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Report

Fly ash treatment technologies

An overview of commercial and upcoming technologies for Norway and Scandinavia

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ABSTRACT

This report presents an evaluation of eleven fly ash treatment technologies of specific interest for Norway and Scandinavia, four commercially available technologies and seven under various stages of development. Eight criteria were used for the evaluation: Treatment method; Process output; Technology Readiness Level; Technology provider and references; Robustness/flexibility; Environmental aspects; Health, Safety and Environment; Process complexity and economy. Background information was collected using open sources and through communication with technology actors. For developing technologies, the time necessary to reach commercial application was estimated. TRL and costs evaluations were challenging given uncertainties in the background material. The following bullet points summarize important findings.

- There is currently no material recovery from WtE fly ash at industrial scale in Scandinavia
- Commercial technologies offering material recovery or fly ash re-use exist outside of Scandinavia. Two European ones are presented in the report
- The technologies under development evaluated in the report include some material recover or fly ash re-use
- Technologies offering material recovery still require landfilling (hazardous and/or ordinary)
- The timeframe for the technologies under development to reach commercial application has been estimated to vary from 3-5 and 6-12 years. High uncertainty is associated with these numbers
- Economic viability/profitability was difficult to assess based on accessible material, but, more complex processes with multiple outputs will often mean higher costs
- Implementation of technologies including materials recovery or re-use will require approval by local authorities

Considerations and comments on the future of fly ash treatment in Norway/Scandinavia are discussed. They emphasized the complexity of the aspects to consider, i.e. overall performance, economy, resources management, environment, regulatory framework, country-specific challenges and society. This complex section (Chapter 5, 2-page) should be read in its entirety.

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Table of contents

1 Introduction and disclaimer

This report presents an overview of technologies to treat fly ash from waste incineration with focus on Norway and Scandinavia. Both established, commercial and novel technologies are included. After a preliminary screening, eleven technologies were evaluated according to eight criteria (+ a short list of advantages and limitations):

1. Treatment method – Gives a succinct description of the principle behind the technology.
2. Process output – Lists the fractions, products and residues, leaving the process (mass balance).
3. TRL (Technology Readiness Level) - Estimates the maturity of a given treatment according to pre-defined key levels. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology. See Appendix for description of each levels as defined by the European Commission.
4. Technology provider(s) and references – Indicates the main actors involved in the development and commercialisation of a given treatment as well as installations using this technology.
5. Robustness/flexibility – Gives an indication of the flexibility of a process regarding fly ash heterogeneity and output quality.
6. Environmental aspects – Focuses on water, energy and other consumables' consumption as well as overall impact on the environment.
7. HSE (Health, Safety and Environment) – Technology-specific HSE challenges and procedures especially concerning the work environment.
8. Process complexity and economy – Gives important elements concerning costs and possible revenues. The overall (i.e. capital and to some extent operating) costs are categorised as low/medium/high. The costs have been indirectly evaluated based on the overall process complexity. This complexity is here related to the number of outputs (both residues and products) and the treatment type. The lower the TRL of a technology, the more uncertain this evaluation is.
9. Advantages and limitations – Summarises key points for each technology.

Based on these criteria, each technology has been given a one-page review presented in alphabetical order in Chapter 2. The estimated TRLs are summarised in Chapter 3. Considered but not reviewed technologies are listed in Chapter 4, including a short explanation why they were not included here. General comments and considerations on the future of fly ash treatment (mainly for Norway and Scandinavia) are presented in Chapter 5. References can be found in Chapter 6.

Acronyms used in the report:

BAT: Best Available Technology; CCS: Carbon Capture and Storage; FGT: Flue Gas Treatment; HSE: Health, Safety, Environment; MSW: Municipal Solid Waste; MSWI: Municipal Solid Waste Incineration; TRL: Technology Readiness Levels; WtE: Waste-to-Energy.

Remark:

Quotation marks (" ") are used when quoting documents from technology developers and providers.

Disclaimer:

This overview should not be used to select or purchase equipment or technologies.

Descriptions and evaluations are based on open information and communication with the technology providers. The evaluations (incl. TRL and costs), comments and considerations expressed here are the ones of the main author based on available information and general expertise on waste management. Costs evaluations are especially difficult to do as they will be very plant-specific and have a high uncertainty.

2 Commercial and upcoming technologies

2.1 ASH2SALT

2.1.1 Treatment method

Before implementing the Ash2Salt treatment *per se*, two preliminary steps are required: in step *one ash washing*, fly ash is washed with water, producing washed ash (mainly sand) and a leachate rich in salts and heavy metals that continues to step two; *water treatment*. In step two, sulphides and/or other chemicals are added to the leachate to precipitate the heavy metals. Thereafter the chloride rich liquid continues to step three, the Ash2Salt process itself. The Ash2Salt process includes the addition of $CaCl_2$ to enable precipitation and separation of NaCl and KCl before evaporation to produce a concentrated $CaCl_2$ solution and ammonia.

2.1.2 Process output

Three fractions are produced: (1) washed ash to be sent to conventional landfill; (2) a solid or slurry, heavy metal rich fraction to be sent to hazardous landfill and (3) pure salts - $CaCl_2$ (solution), NaCl (solids), KCl (solids) and ammonia/ammonium that have the potential to be products.

2.1.3 TRL

The process was patented in Dec. 2015. No information on tests or experiments have been found by the author but the technology developer, EasyMining Sweden AB, indicates that they are making progress, building "a full scale Ash2Salt plant" (exact scale not known), hence ***TRL is evaluated to 5-7 prototype/demonstration*** until the plant has showed successful operation. Timeline to TRL 9 is estimated to 3-6 years.

