilization process.

4.5 Landfill construction

Bottom ash and boiler slag could be used as a drainage material in a covering layer of landfills substituting conventionally used materials. The use of ash in landfill construction was described by Magnusson (2005) and Toller et al. (2009). The thickness of the drainage layer was set to 0.2 m and the materials used was sand. Ash are placed in a landfill between two layers of geofabric, which was assumed to have no leaching. An excavator is used to construct the drainage layer. The geofabric is placed manually causing no environmental impact. The structure of a conventional drainage layer and that using ash is shown in Figure 15.

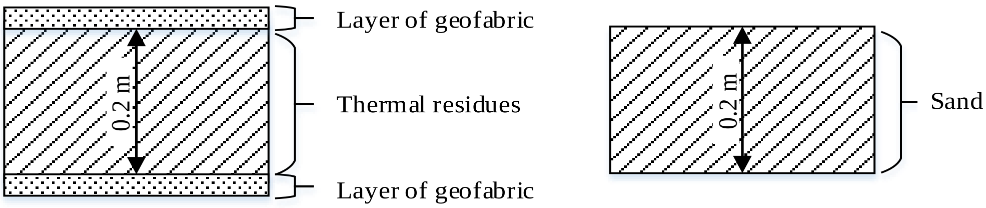


Figure 15: Structure of the drainage layer for landfills construction with ash (left) and sand (right) (Magnusson, 2005; Toller et al., 2009).

5. COMPLIANCE WITH LEGISLATIVE REQUIREMENTS

Utilization of secondary materials is regulated by several decrees and decisions. Landfilling of ash is governed by the Finnish Government Decree on Landfills 331/2013 (Ministry of the Environment, 2013), which determines the limit values for leaching of toxic substances and salts from the materials to be landfilled. Regarding material recovery of ash, Government Decree concerning the recovery of certain wastes in earth construction 591/2006 (Ministry of the Environment, 2006) monitors its utilization in road construction. The use of ash as a forest fertilizer should be in compliance with the Fertilizer Product Act 539/2006 (Maa- ja metsätalousministeriö, 2006) and the Regulation on fertilizer products 24/11 issued by the Ministry of Agriculture and Forestry (MTK, 2011) where the limits for leaching content of heavy metals are set. The limits set for landfilling of ash and their utilization are presented in Table 10.

Table 10: Limit values for total or leaching content of substances included into the Decree on landfilling 331/2013, Regulation on fertilizer products 24/11, and Decree concerning the recovery of certain wastes in earth construction 591/2006.

Substance	Unit	Leaching content for landfilling	Total content for forest fertilizing 1)	Road construction		
				Total content	Leaching content for covered road construction	Leaching content for paved road construction
K+P	%		2			
Ca	%		6			
NV	%		10			
As	mg kg^{-1}	2	40	50	0,5	1,5
Ba	mg kg^{-1}	100		3 000	50	60
Cd	mg kg^{-1}	1	25	15	0,04	0,04
Cl^-	mg kg^{-1}	15 000			800	2400
Cr_{tot}	mg kg^{-1}	10	300	400	0,5	3
Cu	mg kg^{-1}	50	700	400	2	6
DOC	mg kg^{-1}	800			500	500
F^-	mg kg^{-1}	150			10	50
Hg	mg kg^{-1}	0,2	1		0,01	0,01
Mo	mg kg^{-1}	10		50	0,5	6
Ni	mg kg^{-1}	10	150		0,4	1,2
PAH	mg kg^{-1}			20/40 2)		
PCB	mg kg^{-1}			1		
Pb	mg kg^{-1}	10	150	300	0,5	1,5
Sb	mg kg^{-1}	0,7			0,06	0,18
Se	mg kg^{-1}	0,5			0,1	0,5
SO_4^{2-}	mg kg^{-1}	20 000			1000	10000
TOC	mg kg^{-1}	50 000				
TDS	mg kg^{-1}	60 000				
V	mg kg^{-1}			400	2	3
Zn	mg kg^{-1}	50	4 500	2 000	4	12

1) – values for K+P, Ca, and NV are minimal required content;
2) – the former value for covered roads, the latter for paved roads.

Data from Table 10 are required in the assessment of regional optimization of ash utilization in the case-study area in order to define utilization scenarios.

6. DEMAND ON ASH

Demand on ash, unlike its generation and supply, is not constant and depends on multiple factors with economy being the most prominent one. Additionally, seasonality of the demand in road construction and forest fertilization should be acknowledged, making the assessment of precise demand on ash on a regional level rather challenging. Last, the utilization methods studied imply a single-time use of ash in the same place leading to a situation where the demand will have a dynamic nature.

6.1. Forest fertilization

The demand for forest fertilization was calculated based on the area currently fertilized and area subjected to harvesting. Figure 16 represents the area of forest fertilized in Finland over 2000-2013. As can be seen, the forest area fertilized doubled during last 15 years from 21 000 ha up to 41 000 ha. Area fertilized in the case-study area (451 ha) corresponds to 1.1% of total forest area fertilized in Finland in 2013. Figure 17 represents the area treated with fellings in Finland over 2000–2013(METLA, 2014). The area used for wood harvesting continually increases. The area used for wood harvesting in the case-study area corresponds to 5.5% of the overall Finnish area treated with fellings in 2013. Therefore, 5.5% of Finnish area used for wood harvesting receives only 1.1% of overall forest fertilizers. The area, which still can be fertilized with ash in the case-study area is 2 255 ha (equals to 5.5% of total area fertilized in Finland) to reach average Finnish values.

