*This PDF file contain the Energy technology catalogue chapters for the biomass and waste plant types listed below with related data tables (.xls) has been send in external review from July 14 to August 22 2017.*

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# 08 WASTE-TO-ENERGY CHP PLANT

## *Qualitative description*

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### Brief technology description

The major components of a Waste-to-Energy (WtE) plant for energy recovery by combined heat and power (CHP) are: A waste reception area, a feeding system, a grate fired furnace interconnected with a steam boiler, a back pressure steam turbine, a generator, an extensive flue gas cleaning system and systems for handling of combustion and flue gas treatment residues. Process diagram is found in Annex 1.

The plant is primarily designed for incineration of municipal solid waste (MSW) and similar non-hazardous wastes from trade and industry. Some types of hazardous wastes may, however, also be incinerated.

The waste is delivered by trucks and is normally incinerated in the state in which it arrives. Only bulky items are shredded before being fed into the waste bunker.

The design and operation of WtE plants vary depending on the environment of their location. For example, in Scandinavia, revenues gained from the combined sales of district heat and electricity enable relatively low gate fees. In other countries, support for electricity production has encouraged electrical recovery, e.g. Italy and Spain (Ref. 1). This may be supplemented by sale of steam to nearby industries while sale of heating (or cooling) is subject to limitations of the district energy demand and network development.

When it comes to technological maturity, WtE is under Category 4, *Commercial technologies, with large deployment.* The technology has been used for 50 years, and more than 400 WtE plants are currently in operation in Europe many of which are CHP-facilities, mainly in the Northern Europe (ref. 16).

**Input**

The fuels used in WtE plants include mainly MSW and other combustible wastes, and in some cases biomass mainly for starting up and closing down. Some plants in Denmark are feeding green waste from gardens and parks and challenging forest residues such as stubs. In addition, imported Refuse Derived Fuel (RDF) may be used as fuel. Other inputs include water and chemicals for flue gas treatment, and gasoil or natural gas for burners used for start-up and auxiliary firing (if installed).

The fuel, waste, is characterised by being heterogeneous having large variation in physical appearance, heating value and chemical composition. The heating value is a result of controlled mixing of available waste sources fed to the bunker of the WtE facility. It is usually in the range 7-15 MJ/kg, typically averaging 10-11 MJ/kg, referring to the lower heating value, LHV. For instance, the average heating value was 9.5 MJ/kg varying from 8-11 MJ/kg in 2014 in the WtE facility owned by Amager Resource Center (ARC) in the Copenhagen area. At the time ARC had about 50% waste from trade and industry, which is a high ratio in Denmark (Ref. 6).

The table below shows the trend of the heating value at Vestforbrænding I/S – the largest MSW plant in Denmark, and also located in the Copenhagen area.

*Table 1 Development of lower heating value at Vestforbrænding, Denmark. Ref. 7.*

| Year | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|
| **MJ/kg** | 10,32 | 10,30 | 9,80 | 10,0 | 10,4 |

The heating value of the waste received at the WtE plants may be affected by increased focus on recycling, which on one hand may divert organic waste with relatively low heating value and on the other hand divert plastics, paper and wood with relatively high heating value. Many Danish WtE plants are importing RDF waste with relatively high heating value.

**Output**

The products from operating a WtE CHP plant are electricity and heat as steam, hot (> 110$^{o}$C) or warm (< 110$^{o}$C) water, bottom ash (slag), residues from flue gas treatment, including fly ash. Bottom ash making up around 15% of the mass input of waste is sorted to recover metals for recycling and production of aggregates for road construction. Flue gas treatment residues and fly ash (totalling around 2-4% of the mass input of waste) are stored in an underground deposit designed for the purpose. If the flue gas is treated by wet methods, there may also be an output of chloride containing waste water, which is usually treated at the plant to a purity that is acceptable for the municipal sewerage system or discharge to the sea. In case of flue gas condensation, excess condensate (which represents up to 50% of mass input of waste) may be upgraded to high quality water useful for technical purposes such as boiler water or for covering water losses of the district-heating network.

The energy efficiency of the WtE plant has increased over the last decade, driven by focus on combustion control, limiting the flue gas temperature at boiler exit and the excess air level, assisted by the increased use of flue gas condensation, Ref. 7 and Ref. 8.

**Typical capacities**
The capacity of a WtE plant is typically in the range 10-35 tonnes of waste per hour, corresponding to a thermal input of approx. 30 - 110 MJ/s. The furnace capacity is limited to around 120 MW thermal input at the current state of development.

**Regulation ability**
The CHP plants can be down regulated to about 70% of the nominal capacity. Below the limit the boiler may not be capable of providing adequate steam quality and compliance with the requirement of high temperature residence time of the flue gas, cf. environmental section. WtE plants are preferably operated as base load due to high initial investments. In order to be able to maintain a waste treatment capacity during outages WtE plants are sometimes built as 2 (or more) parallel lines instead of one large unit depending on alternative disposal options of waste.

Most CHP facilities are constructed with fully flexible and fast reacting electricity production meaning that the turbine may be taken in or out of operation through the use of a turbine by-pass, which may also be used partly. When the turbine is out, the output is 100% heat for district-heating, and furnace/boiler operation continues unaffected. Turbine operation can usually be maintained down to around 15% of nameplate load.

**Advantages/disadvantages**
A WtE CHP is not just an energy producing plant but a multi-purpose facility. Main purpose is the treatment of waste by which the waste is sterilised and its mass and volume are greatly reduced. Compared to landfilling and anaerobic digestion the WtE prevents emissions of methane, a powerful greenhouse gas, from the waste handling.