2.1.4 Technology provider(s) and references

EasyMining Sweden AB, a subsidiary of Ragn-Sells AB (Sweden), developed and patented the Ash2Salt process in 2015. EasyMining indicates that its parent company Ragn-Sells has "come far in the planning of a full scale Ash2Salt plant at their site in Högbytorp, Sweden."

2.1.5 Robustness/flexibility

According to EasyMining, the process is robust and *can handle different levels of salts* in the fly ash but no details are given concerning flexibility and overall fly ash composition.

2.1.6 Environmental aspects

The process is described as "energy effective" but energy and water consumption is not quantified; it will be dependent on scale and fly ash characteristics. It can be envisioned as a centralized or decentralized solution depending on local conditions. The reduced need for landfilling *is claimed to be* (on average) 20%, and washed ash is to be sent to ordinary landfill. Heavy metals are enriched in another fraction (from step 2) that is hazardous and must be landfilled. Chemicals used include sulphides as well as an undefined "etc.".

2.1.7 HSE

Handling of chemicals requires appropriate routines and procedures for workers on site.

2.1.8 Process complexity and economy

Multi-step chemical method using standard process equipment (tanks, pumps) producing 4-5 fractions is employed. Revenue may be generated from salts and ammonia while the landfill costs will be reduced. Based on these considerations, overall costs are categorised as medium.

2.1.9 Advantages and limitations

+ Recovery of pure salts (and ammonia) with commercialization potential *if approved* by authorities.

+/- Reduction of landfill claimed to be 20% on average, but still need for hazardous and conventional landfill.

- Few data available on tests and performance, including details on flexibility in relation with overall fly ash composition.

2.2 Carbon8

2.2.1 Treatment method

Based on *accelerated carbonation*. Under a gaseous, CO_2-rich (>50 vol.%) atmosphere, the fly ash is encapsulated in a solid, carbonated matrix within 10-20 minutes. This is carried out in the presence of water (and often at slight pressure, e.g. 2 bars) immobilizing most fly ash contaminants. The chemical and physical properties of the aggregate produced (called C8Agg) may allow for construction applications (subject to local regulations, approved in the UK).

2.2.2 Process output

100% fly ash to a lightweight aggregate (C8Agg), either for construction applications (end-of-waste agreement in place in the UK) or to ordinary landfill. Aggregate is made of approximately 50 wt.% fly ash.

2.2.3 TRL

The process is patented and implemented in the UK. ***TRL 9 - fully commercial in the UK.***

2.2.4 Technology provider(s) and references

Carbon8 Aggregates Ltd, daughter company of Grundon, a large UK supplier of integrated waste management, has been developing the process for 15-20 years. Carbon8 has (March 2018) two plants in operation and a third one under construction in Bristol, Aylesford and Leeds respectively. The Bristol plant (first commercial facility, 2012) produces about 50 000 tons C8Agg per year, equivalent to 25 000 tons fly ash.

2.2.5 Robustness/flexibility

The process handles fly ash from several WtE plants, e.g. 5-10 at the Bristol plant where the different fly ashes can be mixed if necessary. Given the large variations in physical and chemical properties of fly ash, it indicates that the process is quite robust and flexible.

2.2.6 Environmental aspects

Energy and water consumption is not quantified. In addition to water and CO_2, cement, sand and sometimes binders and fillers are added to improve hardness. Amounts vary. About 50% of the weight of the aggregate is made of fly ash – reminder is *mostly* carbonates but exact values have not been found by the author.

The process is *claimed to be* CO_2 negative, i.e. "The resulting aggregate has captured more carbon dioxide than is used in the energy required in its manufacture" but no details have been found and it is not clear if CO_2-equivalents from, e.g. transport or construction are included. It is implemented as a centralized solution.

2.2.7 HSE

It is an approved building material in the UK, but the handling of the aggregate during building (dusting) and after demolition in 30-80 years might be problematic.

2.2.8 Process complexity and economy

Carbon8 has been in business for several years so the process is probably commercially viable in the UK but no details were found. The process is mainly based on a single main step (carbonation) and the costs were hence evaluated as low/medium. Marketability of the aggregate will be a central impact.

2.2.9 Advantages and limitations

+ Contaminants are encapsulated in a matrix that is considered stable enough *in the UK* to be used as aggregate.

+ Robust - Handles fly ash from different WtE installations.

+ Proven operation at industrial capacity over several years.

+/- *Claimed to be* CO_2 negative but no details on the overall carbon balance were found.

- Fate of aggregates during and after building demolition in 30-80 years may be problematic.

- Implementation outside the UK must be approved by local authorities. Carbon8 indicates that they could probably handle fly ash from abroad.

2.3 FLUWA/FLUREC

2.3.1 Treatment method

In the FLUWA process, a heavy metal-rich fraction (Zn-rich sludge) is leached from the fly ash using acidic effluents from the wet FGT. It is a multi-stage operation. The remaining filter cake is mixed with the bottom ash and send to non-hazardous landfill *if allowed by local regulation*. In the following FLUREC process, the zinc is recovered as 99.99% metal from the leachate (Zn-rich sludge) by selective-reactive solvent extraction and electrolysis. A mixture of Pb, Cd and Cu is also separated and is fed back as reusable materials to metal recycling facilities. Without FLUREC, the Zn-rich sludge from FLUWA can be sold to smelteries for Zn production.

2.3.2 Process output

For FLUWA. The Zn-containing hydroxide sludge can be sold to smelteries for Zn production while the filter cake is mixed with the bottom ash. Its reuse might be possible in the future (depending on local regulation). On average, 10% of the fly ash (dry basis) will be found as Zn-rich hydroxide sludge and 75% as filter cake.