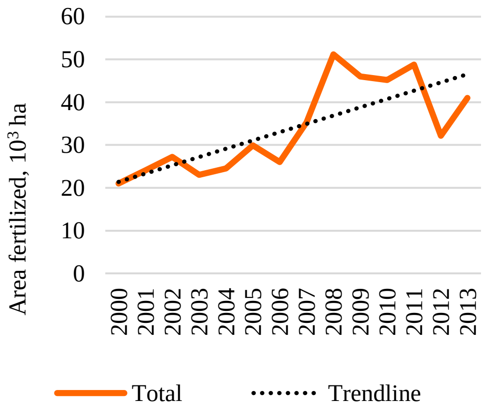


Figure 16: Area of forest fertilized in Finland over period 2000–2013 (METLA, 2014).

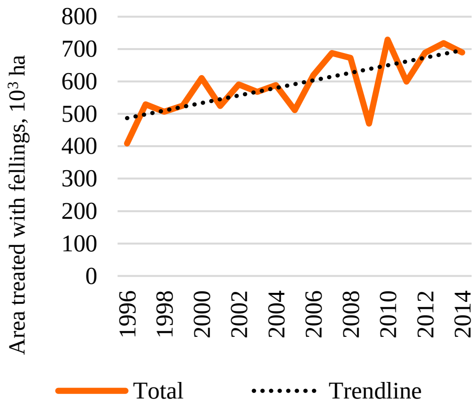


Figure 17: Area treated with fellings in Finland over the period 2000–2013 (METLA, 2014).

6.2. Forest roads stabilization

Fly ash can be used as a stabilizing agent for forest roads construction and renovation. Figure 18 depicts the length of forest roads built and renovated in Finland over the period 1990–2013. As can be seen, fewer forest roads were built over the period studied with more efforts placed on roads renovation. Moreover, it can be anticipated that the forest roads will be rather renovated than built in the future. With regard to the case-study area, 12 km of forest roads was built, whereas 146 km was renovated, what equals to 1.8% and 4.8% of that in Finland in 2013 (METLA, 2014).

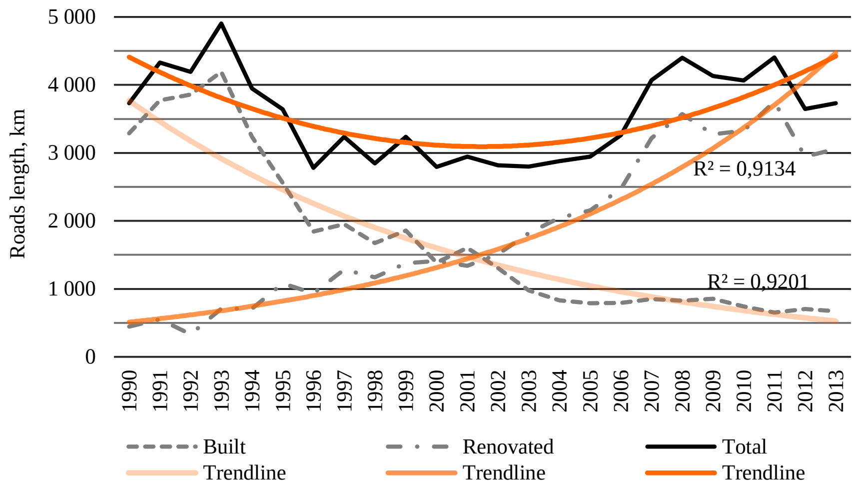


Figure 18: Length of build, renovated, and total forest roads in Finland (METLA, 2014).

6.3. Earth works

Out of all types of earth works possible with ash, only new public roads, streets, bicycle lanes, and pavements could be estimated, since the information about their construction is centrally collected and publically available. Data about road projects in the case-study area are presented in Table 11.

Table 11: Road projects in South-East Finland (Ely-keskus, 2015).

Project	Length and type of road	Milestones
Roads under the construction phase		
– Vt 6 Taavetti-Lappeenranta	30 km, Improvement	2015–2018
– Vt 6, Kärjen kylä, Lappeenranta	2,8 km, Improvement	2012
– Vt 7, Hamina-Vaalimaa	32 km, Change to Motorway	2015–2018
– Mt 14832	2 km, pedestrian and cycling road	2015?
Road projects being planned		
– Vt 6 Tykkimäki-Kaipiainen	19 km, improvement	2009 general plan
– Vt 6 Kouvola	Improvement	2015 general plan
– Vt 6 Utti-Metso	5.5 km, Groundwater protection improvement	2013 road plan
– Vt 6, Hevossuo-Nappa	2 km, Improvement	-
– Vt 6 Orilammi, Ruokolahti	980 m, Noise barrier	2002 road plan is being updated
– Vt 6 Kimonkylä-Heinikallio	20 km, Private interchanges	2013 general plan
– Vt 6 Taavetti	Western junction changed to graded junction	2015 in road planning
– Vt 7 Vaalimaa	Frontier transit point waiting area for trucks	2014–2019 possible construction
– Vt 7 Lahti-Kouvola	60 km, Improvement: passing lanes, barriers	2015 in road planning
– Vt 13 Mikkeli-Lappeenranta	99 km, Improvements on unsafe spots	2015 in road planning, 2016 road plan?
– Vt 13 Lappeenranta-Nuijamaa	18 km, Improvement	2015 general plan

