High Efficient Waste-to-Energy Facilities

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All countries in Europe are working hard to reduce their reliance on fossil fuels in their power and district heating production. However, for many years to come a large share of the energy supply will continue to be based on fossil fuels. Therefore, waste-to-energy (WtE) facilities will also in the future make an important contribution to reaching the climate goals, and high energy efficiency will remain mandatory for all waste treatment facilities in order to maximise utilisation of the European energy resources and limit the climate impact of energy production.

A new generation of WtE facilities replacing existing capacity is being established in several places in Europe, e.g. in Denmark. The majority of these new facilities feature a very high efficiency with respect to both energy recovery and environmental performance. But they not only recover energy from waste, they also have the potential to facilitate a high material recovery.

With their high energy efficiency they contribute even more to the reduction of greenhouse gases than earlier generations of WtE facilities. It is important to have this in mind in the strategic planning of both waste handling and energy production. Strategies may be based on analyses made using key figures from older WtE facilities, not reflecting new modern capacity. This can lead to policies and decisions that do not fully utilise the waste resources. For this reason it is important to ensure that key figures from new modern facilities should be available for the decision makers – whether they are public or private.

This paper focuses on one of these new high efficient facilities, Copenhill, which is under construction in the centre of Copenhagen. Copenhill is a bar-raising project in several respects, e.g. by having a total net energy efficiency of more than 107 percent, and a high potential for recycling and recovery. For instance forty percent of the incoming waste can be recovered as ultra clean reusable water, and 15 to 20 percent of the incoming waste can be reused for road construction.

Additionally, Copenhill boasts outstanding environmental performance and allows access for the public to first class architecture and recreational facilities, e.g. a ski slope on top of the roof.

Such optimal solutions are possible only due to suitable framework conditions, including a long planning horizon, attractive financing as well as access to a large district heating network for energy sales.

Figure 1:

Copenhill WtE facility with recreational areas on the roof top

Source: Amager Resource Center

1. Copenhill WtE facility

Copenhill is established by Amager Ressourcecenter – ARC – in the centre of Copenhagen, adjacent to ARC‘s existing facility and a new housing area and close to the Opera and the Queen’s Palace. ARC is an inter-municipal resource company owned by five municipalities in the Greater Copenhagen area. The company receives and processes waste from approximately 550,000 residents and 45,000 businesses and provides recycled materials, electricity and district heating to the city.

Copenhill WtE facility will be replacing ARC‘s existing, more than forty years old waste treatment facility, which requires high maintenance costs, has only moderate energy efficiency, and does not meet contemporary standards for occupational health and safety.

The concept for the new facility was based on a comprehensive financial and technology review process. The final solution was the best solution with respect to both total economy and lifecycle analysis of the environmental impact.

The financial framework represents a key driver in reaching the high energy recovery and environmental performance. Investments in improved efficiency prove their value when allowed to work over a long financial planning period and with moderate demands for return on investment. The Copenhill WtE facility is financed by a loan guaranteed by the five municipalities. The most important framework conditions are listed hereafter:

- Net present value is an important evaluation parameter when calculated over the financial planning horizon of twenty years and an internal rate of return of 3.9 percent p.a. in addition to the inflation rate. This allows for higher initial investment for high performance solutions;
- Connection to a large district heating network that allows sale of heat year round at almost full load – no cooling is accepted;
- The economic value of electrical power and heat is at ratio 2:1;
- Discharge of treated process wastewater is an option;
- NO_x emission tax of 3.3 EUR/kg.

Additionally, a precondition for the very high energy recovery is the access to the large district heating network of Copenhagen. District heating in Denmark has a long history, going back to 1903 when Denmark built its first WtE facility with heat recovery, and today the vast majority of the households in Copenhagen are heated by district heating, see Figure 2. At national level all WtE facilities for municipal solid waste are connected to district heating networks, and hardly any of the heat produced is cooled away.