For FLUWA + FLUREC. Over 85% of Zn is recovered. Cd, Cu and Pb are recovered as a solid mixture, which may be used by smelteries. The final residue can be fed back to the WtE plant with no detrimental effect.

2.3.3 TRL

FLUWA has been commercially available since the 1990s, FLUREC more recently. Several FLUWA industrial installations are in operation, one using FLUREC. ***TRL 9 - full commercial operation.***

2.3.4 Technology provider(s) and references

BSH Umweltservice AG (Switzerland) is selling FLUWA and FLUREC. Thirteen installations are operating in Switzerland and one in Germany. The increase of deployment in Switzerland of the FLUWA technology can *in large part* be attributed to legislation concerning local treatment of hazardous waste and Zn recovery. One FLUREC plant is in operation in Switzerland, and is reported to produce 400 tons pure Zn/year (as well as some Cu, Cd and Pb) from 7400 tons fly ash collected from several WtE plants.

2.3.5 Robustness/flexibility

The number of plants employing the process indicate that it is robust and flexible.

2.3.6 Environmental aspects

Energy, chemicals and water consumptions are not quantified. Water treatment is necessary. The process can be designed as decentralized or centralized. Landfilling is still required but for less hazardous fractions.

2.3.7 HSE

Routines and procedures similar to chemical industry concerning work environment.

2.3.8 Process complexity and economy

Economic profitability is difficult to evaluate. FLUWA process costs are said to be rather high, values of 150 – 250 € per ton FGT residue are mentioned in the literature but they will be plant-specific. FLUREC will produce marketable Zn metal but will add further to the costs.

2.3.9 Advantages and limitations

+ Combination of two waste streams (effluents and fly ash).

+ Recovery of marketable Zn-rich sludge or 99.99% Zn metal as well as Cd, Cu, Pb with FLUREC.

+ Proven industrial operation (FLUWA, FLUREC) at many sites over 20+ years (FLUWA).

+/- No large reduction of landfill needs but the landfilled material is mainly non-hazardous.

- Mixing residues with the bottom ash and/or the waste may not be allowed in all countries. Such a ban may require process adjustments.

2.4 HALOSEP

2.4.1 Treatment method

Multi-stage extraction/separation/chemical method co-processing fly ash and flue gas wastes together with hot scrubber effluents to produce valuable fractions. Two versions, one for wet FGT and one for semi-dry FGT.

2.4.2 Process output

Wet FGT – four fractions are produced (wt.%, dry fly ash weight basis):

(1) *OS (oversized) material*, ca. 1 wt.% *of the dry fly ash*, is sent back to the WtE furnace;

(2) *X-RGA (treated fly ash)*, 60-61 wt.%, can be deposited in ordinary landfills;

(3) *SP (Salt Product)*, 25-30 wt.%, with a quality satisfying CEN TC337 for de-icing agents;

(4) *TMP (Metal Product)*, 3 wt.%, a metal-rich fraction containing approx. 40 wt% Zn that can be recovered.

Semi-dry FGT – four fractions are produced (wt.%, fly ash including FGT residues (i.e. Ca/lime) basis):

(1) *OS (oversized) material*, ca. 1 wt.%, is sent back to the WtE furnace;

(2) *X-RGA (treated fly ash)*, 40-48 wt.%, can be deposited in ordinary landfills;

(3) *SP (Salt Product)*, 42-50 wt.%, with a quality satisfying CEN TC337 for de-icing agents;

(4) *TMP (Metal Product)*, 2 wt.%, a metal fraction that can be processed for Zn recovery.

2.4.3 TRL

Pilot plant tests were reported in 2015. A EU project (LIFE HALOSEP) started in 2016 and is aiming at demonstrating the technology (13 000 t fly ash/year plant) by December 2019. Currently (March 2018), LIFE HALOSEP project partners indicate that they are in the detailed design phase of a full-scale demo plant at Vestforbrænding, Denmark, indicating that ***TRL can be estimated at 6-7*** and TRL 8 could be reached by 2019.

2.4.4 Technology provider(s) and references

The HALOSEP process main developer is the Stena Metall Group, Stena Metall A/S and Stena Recycling A/S (Sweden/Denmark) in collaboration with Danish WtE plants since at least 2015.

2.4.5 Robustness/flexibility

The process has apparently only been tested in one WtE plant using wet FGT and one WtE plant using semi-dry FGT so robustness is difficult to assess at this stage.

2.4.6 Environmental aspects

The additional electricity required, compared to the current fly ash treatment (landfilling), is about 25 kWh/ton fly ash for a 2-3 ton/hour Halosep plant *according to Stena*. It is a decentralized solution so transport of fly ash to a central location is not necessary. Salts and zinc (and eventually scrubber liquid) can be recovered. Landfill needs could be reduced by up to 40-60%. In addition, the use of *X-RGA* as a concrete additive will be explored.

2.4.7 HSE

Work environment (routines and procedures) expected to be similar to chemical industry.

2.4.8 Process complexity and economy

Stena claims that treatment costs for fly ash and scrubber effluents will be reduced by 20% compared to the current alternatives but it is only based on a desk study. It is a multi-step chemical process producing 4 fractions (including 2 products), hence overall costs are estimated as medium.

2.4.9 Advantages and limitations

+ Two waste streams are co-processed (fly ash and effluents).

+ The process should reduce landfilling by 40-60% (it is a goal of the EU LIFE project).

+/- Halosep facilitates Zn recovery but it will require further treatment.

- New products will require new regulations.

- The technology is not adapted to dry FGT systems.

2.5 NOAH carbonation

2.5.1 Treatment method

Stabilization method based on *accelerated carbonation*. The fly ash is mixed with a CO_2 rich gas (typically 16-18 vol.%) from a cement factory or another industrial process. The fly ash is encapsulated in a carbonated matrix within 1-2 hours depending on operational parameters. Most fly ash contaminants are immobilized. An added benefit is the use of a waste stream of CO_2 from an industrial process rather than CO_2 from gas cylinders.

