# Flue Gas Condensate and Energy Recovery

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ABSTRACT: Energy plants in Europe are increasingly turning to biosolids as an alternative to traditional non-renewable fossil fuels. Biosolids have a high water content, resulting in a flue gas with 30-50% water. Radscan has developed a process to treat and recover 90% of this flue gas condensate for reuse as boiler makeup water, while recovering considerable energy from the hot gas. The process uses a combination of scrubbers, heat exchangers, ultrafiltration, reverse osmosis, membrane degasification and electrodeionization. This report will describe a commercial system that has been in operation for over two years, and paid for itself in energy savings.

## INTRODUCTION

Karlskoga is an industrial town in central Sweden about 240 km west of Stockholm, in a mining region best known for the Bofors Iron Works. It is also the location of the Karlskoga Heat and Power plant (Karlskoga Energi och Miljo AB), a waste-to-energy facility that provides the region with electricity, steam for industrial use, and hot water for district heating.

Picture 1 Karlskoga Heat and Power

In late 2005, Radscan Intervex began construction of a flue gas condensation system retrofit for this facility. The plant employs circulating fluidized bed (CFB) boilers, which can utilize a wide variety of fuel sources [1], including animal waste (Biomal [2]), peat, recycled paper/plastic, and wood chips. Such biofuels contain 35-45% water by weight – up to 60% for the animal waste - resulting in about 0.2 $m^3$/h of water for each MW-h of energy produced. Radscan has developed a process to reclaim the water from the combustion flue gas, but also to recover about 1 MW-h of energy for each $m^3$/h of reclaimed water. An array of water treatment processes is used to convert flue gas condensate to demineralized water suitable for makeup to the boilers. A separate system is used to treat waste water from a quench scrubber, resulting in a system with minimal discharge to sewer.

## PROCESS DESCRIPTION

An overview of the Karlskoga system is given in Figure 1. After incineration of the waste fuel, the resulting flue gas is first treated by a 3-stage electrostatic precipitator, which removes most of the large particulates. The flue gas exiting the precipitator has a moisture content of about 30% by weight, and a temperature of 135-180°C (275-356°F). It then passes to a quench scrubber, where a recirculating water stream is sprayed through the gas, removing more particulates as well as salts and acids resulting from the waste combustion. A portion of the quench water is bled off and sent to a waste water treatment train (Line 2, described later). The bleed water is replaced with first pass RO reject from the flue gas condensate water treatment train (Line 1). After the quench step, the flue gas is saturated with water and at a temperature of about 67°C (150°F).Next the quenched flue gas goes to a two-stage scrubber. The first stage of the scrubber is primarily for removal of sulfur dioxide ($SO_2$), using sodium hydroxide (NaOH) as the scrubber liquid. The second stage is a cooler, which transfers heat from the flue gas to a portion of the boiler feed water, preheating it from 40 to 65°C (104 to 149°F). The cooling stage is the heart of the Karlskoga energy recovery system, reclaiming up to 20 MW-h from the hot flue gas. It also condenses the water vapor contained by the flue gas, producing liquid water used as makeup to the condensate cleaning train (Line 1). The two water treatment trains will now be discussed in more detail.

