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# FUTURE SAFE WTE FLY ASH HANDLING

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# 1. INTRODUCTION

Thermal incineration forms various types of residue originating from the content of non-combustible and non-volatile components in the waste, the ash contents. The vast majority of ash forms on the incineration grate as bottom ash which comprises approximately 18 % of the total waste stream. During cooling of the flue gas ashes also precipitates in the boiler which comprises approximately 2 % of the amount of waste. The last and most fine particles fraction of the formed ash is the so-called fly ash, the fly ash follows the flue gas flow from incineration on the grate through the boilers. The size of the fly-ash particle entails that special treatment procedures are needed, and fly-ash is removed from the flue gas during the flue gas treatment.

The nature of fly-ash depends on the waste incinerated, but due to its formation by relatively low-temperature condensation in the boiler it has increased content of volatile heavy metals like zinc and lead and the fly ash has a high content of chloride.

Today fly-ash from waste incineration in Denmark will be disposed of either to Norway or Germany. In Norway, the alkaline nature of the fly ash is being utilised for neutralization of acid waste streams and subsequent the mixture is solidified (natural process from the reaction) and filled in a former lime mine on Langøya. I Germany the fly ash is being utilised as a backfilling material in salt mines. The choice of Norway or Germany mainly relies on transportation costs and material acceptance fees.

No solution for the treatment of the fly ash exists in Denmark and disposal abroad has become a common practice. In the search for a national solution for fly ash handling a comprehensive study of various treatment techniques have been carried out with a special focus on maturity of the various technologies in respect to technical performance and commercial availability as well as material recycling potential. Life cycle assessment of selected techniques has been performed as well.

Among a vast number of solutions, two treatment techniques are selected for their ability to ensure low environmental impact, maximum recovery potential, minimum need for landfill and safe handling of harmful and unwanted heavy metals. Only treatment techniques with high TRL score (Technology Readiness Level) and techniques that are in commercial trial and that can be implemented in full scale with 5 years did pass the selection.

In this phase various treatment techniques is studied with the aim of a financial feasibility assessment. The assessment will compar future options with the common practice of 2019 in Denmark which is treatment and storage at Langoya, Norway (or treatment and storage in German salt mines).

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# 2. EXECUTIVE SUMMARY

A business case has been evaluated for two future possible methods of treatment of fly ash in Denmark to evaluate the financial impact of introducing such recycling of the fly ash and a potential national solution.

The two methods were fly ash washing with acid scrubber water and production of an aggregate from fly ash to be recycled. These two methods were exemplified by the FLUWA process for washing and the Carbon8 process for use as aggregate and the methods was compared to current costs. These two methods were examined in a number of process variations.

The conclusion is that all assessed options will most probably be more expensive than todays solutions ranging from a similar cost as today for Caron8 and up to more than four times the cost with washing and recovery of zinc as a pure metal for recycling. It is also concluded that the scenarios with most recycling unfortunately also were the most expensive to perform. It is concluded that rising costs from just below 1 000 DKK/tonne of fly ash today to a cost of more than 3 000 DKK/tonne has the potential to ensure recycling of materials with a total value of around 400 DKK/tonne.

# 3. TREATMENT TECHNIQUES

Two treatment techniques are selected for further financial assessment. The selection is based on the ability of the treatment techniques to ensure low environmental impact, maximum recovery potential, minimum need for landfill and safe handling of harmful and unwanted heavy metals. For further description of the various treatment techniques and the technical and environmental assess please refer to memo 02 on *Technology description and factsheet* and report on *Life cycle assessment*. From the shortlisted techniques the following two treatment techniques have been selected for their high score on technology Readiness Level and their ability to be implemented commercially within the short term. The Fluwa/Flurec technique at the same time represent similar processes comprising different types fly ash washing like the Halosep or IPU concept.

- Carbon8
- Fluwa/Flurec

In the following, a short technical description of the processes is provided with key process figures.

## 3.1 Carbon8

Carbon8 is an English treatment process, which uses water and $CO_2$ to stabilize fly ash and inhibit leaching of heavy metals from the final product. Sand and cement are mixed in as well to increase the mechanical stability of the product as well as to decrease leaching. Carbon8 Systems is the first company to use Accelerated Carbonation Technology which is a treatment for industrial wastes and contaminated soils with carbon dioxide.

The stabilized fly ash product (Cement pellet aggregate) is sold as a filler aggregates in concrete blocks.

### 3.1.1 TECHNIQUE DESCRIPTION

Fly ash reacts with carbon dioxide in the same way as lime-based mortar forming insoluble carbonates from the alkaline oxides and hydroxides present in the fly ash. When the reaction conditions are carefully controlled, this reaction can be accelerated, taking place in minutes rather than months or years resulting in the formation of an artificial limestone matrix in the final product and thus many metals become captured as stable carbonates locking up heavy metals.

The process comprises of the following steps

1. Initial carbonation of the fly ash
2. Blending with reagents (cement and sand)
3. Pelletizing/curing and final carbonation

The process is outlined in Figure 3-1

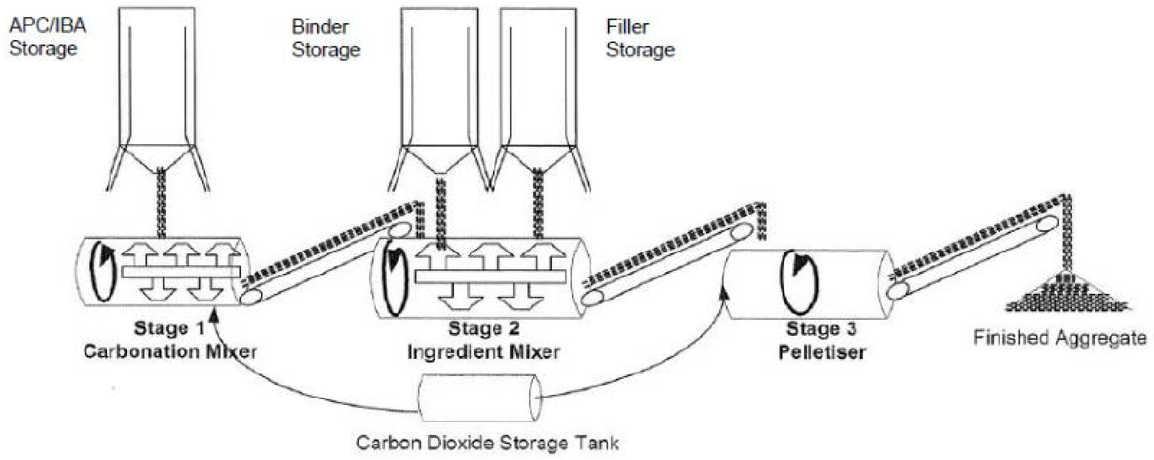

**Figure 3-1 Process flow diagram of the Carbon8 process**

Fly ash is produced and stored temporarily on-site at the waste to energy facility. Cement is a fine powder and storage in silo enable bulk supply of the chemical. 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 as liquid in tank trucks and stored in a tank. Alternative the CO2 from a stack can be ulaised if the location is in the proximity of a flue gas pipe.

Three mixers are used in series to convert the fly ash into the hard rounded pellets, that are suitable as replacement aggregate in concrete blocks.

The process is in commercial application since 2012 and there are three plants operating in the UK from July 2018. The process has a high material recovery rate; however, commercial success 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% $CO_2$ thus production of 15 kg of fly ash per tonne of waste corresponds to an uptake of 3 kg $CO_2$ per tonne of waste. 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. The release of fossil $CO_2$ from the incineration is in the magnitude of 100 times more than this uptake thus a process based on internal carbon capture will not be limited by $CO_2$ availability.

### 3.1.2 KEY FIGURES

Consumption and production for 1000 kg of fly ash (dry matter) with the Carbon8 process is shown in Table 3-1 and from the table it is seen that the process is a “dry” process with no effluent of wastewater and/or production of residues.

| Consumption | Unit | Value |
|---|---|---|
| Fly ash, dry matter | Kg, dry matter | 1,000 |
| Water | Kg | 400 |
| $CO_2$ | Kg | 100 |
| Cement | Kg | 240 |
| Limestone (farmer quality, 10 % $H_2O$) | Kg | 900 |
| Power | kWh | 10 |
| Compressed air | $Nm^3$ | 400 |
| **Production / output** | **Unit** | **Value** |
| Carbon8 aggregate | Kg | 2,500 |

Table 3-1 Overall mass balance of Carbon 8 process with consumables and production figures.

## 3.2 FLUWA / FLUREC

FLUWA and FLUREC are swiss techniques used to extract selected heavy metals from the fly ash in a multistage cascade. The first process step is the FLUWA where acid water from a wet flue gas scrubber is mixed with the fly ash for leaching selected metals in the fly ash. Subsequent filtration and washing create a metal depleted filter cake and a metal enriched filtrate solution. The washed filter cake is then recirculated to the combustion chamber for dioxin destruction. The metal enriched filtrate may be subject for precipitation of metal hydroxides forming a sludge that is exported abroad. The FLUWA process may be combined with the FLUREC process where the metal-enriched filtrate solution is further reprocessed to yield “pure” metal fractions.

