TECHNICAL NOTE

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Memo no.	**1**
Titel	**Technical evaluation of future fly af options in Denmark**
Version	**1**
Prepared by	**CTR, TOH, YRZH, DLB**
Checked by	**TOH, CTR**
Approved by	**CTR**

1. Introduction

This memo is part of the project Future safe handling of waste incineration fly ash aimed at evaluating existing solutions available and producing a short list with the most promising and commercially viable solutions.

2. Methodology

The investigated technologies are mainly from the DRH technology evaluation, the ARC 2013 study on screening of possible treatment technologies, and presentations from this project kick-off meeting (12-03-2018).

The technologies are screened according to following properties:
Technology technical maturity
Technology commercial maturity
Material recycling

The technology maturity is estimated by technology readiness level (TRL) index. This is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the technology development chain, from blue sky research (TRL1) to actual system demonstration over the full range of expected conditions (TRL9). The TRL methodology was developed by Stan Sadin with NASA in 1974. Since then, the process has evolved and is used across a wide range of sectors including renewable energy.

Building on the work of NASA, the Australian Renewable Energy Agency (ARENA) developed a commercial readiness index (CRI), which is applied to complement the TRL by assessing the commercial maturity of technologies across six indicators. The CRI scale (1 to 6, with 6 being the highest level of commercial readiness) assesses a technology commercial readiness against a

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number of practical indicators, including the financial proposition, regulatory environment, industry supply chain and skills, market opportunities and vendor maturity (i.e. established companies with strong credit ratings). Pictorial representations of the TRL and CRI are shown in **Figure 1** and **Figure 2**.

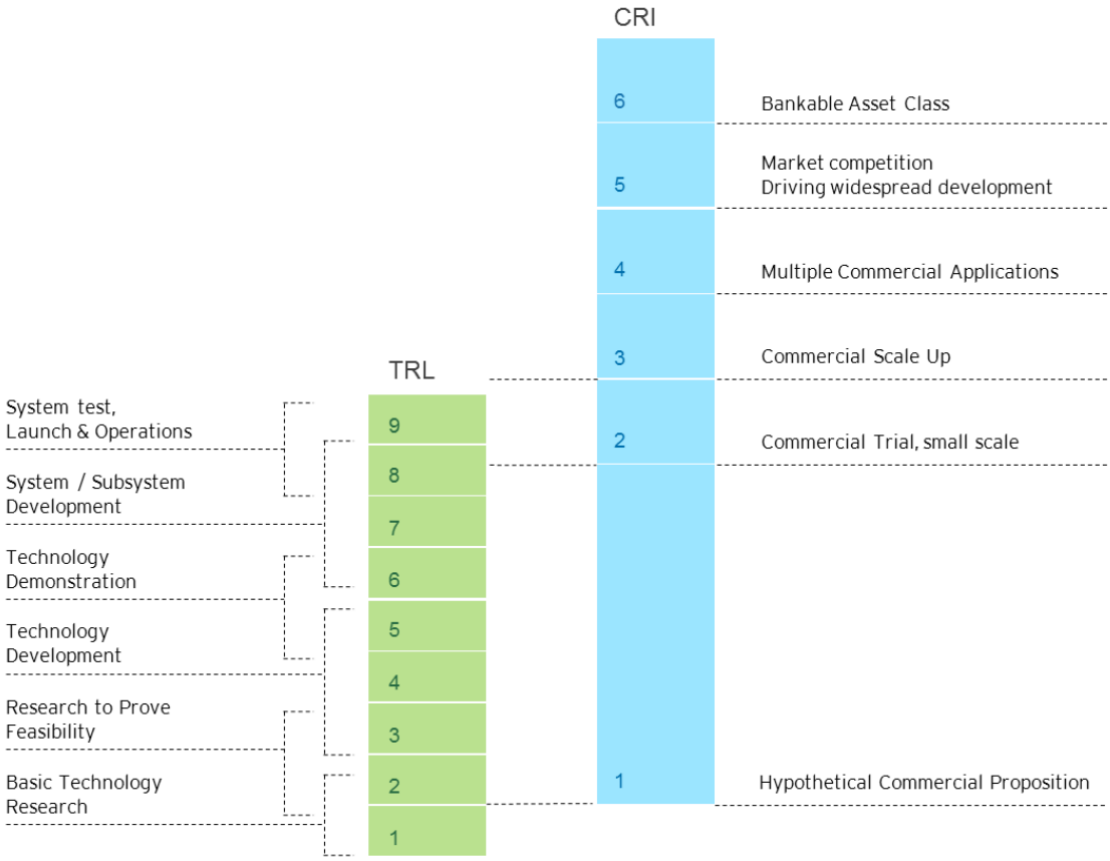

Figure 1. Pictorial representation of the TRL index and the CRI index.

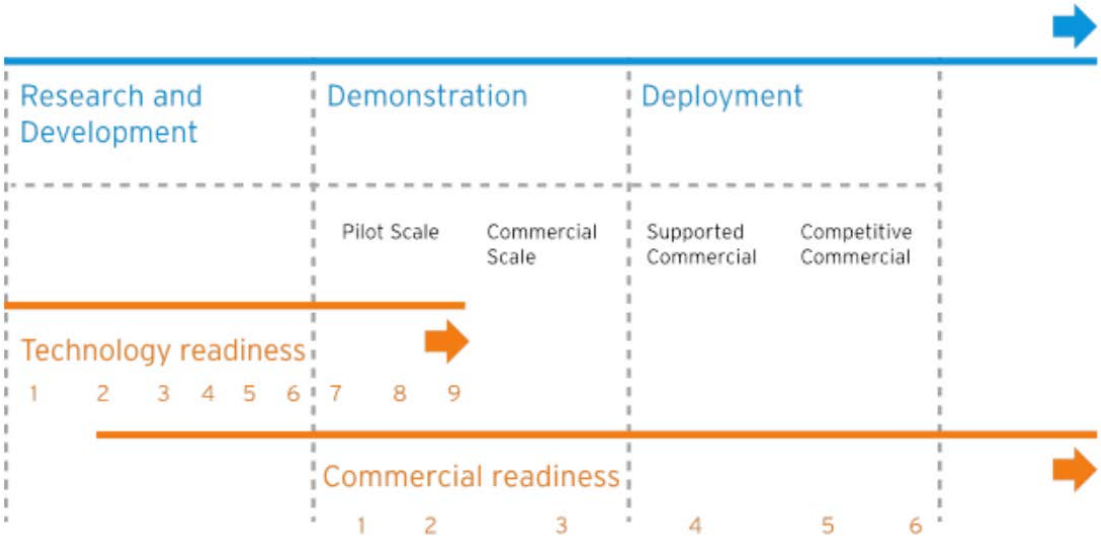

Figure 2. Pictorial representation of the TRL index and the CRI index in a development context.

Material recycling is defined as recycling of metals, salt and/or other material not ending at a landfill or final deposit site (recycling with a low degree of final landfilling). Hence the definition does not match the waste hierarchy definition of recycling, as it is more stringent. In the next phases of the project a more comprehensive definition of this criteria will be developed.

2.1 Criteria

The criteria below in **Table 1** are used when screening according to the three defined properties.

Table 1. The criteria used when screening according to the three defined properties

	Criteria	Minimum criteria
Technical maturity	TRL	TRL 8
Commercial maturity	CRI	CRI 3 within 5 years
Material recycling	Yes/no	Yes

The technical maturity must be almost fully developed with only few modifications on a sub-system level, corresponding to TRL 8. The minimum commercial maturity for solutions for further evaluation is that it is in commercial trial and that can be implemented in full scale within 5 years, corresponding to a CRI of 3.

In future following evaluations more properties will be evaluated and the optimal solution shall be a solution that is economically comparable to the current methods where the fly ash is disposed in Norway or Germany.

3. Screening of technologies

As a start point, a wide range of technologies for treatment of waste from incineration plant flue gas cleaning system are compared and evaluated in **Table 2**. The evaluation is based on available background literature. Since background literature used does not include the presentation of the evaluated IPU processes, descriptions of these processes are included in Appendix A.

The technologies evaluated include treatment of fly ash alone or in combination with sludge and/or gypsum. The grey columns evaluate the approximate mass distribution of treated fly ash outputs in categories related to the end fate. By purpose the methodology from the waste hierarchy is NOT used as it does not fit the purpose of this evaluation. TRL and CRI points are evaluated according to the ARENA method.

Table 2. Overview of the investigated waste incineration fly ash treatment processes.

Treatment method	Output relative to input (fly ash only)				Readiness evaluation		
	Metal/salt recycling	Materials substitution (building, road)	End-product ends at landfill site	Other treatment or discharge	TRL (scale 1 to 9)	CRI (scale 1 to 9)	To CRI 3 within 5 yr
IPU Electrolytic cell, with water washing, scenario A	1	1	60	38	3	1	No
IPU Electrolytic cell, with citric acid washing, scenario B	6	47	0	47	3	1	No
Extraction with microwaves	2	0	0	98	3	1	No
FLUWA/FLUREC	5	0	75	20	9	4	Yes
Filler in asphalt	0	10-60	0	40-90	9	2	Yes
Ferrox	0	0	85	15	6	1	No
Renova/Götaverken miljö	2	78	20	0	8	2	Yes
Solidification	0	0	100	0	9	4	Yes
Geopolymer	0	40-80	0-60	0-20	3	1	No

Treatment method	Output relative to input (fly ash only)				Readiness evaluation		
	Metal/salt recycling	Materials substitution (building, road)	End-product ends at landfill site	Other treatment or discharge	TRL (scale 1 to 9)	CRI (scale 1 to 9)	To CRI 3 within 5 yr
DHI-method	0	0	80	20	6	1	No
HALOSEP	33-53	0	47-67	0	7	1	Yes
Disposal in salt domes (e.g. German salt mines)[1]	0	0	100	0	5	4	Yes
Askepot	0-5	0	0	95-100	4	1	No
AshRock	0	0	100	0	9	4	Yes
INERTEC	0	0	100	0	9	4	Yes
Cement stabilization without washing	0	0	100	0	9	4	Yes
Cement stabilization with washing, LAB	0	0-80	0-80	20	8	2	Yes
Thermal stabilization	0	0	100	0	9	4	Yes
T.I.L	0	0	60-80	20-40	9	4	Yes
WesPhix	0	0	100	0	9	4	Yes
RedMelt, thermochemical treatment in arc furnace	8	87	0	5	4	1	No
CTU	0-5	0-100	0-100	0	3	1	No
Carbon8	0	100	0	0	9	4	Yes
NOAH, fly ash carbonation (existing stabilization process)	0	0	100	0	8	2	Yes
NOAH, road salt by evaporation	30-50	0	50-70	0	7	1	Yes

[1]: Ongoing development at the salt mines towards potential reuse of salts and Zn recovery

Since most of the technologies listed in **Table 2** do not meet the criteria of material recycling and are too far away from full-scale commercial application (CRI 3), the list is shortened using the screening criteria shown in **Table 1**. The shortlisted technologies are presented in **Table 3**. Present disposal at NOAH and German salt mines are included in **Table 3** as reference technologies. A brief description of the selected technologies is given below in section **Error! Reference source not found.**.

Table 3. Short list of waste incineration fly ash treatment processes based on defined screening criterias.

Treatment method	Output relative to input (fly ash only)				Readiness evaluation		
	Metal/salt recycling	Materials substitution (building, road)	End-product ends at landfill site	Other treatment or discharge	TRL (scale 1 to 9)	CRI (scale 1 to 9)	To CRI 3 within 5 yr
Carbon8	0	100	0	0	9	4	Yes
FLUWA/FLUREC	5	0	75	20	9	4	Yes
Renova/Götaverken miljö	2	78	20	0	8	2	Yes
HALOSEP	33-53	0	47-67	0	7	1	Yes
NOAH, road salt by evaporation	30-50	0	50-70	0	7	1	Yes
NOAH, existing stabilization process	0	0	100	0	9	4	Yes
Disposal in German salt mines	0	0	100	0	9	4	Yes

4. Technology description and review

The short-listing of technologies was based on collected information in Appendix 1. A brief description of technologies selected for further analysis and environmental screening is prepared with factsheets for key numbers, installation reference, description of technical and commercial progress including possible continuing development needs.

4.1 Carbon8

Carbon8 is an English solution developed by a spin-off company Carbon8 Systems from the University of Greenwich. Carbon8 Systems is the first company to use Accelerated Carbonation Technology which is a treatment for industrial wastes and contaminated soils with carbon dioxide. Carbon8 Systems has licensed the technology to Carbon8 Aggregates to treat air pollution control residues from waste incineration plants and produce lightweight aggregate.

Many thermal wastes react with carbon dioxide and, if the reaction conditions are carefully controlled, this reaction can be accelerated, taking place in minutes rather than months or years and resulting in the formation of artificial limestone. During the process, significant volumes of carbon dioxide are permanently captured as stable carbonates. The growth of the carbonates chemically stabilizes and encapsulates contaminants reducing the pH of the system and locking up heavy metals.