Project	Length and type of road	Milestones
– Vt 13 Myttiömäki, Savitaipale	Improvement	2012 road plan
– Vt 13 Kuukanniemi-Iitiä	4,5 km, Pedestrian and cycling route	2015 preliminary planning
– Vt 15 Rantahaka-Kouvola	44 km, Improvement	2018 general plan
– Vt 15 Kotka entrance road	4 km, Improvement	2015 in road planning
– Vt 15 Keltakangas, Kouvola	Junction improvements	2011 general plant
– Vt 26 Hamina-Taavetti	50 km, Improvement	2017 general plan
– Kt 62 Huuhkala-Käyhkää, Puumala and Ruokolahti	15 km, Improvement	2009 general plan
– Mt 355 Merituulentie, Kotka	Improvements	2016 general plan
– Mt 362 and 3622	Pedestrian and cycling roads	2013 general plan
– Mt 378, Taavetti-Perälä, Luumäki	1 892 km, Pedestrian and cycling road	2014 general plan
– Mt 408 and 409, Savitaipale	Traffic safety, pedestrian and cycling roads	2013 general plan
– Mt 409	pedestrian and cycling roads	2015 in planning

Table 11 shows that there are four roads under construction in the case-study area. Apart from those roads, there are several roads being prepared and which are under different planning stages shown in Figure 19. Most of the plans are related to roads improvement, which does not require utilization of ash. Another potential for ash utilization is for pedestrian and cycling roads constructions.

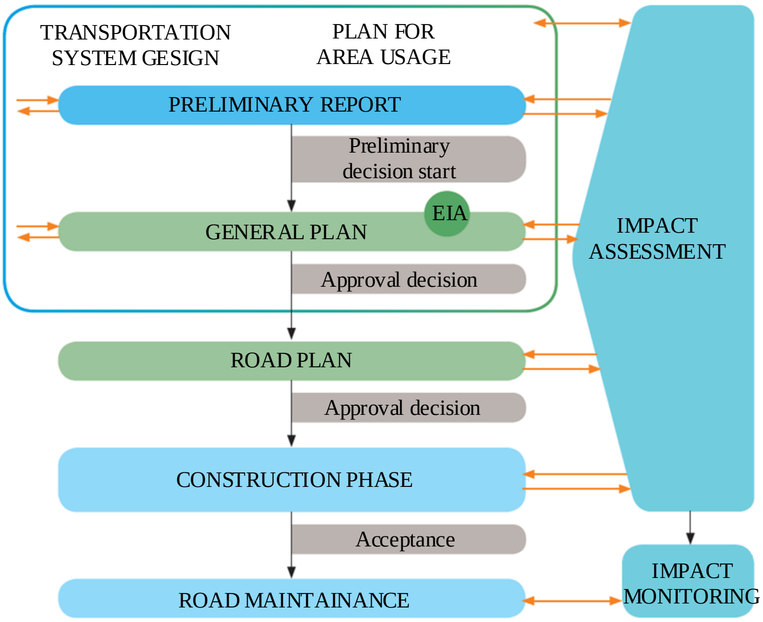


Figure 19: Steps incorporated into the road planning and construction process (Liikennevirasto, 2010).

7. LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) has gained popularity in the field of waste management within last two decades with special attention drawn to municipal solid waste (Laurent et al., 2014; Pires et al., 2011). The methods allows for assessment of environmental performance of products/services, or activities. LCA studies should be performed in accordance with ISO 14040/14044 standards (SFS-EN ISO 14040, 2006; SFS-EN ISO 14044, 2006).

The aim of the life cycle assessment was to quantify the environmental impact of four alternative recovery methods for ash and compare them with landfilling of the residues. The utilization methods were forest fertilization and neutralization, landfill construction, road construction, and road stabilization.