### 3.2.1 TECHNIQUE DESCRIPTION

The FLUWA process is the initial process and the process may be performed as the only process. The FLUREC process is an extension of the FLUWA process which provides further treatment and recovery steps. For this reason, the two processes are described separately.

As the FLUWA and FLUREC process extracts salts (mainly chlorides, sodium, potassium and calcium), the processes may be equipped with a special amendment for salt recovery as a solid product. The aim of this solid salt recovery amendment is to avoid disposal (discharge) of salty water and to gain the value of the salts as road salts. The latter use requires the salt to achieve a certain level of purity although this is expected to be achievable considering the prior wastewater treatment facility. The solid salt recovery process comprises of a combination of evaporation and drying processes, and the process will not be described in further technical terms.

#### 3.2.1.1 FLUWA process

In the FLUWA process the fly ash is leached first with an acid solution (originating from an acid wet scrubber) followed by leaching and rinsing with water in a multistage cascade extraction and the extraction process is controlled by the alkalinity of the fly ash, acidity of the scrub water, liquid to solid ratio, redox potential, temperature and leaching time. To enhance the extracting, the process is maintained oxidized (high redox potential) by addition of an oxidizing agent such as hydrogen peroxide ($H_2O_2$).

Apart from the leaching of heavy metals from the fly ash formation of gypsum ($CaSO_4 \cdot 2H_2O$) does also take place.

After 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 bottom ash.

The metal enriched filtrate is fed to a dedicated wastewater treatment plant, where the soluble metals are transformed to insoluble metal hydroxide precipitates by addition of lime. The metal precipitate is then filtrated and pressed into a metal hydroxide sludge which is then exported abroad, and the metals are recovered in smelting plants.

The metal enriched filtrate may also be used for direct metal recovery in the so-called FLUREC process. See next section. The FLUWA process is illustrated together with the FLUREC process in Figure 3-2.

#### 3.2.1.2 FLUREC process

In the FLUREC process metal enriched filtrate form the FLUWA process is further processed.

In the FLUREC process lead (Pb), copper (Pb) and cadmium (Cd) are separated from the filtrate by a cementation process. Thereby zinc (Zn) powder is added to the filtrate as reducing agent and metals more noble than Zn are reduced and 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 filtrate from the cementation (cement filtrate) process contains Zn, not only from the added Zn powder (the cementation process dissolves the Zn), but the extraction process in the FLUWA dissolves Zn from the fly ash. The soluble Zn is separated selectively from the cement filtrate in a solvent extraction step. For this purpose, the Zn is trapped by a water-insoluble organic complexing phase and up to 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, and the final electrochemical process produces pure Zn. The recycled Zn metal is sold on the market.

The FLUREC process is illustrated together with the FLUWA process in Figure 3-2.

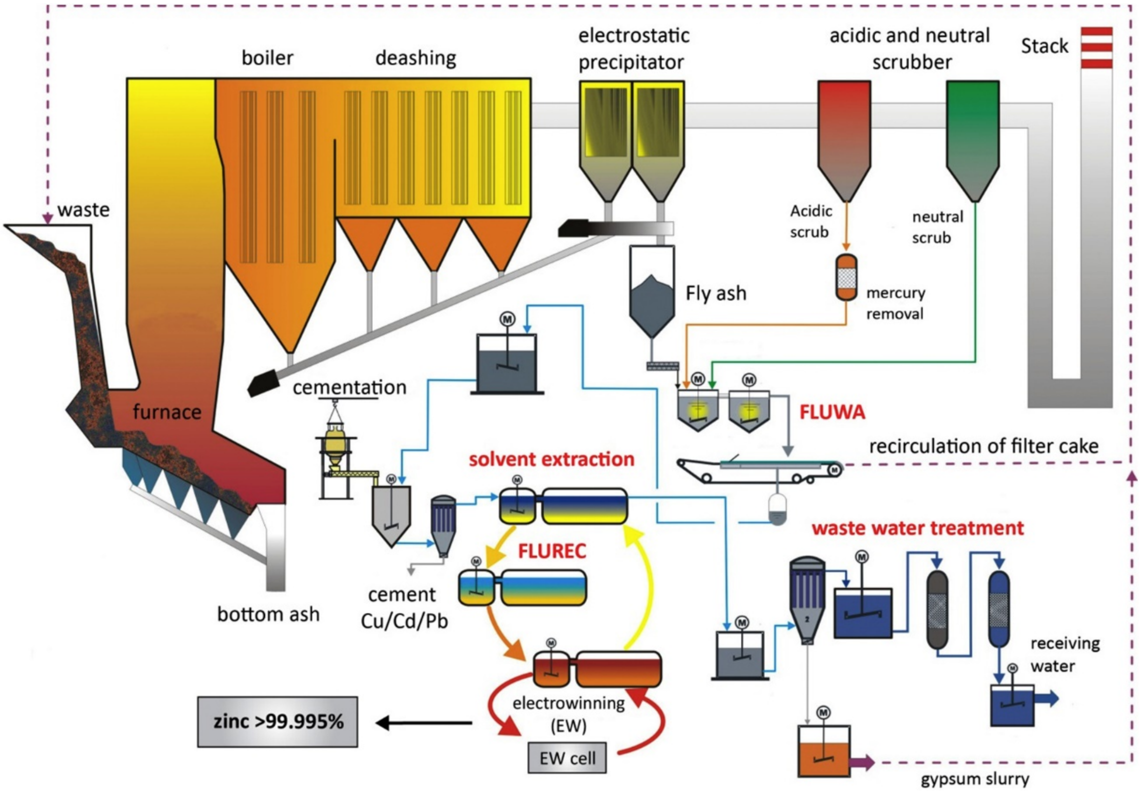

Figure 3-2 Flow diagram of the combined FLUWA and FLUREC process.

### 3.2.2 KEY FIGURES

Consumption and production for 1000 kg of fly ash (dry matter) with the FLUWA/FLUREC process is shown in Table 3-2.

| Consumption | Unit | Value, FLUWA | Value, FLUWA/-REC |
|---|---|---|---|
| Fly ash, dry matter | Kg | 1,000 | 1,000 |
| Process water | Kg | 1,680 | 1,680 |
| Acid scrubber water | Kg | 2,050 | 2,050 |
| Lime - $Ca(OH2)_2$ | Kg | 140 | 140 |
| Hg resin | Kg | 0.5 | 0.5 |
| $H_2O_2$, 50 % | Kg | 85 | 85 |
| HCl, 30 % | Kg | 100 | 100 |
| NaOH (50 %) | Kg | 24 | 24 |
| Zn powder | Kg | - | 5 |
| Power | kWh | 146 | 350 |
| Compressed air | $Nm^3$ | 400 | 400 |
| **Production / output** | **Unit** | **Value** | **Value** |
| Leached ash, dry matter | Kg | 700 | 700 |
| Wastewater | Kg | 3,200 | 3,200 |
| Hydroxide sludge, | Kg | 263 | - |
| Cd, Pb and Cu concentrate | Kg | - | 11 |
| Zn | Kg | - | 50 |
| Sludge, recycle to furnace | Kg | - | 24 |

Table 3-2 Overall mass balance of FLUWA / FLUREC process with consumables and production figures.

The solid salt recovery amendment does not introduce further use of consumables, but consumption of energy increases and production of 3,200 kg of wastewater is converted into 290 kg solid salt. The energy consumption amounts to 2 GJ heat (district heating assumed) and 25 kWh per tonne of treated fly ash.

# 4. METHODOLOGY

When comparing options of different treatment solutions for fly ash from a financial point of view present use of the solution in Germany or Norway will be used as alternative processes. The financial assessment for the waste to Energy facility will include cost related to externalities and general environmental performance and impact.

In general, calculations will be made in absolute terms thus, the treatment cost can be directly compared with the similar cost for export of fly ash. All internal cost that is not related to the subsequent treatment solution will not be included.

In this way differences in CAPEX and OPEX for national treatment solutions can be compared with the experienced treatment and handling cost for utilization in Norway and Germany. All cost etc. as well as performance of systems will be included in the assessment (i.e. considering all other things equal).

The estimated differences in cost and performance is used to calculate the following two financial parameters for the assessment:

- The net present value (NPV) over the life for the project
- The levelized cost of treatment (LCOT) over the life for the project.

The solution with the lowest NPV and LCOT will be the preferred option from a financial point of view.

Detailed mathematical explanation on NPV and LCOT are found later in appendix 2.