A straightforward process flow diagram of the Carbon8 process is shown in Figure 3. The process comprises three stages:

1. Carbonation treatment of the air pollution control residues
2. Blending with reagents
3. Pelletizing/curing

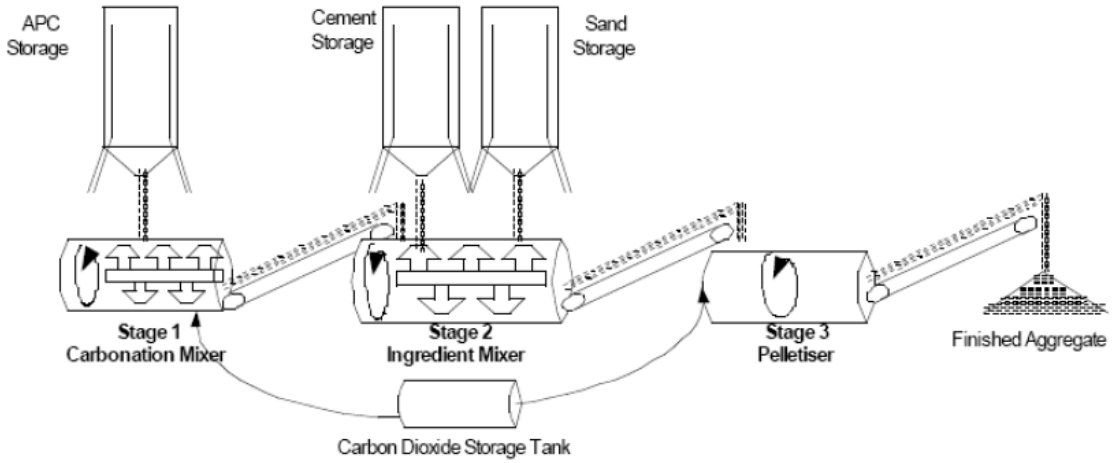

Figure 3 - Process flow diagram of the Carbon8 process.

The process involves blending the wastes with different reagents, including:

- Binder such as Portland cement
- Filler such as sand
- Water
- CO_2

Air pollution control residues and cement are fine powders and can be delivered to site in standard powder tanks and stored in the silos. Sand can be delivered by tipper lorry and/or loading shovel, where it will be placed in an initial receiving hopper for conveying into the process building. Carbon

dioxide can be delivered by liquid tanks and stored in a tank or from a nearby carbon capture facility.

Three mixers are used in series to physically and chemically process the materials, changing their characteristics and properties, converting from fine powders into hard rounded pellets, suitable as replacement aggregate in concrete blocks. CO_2 is added to both stage 1 carbonation mixer and stage 3 pelletizer/mixer.

A quality control for the incoming air pollution control residues shall be carried out to check the percentage of reactive lime within each batch of materials as the mix design is dependent on these levels. The reactive lime will be a mixture of hydrate lime ($Ca(OH)_2$), quick lime (CaO), and a small amount of $CaCO_3$, totaling around 25-30% of the residues. The amount of water added to allow carbonation to take place shall be carefully controlled.

The resulting aggregate has captured more carbon dioxide than that is used in the energy required in its manufacture resulting in carbon negative aggregate.

The carbon8 aggregate properties for block production are given in Table 4.

	Unit	Value
Particle size	mm	0-15
Dry loose bulk density	kg/m^3	950-1100
Particle density	kg/m^3	1.94
Crushing resistance	N/mm^2	5.2-6.6
Moisture content as delivered	wt%	8
Water absorption	wt%	18.8
Water soluble chloride	wt%	4.2
Water soluble sulphate	wt%	0.1
Total sulphate (as SO_3)	wt%	1.78

Table 4 – Properties of Carbon8 aggregate for block and concrete production.

The leaching rates in accordance with EN12457 are given in Table 5.

	Sb	As	Ba	Cd	Cr	Cu	Pb	Mo	Ni	Se	Zn
Max.	0.06	0.5	50	0.04	1.5	0.15	0.5	1.0	0.4	0.1	3.5
Aver.	bdl	0.05	17	bdl	0.5	bdl	0.1	0.2	0.03	0.06	0.26

Table 5 – Carbon8 aggregate leaching rates in accordance with EN12457 in mg/kg. bdl= below detection limit, Max=specification agreed with the Environment Agency in UK, Aver= average levels for Carbon8 aggregate.

However, previous study showed that release of soluble salts, such as SO_4, Cl, was reduced after fly ash carbonation, but is still higher than the landfill acceptance limits for hazardous waste. Although the carbonation reaction also led to a significant reduction of lead mobility, but the cadmium release was increased.

The process is in commercial application since 2012 and there will be three plants in the UK from July 2018. The process has a high material recovery rate; however, it might depend on the national laws regarding the heavy metal leaching rate etc. Although commercial liquid CO_2 is used for aggregate production in the reference plants, more successful and widespread application of

this technology requires readily available, low cost CO_2, such as CO_2 from a nearby carbon capture facility.

Waste incineration fly ash can absorb up to 20% CO_2. However, commercial liquid CO_2 is expensive, and the consumption must be minimized. Approximate 7-10% CO_2 is enough to stabilize the metals and solidify the product. When CO_2 from flue gas carbon capture process or point sources such as cement plant is applied, more CO_2 can be added with an extra benefit of carbon capture.

Further research/development needs of the Carbon8 process include:

- Demonstration direct CO_2 capture from flue gas as CO_2 source for the Carbon8 process
- Optimization of CO_2 usage and avoiding CO_2 release to atmosphere
- Optimization of CO_2 uptake by the fly ash and aggregate
- Optimization of current aggregate products for different applications
- Investigation of the produced aggregate leaching rate

Key facts

Treated waste fraction	Fly ash from waste incineration plant
Metal or salt recycling	no
Materials recovery (building, road)	100%, for block and concrete production
End-product disposal and not recycled	no
Required other treatment or salt discharge	no
CO_2 capture	Yes, 7-10%
Quantity reduction for disposal	100%
Development stage	Full-scale, commercially available
Technology readiness level (TRL)	9
Commercial readiness index (CRI)	4
Possible CR3 within 5 years	Yes
Commercial installation	Brandon 2012 and 2014, Avonmouth 2016, Leeds 2018

Table 6 – Key facts of Carbon8 process.

4.2 FLUWA / FLUREC

FLUWA and FLUREC are swiss solutions with high technical and commercial maturity. The acidic fly ash leaching FLUWA process has been established in Switzerland since 1997. Within the FLUWA process (see Figure 4), the fly ash is leached with both acidic and neutral scrub water in a multistage cascade. Prior to fly ash leaching, mercury dissolved in the acidic and neutral scrub water is separated by selective ion exchanger. The extractability of heavy metals is mainly depending on the alkalinity of the fly ash, acidity of the scrub water, liquid to solid ratio, redox potential, temperature and leaching time. The addition of an oxidizing agent such as hydrogen peroxide (H_2O_2) during fly ash leaching keeps the redox-sensitive metals in solution.

The addition of an oxidizing agent further converts Fe^{2+} to Fe^{3+} which precipitates as Fe-hydroxide and is accumulated in the remaining filter cake. Removing Fe from the extract solution is important when metal recovery is extended by the FLUREC process that is very sensitive to impurities. Another process going on during leaching is the formation of gypsum ($CaSO_4 \cdot 2H_2O$) due to the reaction of dissolved calcium (Ca^{2+}) from the fly ash and sulphate (SO_4^{2-}) from scrub water.

After ca. 60 min of extraction, the suspension is separated by vacuum belt filtration into a metal depleted filter cake and a metal enriched filtrate solution. The washed filter cake is recirculated to

the combustion chamber to assure dioxin destruction, afterwards utilization or landfilling together with the slag.

The metalliferous filtrate is fed to a waste water treatment plant. To transform the dissolved metals into metal hydroxide precipitates, lime is added to the metalliferous filtrate until the ideal pH-value for precipitation of 9.5 is reached. The metal precipitate is then filtrated and pressed into a metal hydroxide sludge with a dry mass of 17-35%, depending on filter system used. This sludge is then exported abroad, and the metals are recovered in smelting plants (FLUWA process) or used for direct metal recovery (FLUREC process).

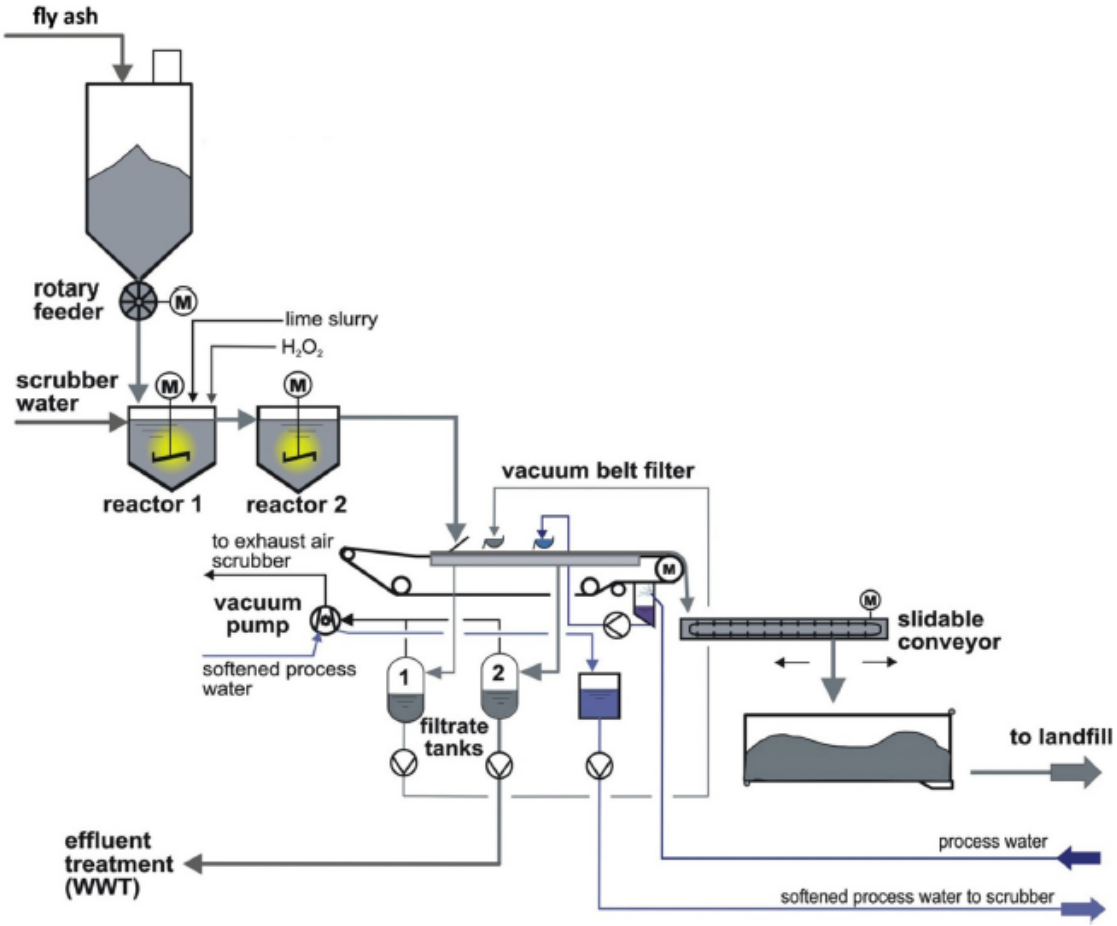

Figure 4 - Flow diagram of the FLUWA process.

The FLUREC process offers a possibility for recovering high-purity zinc (>99.99%) from the heavy-metal enriched filtrate coming directly from the FLUWA process. In the FLUREC process (see Figure 5), lead, copper and cadmium are separated from the filtrate by a cementation process. Thereby Zn powder is added to the filtrate as reducing agent and metals more noble than Zn are separated as metallic cementate which is then filtered. The cementate can be sent to a Pb smelter where the remaining heavy metals are also recovered in the Pb production process.

The Zn in solution is separated selectively from the pre-purified filtrate in a solvent extraction step. For this purpose, the Zn is trapped by a water-insoluble organic complexing phase. The complexation of the Zn is strongly pH dependent and at low pH (pH 2.7-3), 99.5% of the Zn is complexed by the organic phase. In a following washing step, other metals complexed by the organic phase are separated to reduce interferences in the subsequent electrolytic zinc recovery process. The complexed Zn is then transferred to solution again using diluted sulphuric acid where a high-purity zinc sulphate solution is obtained. This solution is then used in a final electrochemical

process where Zn is separated from the solution by applying an electrical DC potential and deposition on an aluminum cathode. The recycled Zn metal is sold on the market.