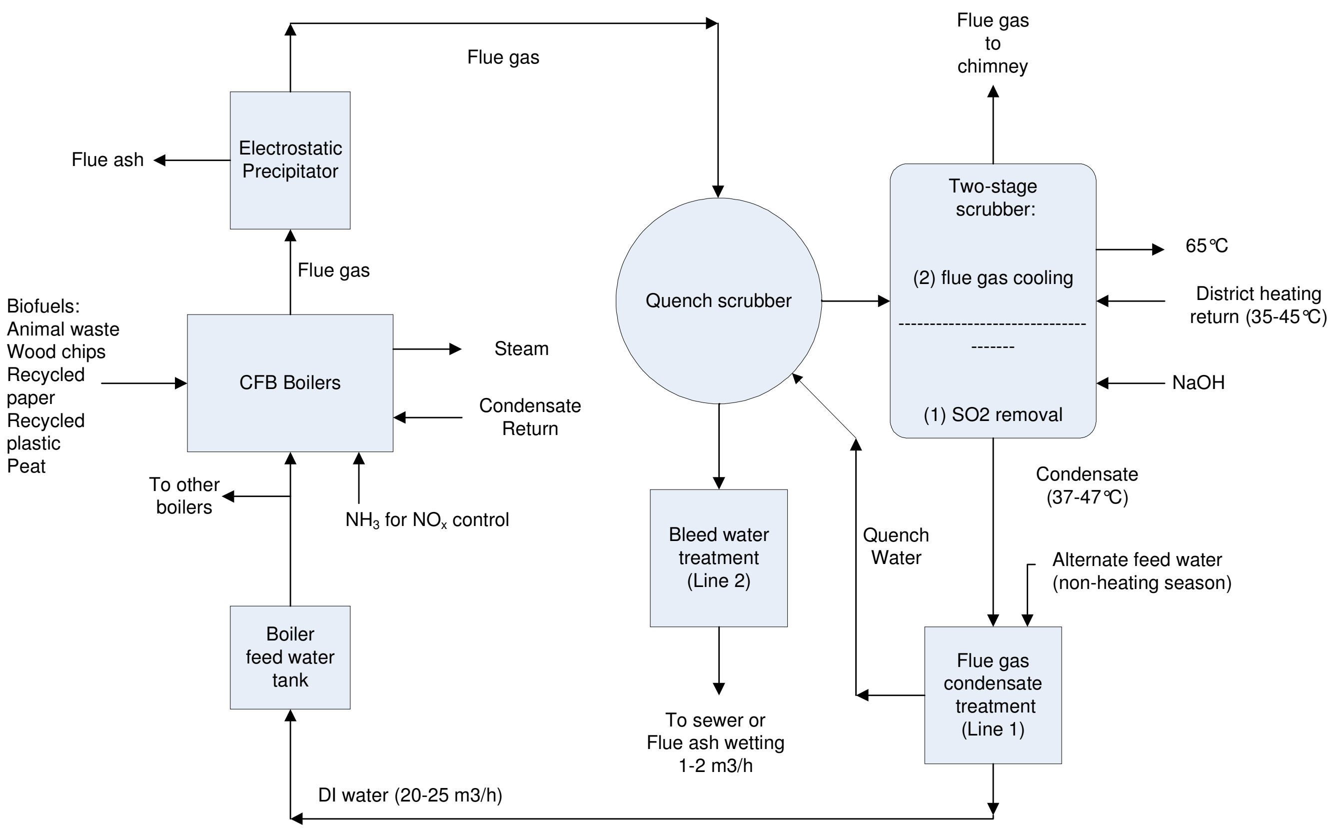


Figure 1 Karlskoga Energy Plant Summary Diagram

Picture 2  Two-Stage Scrubber/Cooler

**CONDENSATE TREATMENT**

Figure 2 is a block diagram of the Line 1 water treatment train used to demineralize the flue gas condensate and make it suitable for use as makeup to the boilers. Design flow rate for the boiler makeup system is 20-25 $m^3$/h. The medium pressure (40-50 bar) boilers require makeup water quality of 0.2 µS/cm, and the design DI water flow rate is 25 $m^3$/h. The deionized water system provides water to several boilers, operating continuously, even when the district heating system is off-line. Therefore it was designed to accept feed water from town water or surface water as well as the flue gas condensate. However, the condensate has the worst quality of the three sources, and thus dictated the equipment required to meet the product water requirements in all cases. For the case of condensate feed, Table 1 provides a profile of the typical water quality as it proceeds through the Line 1 system, illustrating the function of the various unit operations.