The calculations are based on collocating the plant with a Waste to Energy facility thus operational personal and can be shared and external transportation and handling of residues are minimized. To utilize the full treatment capacity of the fly ash treatment installation, reception of supplementary ash will be needed. Another important precondition is access to acid scrubbing water for the FLUWA/-REC process, hence the flue gas treatment is considered to be wet scrubbing with a separate collection of acid wastewater (bleed) thus the acidic wastewater is available for the possible subsequent fly ash treatment.

## 4.1 Calculation precondition

In the following other key assumptions used in the financial and economic assessments for technical and design options are described in more detail.

### 4.1.1 BASIC ASSUMPTIONS

The financial assessment follows the EC guideline *Guide to Cost-Benefit Analysis of Investment Projects, December 2014.* In the following the parameters for the financial calculation are explained more in details.

**Project duration**: All calculations are carried out for a planning period of 20 years operation. Time related to preparatory work like planning, obtaining permissions, tender preparation and contracting as well as construction and commissioning are assumed to be completed beforehand. To simplify the NPV and LCOT calculations it is assumed that all cost related to the preparatory work as well as the investments in equipment and building etc. accrue in year 0 followed by 20 years of operation. All needed maintenance cost and re-investment for this are included in calculations. First year of operation will be 2024.

Project duration is for all assessed techniques 20 years from the reason of comparison. When calculation results are put into perspective and compared with the solution today, sensitivity with shorter project duration will be used as well.

**Price level**: All calculations are made in real terms using 2019 prices.

**Financial Discount Rate:** A real interest rate of 4 % p.a. will be applied (in line with EC guidelines).

**Power Prices:** Prices on power are assumed as outlined in section 4.2.3 below.

**Price on consumables etc.:** Prices on consumables, alternative cost of wastewater treatment and disposal of residues are assumed as outlined in section 4.2.2 below.

**GHG emissions:** The fly ash is alkaline of nature and thus it may inherently capture $CO_2$ either direct during the process or indirect from avoiding use of alkaline products to neutralization of acids elsewhere. All in all, the net impact from possible carbon capture is considered to be identical for all processes and thus on financial impact from saved cost related to $CO_2$ capture is included in the calculation.

**CAPEX*:*** Investment cost will include all necessary preparatory work as explained previously. Investment for the various technical solutions will be specified and elucidated in the relevant section 4.3 below.

**Re-investment:** Where relevant cost related to re-investment for maintaining a total operation period on 20 years for the technical solutions will be included. For calculation purposes, all re-investments are included in the general cost (average cost) of maintenance.

## 4.2 Operational expenditure

The following section describes the approach to the estimation of operational expenditure (OPEX) related to operation and maintenance of the fly ash treatment system.

The OPEX includes all costs related to the operation of the treatment system including operation staff and maintenance etc. The necessary management and other administrative costs are omitted as these functions are considered covered by the existing waste incineration facility. Also cost of consumables like chemicals, water and power for the flue ash treatment is included as well as cost related to discharge of residual products.

External services, supervision during general maintenance, overhaul and annual revision of the system are all normal cost related to the operation and thus part of the OPEX.

The operational expenses consist of the following two main groups

- Fixed costs
- Variable costs

In the following, the two cost groups are briefly described and estimation of the costs are provided and described in more detail.

### 4.2.1 FIXED COST

The fixed costs comprise staffing, maintenance of equipment and buildings as well as cleaning etc.

The needed number of staffs for operating the fly ash systems depends on how intensive the system is operated. The needed staff is expressed as number of full-time working shifts and the fixed cost for one full-time shift operator is set to 0.5 MDKK/Year.

The overall objective of maintenance is to minimize the total maintenance costs and to keep the desired operational availability. Maintenance of equipment depends on equipment cost and equipment wear. Equipment cost is proportional to CAPEX and the average annual cost for maintenance of building and equipment is expressed as a certain proportion of CAPEX. In case the system is operated intensively (multiple shifts operated), the proportion increases compared to singe shift operation. The maintenance cost is expressed as the average cost and the estimate includes cyclic replacements and re-investment.

All office and administration cost including management, office facilities, office cleaning, basic insurance and other unspecified costs like administration and accounts is assumed to be covered by the normal incineration process and the waste to energy facility

### 4.2.2 VARIABLE COST

For financial assessment of the various treatment solution, the following price for consumables, residues and services are used as shown in Table 4-1. All chemicals are assumed to be supplied in bulk and the technical treatment solution comprises all necessary storage facilities for handling and storage of bulk supplies. All residues are considered to be subject to bulk transportation from site.

| Parameter | Price | Unit |
|---|---|---|
| Water | 20 | DKK/m$^3$ |
| Cement | 750 | DKK/t |
| $CO_2$ | 1,600 | DKK/t |
| Limestone (farmer quality, 10 % $H_2O$) | 200 | DKK/t |
| NaOH (50 %) | 2,800 | DKK/t |
| HCl (30 %) | 1,000 | DKK/t |
| Lime, $Ca(OH)_2$, (91 %) | 800 | DKK/t |
| $H_2O_2$ (50 %) | 3,300 | DKK/t |
| Zn-powder | 35,000 | DKK/t |
| Hg-resin | 50,000 | DKK/t |
| Compressed air | 0,15 | kWh/Nm$^3$ |
| Leached ash 1) | 1,000 | DKK/t |
| Wastewater to sewer | 25 | DKK/t |
| Sludge to furnace 3) | 100 | DKK/t |
| Heat (district heating) | 50 | DKK/GJ |
| Net power use 2) | 576 | DKK/MWh |

**Table 4-1 Price indication of consumables, residues, energy etc. 1) Total disposal cost from site to landfill including transportation etc. 2) Financial price in 2030. See further in section 4.2.3. 3) Assumed to end up in bottom ash fraction.**

It shall be noted that consumption of compressed air is converted to power consumption assuming a compressed air station to be included in supply. Alternative compressed air is supplied from existing installation increasing power consumption elsewhere.

### 4.2.3 POWER PRICES

Settlement of power for processes consists basically of two parts. Payment for the power (basic power price) and payment for power transmission, distribution and public obligations (PSO) etc.

Depending on actual power purchase contract the basic power price will to some extent follow the spot market prices as determined by the Nord Pool power exchange stock. Power purchase will take place during operation which takes place in daytime on normal working days. As an estimate for the basic power price the average spot marked price will be used. As the average spot marked price is made for 365 days per year and 24 hr. per day a correction on +6 % to count for the increased spot prices in daytime on normal working days. The 6 % correction is calculated for spot marked process for 2017 and 2018.

From a historical point of view the average spot market prices varied a lot as seen in Figure 4-1.

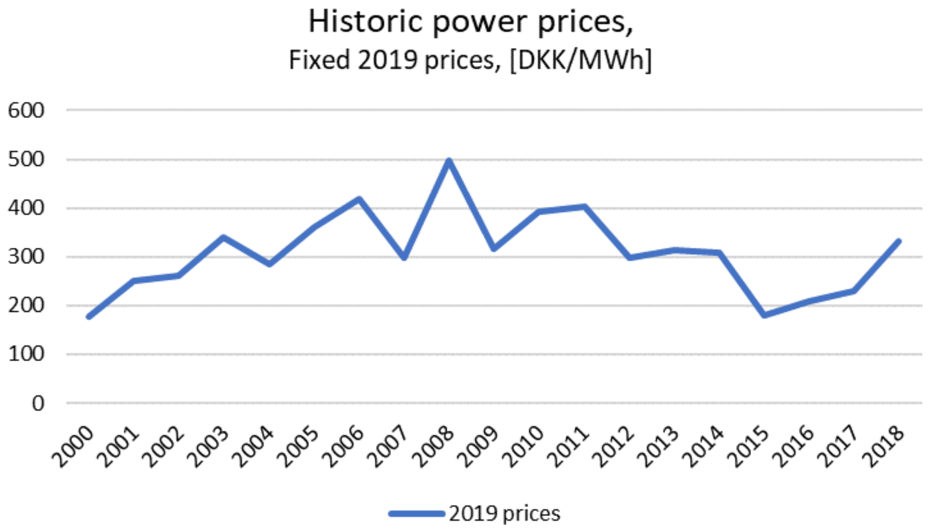

**Figure 4-1 Historic power prices expressed in 2019 fixed prices.**

The future power price is very hard to predict. Marked fluctuations, changed power demand in future and interactions makes it impossible to forecast the future price level as this requires system information. The Danish Energy Agency (Energistyrelsen) makes on regular basis forecast on power prices for the spot market, and as shown in Figure 4-2. The graph shows various forecasts made by the agency. All prices are shown as fixed 2019 prices. Some of the forecasts go to 2030 and others go to 2042. To show forecast prices for the total calculation period, the forecasted prices are extrapolated assuming that the last 5 year of average increase will continue in future.