2.5.2 Process output

100% of carbonated fly ash will go to landfill for hazardous wastes due to contaminants concentrations.

2.5.3 TRL

Two series of tests with real flue gas were carried out in 2015 and 2016, mainly with manual operation of a prototype (1 ton batch, 1/10 of expected full-scale). Challenges (both design and operation) were identified and some of them solved. New tests are planned in an automatized, continuously operated full-scale system (10 ton/hour per reactor, 4 reactors) scheduled for 2018. Estimated ***TRL 5-6 large scale prototype – prototype system per March 2018.*** Given the current situation and information available, first of a kind commercial system (TRL 8) will most probably require 2-4 years and about 2 more years for TRL 9.

2.5.4 Technology provider(s) and references

NOAH AS (Norway) has been working on this process for about 6 years.

2.5.5 Robustness/flexibility

Tests have been carried out on a variety of fly ashes and the process has exhibited satisfying robustness.

2.5.6 Environmental aspects

Energy consumption *for carbonation* was roughly estimated by NOAH at 5-6 kWh per ton carbonated fly ash. Water consumption corresponds to 18-19 wt% of the final carbonated material. No water effluents are produced in the process. No other additive is used in the carbonation process. The process can probably be used either as a centralized or a decentralized treatment system. Concerning CCS, tests indicate that 75 kg CO_2 are captured per ton fly ash but overall CO_2 accounting is not known.

2.5.7 HSE

Manual operation is reported as challenging so automatization is to be implemented.

2.5.8 Process complexity and economy

One main treatment step (using standard equipment) to produce one fraction to be landfilled (no product). Operating costs *are described as* low but no details are given. Unsure if income from CCS can be expected. Overall, given that the process is mainly based on a single step (carbonation), the costs are categorised as low/medium.

2.5.9 Advantages and limitations

+ CO_2 is from an industrial exhaust gas - 75 kg CO_2 captured per ton fly ash. Possibility to use flue gas from WtE plant will be explored – combination of two waste streams.

- No material recovery, the carbonated material goes to hazardous landfill due to its contaminants concentrations.

2.6 NOAH Langøya

2.6.1 Treatment method

Multi-stage acid/base neutralisation process of the alkaline fly ash together with a spent stream of sulfuric acid from Kronos Titan. After the addition of lime, a stable gypsum phase is formed that, under ageing, encapsulates the fly ash contaminants before it is landfilled on-site in an old quarry (hazardous waste landfill) on Langøya island. The landfill capacity will be used by 2022-2026.

2.6.2 Process output

100% of the encapsulated fly ash to landfill for hazardous wastes (Langøya island, Norway).

2.6.3 TRL

In operation since the early 1990s, the process handles several hundred thousand tons hazardous waste (not only MSWI fly ash) each year. ***TRL 9 - fully commercial.***

2.6.4 Technology provider(s) and references

NOAH AS in Norway has developed the process since the early 1990s.

2.6.5 Robustness/flexibility

The process treats fly ash from approximately 80 plants all over Scandinavia, as well as a variety of other wastes streams. Given the large variations in physical and chemical properties of fly ash, hence the process is judged as robust and flexible.

2.6.6 Environmental aspects

Energy consumption is about 7-8 GWh/year to process 300 000 tons ash from waste incineration, 150 000 tons industrial wastes and 50 000 tons spent acid. Fresh water consumption is 30 000 m^3. Process water usage is about 700 000 m^3 (recycled from neutralization process). Surplus water, after cleaning, is discharged to the sea. Centralized solution so transport of fly ash is necessary. Chemicals used on the site include burnt lime (15 000 ton), cement kiln dust (12 000 ton), sodium hydroxide (4000 ton as waste and 320 ton for water purification).

2.6.7 HSE

The handling of large quantities of chemicals and hazardous wastes outdoors requires appropriate equipment and procedures for workers on-site.

2.6.8 Process complexity and economy

NOAH has been in commercial operation since the 1990s and both waste components (fly ash and spent acid) give stable revenues. Multi-stage chemical process producing a single main fraction to be landfilled: overall costs are categorised as low.

2.6.9 Advantages and limitations

+ Two waste streams are combined, fly ash and spent sulfuric acid.

+ Flexible and robust: handles ash from approximately 80 WtE installations and proven operation at large capacity (several hundred thousand tons per year).

- Dependency on a single actor for spent sulfuric acid. Use of new sulfuric acid will increase disposal costs.

- No material recovery.

2.7 NORSEP

2.7.1 Treatment method

Multi-stage acid/base washing/extraction method aiming at producing non-hazardous fractions and valuable products from fly ash. Based on the OiW (Oil in Water) process that was developed to remove water traces from oil.

2.7.2 Process output

Three main fractions: (1) an insoluble fly ash fraction (expected to be non-hazardous) to be further transformed into valuable products; (2) a metal-rich fraction to be sent to further metal recovery and (3) a salt-rich water fraction; its post-treatment is not part of the Norsep process. Mass balance for the concept is not available. Further post-treatment is uncertain. Final need for landfilling uncertain.

2.7.3 Maturity level /TRL

Per March 2018, laboratory tests have been carried out at Herøya Industripark (Porsgrunn, Norway). A prototype is being designed (approximately 1 m^3 slurry per hour) and is expected to be ready summer 2018, with the first tests results in late 2018. If results are satisfying, planning of an industrial pilot, i.e. TRL 6-7, at EGE Oslo Haraldrud WtE plant will start. An EU project application is planned in May 2018. ***Current TRL is estimated at 3-4 – applied research/small-scale prototype.*** A possible timeline: 2-4 years to first pilot followed by 2-4 years to first demonstration of a full-scale system. First commercial operation (TRL 8-9) may take an extra 2-4 years.