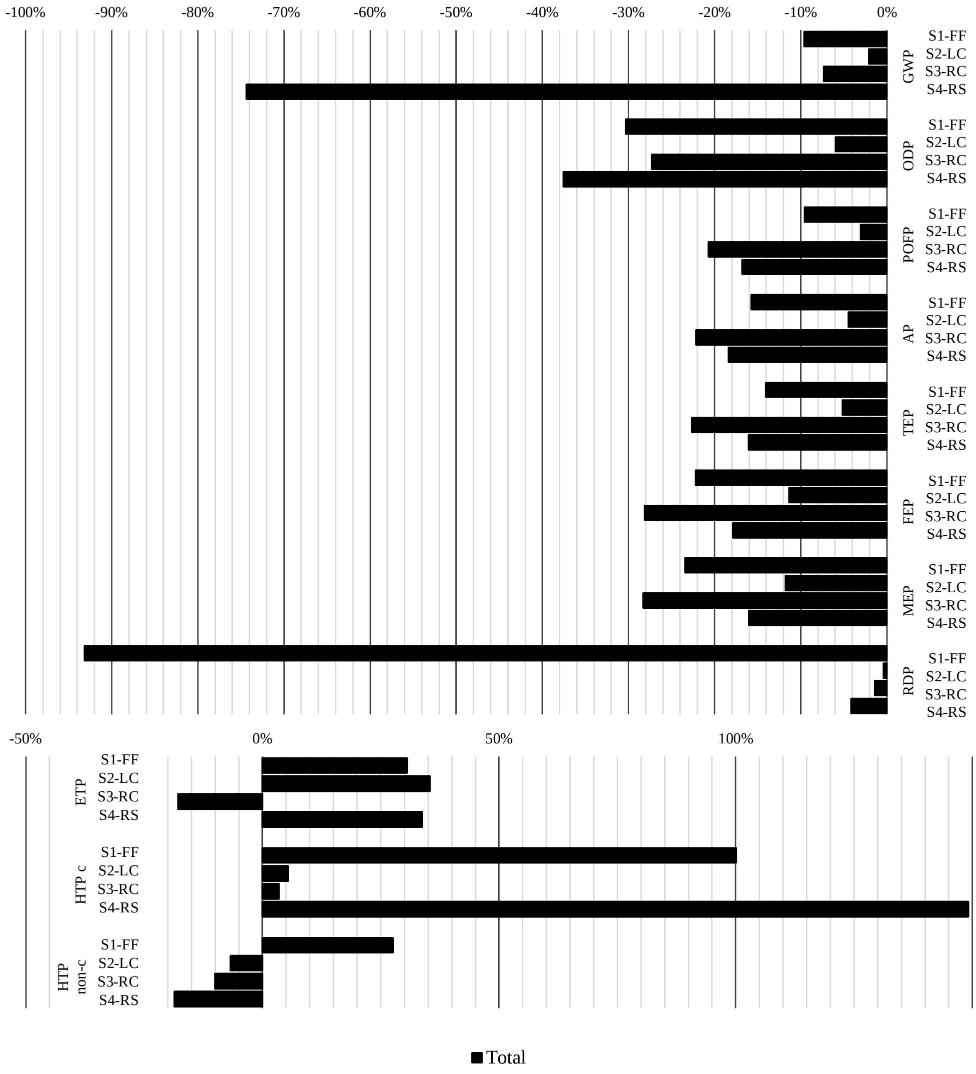


Figure 20: LCA results of four alternative ash utilization scenarios presented relatively to the baseline scenario – ash landfilling.

The system boundaries started from the generation of ash and ended with the incorporation of the residues into a final product. The impact from avoided production of materials substituted with ash was included in the study by expanding original system boundaries. All relevant unit processes were included in the system boundaries. The results of the LCA study are presented in Figure 20.

According to the study, each alternative utilization method is superior to landfilling within all non-toxic impact categories. On average, the environmental impact was reduced by 10-30% when utilizing ash for forest fertilization, road construction, and road stabilization, and 3-12% when utilizing for landfill construction compared to ash landfilling. Global warming potential and abiotic resource depletion potential reduced exceptionally by 74% when using ash for road stabilization, and 93% when using for forest fertilization, respectively.

Regarding toxicity-related impact categories, the use of ash in road construction performed best out of al scenarios. On contrary, the use of ash for forest fertilization and road stabilization led to higher toxic impact on the environment due to higher leaching of heavy metals caused by significant infiltration of precipitations.

The impact of transportation distance variation on the results, as expect to happen when optimizing residues utilization in the case-study area, i.e. on a regional scale, was studied. The results showed that freshwater and marine eutrophication potentials are the most sensitive to the distance change.

Detailed description of the LCA study could be retrieved from (Deviatkin et al., 2016). The study includes initial setting of the LCA study, states defined goal and scope, provides life cycle inventory data, presents the range of impact categories chosen and criteria for their selection, and shows overall results of the study.

7.1. Weighting of LCA results

To compare alternative utilization methods, LCA results for multiple impact categories were weighted in order to obtain a single score for each utilization alternative. According to ISO 14044 standard (SFS-EN ISO 14044, 2006), aggregation of life cycle impact assessment results from multiple impact categories into a single value could not be performed on a scientific basis. However, expert values collected using a panel method could be applied to perform weighting (Itsubo, 2015). Eskola et al. (1999) interviewed a group of experts to rank environmental impacts associated with earthworks in Finland. Thus, the values of the experts could be used in the current study, which partly aims at the utilization of thermals residues in earthworks. Weighing factors for impact categories included in the study are listed in Table 12, along with the corresponding names of the areas of environmental concern from Eskola et al. (1999).

Table 12: Factors used for LCIA results weighting.