The basic forecast from 2017 (BF2017) was announced with a lower and upper limit of the forecasted price, and the interval is shown as a grey area in the figure. The Basic forecast from 2018 (BF2018) does not have the same information. To calculate the economic impact from energy projects the Danish Energy Agency also announce economic power prices, and the most recent forecast from October 2018 is shown in Figure 4-2 as well.

Future payment for power transmission, distribution and public obligations (PSO) are estimated by The Danish Energy Agency together with the economic power price and for cost vary from 190 DKK in 2020 to 196 DKK/MWh. This cost is also called System Tariff.

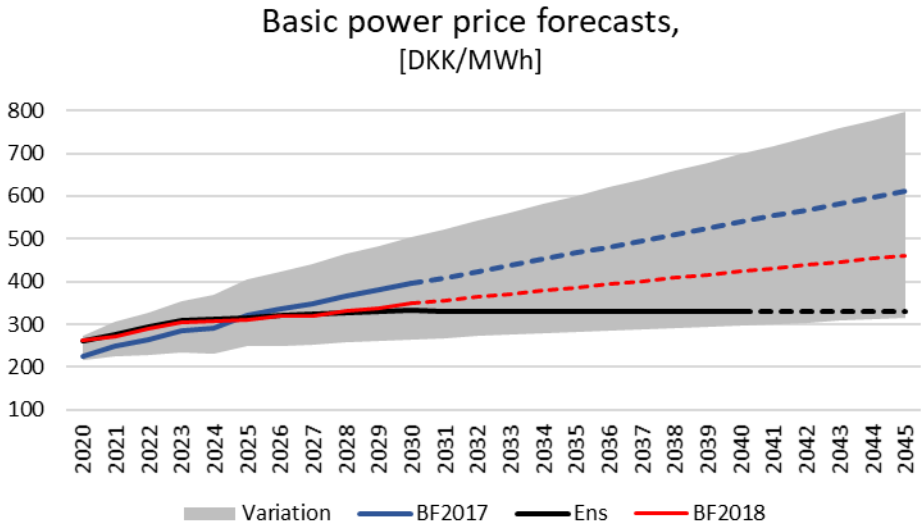

**Figure 4-2 Various forecast of future power prices. Dotted lines indicate extrapolation of available data assuming last 5 year of average increase to continue. The grey area represents the variation (min-max) of the basic forecast from 2017 (BF2017). "Ens" is the economic forecast price from *Economic calculation assumption* from Energistyrelsen, dated October 2018.**

As a central estimate for the future power price for processes, the spot market power price from basic forecast 2018 (BF2018) will be increased by 6 % due to consumption in daytime as previously explained and added with the system tariff. All prices are expressed I fixed 219 prices, and in Figure 4-3, the used central estimate for the power price for processes is shown.

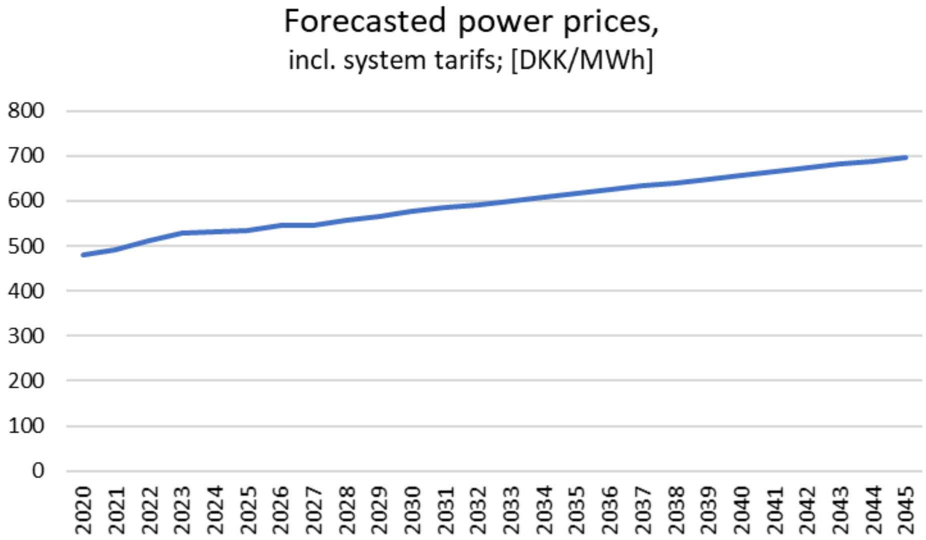

**Figure 4-3 Calculated forecasted financial power priced including system tariff. Power prices expressed in fixed 2019-prices.**

Due to the significant uncertainties both regarding the basic power price as well as the future development of system tariff, a sensitivity test will be run to observe the impacts on the financial performance of the solutions. The sensitivity test for total electricity price will be done in the range between ± 20 %.

### 4.2.4 INCOME

The various treatment techniques do produce product that is subject for and income for the facility operator or owner.

The Carbon8 process produces approximately 2,500 kg of stabilized fly ash product (Cement pellet aggregate) per tonne of fly ash, and the aggregate can be sold as a filler aggregates in concrete blocks. A selling (ex-works) of 50 DKK/tonne of aggregate is assumed corresponding to an income of 125 DKK per tonne of fly ash.

The FLUWA process produces approximately 260 kg of Zn enriched sludge (wet weight), and the sludge can be sold as a Zn supplement to the zinc reprocessing industry and a selling price (delivered) of 100 DKK/tonne of wet sludge is assumed corresponding to an income on 26 DKK per tonne of fly ash.

In the FLUREC process, pure Zinc is produced and a selling price to metal dealer of 1 EUR/kg (approximately 50 % of the world marked price) is assumed. This corresponds to an income of 375 DKK per tonne of treated fly ash assuming a specific Zn production of 50 kg/tonne of fly ash.

The solid salt recovery (an amendment to the FLUWA) process recovers salt as a solid product and a selling price to municipalities of 500 DKK/ton is assumed corresponding to an income of 145 DKK per tonne of treated fly ash assuming a specific production of solid salt of 290 kg per tonne of fly ash.

### 4.2.5 OPEX SUMMARY

OPEX includes all costs related to the operation of the treatment system including operation staff, maintenance, consumables and disposal of residues as well as possible income from products.

Contribution to average OPEX are calculated as further explained in appendix 2 (re. LCOT calculation), and contribution is summarized as shown in Table 4-2. The table thus shows the contribution to the average treatment cost for each of the two treatment techniques.

| Cost element | Carbon8 | FLUWA |
|---|---|---|
| Variable cost, consumables | 528 DKK/t fly ash | 612 DKK/t fly ash |
| Variable cost, residue | 0 DKK/t fly ash | 1.353 DKK/t fly ash |
| Variable cost, power | 42 DKK/t fly ash | 125 DKK/t fly ash |
| Fixed cost, staff | 63 DKK/t fly ash | 83 DKK/t fly ash |
| Fixed cost, maintenance | 95 DKK/t fly ash | 186 DKK/t fly ash |
| Income (aggregate & Zn-sludge) | -125 DKK/t fly ash | -26 DKK/t fly ash |

**Table 4-2 Operational expenditure (OPEX) for the two main processes including income from sales of aggregates (Carcon8 process) and zinc enriched sludge (FLUWA process)**

## 4.3 Capital Expenditure

The objective of the section is to provide an estimate for capital expenditure (CAPEX) for the complete installation of the proposed and described flu ash handling as identified in the previous sections.

In this study, the stipulated CAPEX is estimated as a combination of “top-down” and “bottom-up”. This combined approach is necessary as only limited information on what is commonly referred to as reference project budgeting exists. Further the available budget prices lack completeness and fail to show that they cover a complete installation.

The “top-down” method, is characterized by known contract prices/costs on realized contracts from similar projects, used to develop a price estimate for the current project. In comparison a “bottom-up” method is based on actual market prices on equipment. The top-down approach obviously requires detailed knowledge of the key differences between each priced reference project to correct for these variations and make the information relevant for the project at hand.

The top-down method takes market, overhead, risk, handling of contract interfaces and to some extent unforeseen expenses into account – parameters which have a significant influence on the total price of the project. This method is also referred to as reference class forecasting.

In the “bottom-up” method all single machine elements and erection cost etc. are valued and the sum of elements form the total CAPEX of the project. Even though the “bottom-up” approach may look more accurate, the method lacks information like cost of process design, cost of commissioning and cost related to process risk etc. As all the latter cost elements are best known from actual completed projects the “bottom-up” approach will often not be more accurate than the “top-down”, despite the large level of detail.

It is Ramboll’s experience that the “top-down” method offers the most accurate cost estimation when a sufficient number of reference plants are known.

The CAPEX for the fly ash treatments included in this financial assessment is generally estimated based on budget offers for the core technique supplied by possible contractors, and this can be considered as a quasi “top-down” approach. Even though the offers to some degree include engineering and start-up cost, the offers do however suffer from comprehensive deficits in order to be a complete functional installation. For this reason, the offers are completed with bottom-up approached for cost related to control system, cabling and power connection as well as balance of plant. Also cost for civil structures, additional silos and builders cost are added to the total cost. Finally cost for minor equipment and installations, contingencies and contracting cost are included in the CAPEX.