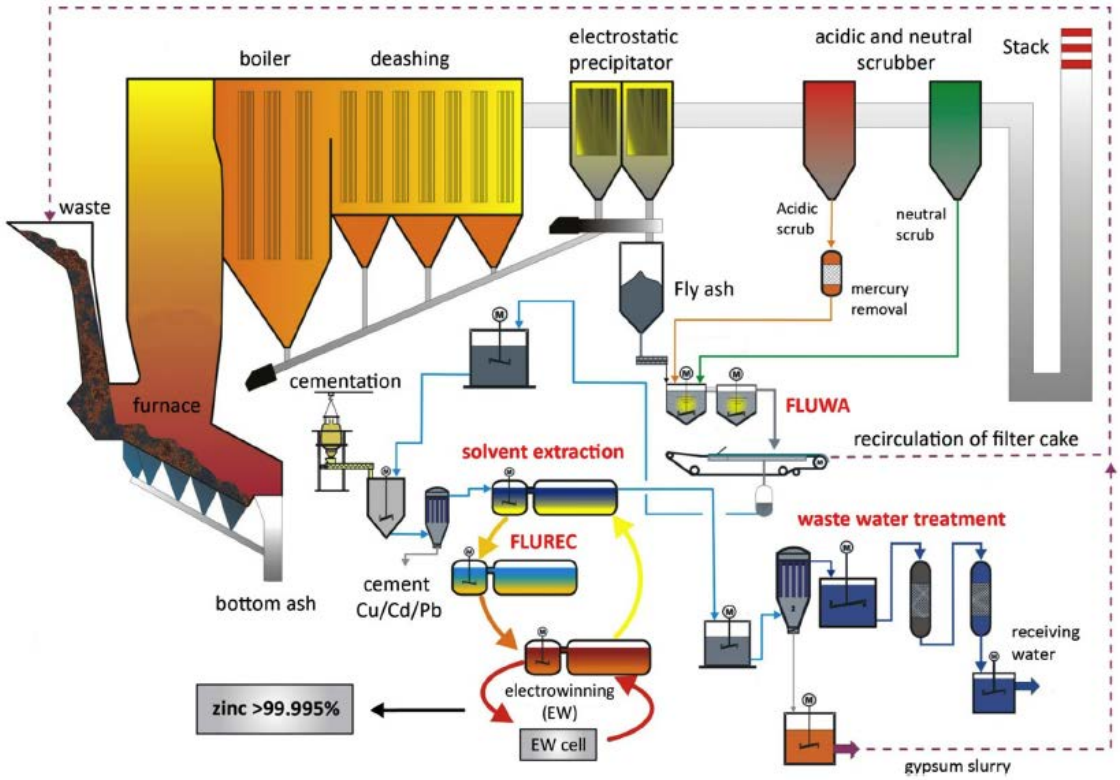

Figure 5 - Flow diagram of the FLUREC process.

The declared extraction yields of different metals from waste incineration fly ash are shown in Table 7.

Metal	Unit	Value	
		Acidic leaching (FLUWA)	Optimized acidic leaching (FLUWA+H_2O_2)
Cadmium (Cd)	%	60-85	85-95
Copper (Cu)	%	0-30	40-80
Lead (Pb)	%	0-30	50-90
Zinc (Zn)	%	60-80	60-80

Table 7 – Typical extraction yields of the FLUWA process.

The material recovery rates of the processes are relative low as majority of the ash still need disposal and further treatment is required. The main condition for implementation of the FLUWA/FLUREC process at a waste incineration plant is that the plant is equipped with a wet flue gas cleaning system.

Key facts

Treated waste fraction	Fly ash from waste incineration plant, scrubber water
Metal or salt recycling	5%, Zn recovery
Materials recovery (building, road)	no
End-product disposal and not recycled	75%
Required other treatment or salt discharge	20%
CO_2 capture	no

Quantity reduction for disposal	25%
Development stage	Full-scale, commercially available
Technology readiness level (TRL)	9
Commercial readiness index (CRI)	4
Possible CR3 within 5 years	Yes
Commercial installation	Mainly in Switzerland, about a dozen plants including one FLUREC plant, treating >60% of incineration fly ash in Switzerland

Table 8 – Key facts of FLUWA/FLUREC process.

4.3 Renova/Götaverken miljö

Swedish municipally owned waste management company Renova and engineering company Götaverken Miljö are developing a technology to recover zinc from incinerator fly ash. The technique washes fly ash with dilute hydrochloric acid obtained from a wet flue gas scrubber. Acidic leaching of the fly ash decreases the heavy metal content in the fly ash.

The method also allows fly ash to be returned to the furnace so remaining organic pollutants such as dioxins can be destroyed. A back delivery of the acid washed fly ash to the furnace results in a transformation to bottom ash.

The pilot-scale tests for leaching and washing fly ash have been performed at the Renova Waste-to-Energy plant in Sävenäs, Sweden in 2016. A sketch of the pilot leaching process facility at Renova incineration plant is shown in Figure 6. For future full-scale installation the acidic scrub water will be treated by a mercury selective ion exchanger before feeding to the fly ash slurry preparation tank. Further treatment of the zinc liquid in the precipitation and filtration set-up is illustrated in Figure 7.

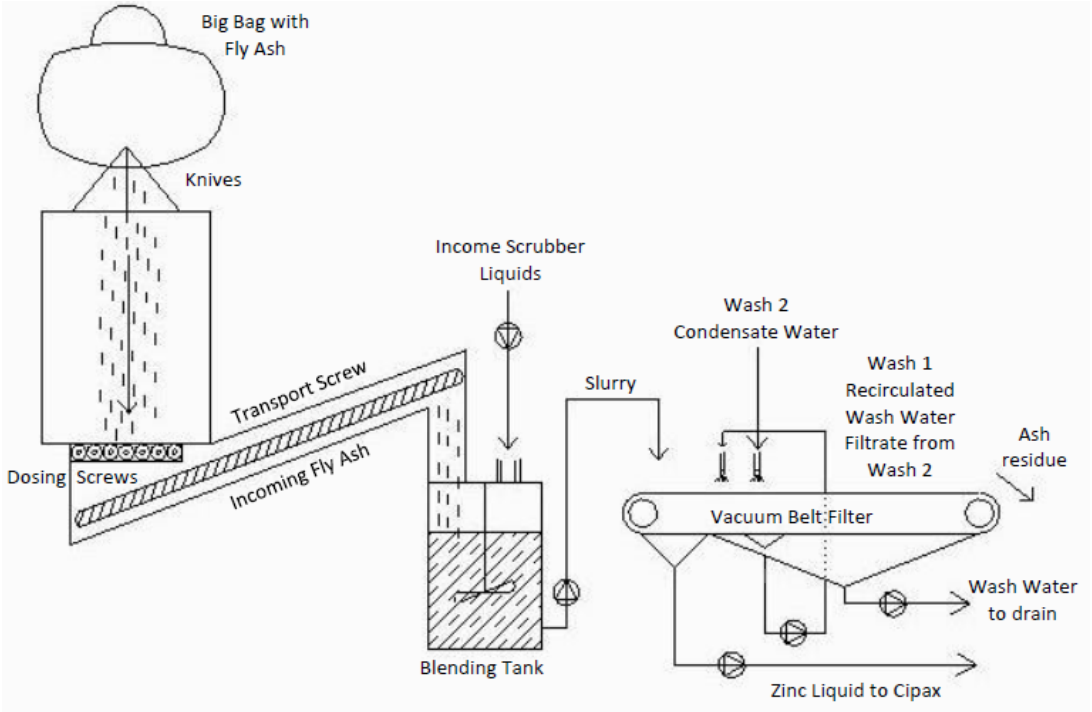

Figure 6 - Sketch of the pilot fly ash leaching facility at Renova incineration plant.

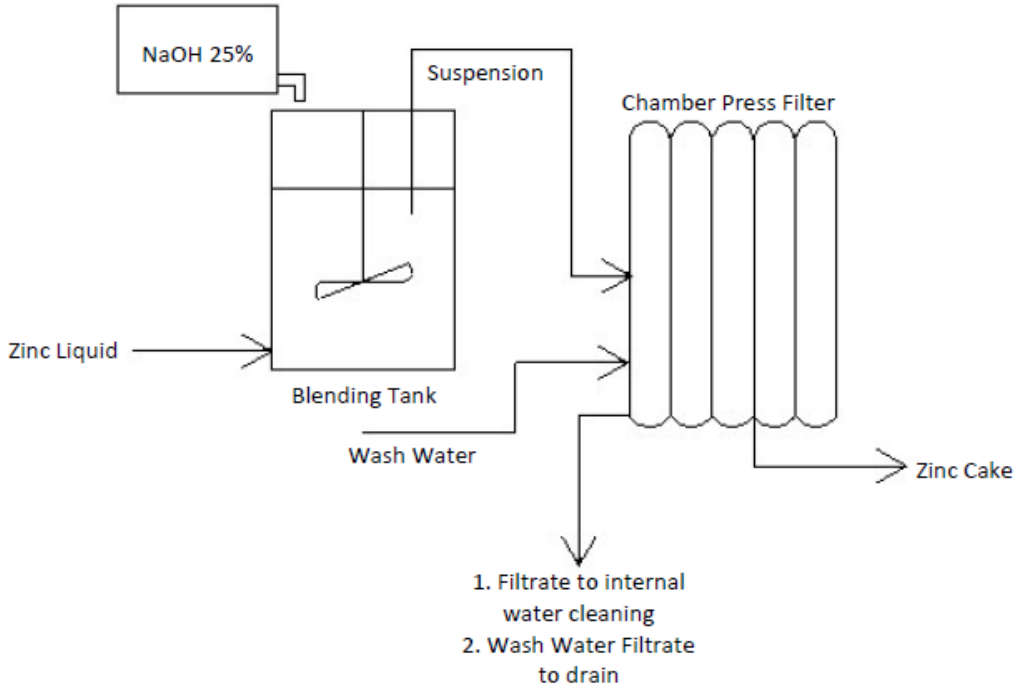

Figure 7 - Set-up for precipitation and filtration of zinc liquid.

About 70% of the zinc in the fly ash could be leached and recovered. However, the produced zinc cake contains impurity such as other metals and chlorine and shall be further treated for high purity zinc production. Part of the filtrate shall be treated in a wastewater treatment plant before discharge.

The washed fly ash has been incinerated in full scale trials, converting fly ash to bottom ash. Approximate 90% of the recycled fly ash is converted to bottom ash with the remaining 10% as fly ash. To avoid high concentration of heavy metals in the fly ash due to thermal treatment of washed fly ash in the furnace, about 30% of the washed fly ash, corresponding to 20% of the un-treated fly ash shall not be recycled back to the furnace. Therefore about 80% of the fly ash disposal can be avoided. The process is evaluated with a TRL 8 and CRI 2. It is expected that the process can be commercially available in relative short time.

Prerequisite for recycling the treated fly ash into the furnace is that there is not too much lime in the fly ash, as the salts will then be bound in the lime and washed out to a high extent. Thus, the Renova fly ash treatment process is not applicable to incineration plant with a dry flue gas cleaning system.

Key facts

Treated waste fraction	Fly ash from waste incineration plant, scrubber water
Metal or salt recycling	2%, Zn recovery
Materials recovery (building, road)	78%, converted to bottom ash
End-product disposal and not recycled	20%
Required other treatment or salt discharge	no
CO_2 capture	no
Quantity reduction for disposal	80%
Development stage	Pilot-scale
Technology readiness level (TRL)	8
Commercial readiness index (CRI)	2

Possible CR3 within 5 years	Yes
Commercial installation	no

Table 9 – Key facts of Renova and Götaverken Miljö process.

4.4 HALOSEP

HALOSEP is a Danish solution developed to remove/recover chlorine from air pollution control residues generated in waste incineration plants equipped with a wet and/or semi-dry flue gas cleaning system, while the leaching properties of the treated solids comply with the EU landfill acceptance criteria.

Besides the recovery of chlorine, the process allows for concentrating of, especially Zn in the form of a filter cake which can be processed at Zn-smelters. Finally, since a large part of solids transforms into recyclable products, the landfilled quantity decreases. More specifically, HALOSEP is based on washing/neutralization of the alkaline fly ash using acidic scrubber liquid generated during the flue gas cleaning at incineration plant equipped with a wet flue gas cleaning system. Typically, the residues from a wet system consist of dry fly ash collected in electrostatic precipitator(s), which may sometimes be mixed with a metal containing sludge from the neutralization of scrubber liquid.

Figure 8 depicts the HALOSEP process, where fly ash reacts with the hot scrubber liquid coming directly from the HCl-scrubber, thereby forming a salt brine, water, CO_2(g) and neutralized/washed fly ash.

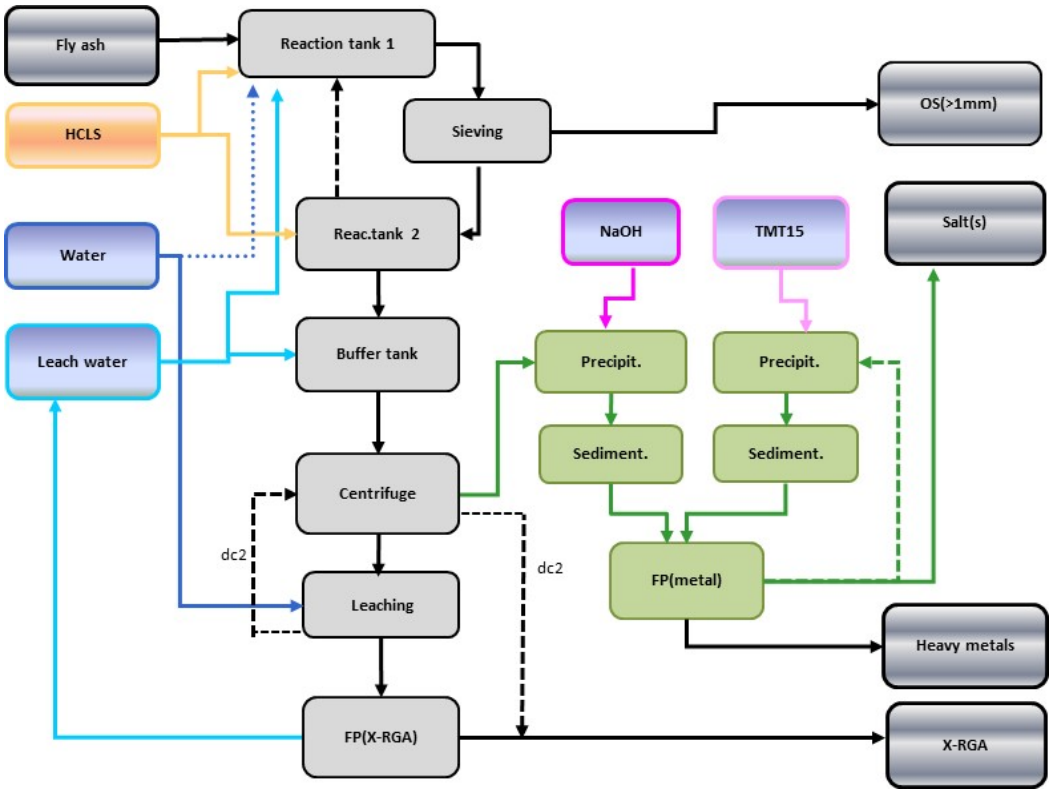

Figure 8 - Process diagram of the pilot HALOSEP process.