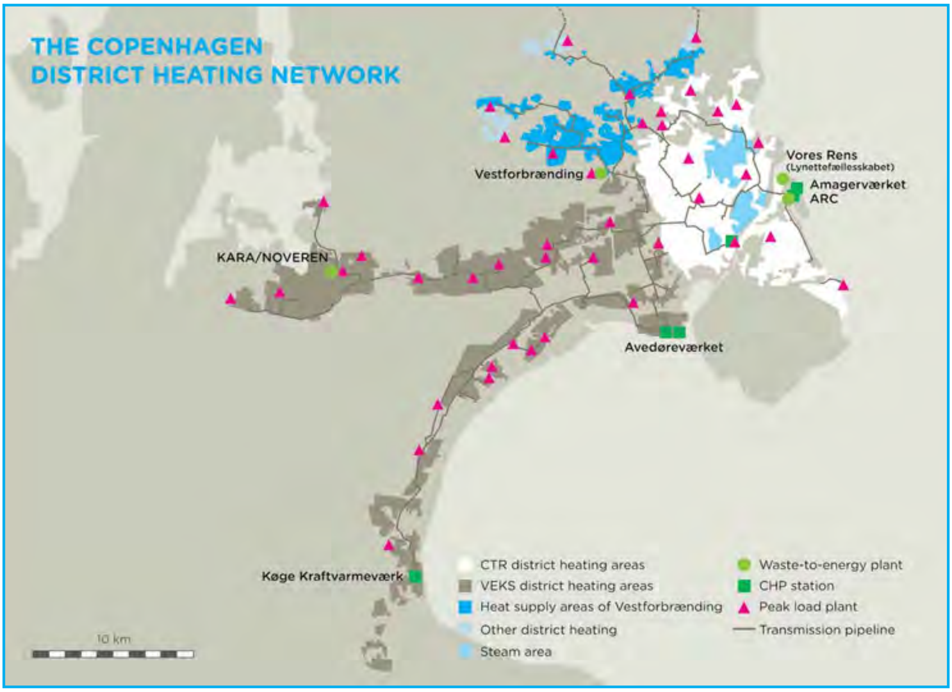

Figure 2: The Copenhagen district heating network, showing several WtE facilities as well as other CHP plants including peak load boilers

For the Copenhill WtE facility it was also a requirement that the technical solutions should be well proven and capable of withstanding large variations in waste composition, and it was taken into consideration that the environmental requirements are relatively strict and ambitions high.

The prospect of being able to sell district heating instead of power only greatly increases the overall energy recovery. As discussed in Waste-to-Energy for District Heating [7] a slight reduction of power may be exchanged to a large heat production in a combined heat and power system compared with a power system only as one MW of electricity can be exchanged to about 18 MJ per second of district heating. An example is given in Figure 3.

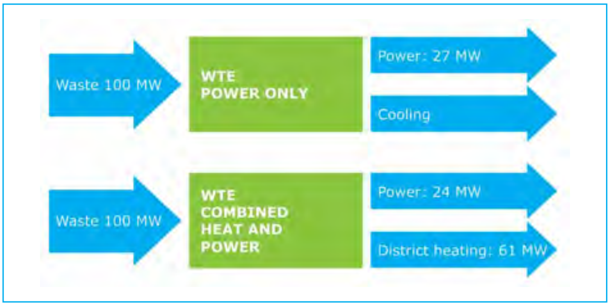

Figure 3:

Example comparing energy flows of a power producing WtE facility and a combined heat and power producing WtE facility without flue gas condensation

The main process flow diagram for the Copenhill WtE facility can be seen in Figure 4, and the main nominal design parameters are listed in Table 1. The electromechanical equipment has been contracted in five major electromechanical packages including 1) boiler and auxiliaries, 2) flue gas treatment and heat pump system, 3) turbine-generator and condensers, 4) electrical system and 5) control system. The facility has two grate-fired 35 ton waste per hour drum-type boilers supplied by Babcock and Wilcox Vølund (112 MW fired per boiler), a wet flue gas cleaning system supplied by LAB including a flue gas condensation system, and finally a high efficiency 67 MWe steam turbine SST-800 from SIEMENS.

Parameter	Unit	Nominal waste
Number of boilers	-	2
Number of turbines	-	1
Waste flow, total	ton/h	70
Lower heating value (nominal)	GJ/t	11.5
Lower heating value (range)	GJ/t	8-15
Thermal energy input, total	MW	223.6
Flue gas flow rate, total	m^3/h, ref. *	438,000
Moisture content in raw flue gas	%	15
HCl in raw gas	mg/m^3, ref.	800
SO_2 in raw gas	mg/m^3, ref.	400

* ref. is reference condition, i.e. 0 °C, 101,325 Pa, dry flue gas at eleven percent O_2.