It must be noted that the competitive market situation at the time of bidding always has a significant influence on the offered prices. Since the contractors of main equipment are limited in number, both the order books of the main contractors as well as the interest in participating in the specific regional market will influence the offered price. Also, current index prices of steel and specific components will influence the final market price as well as labor cost during the manufacturing, erection and construction phase.

It shall also be noted that change in currency exchange rates also affects parts of the project prices which are not fixed to the currency of the project. Generally international steel prices as well as main alloys used for manufacturing of the facility are purchased in USD or EUR, whereas labor and locally manufactured equipment to a larger extent is determined by the local currency.

Due to the above-mentioned reasons price estimates at this stage will always be subject to a certain level of uncertainty.

CAPEX is in the following divided into the core technique provided by the contractor. Addition equipment, installations, site cost and building cost are added as shown in Table 4-3 below.

| Price element | Carbon8 | FLUWA |
|---|---|---|
| Core techniques (Offer)<br>Additional equipment<br>NOS[1)], contingencies and contract | 20 MDKK<br>15 MDKK<br>15 MDKK | 30 MDKK<br>25 MDKK<br>20 MDKK |
| Estimate CAPEX, complete installation | 50 MDKK | 75 MDKK |

**Table 4-3 CAPEX estimated for fly ash treatment installations. [1)] NOS Not Otherwise Specified.**

Additional equipment includes extra silos to handle ashes received from external incineration plants, CMS and cabling cost as well as building cost and cost related to balance of plant. For the FLUWA solution cost for an additional wastewater treatment (WWT) installation is included as well, as the total amount of wastewater increases thus the existing WWT may suffer from insufficient hydraulic capacity.

Contingencies comprise of various elements from not foreseen cost to supplementary equipment and services related to the installation, erection and/or commissioning etc. Contract cost is cost for production of tender documents, contract negotiation and contact follow-up during erection and commissioning of the installation.

The solid salt recovery amendment (only relevant for FLUWA) comprises of equipment for evaporation and drying as well as associated auxiliary equipment and for a complete EPC contract the corresponding additional CAPEX is estimated to 75 MDKK.

### 4.3.1 DECOMMISSIONING

A cost for the final decommissioning and dismantling of the plant at the end of the operation period of 20 years is not included in the feasibility analysis.

# 5. CALCULATION PRINCIPLES

Financial evaluation and assessment of investment are often made as cash flow calculation of investment, the future costs and income related to the project. The most convenient way for this is to make the calculation with all prices (investment, cost and income) expressed in the same price level hence the calculation is expressed in fixed prices 2019 level.

In fixed prices most often costs related to consumables, labour work, disposal cost etc. is considered to follow the inflation, thus the price per unit (e.g. per kg of consumables or MWh of power) becomes constant. Costs related to maintenance are however often increased to express increased wear by time. This increase is then expressed as the rate of real increase.

To compare the investment (cost in year 0) with future cash flows (costs and incomes), the future cash flows must be discounted by the real discount rate. The rationale behind this discounting even though all prices are expressed as fixed prices is money has time value. The owner of the money must defer its use, thus the entity using the money must pay for deferring the benefits. Alternatively, the money could have generated other benefits when used elsewhere.

When all future cash flows (cost and incomes) are discounted and summed together with the investment, we get the net present value (NPV) of the technical solution. When comparing two or more different technical solution for a future fly ash treatment, the option with the lowest NPV becomes the most attractive solution from a financial point of view.

The NPV expresses the total sum of the cost for fly ash treatment for 20 years of operation. NPV often becomes a value on many millions and even the difference in NPV between two technical options are large numbers. From a strictly financial point of with the very high the most attractive solution is the one with the lowest NPV and the magnitude of NPVs are of secondary importance. If the most financial attractive solution also is the preferred solution from a technical, environmental and climate point of view no more financial assessments need to be done.

Often the most financial attractive solution is not the preferred solution from a technical, environmental and climate point of view, and the treatment cost needs to be assessed and expressed in term of cost of treatment per kg or tonnes of fly ash. This is also necessary when the calculations are made for varying amounts of fly ash, and the calculaton is performed by calculating the levelized cost of treatment (LCOT). Eventhough the LCOT calculation provides a better basis for comparison of solutions with different amount of fly ash, one has to be careful comparing the LCOT’s.

LCOT is a measure of a treatment that allows comparison of different treatment techniques on a consistent basis. It is an economic assessment of the average total cost to build and operate a treatment facility over its lifetime divided by the total amount of treated fly ash over that lifetime. The LCOT can also be regarded as the average minimum price at which fly ash treatment must be offered in order to break-even over the lifetime of the project.

When comparing two different technical solutions the difference in LCOT becomes the average difference in cost of treatment per kg or tonnes of fly ash. In this way, a solution with high environmental performance may be compared and assessed whether the difference in average cost is worth paying to gain a certain improved environmental benefit. It must be noted that the latter assessment is a political assessment and thus it is not part of this feasibility study.

# 6. SCENARIOS

To perform and mutually compare the financial calculations various scenarios are made with respect to capacity and utilization of the installation. This leads to a possibility of letting the installation be operated during the normal working hour and thus make use of existing operation personal as much as possible (reducing staff cost as much as possible). Alternatively, the system is utilized to its maximum capacity operating the installation 24/7 and thus hire necessary staff for such operation.

### 6.1.1 CARBON8

The Carbon8 system comprises of a single line with a treatment capacity of approximately 3 tonnes per hour corresponding to 8.000 tonnes per year when operated in one shift and 24.000 tonnes per year when operated in three shifts per day.

Although the system is assumed to be highly automatized, some manual operations are foreseen, and dedicated staff will be needed. To a large extent, existing staff will be able to assist in reception of supplementary ashes and chemicals etc. one additional and dedicated man per shift is foreseen to handle equipment and to supervise the processes.

### 6.1.2 FLUWA & FLUREC

The FLUWA system comprises of various reaction tanks and filters with a maximum treatment capacity of 2.4 tonnes per hour and a limitation of 5.000 operational hours pr. Year. The remaining time up to the full year is assumed to be used for cleaning and maintenance of equipment. When operated in one shift 2.500 operational hours are assumed and the maximum operation capacity of 12.000 tonnes per year is reached when the system is operated in two shifts per day. All data on operation and capacity is obtained from experience at the plants already in operation.

The system is assumed to be highly automatized and to a large extent integrated with the existing wastewater treatment system hence existing staff will be able to assist in daily work routines and operations. Manual operations are however still foreseen, and dedicated staff will be needed to maintain system capacity. One additional and dedicated man per shift is foreseen to handle equipment and to supervise the processes.

In case of the FLUREC process, no further need for operational staff is foreseen.

# 7. RESULTS

In the former section key technical/design aspects and precondition for two different national treatment possibilities are described.

In this chapter, the financial performance of the two main fly ash treatment techniques is assessed and compared. To perform and mutually compare the financial calculations various scenarios are made with respect to capacity and utilization of the installation.

## 7.1 Scenario evaluation

The model assumes the technical solution to operate during normal working hours in daytime (one shift operation) for all scenarios. Operation of the facilities in multiple shifts is assessed in the sensitivity calculation.

For the carbon8 process, the financial net present value (NPV) is 116 MDKK corresponding to a levelized treatment cost of 1.065 DKK per tonne of fly ash. To elucidate the cost and to analyse cost elements contributing to the cost, the individual contributions to average project ash treatment cost (LCOT) is shown in Figure 7-1.