The salt brine is purified by a two-stage precipitation, yielding a salt product and a metal filter cake. In the end, the treated fly ash (X-RGA) has significantly improved leaching properties owing to the removal of salts and lowered pH, while its mass is reduced compared with the incoming fly ash amount.

Air pollution control residues generated from a semi-dry system (mixture of fly ash, neutralization products from scrubber and baghouse filter ash) can also be treated with HALOSEP. However, an external supply of the acidic scrubber liquid must be ensured since it is not produced in the semi-dry system. Like the treatment of fly ash, the air pollution control residues react with the acidic scrubber liquid while both fly ash and the surplus lime present in the residues are utilized in the neutralization reaction; outputs from the process are the same.

As shown in Figure 8, there are four output streams (excluding water and CO_2(g)): treated solids (X-RGA); salt products; metal filter cake/heavy metals; and an oversize (>1 mm) fraction. Note that water and CO_2(g) generated in the neutralization reaction account for 5–12% of the overall outputs (see Table 10).

	Output	
	Wet flue gas cleaning	Semi-dry flue gas cleaning
Treated fly ash/residues (X-RGA)	60-61%	40-48%
Salt product	25-30%	42-50%
Metal product	~3%	~2%
Oversized fraction >1mm	~1%	~1%
H_2O and CO_2(g)	5-8%	8-12%

Table 10 – The weight distribution of different output/process streams in HALOSEP achieved during treatment of fly ash from plant with wet flue gas cleaning system and residues from semi-dry flue gas cleaning.

HALOSEP treatment reduces the quantity of dry residues which need to be landfilled by ≤40% (fly ash) and by ≤60% (residues). Currently, the leaching of As, Ba, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn, chloride, fluoride, sulfate, and dissolved organic carbon (DOC) from treated solids complies with the European leaching limit values for acceptance at landfills for hazardous waste while Stena Recycling A/S is working on improving the leaching of Sb, which would allow for the treated fly ash to be accepted at landfills receiving stable, non-reactive hazardous waste.

Salt products generated by treatment of fly ash and residues correspond to respectively 25–30% and 42–50% by weight of the incoming solid. Different salt products can be generated by HALOSEP based on available management options: brine (10–15%) – currently intended for liquid road salt (Option A) and salt-water (Option B). It is possible to switch between Option A/B without modifying the process based on the actual demand. In winter periods Option A is better, while in summer periods Option B (discharge to a wastewater treatment plant) may be preferred. Approximately 99% of the dry matter content of the salt product
is composed of a mixture of $CaCl_2$, NaCl, and KCl. In addition, 0.5–1% of the dry matter content is composed of $CaSO_4$ and $MgSO_4$. The content of toxic metals in the brine for de-icing is below the limit values for de-icing agents set by CEN TC 337WG1. However, it has not been possible to find similar data for any commercial road salt products.

The amount of the metal filter cake generated by HALOSEP corresponds to approximately 2–3% by dry weight of the incoming solids. It is possible to wash and dry the filter cake to reach a Zn content of 38–40%, which makes it feasible to send the material for recovery at zinc smelters. On the other hand, the filter cake generated by treatment of residues from semi-dry system shows a much lower Zn content (7–10%) and, consequently, the recycling potential of this fraction is limited from an economic point of view.

The oversize fraction, corresponding to <1% by weight of the incoming solids, has a total organic carbon (TOC) of 4-10% and is sent back for incineration.

An evaluation on whether the concentrations of substances in the washed ash leads to a classification of the ash as hazardous waste according to the Danish ordinance on waste "Affaldsbekendgørelsen" BEK 1309 (Ref. 4) has been done. It was found that washed fly ash from the wet flue gas cleaning system should be classified as hazardous waste according to BEK 1309 due to an average Lead (Pb) content of 6.550 mg/kg. The limit Lead (Pb) value for classification of waste as hazardous waste is 5.000 mg/kg. It was also found that washed residues from the semi-dry flue gas cleaning system should be classified as mineral waste according to BEK 1309 due to a lower average Lead (Pb) content of 4.350 mg/kg.

Vestforbrænding and Stena are preparing a full-scale test at Vestforbrænding incineration plant in 2019. Once the successful full-scale demonstration is obtained, the process can be commercially available in relative short time.

Key facts

Treated waste fraction	Fly ash/residues from waste incineration plant, scrubber water
Metal or salt recycling	2-3% for metal, 25-50% for salt
Materials recovery (building, road)	no
End-product disposal and not recycled	40-60%
Required other treatment or salt discharge	no
CO_2 capture	no
Quantity reduction for disposal	40-60%
Development stage	Pilot-scale
Technology readiness level (TRL)	7
Commercial readiness index (CRI)	1
Possible CR3 within 5 years	Yes
Commercial installation	One full-scale demonstration will be installed at Vestforbrænding incineration plant

Table 11 – Key facts of HALOSEP process.

4.5 NOAH road salt by evaporation

The existing NOAH process is based on formation of a gypsum containing product by mixing of residues, water and acid. The residues are suspended in water, and then mixed with waste sulphuric acid and lime at a pH of about 5-7. At this point gypsum precipitates. Finally, pH is increased to around 8-10 by addition of hydrated lime. Heavy metals are co-precipitated with gypsum, which is landfilled.

In present NOAH fly ash handling facility (see Figure 9), the remaining brine contains salt leached from the fly ash and is pumped through a water treatment plant including a sand- and carbon filter, with the aim to remove remaining particles and dissolved organic carbons. After the water treatment the brine is today discharged to Oslo Fjord.

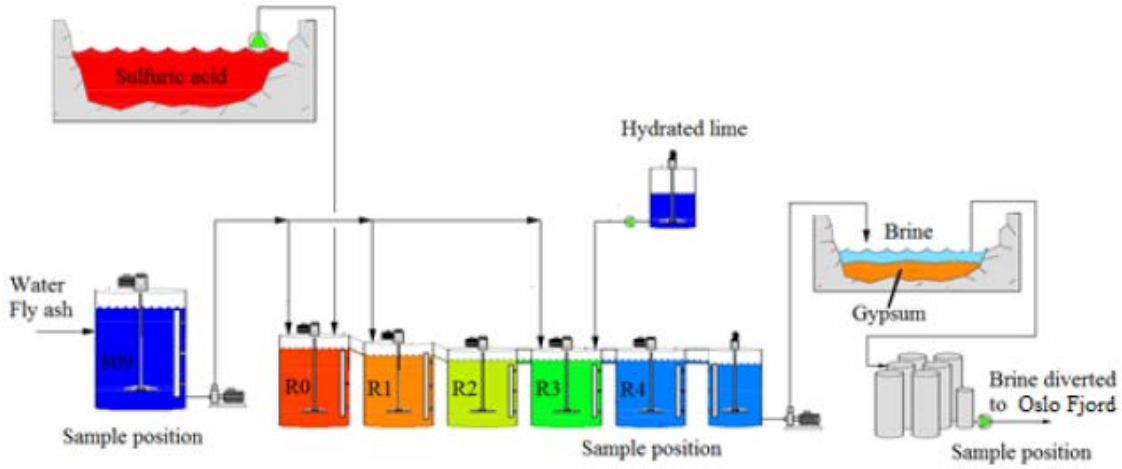

Figure 9 - Simplified flow sheet of the present NOAH process on Langøya.

In cooperation with Chalmers University of Technology, NOAH studied a process based on evaporation of brine for salt recovery from waste incineration fly ash in pilot scale. Ash samples were extracted from three various positions (see Figure 9), fly ash slurry preparation tank 809, R4 tank and brine discharge to Oslo Fjord) in the Langøya process and samples salt solutions were generated from these ash samples. The slats have been dried and crystallized by evaporating the water in the brine. Among the three different samples, only sample with fly ash mixed with sulfuric acid (from R4 tank), the concentrations of toxic metals in the recovered salt are within the limits for road salt in Scandinavia.

The salt extracted from all the samples is a mixture of mainly $CaCl_2$, KCl and NaCl. A small part is $MgCl_2$. Today most of the salt used for de-icing is NaCl, mainly because of the low price. Other salts are also used sometimes for de-icing and $CaCl_2$ and $MgCl_2$ are also used for dust control of gravel roads. A mix of different salts is used sometimes but there are still regulations for the proportions of different salts. The salts extracted from Langøya are not totally within these limits.

There are two ways to solve this problem. One way is to add specific salts to reach the right proportions for the blend. The other way is to separate the different salts from each other. This can probably be done during the crystallization process.

The NOAH facility on Langøya is expected to be fully utilized within a few years and NOAH is working on establishing a new facility in Brevik. The future facility in Brevik will be located close to Norcem AS, which is a cement factory and produces cement, but also waste heat that could eventually be used to evaporate the water from the brine in NOAH's further facility. NOAH has initiated research to recover salt as road salt from the brine using waste heat from the Norcem cement plant.

This cement plant is today emitting waste heat in terms of flue gas. The temperature of the flue gas leaving the furnace is around 380°C. This flue gas is then quenched with water to a temperature around 230°C before it is routed the atmosphere. Both 380°C and 230°C flue gases have been investigated whether it is possible to use this heat source for crystallize salt from the brine.

For the brine generated from fly ash slurry preparation vessel 809, two evaporation and crystallization processes have been designed. The concentration of salts in the brine extracted from vessel 809 is 17 wt%. Two different Heat recovery steam generators (HRSG) were designed, one using flue gas with a temperature of 230°C (Figure 10) and one using flue gas with a temperature of 380°C (Figure 11). By this, saturated steam can be generated at two different pressures.

The salt is not totally dried in the multiple evaporation facility. The concentration is increased to 90 wt% anhydrous salt. The remaining water must be removed in a rotary drier. However, the salt extracted from vessel 809 contains $CaCl_2$ with crystallized water, which means that the final product still contains 7 wt% water molecules. This means that the final product out from the rotary drier contains 93 wt% anhydrous salts.

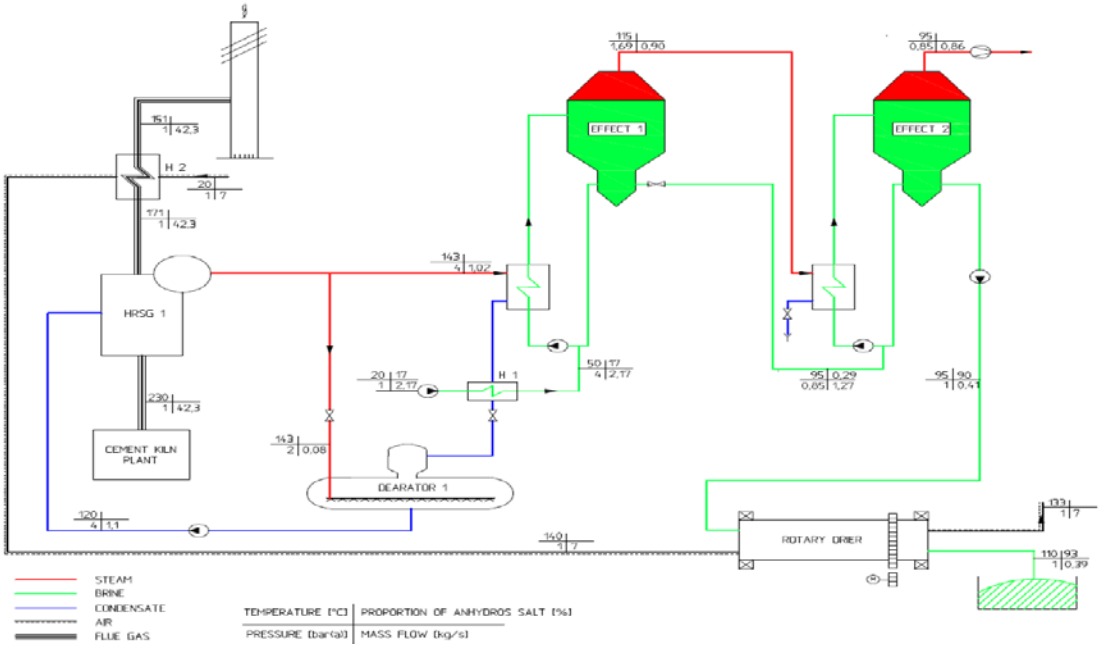

Figure 10 - Flow diagram of NOAH brine evaporation process using 230°C flue gas.