Impact category, IC	Weighting factors, WF_i	Area of concern according to Eskola et al. (1999)
Global warming potential (GWP)	50.6	CO_2 to air
Photochemical ozone formation potential (POFP)	39.9	VOC to air
Acidification potential (AP)	46.2 [a)]	SO_2 and NO_x to air
Terrestrial eutrophication potential (TEP)	49.5	NO_x to air
Freshwater eutrophication potential (FEP)	38.6	COD to water
Marine eutrophication potential (MEP)	39.4	N to water
Ecotoxicity potential (ETP)	66.9	Heavy metals to soil
Carcinogenic human toxicity potential (HTP_c)	66.9	Heavy metals to soil
Non-carcinogenic human toxicity potential ($HTP_{non\text{-}c}$)	66.9	Heavy metals to soil
Resource depletion potential (RDP)	66.6 [b)]	Raw materials and fuels consumption

[a] – calculated as weighted average between the weighting factors of SO_2 and NO_X using characterization factors from GaBi;
[b] – calculated as average between the weighting factors of raw materials consumption and fuels consumption.

The LCA results for each scenario were aggregated into a single score using weighting factors as follows:

$$LCA_W = \frac{\sum_i^n (WF_i \cdot LCIA_i)}{\sum_i^n WF_i}, \%$$

where WF_i – a weighting factor of an impact category *i* (Table 12);

$LCIA_i$ – results of the LCIA for an impact category *i* expressed as relative percentage change, %.

8. COST-BENEFIT ANALYSIS

Undoubtedly, economic feasibility of ash recycling, apart from its technical applicability, is one of the major drivers towards increased ash recycling rates (Ahmaruzzaman, 2010; Niu et al., 2016). However, substitution of conventionally consumed raw materials when recycling ash might be economically unfeasible. This is mainly due to low cost of raw materials substituted and high economic risks associated with utilization of ash, which has rather varying composition. Proper economic incentives, mainly increased landfill taxes (Fischer et al., 2012), promote waste recycling in a way that the benefits of avoided waste landfilling would cover the costs of logistics required for ash recycling and possible risks.

Despite economy is acknowledged as an important factor of recycling, research on economic impact of ash recycling is scarce (Ahmaruzzaman, 2010; Blissett and Rowson, 2012; Iyer and Scott, 2001; Niu et al., 2016). In the study, a cost-benefit analysis (CBA) method as described in James and Predo (2015) based on the findings of Boardman et al. (2010) was applied for assessing the economic feasibility of recycling ash generated in the case-study area. The costs included in the study were possible pretreatment of ash and its utilization into the final product, whereas the benefits were avoided landfilling tax, avoided cost of landfill maintenance, and avoided cost of substituted products. Net present value (NPV) was used for comparison of alternative scenarios in the study and calculated as the difference between the benefits and costs of each scenario within one year. The scenarios included were same as in the LCA part of the study. The costs used in the study are listed in Table 13. The costs from different years were corrected to the year 2014 using the consumer prices index published by the Statistics Finland (2015).

Table 13: Cost and benefit categories used in the study and their values.

Category	Value	Reference
Rental of a single vehicle, €·h^{-1}	70	(Tiainen, 2014)
Granulation unit		
CAPex, €·unit^{-1}	202 000	(Pekkala, 2012)
OPex, €·t^{-1}	1.1	
Spreading in forest		
Aerial of ash, €·t^{-1}	60	
Ground for ash, €·t^{-1}	50	(Pekkala, 2012)
Aerial for fertilizer, €·t^{-1}	200	
Ground for fertilizer, €·t^{-1}	130	
Materials		
Commercial fertilizer, €· t^{-1}	249 [a)]	(Korpilahti, 2004)
Limestone, €· t^{-1}	27.1	(“Kalkkitaulukko, nopeavaikutteinen,” 2012)
Geofabric, €·m^{-2}	2.0	Assumed based on data available on the Internet
Sand, €· t^{-1}	2.8	(Noormarkun Murske Oy, 2014)
Gravel, €· t^{-1}	6.5	(Noormarkun Murske Oy, 2014)
Crushed stone, €· t^{-1}	6.4	(EGSTONE Oy, 2015; Noormarkun Murske Oy, 2014)
Lime, €· t^{-1}	30.8	(“Kalkkitaulukko, nopeavaikutteinen,” 2012)
Waste tax, €·t^{-1}	55	(Valtiovarainministeriö, 2014)
Landfill maintenance, €·t^{-1}	45[b)]	(Kymenlaakson Jäte Oy, 2015)

[a)] – value used by default, variation within 15–55 €· t^{-1} was studied within sensitivity analysis;
[b)] – value used by default, variation within 186–338 €· t^{-1} was studied within sensitivity analysis.

The results indicated that the use of ash in either of scenarios studied resulted in increased NPV. Herein, forest fertilization was the most favorable option with NPV increase of 58% compared to ash landfilling. The increase was primarily determined by avoided fertilizer cost and reduced need for fertilizer and limestone spreading in a forest stand. The NPV increase varied between 11-24% in other scenarios.

Detailed description of the CBA study could be retrieved from [NAME, DATE]. The study includes initial setting of the CBA study, describes the methodology applied, provides data used in the study, and shows overall results of the study.