Table 1:

Waste throughput, energy, flue gas flow and composition of the Copenhill WtE facility

Source: Amager Resource Center and Ramboll: Tender documents, lot L101 and L102, Amagerforbrænding 2010.

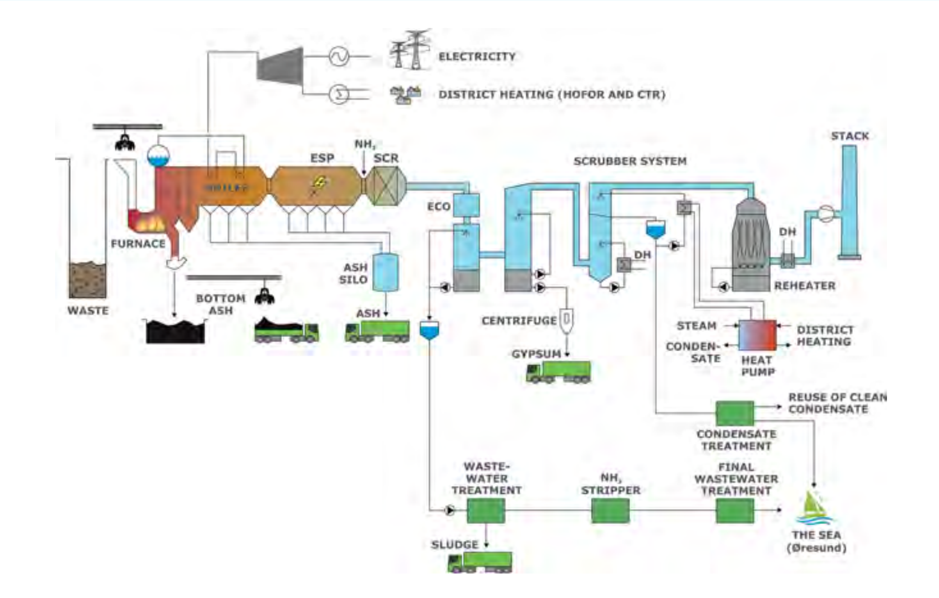

Figure 4: Process flow diagram of the Copenhill WtE facility, here only showing one of the two boilers

2. Energy recovery and flexibility

Energy recovery/optimisation is an integrated part of the Copenhill WtE facility. Every optimisation opportunity is weighed on a financial scale and against other criteria given by the framework conditions, and only attractive solutions are included. At Copenhill the main features are:

- High steam parameters: 440 °C/70 bar, prepared for 480 °C/70 bar.
- The boiler operates at low excess air ratio – only six percent dry O_2 in the flue gas – thus yielding high boiler efficiency.
- A front-end (hot) SCR means high deNOx rates without energy consuming steam-fed flue gas re-heaters that are necessary in systems with a tail-end SCR.
- Low turbine back pressure through large turbine condensers.
- Steam turbine with high isentropic efficiency and many bleeds allow for a complex and efficient water-steam cycle.
- Cooling of flue gas to 160 °C at the boiler exit.
- Two-step flue gas condensation: first step is cooling the flue gas by heat exchange with the district heating return line, yielding ten MW of extra district heating per boiler, and second step is cooling the flue gas down to as low as 20 to 30 °C by using an absorption heat pump, adding another 15 MW of extra district heating per boiler. In total the flue gas condensation adds around twenty percentage points to the energy recovery.

- Recovering heat from component cooling system, which removes heat from a large number of comments.

In addition, the facility is designed to have a very high availability, which is important in relation to continuously harvesting the benefit of having high energy efficiency.

Copenhill has a high degree of operational flexibility – the main energy sales options are illustrated in Figure 5. It is possible to sell heat to two of Copenhagen's sub systems in the district heating network: The local distribution system of HOFOR, and the transmission network of CTR. This is done in novel double tube-bundle condensers.

The turbine has a controlled extraction supplying steam to a heat pump system – which drives the flue gas condensation.

And finally, a full turbine bypass system is implemented, thus allowing for very high heat sales in periods with low power prices, or with high heating demands.