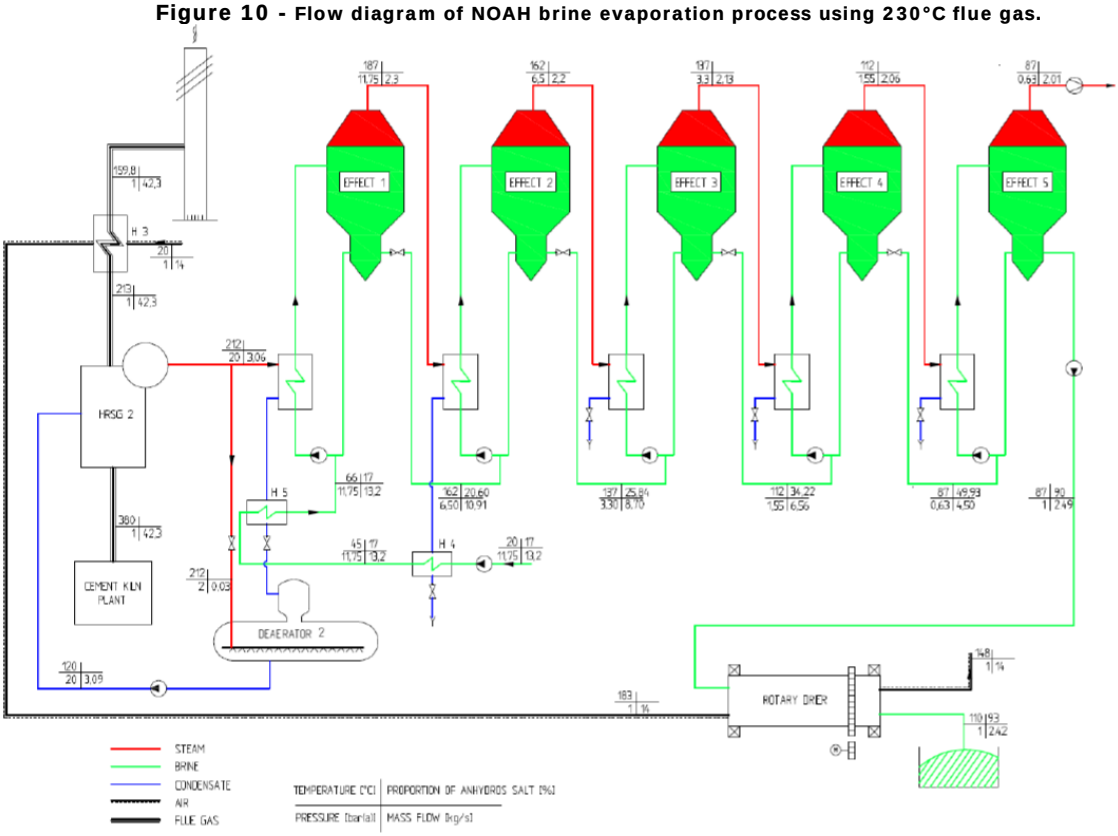

Figure 11 - Flow diagram of NOAH brine evaporation process using 380°C flue gas.

The performance of the two process is summarized in Table 12.

	Unit	Low temperature process (230°C)	Low temperature process (380°C)
Number of effects		2	5
Flue gas energy usage	MW	2.5	7.0
Inert mass flow of brine (17 wt% anhydrous salt)	ktonnes/year	62.5	380.2
Outlet mass flow (93% anhydrous salt)	ktonnes/year	11.2	69.7
Evaporated water	ktonnes/year	50.7	308.2
Efficiency of evaporation	kg product/MJ flue gas	0.2	0.3

Table 12 – Comparison of the NOAH low- and high temperature brine evaporation processes.

In a multiple effect evaporator there are also possibilities to separate different salts from each other, which can be desirable. If the different salts are separated from each other, KCl can be used for production of fertilizer for the agriculture. There is a company that has succeeded to separate salts, with similar compositions, from each other, which prove that this is possible (Ragn-Sells, 2016). There are still some areas, which need to investigate in more detail before a complete concept can be presented.

NOAH has recently initiated a feasibility study including partners from several Nordic waste incineration plants to recover salt from brine previously discharged in their process. The investigated process including following steps:

- Brine and solids are separated by a filter press
- Brine is cleaned for contaminations such as heavy metals, sulphate and ammonia
- Brine is concentrated from 12-15% salt content to 26%
- NaCl and KCl crystallize, are separated and dried
- $CaCl_2$ is concentrated to 60-70% with the help of steam
- $CaCl_2$ crystallizes to either granules or flakes and is dried

Key facts

Treated waste fraction	Fly ash from waste incineration plant
Metal or salt recycling	30-50% for salt
Materials recovery (building, road)	no
End-product disposal and not recycled	50-70%
Required other treatment or salt discharge	no
CO_2 capture	no
Quantity reduction for disposal	30-50%
Development stage	Pilot-scale, feasibility study
Technology readiness level (TRL)	7
Commercial readiness index (CRI)	1
Possible CR3 within 5 years	Yes
Commercial installation	no

Table 13 – Key facts of the NOAH road salt by evaporation process.

5. Process mass balance

For each technology, a mass balance for treating 1000 kg dry fly ash/residues will be presented. In addition, substance balances will be set up for the most important components assessed from both a resource and an environmental point of view. Based on the mass and substance balances set, it

is possible to make an initial assessment of the recycling potential of the individual technology. All mass balances are based on information gathered from literature.

The potential release of contaminant from the treated fly ash/residues to the environment can be evaluated from the mass balance and leaching of following substances:

- Easily soluble salts such as Cl and Na compounds. Although not toxic for humans in typical concentration levels these components may significantly affect ecosystems and spoil drinking water resources.
- Heavy metals and trace elements such as Cd, Cr, Cu, Ni, Pb, and Zn. Heavy metals and trace elements can potentially be present in concentrations harmful for humans as well as for ecosystems.
- Dionxins and furans. Although dioxins and furans do not easily leach, release of these contaminants is of major concern due to their toxicity.

For better comparison of the selected technologies, it is suggested to use common fly ash and scrubber water compositions. Actual tested ash and scrub water composition for each technology in the available reports are presented in this memo. The outputs with the common ash and scrubber composition for each technology will be assessed basing on the available data reported in this section

General compositions stated in text book:

Chandler, A.J., Eighmy, T.T., Hartlén, J., Hjelmar, O., Kosson, D., Sawell, S.E., van der Sloot, H.A., Vehlow, J., 1997. Municipal solid waste incinerator residues. International Ash Working Group (IAWG), Elsiever.

	Concentration (mg/kg)			
Element	**Bottom ash**	**Fly ash**	**Dry-/semi dry APC residues**	**Liquid APC residues**
Al	22'000 - 73'000	49'000 - 90'000	120'000 - 83'000	21'000 - 39'000
As	0.1 - 190	37 - 320	18 - 530	41 - 210
Ba	400 - 3'000	330 - 3'100	51 - 14'000	55 - 1'600
Ca	370 - 123'000	74'000 - 130'000	110'000 - 350'000	87'000 - 200'000
Cd	0.3 - 70	50 - 450	140 - 300	150 - 1'400
Cl	800 - 4'200	29'000 - 210'000	62'000 - 380'000	17'000 - 51'000
Cr	23 - 3'200	140 - 1'100	73 - 570	80 - 560
Cu	190 - 8'200	600 - 3'200	16 - 1'700	440 - 2'400
Fe	4'100 - 150'000	12'000 - 44'000	2'600 - 71'000	20'000 - 97'000
Hg	0.02 - 8	0.7 - 30	0.1 - 51	2.2 - 2'300
K	750 - 16'000	22'000 - 62'000	5'900 - 40'000	810 - 8'600
Mg	400 - 26'000	11'000 - 19'000	5'100 - 14'000	19'000 - 170'000
Mn	80 - 2'400	800 - 1'900	200 - 900	5'000 - 12'000
Mo	2 - 280	15 - 150	9 - 29	2 – 44
Na	2'800 - 42'000	15'000 - 57'000	7'600 - 29'000	720 – 3'400
Ni	7 - 4'200	60 - 260	19 - 710	20 – 310
Pb	100 - 13'700	5'300 - 26'000	2'500 - 10'000	3'300 – 22'000
S	1'000 - 5'000	11'000 - 45'000	1'400 - 25'000	2'700 – 6'000
Sb	10 - 43	260 - 1'100	300 - 1'100	80 – 200
Si	91'000 - 308'000	95'000 - 210'000	36'000 - 120'000	78'000
V	20 - 120	29 - 150	8 - 62	25 – 86
Zn	610 - 7'800	7'000 - 70'000	7'000 - 20'000	8'100 – 53'000

Figure 12 - Concentration ranges for different elements in incineration residues (Chandler, 1997). Liquid APC residues refer to scrub water from wet flue gas cleaning.

Semi-dry flue gas cleaning residues composition (Amagerforbrænding, 1996-2003):

Parameter	Average 1996	Average 1997	Average 1998	Average 1999	Average 2000	Average 2001	Average 2002	Average 2003	Enhed
CaO %	10,8	7,6	7,1	6,9	11,7	15,4	19,4	19,2	%
Calcium	253	228	225	223	260	293	330	290	g/kg DS
Cadmium	193	193	195	185	155	123	104	96	mg/kg DS
Lead	6167	6225	6575	6525	4925	3500	3925	3075	mg/kg DS
Arsenic	96	88	133	153	170	123	168	124	mg/kg DS
Mercury	4,6	16,7	13,8	16,0	20,0	15,3	16,9	15,3	mg/kg DS
Chloride	13,7	13,0	13,0	15,5	13,6	12,0	9,2	8,9	%
Total sulphur				21	15	37	14	12	g/kg DS
Dry Substance	98,4	98,6	98,8	98,5	97,3	95,5	97,4	98,0	%
Copper		1010	815	905	778	635	515	523	mg/kg DS
Chromium		107	108	106	148	89	88	85	mg/kg DS
Manganese		403	435	455	428	393	448	460	mg/kg DS
Nickel		38	47	44	51	27	32	32	mg/kg DS
Tin		647	758	750	650	518	470	405	mg/kg DS
Zinc		22333	22250	21500	20250	14750	15750	12500	mg/kg DS
Aluminium						16667			mg/kg DS
Tot. Al						22000			mg/kg DS
EOCl			1,0						mg/kg
EOX				1,5	1,5	0,2	<2	Average 2004	mg X/kg DS
TOC		3390	3575	3505	3050	6500	4033		mg/kg DS
Loss of Ignition				4,6				3418,9	% of DS
Sum PAH				1,0	1,5	10,5	3,8	3698	mg/kg DS
Dioxins & Furans						1080		3978	I -TEQ ng/kg

Figure 13 – Semi-dry flue gas cleaning residues composition (Amagerforbrænding, 1996-2003).

Parameter	Enhed	Wet 1 (VF)	Wet 2 (VF)	Wet 3 (VF)
Alkalinitet	mg/Kg	181.000	181.000	181.000
TS(Tørstof)	%	98,76	98,95	99,31
GT (glødetab 550 C)	%	1,7	1,1	0,99
Klor (Cl)	mg/kg TS	54.720	45.310	50.020
Silicium (Si)	mg/kg TS	NA	NA	NA
Aluminium (Al)	mg/kg TS	32.000	34.000	34.000
Calcium (Ca)	mg/kg TS	170.000	160.000	160.000
Magnesium (Mg)	mg/kg TS	7.000	6.000	5.000
Natrium (Na)	mg/kg TS	30.000	24.000	17.000
Kalium (K)	mg/kg TS	32.000	23.000	17.000
Sulfat (SO_4)	mg/kg TS	146.880	140.920	137.790
Bly (Pb)	mg/kg TS	4.000	3.100	2.800
Zink (Zn)	mg/kg TS	21.000	17.000	14.000
Kobber (Cu)	mg/kg TS	1.400	2.000	2.500
Krom (Cr)	mg/kg TS	160	150	140
Cadmium (Cd)	mg/kg TS	160	110	74
Kviksølv (Hg)	mg/kg TS	0,95	0,39	0,2
Arsen (As)	mg/kg TS	200	170	160
Dioxiner & Furaner	I-TEQ (ng/kg TS)	-	-	56

Tabel 12: Kemisk sammensætning af wet RGA fra VF. (I-TEQ i ng/kg TS)

Figure 14 – Wet flue gas cleaning residues composition.

Acidic wastewater composition (ARC):

Nominal load data (100 %)	Unit	Acid wastewater
pH	-	1,5*

Cl-	g/L	53
F-	g/L	0,4
Sulphate	g/L	0,7
Ca	g/L	29*
Na	g/L	0,2
Total dissolved salts	g/L	84
NH_3	mg/L	185
Hg	mg/L	9
Zn	mg/L	7
Pb	mg/L	2

Table 14 – Need for adjustment through reduced limestone addition to scrubber foreseen

For the short-listed technologies, a brief description of each technology is prepared with factsheet for key numbers, installation reference, description of technical and commercial progress including possible continuing development needs.