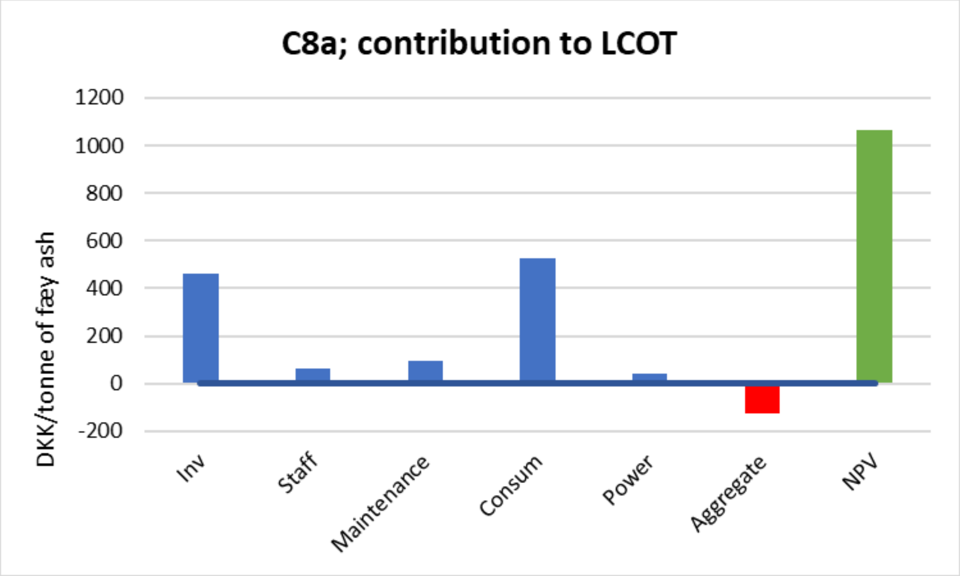

**Figure 7-1 Average project ash treatment cost (LCOT) cost elements to one shift operation of the Carbon8 process.**

As seen from the figure two mayor elements contributing significantly to the NPV namely investment and consumables. Staff cost, maintenance and power consumption are of less importance and sales of aggregates reduce Carbon8 cost. Consumables cannot be reduced from optimisation unless the consumption of cement, limestone and $CO_2$ is affected significantly. This will be further assessed in the sensitivity analysis. Investment is also subject to sensitivity analyses, and this cost element may be altered in two ways. Either the investment cost is reduced, or the utilisation of the installation is increased. Both factors will be further assessed in the sensitivity analysis.

For the FLUWA process, the financial net present value (NPV) is 265 MDKK corresponding to a levelized treatment cost of 3.245 DKK per tonne of fly ash. To elucidate the cost and to analyse the which cost element that contributes to the cost, the individual contribution to the average project ash treatment cost (LCOT) is shown in Figure 7-2.

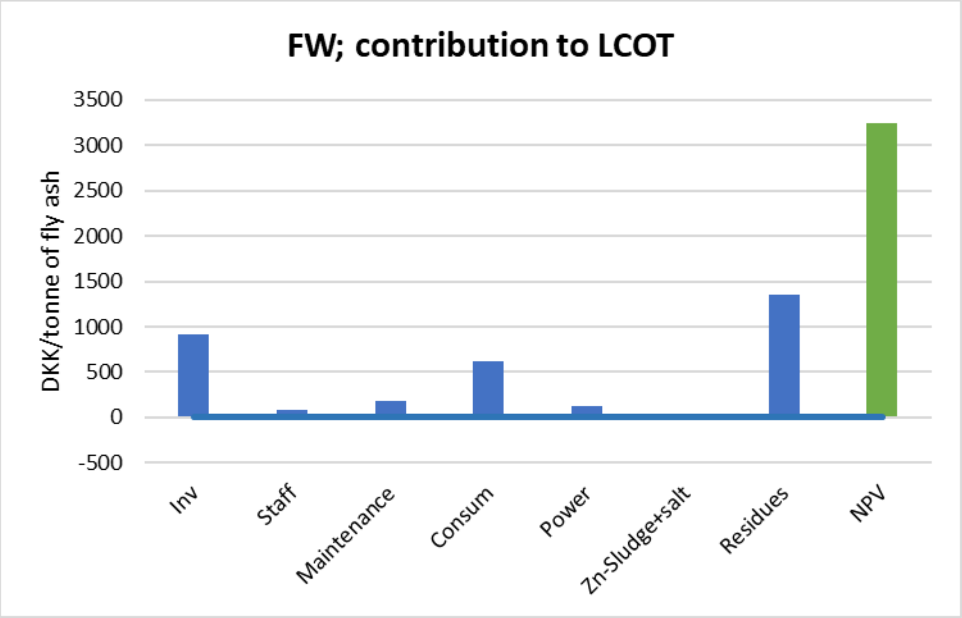

Figure 7-2 Average project ash treatment cost (LCOT) cost elements to one shift operation of the FLUWA process

As seen from Figure 7-1 and Figure 7-2 two mayor elements contributing significantly to the LCOT for both processes namely investment and consumables. For the FLUWA process disposal of residues adds another significant contributor to the treatment cost. Staff cost, maintenance and power consumption are of less importance as well as sales of aggregates and hydroxide sludge. Cost for consumables cannot be reduced from optimisation unless the consumption itself is affected significantly. This will be further assessed in the sensitivity analysis. For the carbon8 process, this means changed consumption of cement, limestone and $CO_2$ and for FLUWA the mayor elements are $H_2O_2$, Lime, HCl and NaOH.

It must be noted that handling of residues from the FLUWA process (leached ash) contribute significantly to the overall average project ash treatment cost (LCOT) for the FLUWA process with approximately 40 % of the total cost. As described previously if it is assumed that leached ash goes to landfill for a cost of 1,000 DKK/tonnes. The fact that FLUWA treatment of one tonne of fly ash produces nearly 1.3 tonnes of leached ash (wet weight) is remarkable and this part of the process must be carefully examined prior to any investment in order to identify alternative handling (cheaper handling). In case the leached ash can be classified recycling or similar other and cheaper ways of disposal may be possible. Sensitivity analyses will included cheaper disposal of leached ash.

Investment is also subject sensitivity analyses, and this cost element may be altered in two ways. Either the investment cost is reduced, or the utilisation of the installation is increased. Both factors will be further assessed in the sensitivity analysis.

### 7.1.1 COMPARATIVE ANALYSIS

The two main processes are financially compared with investment NPV and average project ash treatment cost (LCOT) in Table 7-1.

| Parameter | Carbon8 | FLUWA |
|---|---|---|
| Investment | 50 MDKK | 75 MDKK |
| NPV | 116 MDKK | 265 MDKK |
| LCOT | 1,065 DKK/t | 3,245 DKK/t |

**Table 7-1 Financial comparison of Carbon8 and FLUWA**

## 7.2 Sensitivity evaluation

Sensitivity evaluation is performed assuming various variation of calculation parameters as described more in details below. The sensitivity analyses are performed both as a parameter sensitivity analysis and a scenario sensitivity analysis.

As the amount of treated ash is not the same in all scenarios, all comparisons will be made on relative treatment cost basis (LCOT).

### 7.2.1 PARAMETER SENSITIVITY ANALYSES

As shown in the previous section the Carcon8 solution performs from a financial point of view significantly better than the FLUWA solution with the set-up and prices as previously described. In order to illustrate the robustness of the Carbon8 solution, a sensitivity assessment is made checking how the result changes with changes in certain parameters. The sensitivity analysis will identify the "critical" parameters for the project and perform scenario analysis as follows. Additionally, in the following section (Section 7.2.2) a separate assessment of a number of alternative scenarios is presented.

Part of the sensitivity analysis is the identification of the "critical" parameters (relative sensitivity). "Critical" parameters are input parameters in NPV calculation that have the largest impact on the project’s economic performance. The analysis is carried out by varying one parameter at a time and determining the effect of that change on the NPV. A parameter is defined as "critical" when a variation of ± 1 % of the value gives rise to a variation of more than 1 % in the value of the NPV. A “critical” parameter is identified, when the relative sensitivity number (change in NPV compared to change in parameter) is above 1. The relative sensitivity number is designated RS#.

The following parameters are assessed in the sensitivity analyses:

- Price on consumables
- Price on residues
- Price on power
- Investment cost

The sensitivity calculation is shown in Table 7-2 as the respective average project ash treatment cost (LCOT) and the relative sensitivity number (RS#) for each parameter and for each process is reported in brackets as well.

From the sensitivity analyses above it is seen that none of the tested parameters is critical, as the relative sensitivity number (RS#) is less than 1 in all cases.

| **Variation** | | **Carbon8** | **FLUWA** |
|---|---|---|---|
| Unit | | DKK/ton (change fraction) | DKK/ton (change fraction) |
| No change | | 1,065 | 3,245 |
| Consumables; | - 20 % | 960 (RS# 0.5) | 3,123 (RS# 0.2) |
| Consumables; | + 20 % | 1,171 (RS# 0.5) | 3,368 (RS# 0.2) |
| Residue; | - 20 % | 1,065 (RS# 0.0) | 2,975 (RS# 0.4) |
| Residue; | + 20 % | 1,065 (RS# 0.0) | 3,516 (RS# 0.4) |
| Power price; | - 20 % | 1,057 (RS# 0.0) | 3,220 (RS# 0.0) |
| Power price; | + 20 % | 1,074 (RS# 0.0) | 3,270 RS# (0.0) |
| Investment; | - 20 % | 973 (RS# 0.4) | 3,063 (RS# 0.3) |
| Investment; | + 20 % | 1,158 (RS# 0.4) | 3,427 (RS# 0.3) |

**Table 7-2 Project average ash treatment cost (LCOT) parameter sensitivity analysis and relative sensitivity number (RS#) in brackets.**

### 7.2.2 SCENARIO SENSITIVITY ANALYSES

In addition to the above sensitivity analysis (with respect to variations in selected parameters) also a scenario analysis has been made testing the financial results under the following different scenarios:

A. Utilizing full treatment capacity (both systems);
B. Utilizing $CO_2$ from flue gas (avoid purchase of $CO_2$ – only valid on Carbon8)
C. Include FLUREC – only valid for FLUWA
D. Include solid salt recovery (SSR) – only valid for FLUWA
E. Reduced price on leached ash

As the amount of treated ash is not the same in all scenarios, comparison will be made on LCOT basis.