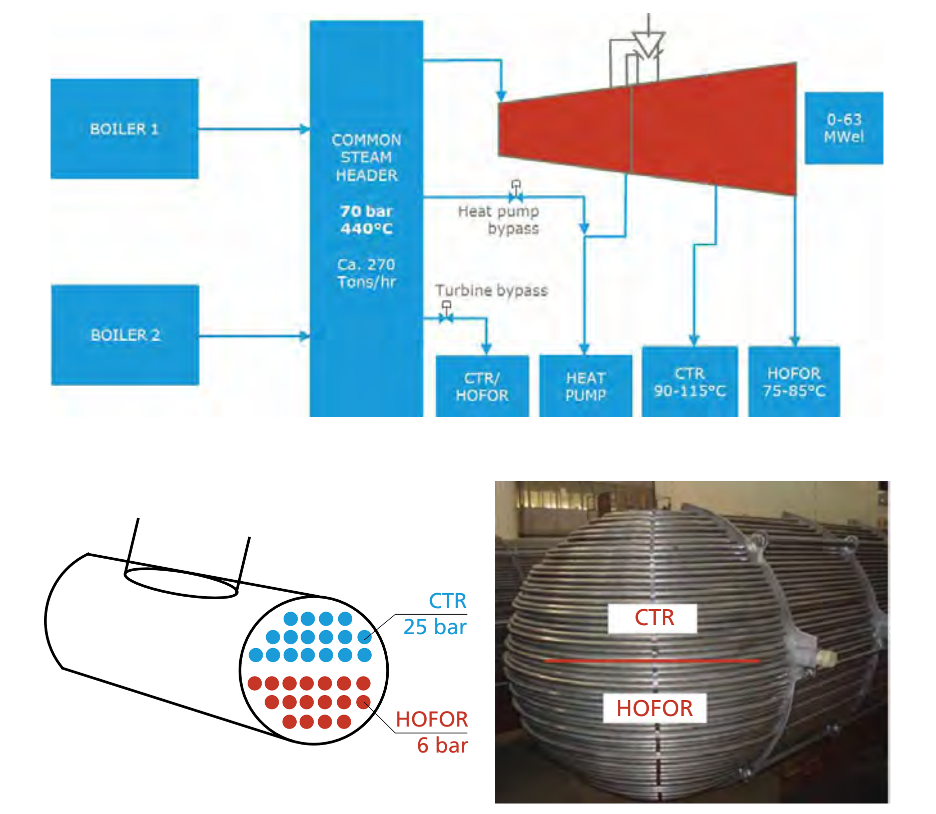

Figure 5: Flexibility in regard to heat and power sales

Source: Siemens AG

The resulting main modes of possible operation are:

- Normal operation with combined heat and power, including direct flue gas condensation

- Same as above but with flue gas condensation boosted by approximately thirty MW with heat pumps in operation.
- Complete turbine bypass operation with heat pumps in operation.

In addition, there are a number of combinations operating one/two boilers and part/full load.

The nominal energy production for two boiler operation is illustrated in Figure 6 below.

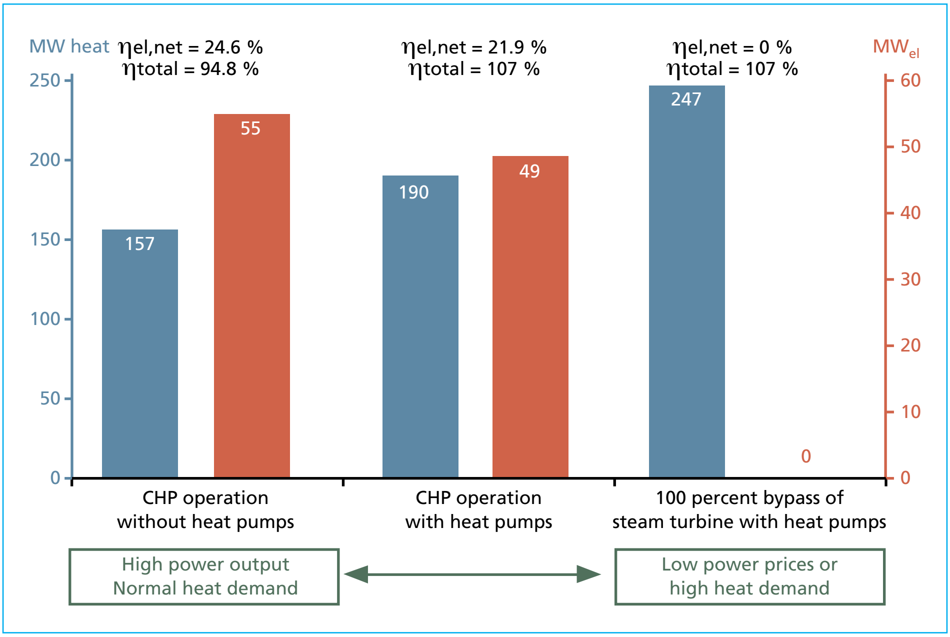

Figure 6: Modes of operation in relation to energy recovery at Copenhill; assuming operation is at nominal conditions; outputs and efficiencies are net, i.e. after subtraction of parasitic consumption