**Table 1 - Line 1 Water Quality Profile**

| **Location** | **Typical Water Quality** |
|---|---|
| Scrubber out (MF in) | 500-8000 µS/cm<br>100-200 ppm TSS<br>< 20 ppm COD<br><5 ppm hardness as $CaCO_3$<br>37-47 °C |
| MF out (Cooler in) | 10-100 ppm TSS |
| Cooler out (UF in) | 35-40°C |
| UF out (IX Softener in) | 0 ppm TSS<br><5 ppm COD |
| IX Softener out (MD in) | <1 ppm hardness as $CaCO_3$<br>100-300 ppm $CO_2$ |
| MD out (RO 1 in) | < 5 ppm $CO_2$<br>500-8000 µS/cm |
| RO1 out (RO2 in) | 40-300 µS/cm |
| RO2 out (CEDI in) | 5-20 µS/cm |
| CEDI out (MB in) | <0.1 µS/cm |

The first step is a vibrating-screen cross-flow microfiltration device, designed to remove particulate matter larger than 100 microns. This type of device was selected because of the high suspended solids loading of the flue gas condensate, which would have quickly plugged cartridge or bag filters.

After the microfiltration system comes a regenerative heat exchanger that reduces the water temperature to 40°C, required by the several downstream devices employing polymeric membranes. The first of these devices is a hollow-fiber ultrafiltration system with a nominal molecular weight cutoff of 150,000 – 200,000. The primary purpose of the UF is to remove small particulates and COD (high molecular weight organic substances such as oils and resins), and thereby prevent fouling of downstream gas transfer and reverse osmosis membranes. The selected UF is an "inside-out" type, with the condensate fed into the fiber lumens and permeate drawn off the outside of the fibers.

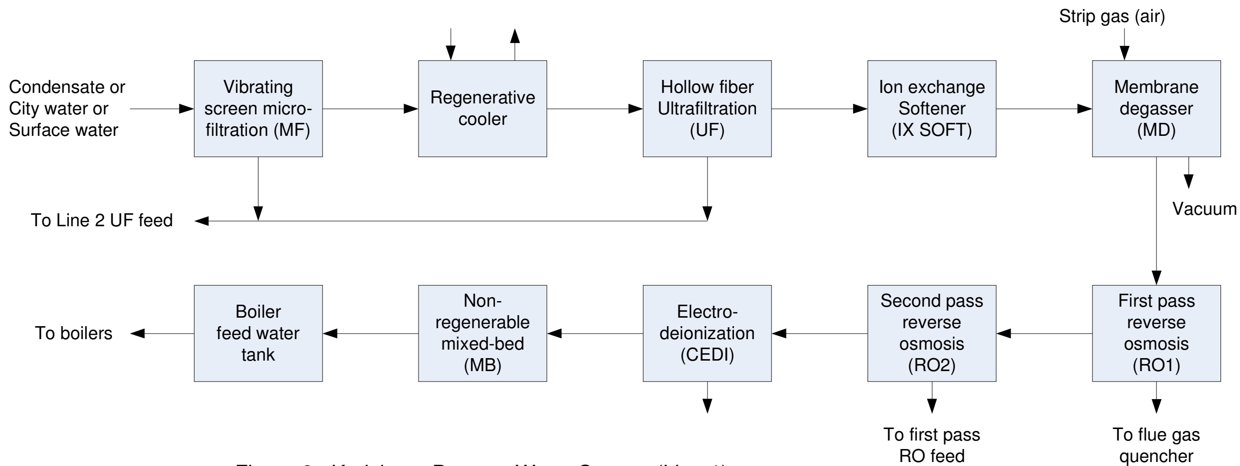


Figure 2 Karlskoga Process Water System (Line 1)

Typical flux for this system is about 100-150 l/m$^2$-h (60-90 gfd).

To protect the reverse osmosis (RO) system from scaling, this system was fitted with a sodium-cycle countercurrent softener using conventional gel-type strong-acid cation exchange resin. However, the softener seldom regenerates during the heating season when the water purification system is fed with flue gas condensate, as this source is normally low in hardness. The softener is present primarily for periods when the system is fed by one of the alternative water supplies, or for upset conditions.

The condensate water is saturated with $CO_2$ (100-300 ppm), which will not be removed by the RO system. Therefore it was necessary to employ some sort of decarbonator to reduce the ionic load on the electro-deionization system. Instead of conventional forced-draft degasification a gas transfer membrane system was chosen [3], as this employs a hydrophobic gas transfer membrane between the strip gas and the water stream. The membrane degasser takes up less space than a degasifier tower and associated clearwell, and avoids airborne contamination of the water. To improve effectiveness the system employs 2 gas transfer membrane contactors in series, with air as the strip gas and 200 $mbar_a$ vacuum assist on the air outlet.