9. RESULTS AND DISCUSSION

To provide an overall picture, the scenarios studied were compared against each other in terms of their environmental and economic performance. The results of weighted LCA and CBA studies for alternative scenarios are plotted in Figure 21. A horizontal axis depicts economic performance through the NPV value, whereas the impact on environment is presented on a vertical axis. The values are relative changes achieved when implementing certain scenario compared to residues landfilling.

As can be seen, none of the alternatives studied was superficial to others in terms of both environmental impact reduction and improved economic performance. At the same time, all scenarios resulted in increased NPV. Regarding environmental aspects, each scenario, except for Scenario 2 – Landfill construction, led to a reduced impact.

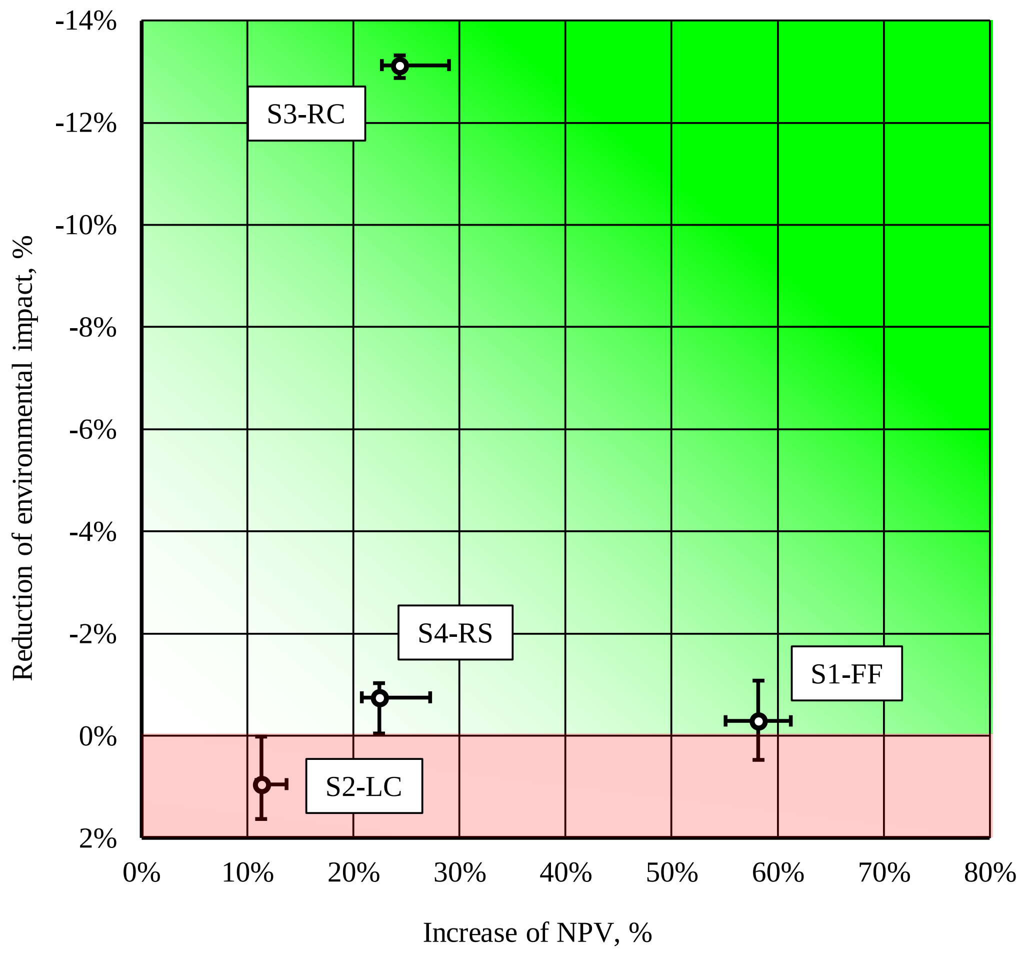


Figure 21: Combined LCA and CBA results of four alternative utilization methods for ash generated in the case-study area.

Environmentally, utilization of fly ash for construction of 11 km of roads resulted in the largest reduction of environmental impact by 13% compared to ash landfilling. First of all, the reduction was due to avoided emissions from substituted product acquisition and transportation. Moreover, utilization of ash requires less machinery compared to conventional road construction process. Finally, reduced leaching of toxic substances due to prevention of precipitation through a pavement layer did not increase the environmental impact as in other scenarios.

Utilization of same amount of fly ash to stabilize soil for construction of 3.8 km of roads resulted in reduced environmental impact by only about 1%. The difference in scenarios was due to methodological choices and different road structures. In scenario, global warming potential was reduced exceptionally compared to other scenarios. The reduction was determined by reduced carbon dioxide emissions from the production of lime substituted with ash.

Utilization of a mixture of fly and bottom ash for fertilization and neutralization of 17 600 ha of forest led to a slight reduction of environmental impact by 0.3%. The largest reduction was achieved due to avoided emissions from the production of commercial fertilizer. However, this scenario could also induce additional environmental impact if the input data for the model were uncertain.