2.7.4 Technology provider(s) and references

Norsep AS (parent company: OiW Process AS) was established in 2015 to develop the process, building upon the OiW process. Cooperation is underway with other actors, e.g. Scanwatt (see 2.10).

2.7.5 Robustness/flexibility

Robustness is not proven yet due to early development stage and limited operational data.

2.7.6 Environmental aspects

Energy and water consumption not quantified. Surplus water is expected to be released after cleaning.

It is a decentralized solution, on-site at each WtE plant.

The main chemicals used in the extraction processes *are expected to be*, at least partly, from industrial waste streams, e.g. scrubber effluents for acid, to limit the use of new resources.

Final need for landfilling is not specified.

2.7.7 HSE

The handling of large quantities of chemicals requires appropriate equipment procedures for the workforce.

2.7.8 Process complexity and economy

Economy is difficult to assess at this stage. It is a multi-stage chemical process producing 3 main fractions that may require various post-treatments to become marketable products so costs will probably not be in the low category.

2.7.9 Advantages and limitations

+ Aiming for materials recovery and marketable products.

+ Use of waste acid and base = limited use of virgin resources.

- Early stage of development and limited data available, difficult to evaluate all aspects. Especially, no details have been found on amounts and properties of final fractions and the eventual post-treatments.

- New products = need for new regulation.

2.8 Renova

2.8.1 Treatment method

The fly ash is washed with acidic process water from scrubber leading to the formation of (1) a washed fly ash residue that is brought back to the WtE furnace and (2) a Zn-rich leachate containing up to 70 wt.% of the original Zn and heavy metals. Zn is recovered from the Zn-fraction using precipitation, flocculation, filtration and water washing to obtain a raw material suitable for Zn production. The Zn cake contains 50-80 wt.% Zn as $Zn(OH)_2$ on dry basis.

2.8.2 Process output

Two fractions: (1) Washed fly ash residue back to WtE furnace (approx. 70wt% of total fly ash according to lab tests) – 90% stays in the bottom ash with no detrimental effects reported, 10% as fly ash. The residue could be directly landfilled as ordinary waste (post-treatment may be necessary); (2) $Zn(OH)_2$-rich cake with potential for Zn recovery.

2.8.3 TRL

After successful laboratory tests, pilot scale studies (100 kg/h ash, which corresponds to 1/16th of the total ash flow from the full-scale plant) were carried out and evaluated at Renova WtE plant (550 000 t MSW/y) in Gothenburg, Sweden in 2016, confirming the potential of the treatment method. ***TRL 6-7 – prototype/demonstration system***. Reasonable timeline to TRL 9 is estimated to approx. 3-5 years.

2.8.4 Technology provider(s) and references

Renova and Chalmers University of Technology (Sweden) are the main developers of the technology.

2.8.5 Robustness/flexibility

It seems that pilot scale studies have only been carried out at a single WtE plant so far. Tests need to be repeated with various fly ashes. Fly ash from dry FGT could in principle be treated (despite their high Ca content) but no acid effluent is readily available in this case.

2.8.6 Environmental aspects

Energy and water consumption is not quantified.

Washed fly ash is sent back to the furnace and 90 wt.% stay with the bottom ash with no detrimental effects reported on its overall quality according to conducted tests. Uncertain if this can be applied in all countries and installations as it may be considered as a way to dilute the washed fly ash with the bottom ash.

2.8.7 HSE

Work HSE procedures are assumed to be similar to existing chemical industry practices.

2.8.8 Process complexity and economy

Multi-step chemical & thermal process producing 3 fractions including $Zn(OH)_2$ (lower value than metal Zn); overall costs are expected to be medium.

2.8.9 Main advantages and limitations

+ Combines two waste streams.

+/- Zn recovery as $Zn(OH)_2$, not Zn metal.

- Putting back the washed ash into the WtE furnace may not be allowed in all countries as it could be seen as fly ash dilution. This ban may require process adjustments.

- Quite similar to the already commercial FLUWA technology (except for the thermal part), see chapter 2.3.

2.9 SCANARC ARCFUME

2.9.1 Treatment method

ARCFUME is a thermal fly ash treatment method using a plasma. The fly ash is melted and vitrified at approximately 1250°C. It is converted into a zinc- and lead-rich filter product for metal extraction, and a metallurgical slag, free from heavy metals, with potential to be classified as a product.

2.9.2 Process output

From a 2016 pilot-scale test campaign in Hofors, Sweden: 3890 kg input (80% fly ash, 9% sand, 8% water and 3% coal) produced 3905 kg slag and 208 kg filter cake (65% moisture) containing about 95% of original Zn and Pb. The slag is expected to be non-hazardous (low leaching) and could be sold for metallurgical purposes while Zn and Pb may be extracted from the filter cake.

2.9.3 TRL

Industrial sites are or have been using this technology in Europe but mostly in the metallurgical sector. No plant processing fly ash from MSW. Given the pilot-scale campaign carried out in 2016, ***TRL is estimated to 5-7 for fly ash from MSW incineration***. Reasonable timeline to TRL 9 is estimated to 3-6 years.

2.9.4 Technology provider(s) and references

SCANARC Plasma technologies AB (Sweden) and its predecessors have been developing the process since the 1970s. Nine industrial sites are or have been using the technology but not for fly ash from WtE. Plasma-based solutions for fly ash (but also MSW thermal conversion) are available from Asian companies but in this report priority is given to solutions designed for the European market.