3. Environmental performance

The choice of flue gas treatment – FGT – technology was based on a range of criteria applied on a number of potential process configurations and taking into consideration the frame conditions given by the location, ownership, regulatory framework, etc. cf. Figure 2.

The FGT concept is shown in Figure 5, and includes a SCR system for NO_x abatement, a wet scrubbing system and flue gas condensation. This was deemed attractive because of its high flexibility with respect to very tough environmental requirements, robustness towards relatively high raw gas pollutant loads, environmentally friendly nature of consumables – limestone instead of burnt lime, in particular –, relatively low raw materials consumption, limited amount of solid residues, high energy recovery, possibility of recycling water generated from condensation, and low net present value over the planning period compared with other options despite the relatively high investment.

It was also of importance that the FGT concept had a solid track record in the field with numerous years of operation and that a sufficient number of qualified suppliers were available.

The deNO_x concept is a front end low dust SCR system with a three layer catalyst located downstream a high temperature electrostatic precipitator operating at around 270 °C, which in turn requires the boiler economiser to be located downstream the SCR system. In the system there is no need for flue gas reheating and associated systems, which are draw-backs of conventional tail-end solutions. The catalyst also destroys dioxins and furans. The tax on NO_x emissions facilitated the choice of the highly efficient SCR system over the conventional SNCR system.

The four-stage wet scrubbing system removes in the first stage HCl, HF and most of the heavy metals which have not been completely captured by the ESP. SO_2 is removed in the second-stage limestone scrubber, and two-stage flue gas condensation not only ensures heat recovery; it also provides two-stage polishing of the flue gas including an additional dioxin and mercury removal stage through injection of activated carbon. The outstanding efficiency of the flue gas treatment system hardly leaves any trace of pollutants in the flue gas when emitted into the ambient air (compare Table 2).

Table 2: Flue gas emissions (daily average/spot mg/Nm^3): EU directive, Environmental permit and expected operational emissions

Air Emission, daily average	**EU Industrial Emissions Directive (IED)**	**Environmental permit**	**Expected operational emissions**
	mg/m^3, ref.*		
CO	50	39	10
Total organic carbon	10	8	1
Dust	10	5	3
HCl	10	5	0.5
HF	1	1	0.05
SO_2 and SO_3 (as SO_2)	50	30	2
NO_x (as NO_2)	200	100	15
NH_3	-	3	0.5
N_2O	-	-	0.5
Cd + Tl	0.05	0.025	0.001
Σ 9 metals[1)]	0.5	0.25	0.015
Hg	0.05	0.025	0.001
PAH	-	0.0025	0.002
	ng/m^3, ref.*		
Dioxins and furans, TEQ	0.1	0.1	0.02

* ref. is reference condition, i.e. 0 °C, 101,325 Pa, dry flue gas at 11% O2.

1) Sb+As+Pb+Co+Cr+Cu+Mn+V+Ni

Sources:

EU Industrial Emissions Directive (IED): Environmental Protection Agency of Denmark, Miljøstyrelsen. Environmental Permit, http://mst.dk/media/mst/68354/AMF6_Miljogodkendelse_Amagerforbraending.pdf. 2012

Einvironmental permit: The European Parliament and of the Council: Waste framework directive, DIRECTIVE 2008/98/EC of 19 November 2008 on waste and repealing certain Directives.

The flue gas condensation also removes water vapour and turns it into a valuable source of water for the entire facility and for potential purposes outside the facility such as make-up water to cover the water loss of the district heating network of Copenhagen.

Treated wastewater and excess condensate is discharged to the adjacent sea (Øresund), which is why its treatment must comply with very strict requirements for discharge, Table 3. These requirements surpass the EU directive requirements for most heavy metals by a factor of ten or more and even surpass drinking water requirements on several parameters.