6. Conclusion

The shortlisted technologies for fly ash treatment were described with key numbers, installation reference, description of their technical and commercial progress and mass balances based on literature of each technology were prepared. These were used for comparison between technologies and generate overviews of inputs and outputs of the different systems. The different technologies including present solutions fly ash treatment are presented in Figure 15.

Treatment method	TRL	CRI	Possible CRI3 within 5 years
Carbon8	9	4	Yes
FLUWA/FLUREC	9	4	Yes
Renova/Götaverken miljö	8	2	Yes
HALOSEP	7	1	Yes
NOAH, road salt by evaporation	7	1	Yes
NOAH, existing stabilization process	9	4	Yes
Disposal in German salt mines	9	4	Yes

Figure 15 – Analysed technologies for fly ash treatment. Parameters TRL and CRI are abbreviations for technology readiness level and commercial readiness index, respectively.

As can be seen on Figure 15 from the analysed technologies only Carbon8 and FLUWA/FLUREC are rated as equally accessible both technologically and commercially as the two existing solutions. Both technologies are used in full scale plants and have therefore been profoundly tested. FLUWA, Renova and HALOSEP are relatively similar and all share basic principals in their cleaning process steps. Distinct variations in their individual processes are present and their end products vary. The reason for their lowered TRL and CRI scores is mainly due to not being well tested in full scale over

an extended time period. Renova and HALOSEP have both been tested in pilot-scale but only Renova was tested on an incineration plant site, which is the reasoning behind its higher scores in both parameters. All five technologies were deemed ready to reach a CRI of 3 within five years and will therefore be investigated in the upcoming environmental screening.

Appendix 1.

Mass balances of technologies reviewed.

6.1 Carbon8

An overall mass balance of treatment of 1000 kg dry fly ash by Carbon8 process is shown in and **Error! Reference source not found.**.

	Unit	Value
Inputs		
Fly ash	kg, dry	1000
Water	m^3	0.4
CO_2	kg	100
Cement	kg	500
Sand	kg	500
Other consumptions		
Power	kWh	10
Compressed air, ash transport	Nm^3	400
Compressed air, ash transport	kg	515
Outputs		
Lightweight aggregate	kg	2500
Compressed air, ash transport	Nm^3	400
Compressed air, ash transport	kg	515

Table 15 – Overall mass balance of Carbon8 process.

The effect of the carbonation process on the leached metals from the incineration fly ash source 1 is shown in **Error! Reference source not found.**.

Element	Untreated fly ash	Leaching results	
		Untreated fly ash	Treated fly ash
Sb	346	0.07	0.03
As	485	0.1	0.07
Ba	196	42.3	19.7
Cd	22	<0.01	<0.01
Cr	48	3.3	1.8
Cu	315	0.77	<0.04
Pb	6774	68.4	<0.09
Hg	2.7	<0.01	<0.01
Mo	2.4	0.72	0.16
Ni	7.4	<0.03	<0.03
Se	0.9	0.06	<0.02
Zn	6110	3	<0.02

Table 16 – Leached metals from the untreated and carbonation treated incineration fly ash source 1. All in mg/kg.

The effect of the carbonation process on the leached metals from the incineration fly ash source 2, aggregate and block produced from the treated fly ash is shown in **Error! Reference source not found.**.

Element	Untreated fly ash	Leaching results		
		Untreated fly ash	Aggregated from treated fly ash	Aggregated block from treated fly ash
Sb	24.3	<0.03	<0.03	0.08
As	<0.5	<0.01	<0.01	0.02
Ba	476	5.8	12.3	0.9
Cd	123.1	<0.01	<0.01	<0.01
Cr	109.3	3.4	9.2	0.2
Cu	480	0.4	<0.1	<0.1
Pb	1449	143.9	1.8	0.01
Hg	3.3	0.02	<0.001	0.1
Mo	7.9	2.1	0.8	0.6
Ni	36	<0.06	<0.06	<0.06
Se	3	0.12	0.08	0.08
Zn	560	37.8	0.6	0.6

Table 17 – Leached metals from the untreated fly ash, aggregate and block produced from carbonation treated incineration fly ash source 2. All in mg/kg.

6.2 FLUWA/FLUREC

The overall mass balance of FLUWA process is given in **Error! Reference source not found.**. Consumption of compressed air includes application for fly ash storage and transportation.

	Unit	Value
Inputs		
Fly ash	kg, dry	1000
Lime	kg	110
Process water	m^3	1
Soft process water	m^3	1.3
Acidic scrub water	m^3	1.3
Hg selective resin	kg	0.5
H_2O_2 (50%)	kg	85
HCl (30%), wastewater treatment	kg	33
NaOH (50%), wastewater treatment	kg	125
Other consumptions		
Power, including wastewater treatment	kWh	150
Compressed air for ash transport	Nm^3	400
Compressed air for ash transport	kg	515
Outputs		

Leached ash (45% water)	kg, wet	1273
Leached ash	kg, dry	700
Wastewater to neutralization	m^3	3.52
Zinc-enriched sludge	kg, dry	160
Spent Hg resin	kg	0.5
Exhaust air, ash transport	Nm^3	400
Exhaust air, ash transport	kg	515

Table 18 – Overall mass balance of FLUWA process.

Overall mass balance of FLUREC process is presented in **Error! Reference source not found.**.

	Unit	Value
Inputs		
Fly ash	kg, dry	1000
Lime	kg	110
Process water	m^3	1
Soft process water	m^3	1.3
Acidic scrub water	m^3	1.3
Hg selective resin	kg	0.5
H_2O_2 (50%)	kg	85
HCl (30%), wastewater treatment	kg	33
NaOH (50%), wastewater treatment	kg	125
Zn powder	kg	5
Other consumptions		
Power	kWh	350
Compressed air for ash transport	Nm^3	400
Compressed air for ash transport	kg	515
Outputs		
Leached ash (45% water)	kg, wet	1273
Leached ash	kg, dry	700
Wastewater to neutralization	m^3	3.6
Concentrate (Cd, Pb, Cu)	kg, dry	11
High purity zinc	kg, dry	50
Residual sludge (recycle to incinerator)	kg, dry	24
Spent Hg resin	kg	0.5
Exhaust air, ash transport	Nm^3	400
Exhaust air, ash transport	kg	515

Table 19 – Overall mass balance of FLUREC process.

The FLUWA process can be divided to a series of steps as in **Error! Reference source not found.**.

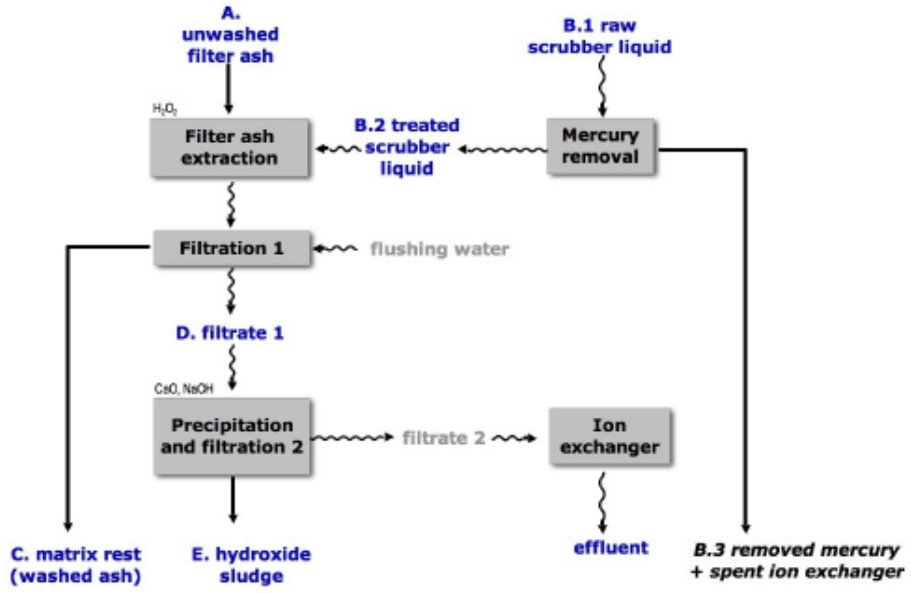

Figure 16 – Breakdown of the FLUWA process into a series of steps.

The transfer coefficients determine the fate of chemical elements. Oxygen mass in outputs is corrected based on oxidized masses of the chemical elements in the outputs. Based on the obtained total dry mass, additional water content is calculated, to arrive at the total wet mass of the outputs. The reported element transfer coefficients of the FLUWA process are presented in **Error! Reference source not found.**.

Element	Matrix rest (washed ash)	Hydroxide sludge	Final effluent
O	88.79	11.21	
H	88.79	11.21	
C	88.79	5.6	5.6
S	65.44	29.79	4.77
N		0	100
P	70.21	29.23	0.56
B	65.44	29.79	4.77
Cl	1.03	5.28	93.69
Br	1.03	5.28	93.69
F	1.79	5.44	92.77
I	1.03	5.28	93.69
Ag	99.19	0.81	
As	97.10	2.90	
Ba	99.76	0.12	0.12
Cd	20.95	79.03	0.02
Co	75.87	24.12	0.01
Cr	97.73	2.23	0.04
Cu	99.19	0.81	
Hg	98.94	1.05	0.01
Mn	99.42	0.57	0.01
Mo	43.67	55.53	0.80
Ni	96.61	3.36	0.03
Pb	92.47	7.53	
Sb	95.20	2.40	2.40
Se	95.20	2.40	2.40
Sn	99.39	0.3	0.31

V	97.73	2.23	0.04
Zn	45.78	54.22	
Be	75.87	24.12	0.01
Sc	99.92	0.08	
Sr	91.45	2.74	5.81
Ti	99.92	0.08	
Tl	96.61	3.36	0.03
W	83.68	8.16	8.16
Si	99.75	0.12	0.13
Fe	99.21	0.78	0.01
Ca	83.68	8.16	8.16
Al	99.92	0.08	
K	55.72	2.36	41.92
Mg	91.45	2.74	5.81
Na	42.01	3.09	54.90

Table 20 – Transfer coefficients for the FLUWA process. All in %. 100% is the input to the FLUWA extraction step, i.e. filter ash and scrubber liquid after Hg selective ion exchanger treatment.

6.3 Renova/Götaverken miljö

The overall inputs and outputs of the Renova process are presented in **Error! Reference source not found.**. Consumption of compressed air includes application for fly ash storage and transportation.

	Unit	Value
Inputs		
Fly ash	kg, dry	1000
Acidic scrub water	m^3	3.1
Hg selective resin	kg	0.5
HCl (30%), wastewater treatment	kg	30
25% NaOH, for Zn precipitation	kg	30
Other consumptions		
Power, including wastewater treatment	kWh	150
Compressed air for ash transport	Nm^3	400
Compressed air for ash transport	kg	515
Outputs		
Fly ash after recirculation	kg, dry	200
Washed ash recirculation to furnace	kg, dry	500
Recirculated ash converted to bottom ash	kg, dry	450
Recirculated ash converted to fly ash	kg, dry	50
Wastewater to neutralization	m^3	3.3
Zinc-enriched sludge (50-80% as $Zn(OH)_2$)	kg, dry	160
Spent Hg resin	kg	0.5
Exhaust air, ash transport	Nm^3	400
Exhaust air, ash transport	kg	515

Table 21 – Overall mass balance of the Renova process.

Although scrubber liquids from the HCl, SO_2 and condensing stages have been tested for fly ash leaching, only tests with acidic water from HCl stage is included here for comparison with other technologies.

The composition of the untreated fly ash is shown in **Error! Reference source not found.**.

Item	Unit	Value	Item	Unit	Value
Moisture	wt%	0.7-2.8	K	g/kg, dry	37-65
Cl	wt%	8.9-12.5	Mg	g/kg, dry	11-15
Zn	g/kg, dry	22-28	Mn	mg/kg, dry	660-760
Al	g/kg, dry	22-38	Mo	mg/kg, dry	27-33
As	mg/kg, dry	500-1700	Na	g/kg, dry	55-68
B	mg/kg, dry	200-230	Ni	mg/kg, dry	84-110
Ba	mg/kg, dry	1100-1700	P	mg/kg, dry	6600-7300
Ca	g/kg, dry	160-200	S	g/kg, dry	39-57
Cd	mg/kg, dry	190-270	Sb	mg/kg, dry	1500-2000
Co	mg/kg, dry	23-32	Si	g/kg, dry	49-65
Cr	mg/kg, dry	470-650	Sn	mg/kg, dry	850-1000
Cu	mg/kg, dry	1700-2700	Ti	g/kg, dry	11-14
Fe	g/kg, dry	15-17	V	mg/kg, dry	43-67

Table 22 – Composition of untreated fly ash for HCl scrub water leaching.

The composition of the HCl scrub water is shown in **Error! Reference source not found.**.

Item	Value	Item	Value	Item	Value
Cl	40000	Be	<0.002	Ni	0.046
Na	730	Pb	11	Se	0.013
K	120	B	14	Ag	0.045
Ca	17	P	1.9	Sr	0.065
Fe	6.6	Cd	0.6	S	490
Mg	<2	Si	19	Tl	0.01
Mn	0.5	Co	0.006	Sn	1.6
Al	3.9	Cu	3.1	Ti	1400
Sb	2.9	Cr	0.088	U	<0.0004
As	0.3	Li	<0.2	V	0.013
Ba	0.55	Mo	0.037	Zn	68

Table 23 – Composition of the HCl scrub water. All in mg/l.