2.9.5 Robustness/flexibility

In addition to the pilot test using fly ash from a WtE plant (fluidized bed), SCANARC indicates that other fly ash samples have been tested with good results but results have not been published. Assessing overall robustness will require more data. A key aspect is the additive (e.g. sand) to ensure vitrification.

2.9.6 Environmental aspects

A 2016 feasibility study by Avfall Sverige and SCANARC for a 100 000 ton fly ash per year installation - the maximum SCANARC could deliver - indicated an energy use of 633 kWh per ton wet raw material (i.e. fly ash and additives such as sand). In addition, 185 kg water and 21 Nm^3 LNG are necessary per ton raw material. It is a centralized solution so transport of fly ash is necessary. The gas treatment system will be like the ones found in high temperature metallurgical industries.

2.9.7 HSE

HSE requirements and work environment are similar to high temperature metallurgical processes (dust, heat, noise, melting masses).

2.9.8 Process complexity and economy

The 2016 feasibility study indicates a treatment cost per ton fly ash of about 1300 SEK (130-140 €), the main cost being electricity. Thermal treatment methods have high treatment costs and are sensitive to electricity prices. Another reference indicates costs of 100-600 € per ton ash. The total investment was estimated to 200 MSEK for 100 000 tons fly ash per year. Metal recovery and sale of slag could reduce the costs, but probably to a limited extent. Amount and nature of additives ensuring proper vitrification will also impact economy.

2.9.9 Advantages and limitations

+ Pb and Zn may be extracted, while the slag may be a metallurgical product (not fully specified).

- High operation costs sensitive to electricity prices and high investment costs.
- Energy-intensive process.

2.10 SCANWATT

2.10.1 Treatment method

The ash is washed (salts) with water and dried at the WtE plant. Then, the fly ash is transported to a central facility where it is thermally treated, i.e. vitrified, at high temperature (range not known) by mixing with a liquid metallurgical slag. The vitrified slag mixture has the potential to be used in road building applications *if regulations allow* (composition and leaching properties to be assessed).

2.10.2 Process output

If leaching of contaminants is below legislated values *and* legislation allows, 100% of the vitrified material could be used as material for road building. The alternative would be landfilling.

2.10.3 TRL

Tests (exact scale unknown, they are described as "run trials in tons scale") have been performed at Elkem research centre in Kristiansand in 2013-2016. The results show that almost all contaminants (metals) are satisfactorily immobilized (except for Sb), i.e. exhibit low leaching values. Scanwatt indicated in 2016 that 5 to 7 years would be necessary to fully develop the concept but TRL is difficult to ascertain due to limited details – ***TRL is estimated at 3-6 laboratory tests – (small/large) scale prototype – prototype system.***

2.10.4 Technology provider(s) and references

Scanwatt AS in Norway has been developing the concept since 2013. Scanwatt is currently cooperating with Norsep (see 2.7) on an EU proposal (deadline May 2018).

Similar high temperature solutions are commercially available from Asian technology providers but focus in this report is on technologies adapted for the European market.

2.10.5 Robustness/flexibility

Robustness is difficult to assess. However, high-temperature thermal treatments are usually reported as flexible.

2.10.6 Environmental aspects

Water consumption (for washing) is not quantified. Surplus water is discharged to the sea.

Energy consumption is not quantified but high temperature thermal treatments are energy-intensive. It is indicated that the process should be integrated with metallurgical processes but no details have been found, also concerning emissions.

Using the vitrified fly ash as a construction material will have to fulfil environmental standards.

Scanwatt states that it could be operated both as a centralized or a decentralized solution.

2.10.7 HSE

Work environment and procedures are expected to be similar to high temperature metallurgical processes (dust, heat, noise, melting masses).

2.10.8 Process complexity and economy

Investment and operating (i.e. energy) costs are usually high for high-temperature thermal treatment methods.

Energy prices will be a key economical factor. If the vitrified residue can be sold, it may provide additional revenues.

2.10.9 Advantages and limitations

+/- Ash stabilization and utilization would mean no need for landfilling but legislative uncertainty concerning both mixing with metallurgical slag and utilization of the vitrified product could hinder concept.

- Energy-intensive process.

2.11 Terrateam

2.11.1 Treatment method

Cement solidification/stabilisation of fly ash before landfilling in a closed down zinc, lead, copper mine. Landfill capacity will be utilized by approximately 2031 (with a treatment rate of 100 000 tons hazardous waste/year).

2.11.2 Process output

100% of the solidified fly ash to landfill for hazardous wastes in Mofjellet, Norway.

2.11.3 TRL

In operation since the early 1990s, the process is mature and now handles 100 000 tons hazardous waste each year out of which about 15 000 tons fly ash from WtE. ***TRL 9 - fully commercial.***

2.11.4 Technology provider(s) and references

Miljøteknikk Terrateam AS in Mo i Rana, Norway, has been operating the landfill since 1993. The treatment method is similar to solutions used in other EU countries.

2.11.5 Robustness/flexibility

The process receives fly ash from many plants as well as other industrial wastes. Given the variations in physical and chemical properties, this indicates that the process is robust and flexible. However, ashes must fulfil pre-defined criteria so not all will be accepted.

2.11.6 Environmental aspects

The total energy consumption in 2014 was 1917 MWh diesel and 799 MWh electricity for the handling, treatment and storage of approximately 140 000 tons of hazardous waste.

Water, cement and additives consumption for solidification is not quantified. The addition of cement and additives increases the amount of waste to landfill: *typically*, about 50% of the fly ash dry weight is added as cement and additives and 30-100% as water.

It is a centralized solution so transport of fly ash is necessary.

2.11.7 HSE

Equipment and method used for solidification are comparable to standard practices in concrete/cement industry. The solidified product is easy to handle and the risk of dusting is low.