Utilization of bottom ash and boiler slag for construction of 14.6 ha of landfills was the least favorable option with increased environmental impact of 1%. Even though the toxicological impact in the landfill construction scenario was lower than in scenario of forest fertilization and road stabilization, avoided impact from substituted product acquisition was significantly lower resulting in overall negative impact.

Economically, utilization of fly and bottom ash for forest fertilization and neutralization was the most favorable option with the NPV increase of 58%. The largest increase was caused by avoided fertilizer acquisition (21%) and spreading of fertilizer and limestone in a forest stand (34%). Moreover, the cost of ash granulation, transportation and spreading was lower than the benefit of avoiding commercial fertilizer and limestone acquisition and transportation resulting in overall positive change.

Regarding the results of the economic analysis for other scenarios, NPV increase ranged between 11% in scenario implying residues utilization for landfill construction to 24% in scenario where residues were used for road construction. When utilizing bottom ash and boiler slag for construction of 14.6 ha of landfills, 90% of the NPV increase originated from avoided landfilling of ash utilized in landfills construction. Moreover, the cost of ash transportation and additional cost of geofabric together were slightly higher than the benefit of avoided sand provision (11.5% of NPV change). Thus, the choice between sand and ash for landfill construction did not significantly affect the results of the economic analysis.

Similarly to landfill construction scenario, most of the overall NPV change in road construction and road stabilization scenarios (83–90%) resulted from avoided cost of ash landfilling. However, unlike in landfill construction scenario, the benefits of avoiding substituted materials acquisition and transportation (18.2–21.6% of NPV change) were remarkably higher than the additional cost of ash utilization (1.7–1.9% of NPV change), thus, making the choice of ash economically more feasible.

Segregation of cost-benefit analysis results enabled disclosure of cost and benefit categories, which exerted highest impact on the results. The cost of substituted products was mostly important in the forest fertilization scenario. The rest scenarios were dominated by avoided tax for landfilling and avoided cost of landfill maintenance.

The impact of the change of the transportation distance on both CBA and LCA results was studied. Analysis showed that the results were relatively robust to the change of the transportation distance in local, regional, and the case-study area wide scenarios. Therefore, if needed, a centralized collection system for ash could be installed either on a regional or case-study area-wide level without significantly undermining economic and environmental benefits.

Apart from economic and environmental applicability, the local demand on ash was studied. Considering forest fertilization, only 451 ha of forest was fertilized in 2013 with possible increase up to 2 255 ha to reach the average fertilization values practiced in Finland. However, the potential could be even higher provided that 39 236 hectares of forest was treated with fellings in the case-study area in 2013 and this area might can be fertilized to accelerate wood growth. In general, there was an upward trend in forest fertilization in Finland, so it can be assumed that the demand will increase in the future. Considering forest roads stabilization, 12 km of forest roads was built and 146 km renovated in the case-study area in 2013. Over last 13 years, there was a downward trend in the length of forest roads built, and an upward trend in the length of roads renovated. Therefore, it could be assumed that there will not be growing demand on ash for forest road stabilization in the future. Considering roads construction, a number of project is being developed and implemented in the case-study area. However, the majority of the projects is related to the improvement of currently exploited roads. No projects for roads construction was identified in the case-study area in the near future. Still, there might be significant potential in the construction of other earth works, such as parking areas, sports grounds, railway yards and roads in industrial areas. Yet, there is no centralized information available about projects for the abovementioned types of construction works. Considering landfills construction, it can be assumed that the demand will decrease in the future as the amount of waste being landfilled and consequently the number of landfills in operation is constantly declining throughout Finland.

10. CONCLUSIONS

In the study, several alternative utilization possibilities for ash generated in the case-study area of South-East Finland were studied. The alternative utilization methods were forest fertilization, road construction, road stabilization, and landfill construction. Life cycle assessment was used for environmental analysis of the utilization methods. Economic assessment was performed using the cost-benefit analysis methodology.

Even though none of the utilization methods proved to be both environmentally and economically sustainable, a significant reduction of environmental impact or increase of economic value is possible when implementing different alternatives. To optimize the recovery of ash generated in the case-study area, a recovery combination illustrated in Figure 22 should be favored. Where possible and legally acceptable, recycle fly and bottom ash for forest fertilization, which has strictest requirements out of all studied methods. If the quality of fly ash is not suitable for forest fertilization, then it should be utilized, first, in paved road construction, second, in road stabilization. Bottom ash not suitable for forest fertilization, as well as boiler slag, should be used in landfill construction. Landfilling should only be practiced when recycling by either of the methods is not possible due to legal requirements or there is not enough demand on the market.