Because of the very high dissolved solids content of the flue gas condensate, it was decided to use two-pass reverse osmosis as a roughing demineralization step. The first pass is operated at a flux of about 20-25 l/m$^2$-h (12-15 gfd) and the second pass operated at <50 l/m$^2$-h (30 gfd). The second pass RO reject is returned to the inlet of the first RO, and the first-pass reject used as makeup to the quench scrubber. First pass water recovery is 75% or more, resulting in a first-pass reject conductivity of up to 32000 µS/cm.

In this system, continuous electrodeionization (CEDI) is used as the polishing deionizer, in order to avoid the need for storage, handling and neutralization of regenerant chemicals. The CEDI system consists of two stacked-disk type modules [4], each with a nominal flow rate capacity of 11.4 m$^3$/h (50 gpm). Water recovery is 90-95% and power consumption about 0.25 kwh/m$^3$ (1 kwh/kgal) The product conductivity is typically < 0.1 µS/cm. Since the CEDI system easily meets the specifications for boiler makeup water quality, the non-regenerable mixed-bed ion exchange was installed only for insurance, to protect against a possible system upset. It is normally bypassed.

The CEDI product water is sent to the boiler feed water tank. From here it is pumped to the boilers, with ammonia added to increase the pH to about 9, for corrosion control.

## QUENCH BLEED TREATMENT

The Line 2 waste water treatment system for the quench bleed stream is much smaller than Line 1, with a design flow of 2 m3/h (9 gpm). In practice this flow has typically been less than 1 m3/h. Figure 3 is a block diagram of the quench bleed treatment system, the purpose of which is to produce water that meets local discharge limits for suspended solids and heavy metals.

Table 2 provides a profile of the water quality through the treatment processes of the Line 2 system, illustrating the function of the various unit operations.

**Table 2 - Line 2 Water Quality Profile**

| Location | Typical Water Quality |
|---|---|
| Quench out (MF in) | 10000-30000 ppm NaCl<br>100-500 ppm TSS<br>50-100 ppm COD<br>(water is whiskey-colored)<br>pH 0.5-1.0<br>65 °C<br>>1000 ppm $NH_3$ |
| MF out (UF tank in) | 10-100 ppm TSS |
| UF tank out (UF in) | pH 10.5-11.0 |
| UF out (HX in) | <1 ppm TSS |
| HX out (MD in) | 50 °C |
| MD out (S-IX in) | <15 ppm $NH_3$ |
| S-IX out | <1 ppm total heavy metals |

The first step in the wastewater system is a 100 micron vibrating-screen cross-flow microfiltration device, like that used in the condensate water system. Because the water that is bled off the recirculating quench stream is hot and higher in suspended solids, ceramic ultrafiltration was selected in this case for COD removal. The UF is a tubular configuration, the tube diameter about 3-4 mm. The ceramic membrane will remove particles down to 0.05 µm. The UF feed water is adjusted to pH 10.5-11.5 using NaOH, to convert ammonium ion to ammonia and allow downstream removal of $NH_3$ with a gas transfer membrane. The concentrate from the UF system is send to the ash transportation system, to wet the flue ash before shipment.

The ammonia removal system [5] feeds the wastewater to the shell side of the membrane contactor (outside the hydrophobic hollow fibers) and a sulfuric acid solution (pH 1.5-2.0) flows countercurrent through the lumen side (inside the hollow fibers). The ammonia transfers through the membrane and then reacts with the acid to form a dilute ammonium sulfate solution, which sent back to the boiler for use as a corrosion inhibitor and to inhibit formation of CO and $NO_x$.

The final wastewater treatment step is heavy metal removal, accomplished with a chelating ion exchange resin (Lewatit TP214). This resin has much higher selectivity for heavy metal ions (Cd, Cr, Co, Cu, Fe, Mn, Hg, Ni, Ag, Zn) than for sodium, potassium or calcium. The effluent from the selective ion-exchange column must meet the EU discharge limits shown in Table 3. The selective ion exchange system was not designed for in-place regeneration, so the resin bed was sized to operate for at least two years before requiring resin replacement. The final treated wastewater is sent to the sewer or used for flue ash wetting.