2.11.8 Process complexity and economy

Cement solidification costs are quite country-specific. A EU reference estimates it to about 25 €/ton residue. It is an established method with a single main step to produce one fraction for landfilling, so overall costs are estimated to be low.

2.11.9 Advantages and limitations

+ The fly ash is stabilized using readily available technologies. Proven operation over many years.

+ Robust technology, handles fly ash from different WtE plants.

- No material recovery.

- Cement solidification usually increases the amount of material to landfill by a factor 2-3.

3 TRL evaluation: overview

Estimated TRL overview for all technologies considered in this report. Commercial technologies first (in alphabetical order) followed by upcoming technologies in decreasing TRL order. Countries of application are mentioned.
The column on the right gives an approximate evaluation of the time necessary to full industrial application (TRL 9) based on estimated TRL and current activities.
These estimates were made using experience from previous technology development/demonstration projects, in short: each "jump" (from lab to first prototype to full-scale demo to commercial system) usually takes a minimum of 2-4 years. The lower and/or broader the TRL evaluation, the more uncertain the evaluation is.

Treatment technology	**TRL estimate**	**Countries of application**	**TRL 9 expected within***
Carbon8 – solidification (carbonation)	TRL 9	UK. Will probably require new legislation in Norway.	n.a.
FLUWA/FLUREC – chemical extraction/stabilization (and thermal treatment)	TRL 9	Switzerland, Germany. Will probably require new legislation in Norway.	n.a.
NOAH - chemical neutralisation/stabilisation**	TRL 9	Norway/Scandinavia	n.a.
Terrateam – cement solidification**	TRL 9	Norway/Scandinavia	n.a.
Renova – chemical extraction (and thermal treatment)	TRL 6-7	Will probably require new legislation for Norway	3-5 years
Halosep – chemical extraction/stabilization	TRL 6-7	Will probably require new legislation for Norway	3-5 years
Scanarc – plasma vitrification	TRL 5-7	Will probably require new legislation for Norway	3-6 years
Ash2Salt – salts extraction	TRL 5-7	Will probably require new legislation for Norway	3-6 years
NOAH – carbonation**	TRL 5-6	Will probably require new legislation for Norway	4-6 years
Scanwatt – furnace vitrification	TRL 3-6	Will probably require new legislation for Norway	5-8 years
Norsep – chemical extraction/stabilization	TRL 3-4	Will probably require new legislation for Norway	6-12 years

* The evaluation does not consider additional time that may be necessary to obtain approval by authorities.
** No material recovery or re-use.
n.a.: not applicable.

4 Other options

Several other technologies at various stages of development were considered for the current evaluation. However, ultimately, they were omitted from further review. The omitted technologies are given in the list below together with a brief motivation to why they were omitted.

- COSMOS Fenix (stable fly ash silica-based materials for various applications) – early stages of development and unclear future
- Ferrox – was offered commercially in the early 2000s but no information found concerning recent industrial application
- Fly ash mixing in asphalt or cement – in use in several countries (for various waste fractions) and has both advantages and disadvantages but it seems that there is no/little political will in Norway to promote such solutions (similar known R&D activity in Norway: "Gjenbruksprosjektet" by Vegvesen)
- Bioleaching – early stage of development
- Advanced electrochemical/electrolysis-based methods – early stages of development (activities at DTU in Denmark)
- Microwave treatment – early stage of development
- DHI, VKI, DRH methods – no recent information found
- Other thermal (plasma, furnace) technologies (mainly from Asia) – technologies adapted to European market have been prioritized in this review
- Solidification/stabilization processes (e.g. Inertec) – similar technologies evaluated in this report
- 3R, similar to FLUWA and consequently not evaluated

5 Comments and considerations on the future of fly ash treatment

Looking at this overview, one question remains - what is the best technology for fly ash treatment in Norway/Scandinavia in the coming years? The answer is simple: there is *no silver bullet* given the existing legal framework and the current technological status.

The **current EU/Norwegian framework** sets *clear* boundaries – when it comes to waste treatment, material recovery and re-use is to be implemented but one must also integrate environmental considerations, resources supply and demand and economic profitability/viability. Having said that, one has not progressed an iota towards selecting a solution, but it seems that no single solution currently answers the call for a strong move towards large-scale material recovery while ticking all the boxes (environment, resource management, economy).

While **the current solutions in Norway** (NOAH and Terrateam) are viable economically and answer to several BAT requirements for the physico-chemical treatment of waste, they do not allow for any material recovery. Both actors have R&D initiatives to improve the situation but large-scale implementation is still unsure.

Other commercial solutions (e.g. FLUWA-FLUREC, Carbon8) have different approaches but they are *mainly* implemented because of local, country-specific decisions: FLUWA/FLUREC in Switzerland because of limitations concerning the treatment of hazardous wastes and requirements concerning metal recovery and Carbon8 to promote fly ash re-use (an end-of-waste agreement is in place for the UK). Their implementation in other EU countries would probably not be straightforward as they will require approval by local authorities. Some technologies *are said to be near commercial application*, in the sense that the technology providers affirm that they are ready to enter discussions for the erection of full-scale installations with any interested parties, but no full-scale commercial plants using WtE fly ash is operating yet (Scanarc, Halosep, Ash2Salt). These, together with other **upcoming technologies** (Renova, Scanwatt, Norsep, NOAH carbonation), all offer a proportion of materials recovery and/or fly ash re-use. Their overall cost-benefit and robustness, i.e. their ability to treat all types of highly heterogeneous fly ash, are often difficult to evaluate but the need for landfilling will not be completely removed. Several new methods also aim at, parallel to material recovery, producing fractions that can be disposed of in landfills for non-hazardous wastes. This two-prong effort - materials recovery and less-hazardous remaining fractions - is important and should be preferred when determining the *overall performance* of a novel technology. New technologies often refer to processes with multi-outputs. This allows for tailored-made treatment of the various fractions but results in a more complex process design with increased costs. Two additional and intertwined aspects of any technology should also be considered: economies of scale and optimal treatment capacity per installation.