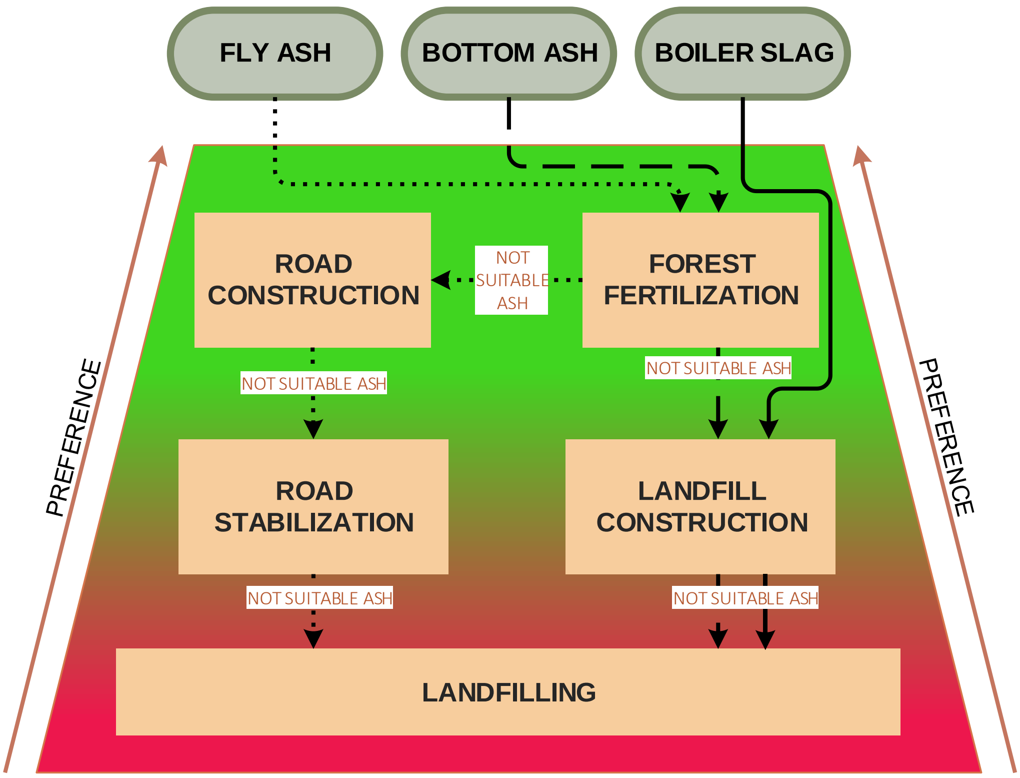


Figure 22. An optimal route for recovery of ash generated in the case-study area.

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ANNEX I: QUESTIONNAIRE SENT TO COMPANIES

1. Ash generating unit					
2. Amount of heat		GWh/a and electricity		GWh/a produced.	

3. Fuel used in the boiler and their shares are:

	share (mass-%/energy-%) (underline the unit used)
coal	
peat	
natural gas	
forest fuel	
wood residues	
bark	
sewage sludge	
RDF	
PDF	
other mixed fuels	
other, specify:	
-	
-	

4. Are the shares of fuels equal all year round? If not, how do they change and when?

5. Amounts of ash generated are:

2014	t/a (on dry basis)	up to 2013	t/a (on dry basis)	2015 and later	t/a (on dry basis)
fly ash		fly ash		fly ash	
bottom ash		bottom ash		bottom ash	
mixed ash		mixed ash		mixed ash	
boiler slag		boiler slag		boiler slag	
FBC ash		FBC ash		FBC ash	

6. How ash is stored?

fly ash is stored in		which have volume of	
bottom ash is stored in		which have volume of	
mixed ash is stored in		which have volume of	
boiler slag is stored in		which have volume of	
FBC ash is stored in		which have volume of	

7. How often ash is transported away?

fly ash		times/day,week,month,year (underline)	
bottom ash		times/day,week,month,year (underline)	
mixed ash		times/day,week,month,year (underline)	
boiler slag		times/day,week,month,year (underline)	
FBC ash		times/day,week,month,year (underline)	

8. How ash is transported?

fly ash is transported by		which have volume of	
bottom ash is transported by		which have volume of	
mixed ash is transported by		which have volume of	
boiler slag is transported by		which have volume of	
FBC ash is transported by		which have volume of	

9. Ash utilization.

fly ash is currently	
bottom ash is currently	
mixed ash is currently	
boiler slag is currently	
FBC ash is currently	

10. Other utilization possibilities assessed.

fly ash	
bottom ash	
mixed ash	
boiler slag	
FBC ash	

11. Description of current utilization possibilities (benefits, drawbacks, need for ash pretreatment)

Fly ash:

Bottom ash:

Mixed ash:

Boiler slag:

FBC ash:

12. Chemical properties of ash.

Composition: (wt-%/mass-%) (underline the unit used)

SiO2	
Al2O3	
Fe2O3	
CaO	
MgO	
MnO	
TiO2	
SO3	
Cl	
Na2O	
K2O	
P2O5	
LOI	

Concentration of trace elements (mg/kg dry matter)

	Content	Leaching (L/S= l/kg)
PCB		
PAH		
DOC		
As		
Ba		
B		
Cd		
Cr		
Cu		
Pb		
Hg		
Mo		
Ni		
Sb		
Se		
Sr		
V		
Zn		
F^-		
$SO4^-$		
Cl^-		

13. Physical properties of ash

Bulk density, kg/m3	
Particle density, kg/m3	
Water content, %	

Particle size distribution

sieve size, mm	comulative weight, %

14. Additional comments

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