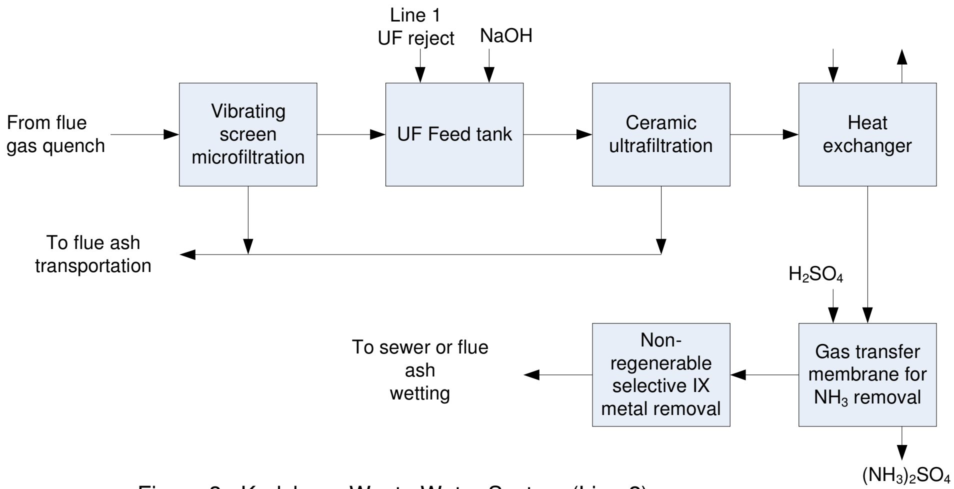


Figure 3 Karlskoga Waste Water System (Line 2)

| **Table 3 - Line 2 Discharge Limits** | |
|---|---|
| **Contaminant** | **Maximum, ppm** |
| TSS | 10 |
| Hg | 0.03 |
| Cd | 0.05 |
| Tl | 0.05 |
| As | 0.15 |
| Pb | 0.2 |
| Cr | 0.5 |
| Cu | 0.5 |
| Ni | 0.5 |
| Zn | 1.5 |

## OPERATING RESULTS

Most waste-to-energy plants have overall energy efficiency of less than 60% [6]. While district heating energy plants generally have higher efficiency (60-70%) than those that only generate electricity (35-40%), there is still significant room for improvement. The Radscan flue gas condensation system for energy and water recovery has been demonstrated to increase plant efficiency to >90% during heating season.

The flue gas condensation system at Karlskoga has now been in operation for about two years. The energy savings realized by operation for two heating seasons (in Sweden a typical heating season is 5,000-6,000 hours) has already paid off the $10M investment in capital equipment.

Based on continuous production of deionized water from flue gas condensate at 20 $m^3$/h (88 gpm), during the two heating seasons the plant has saved 100,000 $m^3$ (26,000,000 gallons) of water.

The conservative design of the Line 1 process water system and Line 2 waste water system has resulted in reliable operation with minimal maintenance. For example, chemical cleaning is performed only twice per year on the reverse osmosis system (as preventative maintenance during system stoppage) and has not been required for the electro-deionization system.

Picture 3 Line 1 RO and EDI Systems

The US EPA estimates that every ton of municipal solid waste that is burned avoids the release of one ton of CO2 into the atmosphere [7]. By this estimation (based on an average of 40 tons/hour and operation 5,000 hours/year), the Karlskoga waste-to-energy plant saves the atmosphere from 200,000 tons of $CO_2$ per year. The use of the flue gas energy recovery has avoided release of an additional 40,000 tons of $CO_2$.

## SUMMARY

Waste-to-energy plants utilizing biomass already conserve non-renewable fossil fuels while reducing $CO_2$ and disposing of solid waste. The environmental issues (such as dioxins) that represented the main hurdle to widespread adoption of W-T-E have been resolved [8]. Further advances such as flue gas condensate and energy recovery can significantly improved the efficiency of these plants, to a level of environmental friendliness that is unsurpassed.

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