Why is **material recovery** still so elusive? It is a strong component of the upcoming circular economy but the technologies offering material recovery processes do not appear cost-efficient given the current conditions and often only consider a limited portion of the fly ash (Zn, salts). There are large numbers concerning the millions of NOK being buried within the fly ash, but it is not so easy so as to pick up these metals and collect the revenues. Fly ash are not mineral ores, some metals can be found at high concentrations but they are difficult to extract because they are often found in various chemical forms in a complex, heterogeneous mixture, and, while being extracted, they are collected in forms that have limited economic value, e.g. $Zn(OH)_2$ is not the same as metal Zn. R&D efforts should intensify to make recovery an integral part of fly ash treatment.

Security of supply considerations, for rare metals that can only be purchased from a handful of faraway countries for example, can and should come into account but other waste streams may be more relevant to obtain them in satisfying quantities (and cost-efficiently), e.g. EE wastes.

The elaboration of **new products**, mainly for the building sector, incorporating the bulk of the fly ash after solidification or vitrification seems like an attractive solution. In other words, immobilizing the fly ash contaminants in a glassy or carbonated matrix and then re-use them in roads and/or buildings. However, this raises several points: incorporating large quantities of additives could be regarded as a way of diluting the fly ash before re-introducing them into in the environment and vitrification is very energy-intensive. True, the materials are stable (within accepted leaching limits) and will have to answer to established standards but the monitoring of their fate during a life cycle over several decades might be difficult. Not to say that they are *bad* but that the large-scale introduction of secondary products is also a political, societal decision, not only a technological and economic one.

Again, it seems that there is *no universal method yet*. Tailor-made solutions for multi-flow treatment and different arrangements of a given method for different qualities, country-specific regulations (and scale) will be an important part of the *complete solution(s)* in the future. In any case, important questions are still technological development and cost-efficiency but they cannot, they should not, be the only criteria. Research and innovation should continue and be encouraged.

Legislation. Contrary to many WtE aspects, there is no consensus concerning ash at the EU level, including key aspects such as leaching tests and limits. The regulatory framework is adapted to the needs, limitations and long-term vision of a given country concerning waste management. The lack of landfilling space in Japan for example, makes it acceptable to use expensive slagging reactors to stabilize the ash and acceptable to re-use the resulting materials. Country-specific challenges will guide the future of fly ash treatment, also in Scandinavia.

Future. What about the future of fly ash treatment in Scandinavia? **Important trends** may be foreseen:

- Circular economy will impact WtE, especially MSW composition and amounts, that will in turn impact fly ash quality and quantities.
- Innovation and R&D is constantly improving the feasibility of cost-efficiently recovering more materials in marketable forms. The exact timeline is difficult to assess and will depend on the intensity (and success) of the present and future efforts and investments of both private and public actors.
- For metals – traditional mining may become more expensive for some scarce elements and secondary sources, such as fly ash, will become relevant in the medium or long run.
- Combining technologies (chemical and thermal for example) may be the road to *complete solutions* with limited landfilling needs but more complex solutions mean higher costs.
- Recovery should go hand in hand with reducing the hazardousness of the fractions to be landfilled.
- Common and clear EU regulations, joint standards and goals are challenging but EU is still an important arena to exchange opinions, knowledge and experience.

The **timeframe** concerning the arrival of new technologies (1) proposing a significant materials recovery rate for scarce or strategic elements; (2) limiting the need for hazardous landfill and (3) achieving (1) and (2) in a cost-effective manner is probably a few years away, maybe in a 5-10 years perspective, and several challenges may still appear before they reach commercial stage. Sufficient (private and public) support should be given to present and future R&D and innovation on the topic. Competition and emulation between the various technologies will drive forward technological and environmental development to the benefit of all.

Not surprisingly, the implementation of the preferred solutions will evolve along the technological and economic lines with some push (or pull) from the society and regulative bodies. Are there any upcoming **(non-technological) game changers?** Several long-term strategic decisions, not related to technology development, might significantly affect the future, here are some examples: a different Scandinavian fly ash treatment strategy (e.g. fly ash to be nationally treated), incentives to achieve specific goals (e.g. mandatory recovery of Zn or Pb or other elements, focus on CCS, etc.), bans or increased taxes on landfills over time and such.

What to do now? Promoting technological development together with long-term strategic thinking should ensure that Norway and Scandinavia make choices beneficial to the whole society.

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A Appendix

A.1 Technology Readiness Levels

Each level is roughly described (reference: European Commission).

TRL 1: Idea. Unproven concept, no testing has been performed.

TRL 2: Basic research. Principles postulated and observed but no experimental proof available.

TRL 3: Applied research. First laboratory tests completed; proof of concept.

TRL 4: Small scale prototype built in a laboratory environment ("ugly" prototype).

TRL 5: Large scale prototype tested in intended environment.

TRL 6: Prototype system tested in intended environment close to expected performance.

TRL 7: Demonstration system operating in operational environment at pre-commercial scale.

TRL 8: First-of-a-kind commercial system. Manufacturing issues solved.

TRL 9: Full commercial application, technology available for consumers.

"Time to TRL 9" estimates were made using experience from previous projects. In short: each "jump" (from lab to first prototype to full-scale demo to commercial system) usually takes a minimum of 2-4 years. The lower and/or broader the TRL evaluation, the more uncertain the evaluation is.

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