Below first the results of the scenario analysis are reported

| **Variation** | | **LCOT** | **Carbon8** | **FLUWA** |
|---|---|---|---|---|
| No change | | DKK/t | 1,065 | 3,245 |
| A – Full utilization | | DKK/t | 808 | 2,831 |
| B – $CO_2$ from flue gas | | DKK/t | 906 | N/A |
| C – Include FLUREC | | DKK/t | N/A | 4,098 |
| D - Include SSR | | DKK/t | N/A | 4,244 |
| E – Red. L. ash cost; | 500,-/t | DKK/t | 1,065 | 2,609 |
| | 0,-/t | DKK/t | 1,065 | 1,972 |

**Table 7-3 average project ash treatment cost (LCOT) scenario sensitivity table for Carbon8 and FLUWA**

If the two process amendments to FLUWA (Zn-recovery in FLUREC) and recovery of solid salt (SSR) are considered as true amendments the incremental average project ash treatment cost (LCOT) can be calculated assuming the amendments to be established as an add on process to the existing process.

The incremental average project ash treatment cost (LCOT) of FLUREC becomes 850 DKK/tonne of fly flash if the facility is operated in one shift operation and with maximum utilisation, the incremental LCOT is 550 DKK/tonne of fly flash.

The incremental LCOT of SSR becomes approximately 1000 DKK/tonne of fly flash if the facility is operated in one shift operation and with maximum utilisation, the incremental LCOT is 540 DKK/tonne of fly ash.

## 7.3 Perspectivation

The calculated average project ash treatment cost (LCOT) values represent the average payment in fixed values necessary to ensure a certain return on the investment. For further on this please refer to section 4.1 and appendix 2.

Even though the FLUWA process does not have high relative sensitivity to the tested parameters, FLUWA does suffer from high investment cost relative to treatment capacity. Another major contributor to the treatment cost is disposal of leached ash and in case the FLUWA process should be further considered, alternatives to landfilling must be identified.

When FLUWA is combined with either Zn-recovery (FLUREC process) or with recovery of solid salt (SSR), the treatment cost of fly ash increases significant, hence neither FLUREC nor SSR may contribute to making FLUWA more feasible from a financial point of view.

From the above calculations on the average project ash treatment cost (LCOT) it appears that Carbon8 is far the cheapest fly ash treatment technique (among the techniques considered in the feasibility study).

Carbon8 process does not have high relative sensitivity to the tested parameters, but the process has relative high investment cost and cost of consumables. All of the consumables are considered to be the cheapest commodity available in Denmark, but one chemical stick out. Consumption of $CO_2$ is relatively costly, and if the Carbon8 process is located beside a WtE facility treatment cost can be reduced by utilizing $CO_2$ from the flue gas stream.

Comparison of the calculated treatment cost (LCOT) with the alternative cost at eq. NOAH on approximately 850 DKK/ton does not immediately form a reasonable base for assessing the processes due to different risks and time frame of the projects.

The lowest calculated treatment cost, assuming maximum utilisation of the Carbon8 process is 808 DKK per tonnes of fly ash (operating the Carbon8 process on full capacity - 24/7 operation) and compared with the experienced NAOH price on 850 DKK per tonnes of fly ash this could indicate a potential saving. It must, however, be noted that the calculated price for the Carbon8 process is valid only, when/if the system is operated in 20 years. As the capacity and demand for fly ash to have full utilisation causes the facility owner to enter contracts for delivery and treatment of ashes from external parties, a shorter period of depreciation might be desired.

With a 10-year depreciation operating philosophy for the Carbon8 process, the calculated average project ash treatment cost (LCOT) with full utilization of the system increases from 808 DKK/tonne to 910 DKK/tonne.

## 7.4 Fate of fly ash

The fate of fly ash in either by the Carbon8 system of the FLUWA/FLUREC system may be perspectived from the distribution in the utilysation categories *landfill, recovery* and *recycling* and as *loss* to the surrounding. The utilysation category *recycling* is the most desirable categori and landfill is the least desirable utilysation categori. *Loss* is not desirable at all.

In Table 7-4 a split in utilysation categories for the various treatment techniqies is shown. Carbon8 aggregates will replace gravel in the concrete industry and hence the process can be characterised as 100 % recycling.

In the FLUWA and FLUREC process 29 % of the fly ash will be washed out and discharged as salty waste water which is categorized as a loss and the recovery of zinc is characeterised as recycling. The fate of the leached fly ash depends on the futher handling. Landfilling if of course *landfill* but if the leached fly ash is used as landfill cover it may be characterised as *recovery*. Eventhough the weight of the leached fly ash exceeds the weight of the incoming fly ash, the degree of landfill/recovery is related to the received weight of fly ash.

If the FLUWA process is combined with solid salt recovery (SSR), the loss of salts is converted to recycling.

| Process | Loss | Landfill | Recevery | Recycling |
|---|---|---|---|---|
| Carbon8 | | | | 100 % |
| FLUWA | 29 % | ←------ 64 % ------→ | | 5 % |
| FLUWA+FLUREC | 29 % | ←------ 64 % ------→ | | 5 % |
| FLUWA + SSR | | ←------ 64 % ------→ | | 34 % |

Table 7-4 Distribution of utilysation in the categories

# 8. UNCERTAINTIES AND FUTURE WORK

The main uncertainties in the business case are related to the consumables and their amount as this remains an important parameter in the average project fly ash treatment cost and the available data is somewhat uncertain. Understanding the consumables consumption rate is hence a key issue for further study and analysis.

Further understanding of the experienced economy of use cases in Switzerland and the UK would further strengthen the business case on a number of issues relevant for both the evaluated operational and the capital expenses.

Another uncertainty is the usage and value of products produced for recycling. Further information could be collected to clarify the produced amounts, their quality, transportation costs and the market prices.

Alternative uses for aggregate such as use as road base or similar might affect the market price and relevant scenarios for use should be studied to make sure pricing is relevant for potential solutions.

# 9. CONCLUSIONS

The most feasible treatment option from a financial perspective is the option with the lowest cost pr. treated tonne of ash as an average figure over the time horizon of the project. This is calculated as the net present value (NPV) of the option including capital cost (investments), operational costs and generated income. When the NPV is compared to the amount of treated fly ash the levelized cost of treatment (LCOT) or the average project treatment cost. The Average Project treatment cost is evaluated for the two main scenarios also evaluated by the LCA namely:

- Flue gas washing – exemplified by the FLUWA process
- Dry recycling as aggregate – exemplified by the Carbon8 process

The key financial figures of the two assessed processes are outlined in Table 9-1 below, and the table show figures for facilities operating in one shift. LCOT figures are rounded, for details please refer to the relevant section.

| Price element | | Carbon8 | FLUWA |
|---|---|---|---|
| CAPEX, complete installation | MDKK | 50 | 75 |
| OPEX, total cost | MDKK | 79 | 140 |
| OPEX, total income | MDKK | -14 | -2 |
| **NPV** | MDKK | **116** | **265** |
| **LCOT** | DKK/ton | **1.065** | **3.245** |

Table 9-1 CAPEX and treatment costs estimated for fly ash treatment options (rounded numbers)

It must be concluded that recycling of fly ash as aggregate, as illustrated in the Carbon8 process, is significantly cheaper than washing the fly ash and sending Zn rich sludge for recycling.

Eventhough the treatment cost pr tonne (LCOT) calculations for Carbon8 and FLUWA are not made on the same amount of treated fly ash pr year, the results show a clear and significant price difference.

Further, the options of making recycling salt for road de-icing and upgrading the Zinc enriched sludge to pure metallic Zinc was financially evaluated. The treatment costs and obtained value of recycling (sales of aggregates are summarized as rounded figures in Table 9-2 below. Please note that the treatment cost and value of recycling are shown as rounded figures. Value of recycling is included in the treatment cost, but the figures are shown separately to illustrate the potential value of the treatment process.

| Price element | Treatment cost | Value of recycling | Recycled |
|---|---|---|---|
| Baseline (NOAH current cost) | 850 DKK | 0 DKK | None |
| Carbon8 | 1.050 DKK | 125 DKK | Aggregate |
| FLUWA | 3.250 DKK | 25 DKK | Zn rich sludge |
| FLUWA and salt recycling | 4.250 DKK | 170 DKK | Zn sludge and salt |
| FLUWA and Zn recycling | 4.100 DKK | 375 DKK | Zn in metal form |

Table 9-2 Evaluated costs of treatment and value of recycled products for one tonne of fly ash

Evaluating further sensitivities conclude that the results were robust against changes in changing investment, consumables, and residue costs and in addition the power price influence was not significant. Evaluation of high capacity sceneries have shown that the influence of the investment decreases drastically and the operational costs per tonne of fly ash consequently decreases. The treatment for the various combinations is shown in the figure below. It seems to be a good business case to use maximum capacity as it results in lower treatment costs for all scenarios.