Table 3: Wastewater requirements (extract), process wastewater and condensate, respectively; emission requirements, EU directive, Bat reference note and drinking water values for comparison

Parameter	Unit	IED limit values	BREF, BAT operational levels* (at tap)	DK drinking water limit values discharge	Environmental permit, process waste water discharge	Environmental permit, condensate
pH -	-	6,5-11	7-8.5	6.5-9.0	6,5-9,0	
Suspended matter (100 %)	mg/l	45	10-45	-	30	30
Suspended matter (95 %)	mg/l	30	10-30	-	-	-
Mercury, Hg	µg/l	30	1-30	1	1	0.1
Cadmium, Cd	µg/l	50	10-50	5	3	1
Thallium, Tl	µg/l	50	10-50	-	3	2
Arsenic, As	µg/l	150	10-150	10	8	5
Lead, Pb	µg/l	200	10-100	10	10	1
Chromium, Cr	µg/l	500	10-500	50	10	3
Copper, Cu	µg/l	500	10-500	2,000	10	5
Nickel, Ni	µg/l	500	10-500	20	10	3
Zinc, Zn µg/l	1,500	10-1000	3,000	300	50	
Dioxins and furans, TEQ	ng/l	0.3	10-100	-	0.01	0.01
Temperature	°C	-	-	-	50	30
Reference flow per tonne waste input	litres/tonne			110	360	

Sources:

DK drinking water limit values (at tap): Danish Ministry of the Environment. Official Order on Water Quality in Denmark, in Danish. BEK nr 292 af 26/03/2014, Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg, https://www.retsinformation.dk/Forms/R0710.aspx?id=160400.

Environmental permit, process waste water discharge and Environmental permit, condensate discharge: Environmental Protection Agency of Denmark, Miljøstyrelsen. Environmental Permit, http://mst.dk/media/mst/68354/AMF6_Miljogodkendelse_Amagerforbraending.pdf. 2012.

BREF, BAT operational levels: European Commission: BAT reference note on waste incineration, Aug. 2006: Integrated Pollution Prevention and Control, Reference Document on the Best Available Techniques for Waste Incineration, August 2006. 2006.

IED limit values: The European Parliament and the Council: Industrial Emissions Directive, DIRECTIVE 2010/75/EU of 24 November 2010 on industrial emissions (integrated pollution prevention and control). s.l. : EU, 2010.

The wastewater discharge therefore represents a mass flow of pollutants that is insignificant to the environment. The process wastewater is treated in a conventional precipitation system, supplemented by a fine treatment with sand filters, carbon filters and ion exchangers and an ammonia stripper that recycles liberated ammonia to the furnace. Condensate is treated in its own system including reverse osmosis (RO) to produce very clean water that is virtually free of salt and pollutants. In principle it is too valuable just to discharge. It is made available for use as make-up water for the boilers and district heating network.

The use of SCR for $DeNO_x$ and a wet FGT process limit the amount of consumables and residues to a level close to theoretical minimum, (compare Table 4) in which the values are to be seen together with the raw flue gas flow rate and relatively high pollutant load, Table 1, and the expected flue gas treatment efficiency, Table 2.

Mass flows	Unit	Expected consumption/ production
Ammonia water (25%)	kg/tonne	3.0
Limestone (95% CaCO3)	kg/tonne	12
NaOH (27 %)	kg/tonne	1
Activated carbon	kg/tonne	0.3
Other (TMT, FeCl3, flocculant, anti scalant)	kg/tonne	0.04
HCl	kg/tonne	0.5
Water consumption *	litres/tonne	0
Electrical power consumption	kWh/tonne	105
Production/discharge		
Bottom ash	kg/tonne	150-200
Process wastewater for discharge	litres/tonne	110
Condensate discharge or export for recycling *	litres/tonne	400
Fly ash	kg/tonne	15-20
Gypsum	kg/tonne	5
Hydroxide sludge (dry matter)	kg/tonne	2

*with flue gas condensation in operation

Table 4:

Expected consumption data and residues production per tonne of input waste

4. Materials recovery and recycling

Optimal resource management is a key topic in waste management. At the Copenhill WtE facility the incineration process provides the opportunity for material recycling through recovery of resources that would not otherwise be recycled.