The composition of the filtrate after the vacuum belt filter, before zinc precipitation treatment is given in **Error! Reference source not found.**.

Item	Value	Item	Value	Item	Value
Cl	61000	Be	<0.002	Ni	0.49
Na	21000	Pb	61	Se	0.033
K	19000	B	45	Ag	0.065
Ca	9300	P	<120	Sr	28
Fe	5.5	Cd	66	S	850
Mg	1100	Si	<200	Tl	0.28
Mn	39	Co	0.83	Sn	1.6
Al	13	Cu	4.7	Ti	<20
Sb	9.1	Cr	0.34	U	<0.0007
As	7.2	Li	<20	V	0.013
Ba	11	Mo	0.44	Zn	4700

Table 24 – The composition of the filtrate after the vacuum belt filter, before zinc precipitation treatment. All in mg/l.

Leaching test of HCl scrub water washed fly ash is presented in **Error! Reference source not found.**.

Item	Value	Item	Value	Item	Value
Sb	1.1	Cr	4.5	Cl	6400
As	1.5	Hg	<0.0013	F	12
Ba	<2	Mo	8.6	SO_4^{2-}	14000
Pb	0.1	Ni	<0.04	DOC	150
Cd	<0.004	Se	0.07	Total solids of solved subjects	35000
Cu	<0.2	Zn	<0.4		

Table 25 – Leaching test results of HCl scrub water washed fly ash according to EN 12457-3 with L/S=10. All in mg/kg, dry.

The effects of 100% recycling washed fly ash to the furnace on the produced fly ash composition are shown in **Error! Reference source not found.**. As shown in **Error! Reference source not found.**, there is a general increase of the heavy metal content in the fly ash after recycling the washed ash to the furnace. To avoid high concentration of heavy metals in the fly ash due to thermal treatment of washed fly ash in the furnace, about 30% of the washed fly ash, corresponding to 20% of the un-treated fly ash shall be disposed.

	HCl scrub water washed fly ash	Fly ash without washing and recycling	Fly ash after washing and recycling to furnace	Change (%)
Al	43750	36250	35500	-2
P	9200	6300	6450	2
Fe	21000	16500	22750	38
Cd	89	36	49	35
Ca	225000	190000	170000	-11
K	8050	17500	16750	-4
Mg	12500	14000	14250	2
Mn	810	688	913	33
Na	7925	21500	19000	-12
Ti	15250	11600	10950	-6
As	2200	335	1625	385
Sb	2275	708	935	32
Ba	835	1105	1315	19
Pb	8125	958	1925	101
Co	28	30	45	51
Cu	2673	4325	4375	1
Cr	840	1668	3150	89
Mo	40	123	185	51
Ni	125	1128	1678	49
Sn	1375	310	598	93
V	59	37	53	44
Zn	17250	11450	13500	18
Dust level before ESP (mg/Nm^3)		3240	3495	8

Table 26 – Composition of fly ash after all washed ash recycling to furnace. All in kg/kg, dry.

The effects of recycling 100% washed fly ash to the furnace on the slag composition is shown in **Error! Reference source not found.**.

	Slag without fly ash washing and recycling	Slag after fly ash washing and recycling	Change (%)
Cl	0.77	0.62	-19
Al	71000	53200	-25
P	6640	5720	-14
Fe	64600	64000	-1
Cd	3.22	0.69	-78
Ca	166000	152000	-8
K	12400	14200	15
Si	134000	148000	10
Mg	13000	13600	5
Mn	1350	994	-26
Na	24000	21800	-9
Ti	11560	9220	-20
As	20.4	14.2	-30
Sb	61.2	73.8	21
Ba	1960	1300	-34
Pb	228	280	23
Co	21.2	35.4	67
Cu	4040	3430	-15
Cr	590	894	52
Ni	450	920	104
S	13320	12600	-5
Sn	89.6	126.8	42
V	69.6	74.2	7
Zn	4420	6920	57
B	186	216	16

Table 27 – Composition of slag after all washed ash recycling to furnace. All in kg/kg, dry.

6.4 HALOSEP

An overall mass balance of the HALOSEP process is shown in **Error! Reference source not found.**.

	Unit	Value	
		Fly ash from wet flue gas cleaning	Residues from semi-dry flue gas cleaning
Inputs			
Fly ash	kg, dry	1000	1000
Process water	m^3	1	1
Soft process water	m^3	1.3	1.3
Acidic scrub water	m^3	1.4	2.8
NaOH (50%), for salt production	kg	15	15
Other consumptions			
Power	kWh	40	40

Compressed air for ash transport	Nm^3	400	400
Compressed air for ash transport	kg	515	515
Outputs			
Leached ash (30% water)	kg, wet	857	629
Leached ash	kg, dry	600	440
Salt product	kg, dry	300	450
Metal products	kg, dry	30	20
Oversized fraction >1mm (50% as sand, 50% as carbon)	kg, dry	10	10
H_2O and CO_2	kg	60	80
Wastewater to neutralization	m^3	3.46	4.93
Exhaust air from ash transport	Nm^3	400	400
Exhaust air from ash transport	kg	515	515

Table 28 – Overall mass balance of the HALOSEP process.

For the untreated fly ash, it will be humidified with 25% water before disposal. After HALOSEP treatment of 1000 kg dry fly ash, the amounts of ash disposal reduced are shown in **Error! Reference source not found.**.

	Unit	Value	
		Fly ash from wet flue gas cleaning	Residues from semi-dry flue gas cleaning
Untreated ash with 25% H_2O	kg	1333	1333
HALOSEP washed with 30% H_2O	kg	857	629
Reduction in ash disposal	%	35.7	52.8

Table 29 – Reduction of ash disposal amount by HALOSEP process.

The compositions of fly ash from wet flue gas cleaning system in Vestforbrænding, semi-dry residues from old Amagerforbrænding plant and tested in HALOSEP pilot plant are shown in **Error! Reference source not found.**.

	Unit	Value	
		Wet flue gas cleaning	Semi-dry flue gas cleaning
Dry matter	wt%	96-99	99
Dioxin and furans	I-TEC (ng/kg, dry)	134	142-145
Alkalinity	mmol/kg, dry	6700-7000	11000-12000
TOC	mg/kg, dry	4200-7600	3300-4000
Al	mg/kg, dry	32000-33000	8900-19000
Sb	mg/kg, dry	400-500	410-490
As	mg/kg, dry	280-290	120-180
Ba	mg/kg, dry	840-860	260-650
Pb	mg/kg, dry	5400	2300-2400
Cd	mg/kg, dry	240-280	71-74

Ca	mg/kg, dry	200000-210000	280000-300000
Cl	mg/kg, dry	59000-83000	120000-150000
Cr	mg/kg, dry	160	96-150
Co	mg/kg, dry	23	9-16
F	mg/kg, dry	180-200	160-220
K	mg/kg, dry	51000-62000	25000-27000
Cu	mg/kg, dry	1200-1400	310-420
Hg	mg/kg, dry	3	7-8
Mg	mg/kg, dry	17000-18000	300-410
Mo	mg/kg, dry	19-21	5-6
Na	mg/kg, dry	48000-58000	15000-22000
Ni	mg/kg, dry	64-70	20-34
Se	mg/kg, dry	9-11	-
S	mg/kg, dry	41000-53000	16000-24000
Zn	mg/kg, dry	35000-37000	9900-12000
Sn	mg/kg, dry	963-1121	440-490
Si	mg/kg, dry	790-910	500-9900

Table 30 – Compositions of fly ash from wet flue gas cleaning system and residues from semi-dry flue gas cleaning system and tested in HALOSEP pilot plant.

The composition scrub water from Vestforbrænding wet flue gas cleaning system is shown in **Error! Reference source not found.**.

	Unit	Value		Unit	Value
pH		-0.11-- -0.44	Sn	mg/l	0.02-15
HCl	mol/l	1.95-3.03	Sb	mg/l	0.04-15
HCl	g/l	71-110	As	mg/l	0.005-11
NVOC	mg/l	4-18	Ba	mg/l	0.055-1.6
NH_4^+	mg/l	14-160	Pb	mg/l	0.07-77
Al	mg/l	0.17-25	Cd	mg/l	0.0003-3.7
B	mg/l	5.5-25	Cr	mg/l	0.005-0.49
Br	mg/l	120-360	F	mg/l	37-710
Ca	mg/l	110-420	K	mg/l	3.8-820
Cl	mg/l	27000-82000	Cu	mg/l	0.03-15
Fe	mg/l	5-70	Hg	mg/l	0.04-10
Mg	mg/l	15-56	Mo	mg/l	0.002-0.087
Mn	mg/l	0.13-1.7	Ni	mg/l	0.005-0.19
Na	mg/l	96-1700	Se	mg/l	0.001-0.034
S	mg/l	400-3000	Zn	mg/l	0.36-450

Table 31 – Composition scrub water from Vestforbrænding wet flue gas cleaning system.

The compositions of the oversized parts are shown in **Error! Reference source not found.**.

	Unit	Value	
		Wet flue gas cleaning	Semi-dry flue gas cleaning
Dioxin and furans	I-TEC (ng/kg, dry)	211	211
Alkalinity	mmol/kg, dry	2900-3900	6900-11000
TOC	mg/kg, dry	31000-74000	4000-7800
Al	mg/kg, dry	25000-39000	19000-20000
Sb	mg/kg, dry	110-260	490-510
As	mg/kg, dry	160-330	150-180
Ba	mg/kg, dry	510-780	530-650

Pb	mg/kg, dry	4300-11000	2400-2700
Cd	mg/kg, dry	64-140	71-83
Ca	mg/kg, dry	150000-160000	130000-280000
Cl	mg/kg, dry	17000-34000	50000-150000
Cr	mg/kg, dry	140-160	150-200
Co	mg/kg, dry	16-22	16-19
F	mg/kg, dry	8-65	55-220
K	mg/kg, dry	18000-60000	14000-27000
Cu	mg/kg, dry	680-1100	410-420
Hg	mg/kg, dry	2-16	7-9
Mg	mg/kg, dry	9700-13000	400-410
Mo	mg/kg, dry	8-14	6-8
Na	mg/kg, dry	10000-27000	6900-22000
Ni	mg/kg, dry	54-60	34-47
Se	mg/kg, dry	2-6	-
S	mg/kg, dry	21000-80000	16000-19000
Zn	mg/kg, dry	16000-27000	12000-13000
Sn	mg/kg, dry	410-722	450-490
Si	mg/kg, dry	790-1550	9900-22000

Table 32 – Compositions of the oversized fly ash / residues.

For fly ash from wet flue gas cleaning, the compositions of the salt product are shown **Error! Reference source not found.**. Both the salt compositions before and after precipitation by TMT15 or granular activated carbon are presented.

	Unit	Before precipitation		After precipitation	
		Option A, liquid salt product	Option B, discharged salt solution	Option A, liquid salt product	Option B, discharged salt solution
pH		8.8-8.9	8.6-8.9	8.7-9.0	7.85
NVOC	mg/l	1.3	1.2-1.3	3.5-16	13-25
NH_4^+	mg/l	6.1-8.8	3.5-4.5	5.9-8.8	7.2-7.3
Al	µg/l	<30	<30-110	<30	<30
B	mg/l	18	10-12	17-19	3.4
Br	mg/l	340	160-170	280-340	120-140
Ca	mg/l	11000	1800-5000	9800-10000	9200
Cl	mg/l	41000-42000	16000-18000	40000-43000	24000
Fe	mg/l	<0.05	<0.05	0.09-0.15	0.11-0.12
Mg	mg/l	400-450	310	400-420	190
Mn	mg/l	<0.005-0.008	<0.005-0.07	<0.005	0.0069-0.0076
Na	mg/l	7700-7900	3800-5300	8300-8400	2700
S	mg/l	920-950	1200-1800	940-960	630-640
Sn	mg/l	<3	<3	<3	<3
Sb	mg/l	0.03-0.04	0.04-0.19	0.03-0.04	0.076-0.078
As	µg/l	<0.8	<0.8-0.95	<0.8-3.8	0.009-0.012
Ba	mg/l	3.4-4.1	1-1.6	2-2.7	0.5-0.54
Pb	mg/l	0.006-0.009	0.005-0.007	0.0006-0.0023	0.0039-0.0083
Cd	mg/l	5.2-5.5	0.8-0.9	0.003-3.9	0.063-1
Cr	µg/l	1.1-1.8	1.3-1.6	1.2-2.5	3.9
F	mg/l	4.9-7.5	8.9-9.8	4.7-4.8	3.9-4
K	mg/l	7700	3200-4100	6900-7000	2500

Cu	mg/l	0.0014-0.0039	0.0013-0.0015	<0.001	2.1-12
Hg	mg/l	0.0005-0.0008	<0.00005	0.00022-0.00081	<0.05-0.4
Mo	mg/l	0.09-0.1	0.06-0.08	0.092-0.096	0.22
Ni	µg/l	<1	<1	<1	<1-27
Se	mg/l	0.025-0.029	0.018-0.026	0.02-0.023	0.015-0.016
Zn	mg/l	0.13	0.02-0.12	0.011-0.094	0.023-0.071

Table 33 – Compositions of the salt solution products for fly ash from wet flue gas cleaning system before and after precipitation.