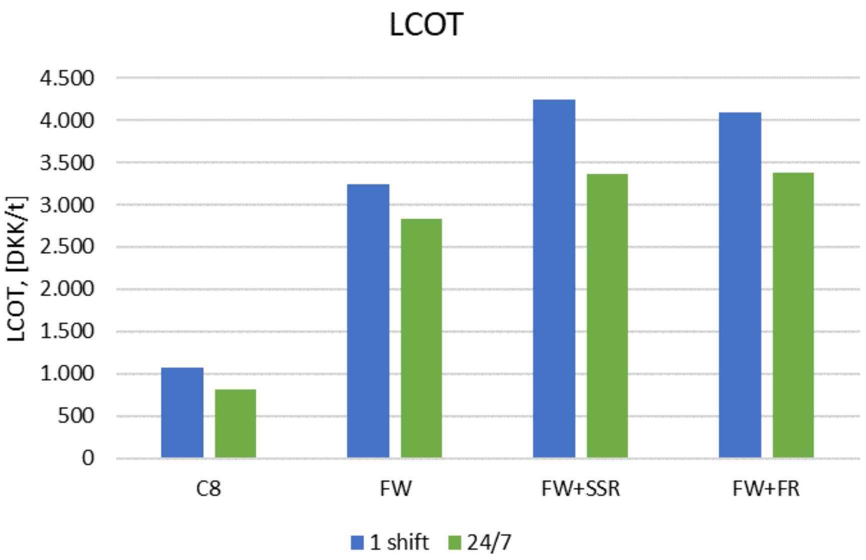

**Table 9-3 Estimated average project ash treatment costs in base scenarios and utilizing max capacity. Scenarios: C8 Carbon8, FW FLUWA, FW+SSR FLUWA and salt recycling, FW+FR FLUWA and Zn recycling**

The influence of the period of depreciation was evaluated by shortening it to 10 years in one scenario (Carbon8) and it was concluded that this would add 100 DKK/ton of ash treated.

Only the Carbon8 scenario shows comparable prices to what is paid today but offers only a limited recycling value. Scenarios with high recycling value also have high costs.

Finally, it is noted that treatment cost for fly ash corresponds approximately to 13 DKK/tonne of waste assuming the waste incinerating to generate 1.5 % fly ash. The Carbon8 process might raise the waste gate-fee by approximately 3 DKK/tonne of waste. The FLUWA process might raise gate-fees by approximately 25 DKK/tonne of waste.

# APPENDIX 1
# CALCULATION DETAILS

# APPENDIX 2
# MATHEMATICS ON NPV AND LCOT

**Mathematical explanation on NPV and LCOT**

Consider a project with an investment (*Inv*) in year 0 followed by *n* years of operation each with cost and income designated with $I_n$ and $C_n$. In Figure 9-1 below this cash flow is illustrated.

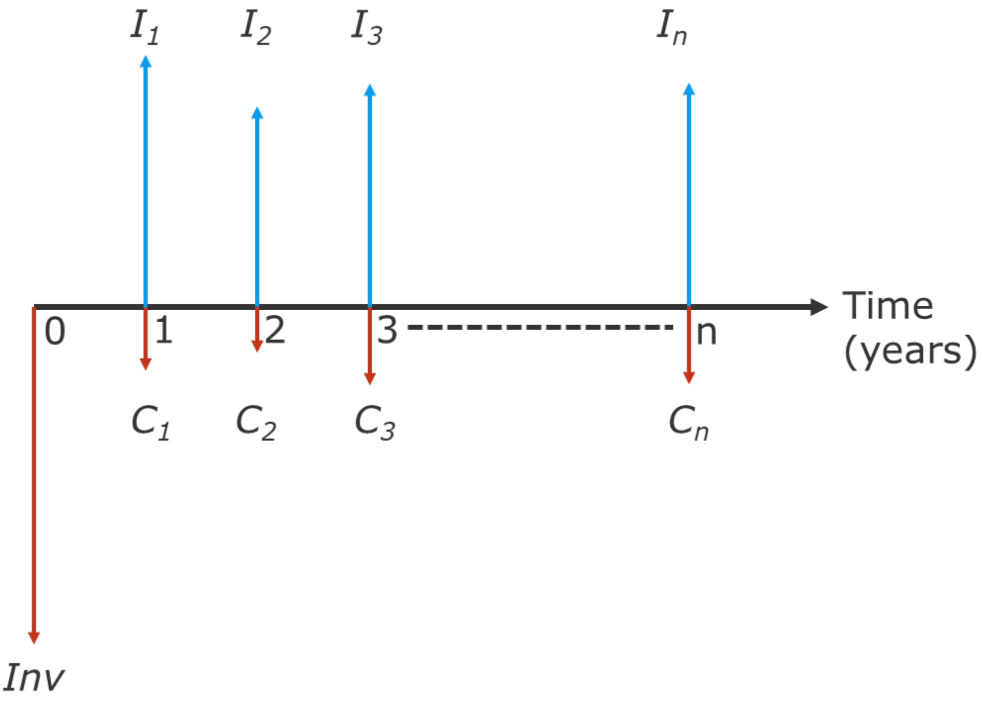

**Figure 9-1 Graphic illustration of investment and corresponding cash flow. *Inv* is the investment in year zero and $C_i$ and $I_i$ are the cost respective income in year i.**

NPV for the project in calculated as the accumulated discounted value of the annual cost and income from the project added with the investment assumed to be made (paid) in year zero.

The mathematic calculation is made with the following equation:

$$NPV = Inv + \sum_{i=1}^{n} (C_i - I_i)(1+r)^i$$

As it appears from the above equation that the calculated NPV expresses the sum of cost thus any positive income (positive $I_i$) must be subtracted from the annual cost.

The *r* is often defined as the rate of return that could be achieved otherwise, or simply expressed as the cost of capital. As explained previous all cost and incomes are expressed in fixed prices thus the rate of return must be the real interest rate of return.

With the aim to find the levelized cost of treatment (LCOT), an average price treatment fee must be identified hence the accumulated and discounted treatment (NVP) is balanced by income from the treatment fees. If the treatment fees are calculated as an income in the NPV expression above, the NPV equation must be solved for NPV=0.

The annual treatment fees is calculated as the levelized cost of treatment multiplied with the annual amount of fly ash hence the annual income form treatment in year "i" ($I_{Tr,\,i}$) is calculated as $I_{Tr,i} = LCOT \cdot M_i$, *where* $M_i$ is amount of ash in year i.

It must be noted that LCOT is constant in all years expressed in fixed prices. In real world inflation increases the annul treatment fee, but the price will follow the inflation.

By introducing these preconditions in the NPV equation above we get:

$$NPV = Inv + \sum_{i=1}^{n} (C_i - I_i - (M_i \cdot LCOT))(1+r)^i = 0$$

Rewriting the NPV equation be get the following:

$$Inv + \sum_{i=1}^{n} (C_i - I_i)(1+r)^i = \sum_{i=1}^{n} (M_i \cdot LCOT)(1+r)^i$$

Recognizing the left-hand side of the equation as the NPV value from the NPV equation and recalling that LCOT is a constant, LCOT can be calculated as follows:

$$LCOT = \frac{NPV}{\sum_{i=1}^{n}(M_i)(1+r)^i}$$

The factor $\sum_{i=1}^{n}(M_i)(1+r)^i$ is recognised as a NPV-calculation of the annual amount of fly ash. Often Economics argue that NPV of other things than money does not give sense and from a financial point of view this is probably right, however from a mathematical point of view the calculation is exactly identical.

Consequently, to the above calculation there is not any mathematically difference between NPV of costs and NPV of Incomes. Therefore, LCOT is often expressed in a condensed formula with LCOT = NPV(Net cost)/(NPV(amount).

Often the annual amount to be treated is constant ($M_i$ = constant) and the factor $\sum_{i=1}^{n}(M_i)(1+r)^i$ can be rearranged as $M_i \sum_{i=1}^{n}(1+r)^i$. The sum $\sum_{i=1}^{n}(1+r)^i$ is often referred as “factor of recovery” and the factor calculated as follows:

$$\sum_{i=1}^{n}(1+r)^i = \frac{1-(1+r)^{-n}}{r} = \alpha(n,r)$$

With a constant annual amount of fly ash ($M_i$) the levelized cost of treatment (LCOT) is calculated as:

$$LCOT = \frac{NPV}{M_i \cdot \alpha(n,r)}$$