Metal segregation from bottom ash is expected to reach more than ninety percent of the potential for most ferrous and non-ferrous metals when modern techniques are deployed. Few other metal segregation systems for municipal solid waste management reach a similar efficiency. The recovered metals are sold at high prices to replace virgin materials. The bottom ash will be used for road construction and similar construction purposes under strict requirements for heavy metal content and leaching behaviour. Thereby the bottom ash replaces natural resources of similar nature, i.e. sand and gravel.

The water contained in the waste is recovered in the flue gas condensation stage and is foreseen to replace other water resources, e.g. for covering the losses of the district heating network. No other known treatment processes recover clean water. The total *true recycling* from the incineration of residual waste would thereby exceed fifty percent.

According to current EU definitions of *recycling* none of these activities are considered recycling as the WtE facility as such is defined as a *recovery* operation from which no official *recycling* is possible – as far as Ramboll understands common interpretations of these matters. This illustrates that EU and government recycling targets based on calculated recycling rates according to the present definitions give little information on the true resource recycling amounts, let alone the true resource value in the local context.

It further illustrates that defining certain processes as *recycling* and others as *recovery* may be counterproductive when it comes to optimal resource management and protection of the environment, particularly in the local context. Development has overtaken the definitions of *recycling* and *recovery* and calls for rethinking of the definitions related to the waste hierarchy.

5. Conclusion

The Copenhill WtE facility is under construction and will feature outstanding energy and environmental efficiency. These features are realised within the local framework conditions which permit harmony between the financial optimisation and the ideals of striving for the best possible utilisation of the resources of waste, limiting the use of fossil fuels and ensuring the close-to-zero impact on the environment.

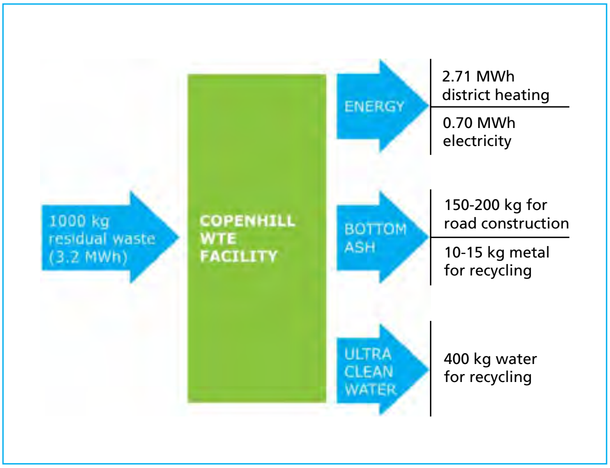

Figure 7:

Summary of useful outputs from the high efficient waste-to-energy facility of Copenhill

Important framework conditions include a long financial planning period, moderate demands for return on investment, access to a large district heating network and the possibility of recycling or discharging excess clean condensate for full exploitation of the energy recovery potentials of flue gas condensation.

WtE facilities can also be an important tool for material recycling through recovery of metals, use of bottom ash for construction purposes and export of clean water. Figure 7 shows the useful outputs from Copenhill WtE facility.

6. References

[1] Amager Resource Center and Ramboll: Tender documents, lot L101 and L102, Amagerforbrænding 2010.

[2] Danish Ministry of the Environment. Official Order on Water Quality in Denmark, in Danish. BEK nr 292 af 26/03/2014, Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg, https://www.retsinformation.dk/Forms/R0710.aspx?id=160400.

[3] Environmental Protection Agency of Denmark, Miljøstyrelsen. Environmental Permit, http://mst.dk/media/mst/68354/AMF6_Miljogodkendelse_Amagerforbraending.pdf. 2012.

[4] European Commission: BAT reference note on waste incineration, Aug. 2006: Integrated Pollution Prevention and Control, Reference Document on the Best Available Techniques for Waste Incineration, August 2006. 2006.

[5] The European Parliament and the Council: Waste framework directive, DIRECTIVE 2008/98 EC of 19 November 2008 on waste and repealing certain Directives.

[6] The European Parliament and the Council: Industrial Emissions Directive, DIRECTIVE 2010/75/EU of 24 November 2010 on industrial emissions (integrated pollution prevention and control). s.l. : EU, 2010.

[7] Tobiasen, L. Kamuk, B.: Waste-to-Energy for District Heating. In Encyclopedia of Sustainability Science and Technology. 2012.