For residues from semi-dry flue gas cleaning, the compositions of the salt product are shown **Error! Reference source not found.**. Both the salt compositions before and after precipitation by TMT15 are presented.

	Unit	Before precipitation	After precipitation	
			Option A, liquid salt product	Option B, discharged salt solution
pH		7.1-10.6	7.5-10.4	9.5-10.4
NVOC	mg/l	6.1-14	19-25	6.2-20
NH_4^+	mg/l	20-77	21-67	62-67
Al	µg/l	<30-110	<30	<30
B	mg/l	4.7-19	4.7-18	4.3-6.2
Br	mg/l	120-350	130-390	130-200
Ca	mg/l	26000-32000	11000-28000	11000-14000
Cl	mg/l	16000-70000	26000-68000	25000-34000
Fe	mg/l	0.16-0.37	0.16-0.43	0.16-0.23
Mg	mg/l	26-250	25-280	23-78
Mn	mg/l	<0.005-0.28	<0.005-0.3	<0.005
Na	mg/l	1900-5300	1700-5200	1700-2500
S	mg/l	710-790	730-1100	910-1100
Sn	mg/l	<3	<3	<3
Sb	mg/l	0.5-1.9	0.6-1.8	1.1-1.4
As	µg/l	<0.8	<0.8	<0.8-6.1
Ba	mg/l	2.4-8.9	2.5-8.4	2.5-4.6
Pb	mg/l	0.002-0.049	0.0019-0.0083	0.0019-0.0077
Cd	mg/l	0.044-4.3	0.0008-0.079	0.0008-0.23
Cr	µg/l	2.3-22	2.4-15	13-15
F	mg/l	6.4-8.7	4.4-13	4.3-8.2
K	mg/l	1600-4400	1600-4300	1600-2100
Cu	mg/l	0.001-0.21	<0.001-0.016	<0.001-0.005
Hg	mg/l	<0.00005-0.0078	<0.00005-0.0061	<0.00005-0.0009
Mo	mg/l	0.19-0.3	0.19-0.27	0.19-0.27
Ni	µg/l	<1	<1	<1
Se	mg/l	0.013-0.027	0.011-0.026	0.011-0.014
Zn	mg/l	<0.005-0.055	<0.005-0.095	<0.005-0.033

Table 34 – Compositions of the salt solution products for residues from semi-dry flue gas cleaning before and after precipitation.

The compositions of the dry salt products are shown in **Error! Reference source not found.**.

	Unit	Value	
		Fly ash from wet flue gas cleaning	Residues from semi-dry flue gas cleaning
$CaCl_2$	%	57-62	75-80
NaCl	%	23-26	12-14
KCl	%	14-16	8-10
$CaCl_2$, NaCl, KCl	%	99	99
$CaSO_4$, $MgSO_4$	%	0.5-1	0.5-1
As	ppm	<0.01-0.04	<0.01
Ba	ppm	20-26	57-60
Cd	ppm	0.03-0.75	0.1-0.6
Cr	ppm	0.01-0.02	0.02-0.1
Cu	ppm	<0.01	<0.01-0.1
Hg	ppm	0.01	0.003-0.004
Mo	ppm	0.92	1.6-1.9
Ni	ppm	<0.01	<0.01
Pb	ppm	0.01	0.06
Sb	ppm	0.3-0.42	4-13
Se	ppm	0.2-0.22	0.14-0.19
Zn	ppm	0.11-0.21	0.3-0.68

Table 35 – Comparison of the road salt in dry matter.

The compositions of heavy metal products are shown in **Error! Reference source not found.**.

	Unit	Value		
		Wet flue gas cleaning		Semi-dry flue gas cleaning
		Option A, liquid salt product	Option B, discharged salt solution	
Alkalinity	mmol/kg, dry	9100-9400	5600-6100	4700-7100
TOC	mg/kg, dry	-	500-840	840-3600
Al	mg/kg, dry	1200-7100	8000-12000	2500-19000
Sb	mg/kg, dry	490-1300	710-830	440-1900
As	mg/kg, dry	22-200	160-180	74-400
Ba	mg/kg, dry	110-600	280-380	310-550
Pb	mg/kg, dry	4400-6600	5700-7100	1500-8400
Cd	mg/kg, dry	3200-4200	2100-2900	300-1200
Ca	mg/kg, dry	77000-83000	52000-62000	180000-230000
Cl	mg/kg, dry	190000	97000-120000	79000-190000
Cr	mg/kg, dry	15-96	81-92	41-260
Co	mg/kg, dry	56-58	52-73	18-28
F	mg/kg, dry	330-700	91-170	64-260

K	mg/kg, dry	40000-48000	20000-35000	5100-120000
Cu	mg/kg, dry	570-840	750-920	470-1000
Hg	mg/kg, dry	7.2-39	6-36	2-54
Mg	mg/kg, dry	47000-48000	27000-31000	630-30000
Mo	mg/kg, dry	4.3-13	8.2-11	3-13
Na	mg/kg, dry	52000-55000	25000-48000	4400-12000
Ni	mg/kg, dry	98-120	94-150	58-81
Se	mg/kg, dry	3.3-8.9	6.3-6.5	-
S	mg/kg, dry	6800-10000	17000-35000	8200-28000
Zn	mg/kg, dry	290000-310000	250000-330000	37000-57000
Sn	mg/kg, dry	265-1642	1130-1500	340-1600
Si	mg/kg, dry	960-1400	<500-1100	<500-18000

Table 36 – Compositions of heavy metal products.

The compositions of the washed ash and changes in relation to the unwashed ash are shown in **Error! Reference source not found.**.

	Unit	Value			
		Wet flue gas cleaning		Wet flue gas cleaning	
		After washing	Change (%)	After washing	Change (%)
Dioxin and furans	I-TEC (ng/kg, dry)	104-320	7		
Alkalinity	mmol/kg, dry	2900-4100	-67	4100-7400	-74
TOC	mg/kg, dry	4500-130000	-15	6000-8600	5
Al	mg/kg, dry	35000-47000	-26	26000-33000	16
Sb	mg/kg, dry	110-310	-69	600-1000	-14
As	mg/kg, dry	170-400	-35	160-300	-29
Ba	mg/kg, dry	290-1100	-60	660-860	-9
Pb	mg/kg, dry	3700-11000	-25	3900-5000	-4
Cd	mg/kg, dry	51-91	-86	37-95	-49
Ca	mg/kg, dry	140000-200000	-49	180000-200000	-66
Cl	mg/kg, dry	1700-3600	-98	790-3500	-99
Cr	mg/kg, dry	160-250	-25	190-330	11
Co	mg/kg, dry	18-25	-42	27-32	18
F	mg/kg, dry	21-200	-61	24-71	-87
K	mg/kg, dry	6200-9300	-91	5100-8300	-86
Cu	mg/kg, dry	1100-1800	-34	710-1200	25
Hg	mg/kg, dry	2-50	522	19-59	135
Mg	mg/kg, dry	11000-16000	-54	480-660	-15
Mo	mg/kg, dry	13-23	-43	7-9	-22
Na	mg/kg, dry	7200-9700	-90	5200-7900	-82
Ni	mg/kg, dry	54-73	-39	60-79	30
Se	mg/kg, dry	5-12	-43	-	-

S	mg/kg, dry	15000-38000	-65	16000-17000	-58
Zn	mg/kg, dry	11000-28000	-66	14000-23000	-16
Sn	mg/kg, dry	260-519	-77	630-1100	-11
Si	mg/kg, dry	<600	-	32000-63000	-

Table 37 – Compositions of the washed ash and changes in relation to the unwashed ash.

6.5 NOAH road salt by evaporation

The overall mass balance of NOAH salt process is given in **Error! Reference source not found.**.

	Unit	Value	
		Evaporation by 230°C flue gas	Evaporation by 380°C flue gas
Inputs			
Fly ash	kg, dry	1000	1000
Process water	m^3	1	1
Waste sulfuric acid 25%	m^3	1.35	1.35
Waste sulfuric acid 25%	kg	1600	1600
Hydrated lime	kg	20	20
Other consumptions			
Power	kWh	40	40
Heat from flue gas	MJ	900	600
Outputs			
Gypsum with treated residue for disposal	kg, wet	3270	3270
Brine before evaporation	kg, wet	1700	1700
Salt products	kg, dry	235	235
Evaporated water	kg	1465	1465

Table 38 – Overall mass balance of NOAH salt process.

The compositions of the treated residues for disposal are shown in **Error! Reference source not found.**.

	Unit	Value
pH		9.5
Cl	mg/kg, dry	35000
Cd	mg/kg, dry	50
Cr	mg/kg, dry	50
Cu	mg/kg, dry	50
Hg	mg/kg, dry	10
Pb	mg/kg, dry	200
Zn	mg/kg, dry	500
Dioxins/furans	ng-TEQ/kg, dry	0.0012

Table 39 – Compositions of the treated residues for disposal.

Compositions of the brines taken at various locations of the NOAH process are shown in **Error! Reference source not found.**.

	Unit	Slurry preparation tank 809	Tank R4 after addition of sulfuric acid and lime	Diverted brine to Oslo Fjord
pH		11.3-11.8	8.1-8.3	7.8-8.9
As	mg/kg, dry	0.4	0.4	0.4
Ba	mg/kg, dry	81-110	42-78	21-23
Cd	mg/kg, dry	0.02	0.36-0.65	0.02-0.03
Co	mg/kg, dry	0.1	0.1	0.1-0.49
Cr	mg/kg, dry	0.1	0.1	0.1
Cu	mg/kg, dry	0.1	0.1	0.1
Mo	mg/kg, dry	0.3-2.7	0.2-0.49	0.39-0.49
Ni	mg/kg, dry	0.2	0.2	0.2
Pb	mg/kg, dry	0.43-2	0.2	0.2
Sb	mg/kg, dry	0.4	1.7-2.4	0.78-0.82
Se	mg/kg, dry	0.3	0.3	0.3
Sn	mg/kg, dry	0.1	0.1	0.1
Tl	mg/kg, dry	0.3	0.3	0.3
V	mg/kg, dry	0.1	0.1	0.1
Zn	mg/kg, dry	3.2-29	0.1-0.44	0.1
THC	mg/kg, dry	20.19-20.58	20-20.58	20.18-20.92
TOC	%, dry	0.1-97	0.1	0.1
Total nitrogen	mg/kg, dry	7.5-13	430-860	260-460
Al	mg/kg, dry	2.75-6.67	2.59-3.94	3.03-3.2
Hg	mg/kg, dry	0.02	0.01-0.02	0.02
Cl	mg/l	105000-121200	70000-84800	49350
F	mg/l	25-50	18-50	26
NO_3	mg/l	20-50	10-50	31
PO_4	mg/l	1-5	1-5	1
SO_4	mg/l	753-938	1200-1220	1570
Ca	mg/l	26200-27300	12000-16800	7700
K	mg/l	22400-23800	17100-18200	10300
Mg	mg/l	2-5	647-778	347
Na	mg/l	31300-32000	23300-26700	15600
Sr	µg/l	62500-67100	25000-28100	20400

Table 40 – Compositions of the brines taken at various locations of the NOAH process, ion dissolved elements.

The amounts of different salts dissolved in the brine is presented in **Error! Reference source not found.**.

	Slurry preparation tank 809	Tank R4 after addition of sulfuric acid and lime	Diverted brine to Oslo Fjord
NaCl	7.0	5.5	3.5
KCl	3.8	2.9	1.7

$MgCl_2$	0	0.2	0.1
$CaCl_2$	6.4	3.5	1.9
Sum anhydrous salt	17.3	12.2	7.1
Crystallized water	2.1	1.4	0.7
Sum salt, crystallized water	19.4	13.6	7.9

Table 41 – Salt concentration in brines from three various positions in the NOAH process. All in wt%.

Compositions of the produced salts from the brines are shown in **Error! Reference source not found.**.

	Unit	Slurry preparation tank 809	Tank R4 after addition of sulfuric acid and lime	Diverted brine to Oslo Fjord
Proportion of different salts for anhydrous products				
NaCl	wt%	40.5	45.4	48.4
KCl	wt%	22.2	24.1	24.0
$MgCl_2$	wt%	0	2.0	1.7
$CaCl_2$	wt%	37.3	28.5	26.0
Sum	wt%	100	100	100
Proportion of different salts for salt with crystallized water				
NaCl	wt%	36.1	40.8	43.9
KCl	wt%	19.8	21.6	21.7
$MgCl_2.2H_2O$	wt%	0	3.8	3.2
$CaCl_2.2H_2O$	wt%	44.1	33.9	31.2
Sum	wt%	100	100	100
Toxic substances in anhydrous products				
Al	mg/kg, dry	4.4	3.2	3.1
As	mg/kg, dry	0.4	0.4	0.4
Cd	mg/kg, dry	0.02	0.5	0.03
Co	mg/kg, dry	0.1	0.1	0.3
Cr	mg/kg, dry	0.1	0.1	0.1
Cu	mg/kg, dry	0.1	0.1	0.1
Hg	mg/kg, dry	0.02	0.02	0.02
Ni	mg/kg, dry	0.2	0.2	0.2
Pb	mg/kg, dry	1.0	0.2	0.2
Zn	mg/kg, dry	18.7	0.3	0.2
THC	mg/kg, dry	20.4	20.2	20.6

Table 42 – Compositions of the produced salts from the brines.