Recovery of energy from waste is a main feature for resource recovery as part of the circular economy system for waste. It provides the opportunity of recovering resource from wastes that are not recyclable, e.g. contaminated waste, rejects from recycling operations and wastes that are too demanding to recycle, ref 14.

The energy recovery process also provides the opportunities of recovering secondary raw materials from waste such as metals eventually replacing virgin metals produced from excavated metal ore. Metals (including iron, steel, aluminium and copper) are recovered from the bottom ashes. Metals contained in compound waste products that would otherwise be difficult to recycle may be recycled after the thermal treatment in the WtE facility. The remaining bottom ash may be used as aggregate for road construction. Furthermore, clean water may be recovered as a result of flue gas condensation.

The disadvantage is that a polluted, corrosive flue gas is formed, requiring extensive treatment, and that the flue gas treatment generates residues usually classified as hazardous waste. The capital costs are relatively high due to the flue gas treatment system, other environmental requirements, the heterogeneous nature of the fuel and corrosive properties of the flue gas. The corrosive nature of the flue gas also limits the permissible steam data to approximately 40 - 70 bar and 400-440 $^{o}$C (Ref.

10) and hence the net power efficiency to around 20-30%. Due to the corrosive flue gasses the hottest parts of new boilers are often coated with expensive corrosion resistant alloys (Inconel).

**Environment**
The air emissions from energy recovery of waste must comply with the environmental permit setting limit values on a range of pollutants including dust, CO, total organic carbon (TOC), HCl, $SO_2$, HF, $NO_x$, heavy metals and dioxins/furans. The limit values are based on the EU Industrial Emissions Directive (IED, ref. 15) of 2010 and the EU reference note on best available techniques for waste incineration (BAT-reference note or BREF, ref. 1) supplemented by assessment of local conditions. Energy recovery also involves the generation of climate-relevant emissions mainly $CO_2$, and $N_2O$ may be contributors.  $CH_4$ is not generated in in any significant amount (it is included under the restrictive limit value of TOC).

Waste is a mixture of $CO_2$ neutral biomass and products of fossil origin, which is mostly plastics (the $CO_2$-emission from energy recovery of plastics is defined as fossil $CO_2$ emitted from the WtE). A typical $CO_2$ emission factor is 37.0 kg/GJ for the waste mixture currently incinerated in Denmark. Typically, 32% ±5% of the emitted $CO_2$ originates from fossil source (Ref. 3).

The IED includes a residence time requirement of the hot flue gas, meaning that the flue gas must be heated to min. 850°C for at least 2 seconds after the last air injection. This is to ensure conditions for complete burnout of the combustible gases and hence, ensure low emissions of CO, TOC and dioxins. HCl, HF and $SO_2$ are captured in the course of flue gas treatment and leave the facility in the solid flue gas treatment residue. In case HCl, HF and $SO_2$ are removed by wet processes, the chloride in HCl will, however, leave the facility in a chloride containing wastewater stream, which must be treated to fulfil the local water emission limit values in addition to the IED limit values.

In general, political and economic framework conditions define the emission limits from WtE. A revised BAT reference note has been published in draft in 2017. The implications in terms of revised environmental requirements in the final version are uncertain.

Decision on pollutant abatement technology and hence, emission levels, are also affected by taxation. Currently (2017) emission tax is imposed on NOx and $SO_2$, at around 0.8 €/kg for NOx and 1.3 €/kg for $SO_2$.

Technical development in deNOx-technology and gradually more stringent emission requirements are expected to lower emissions of NOx for new facilities.

The solid residues from treatment of flue gas and wastewater are classified as hazardous wastes and are often placed in an underground storage for hazardous waste (cf. Council Decision 2003/33), ref. 17.

Ecological footprints include air and water emissions as well as solid residues to be disposed of. On the positive side the recovered energy replaces energy produced from other resources and the emissions from this production, and recovered metals replace metals production from virgin ore.

**Total energy efficiency determination with flue gas condensation**
Flue gas condensation technology was introduced at WtE plants in Denmark 2004. It recovers the evaporation energy of the flue gas water content as low temperature heat and thereby increases the

energy efficiency by additional 10-25% for mixed waste. Since 2007 every new built WtE line in Denmark has been designed with flue gas condensation, and numerous existing lines have retrofitted flue gas condensation into their plants. With the inauguration of Amager Bakke in Copenhagen and implementation of flue gas condensation at Fjernvarme Fyn in Odense in 2017, two thirds of the Danish WtE capacity is equipped with flue gas condensation heat recovery. It is expected that most of the remaining WtE plants will retrofit flue gas condensation within the coming decade.

Figure 1 shows the calculated net boiler efficiency and net total efficiency for a WtE plant (CHP or heat only) equipped with flue gas condensation connected to a 40/80 °C district heating network, 40/80 °C meaning that the district-heating return temperature is assumed at 40 °C and the flow temperature at 80 °C.

In Figure 1 and the data tables, it is assumed that the flue gas condensation is applied only by direct condensation by which heat recovery happens by simple heat exchange between a scrubbing liquid (or flue gas) and district-heating water. The temperature of the district-heating return water is therefore the limiting parameter for the flue gas condensation output. The use of a heat pump to provide a cold media for extended flue gas condensation is considered an add-on, the feasibility of which is judged as a separate project (cf. technology sheets on heat pumps). The heat pump constitutes the vast majority of the necessary additional investment.

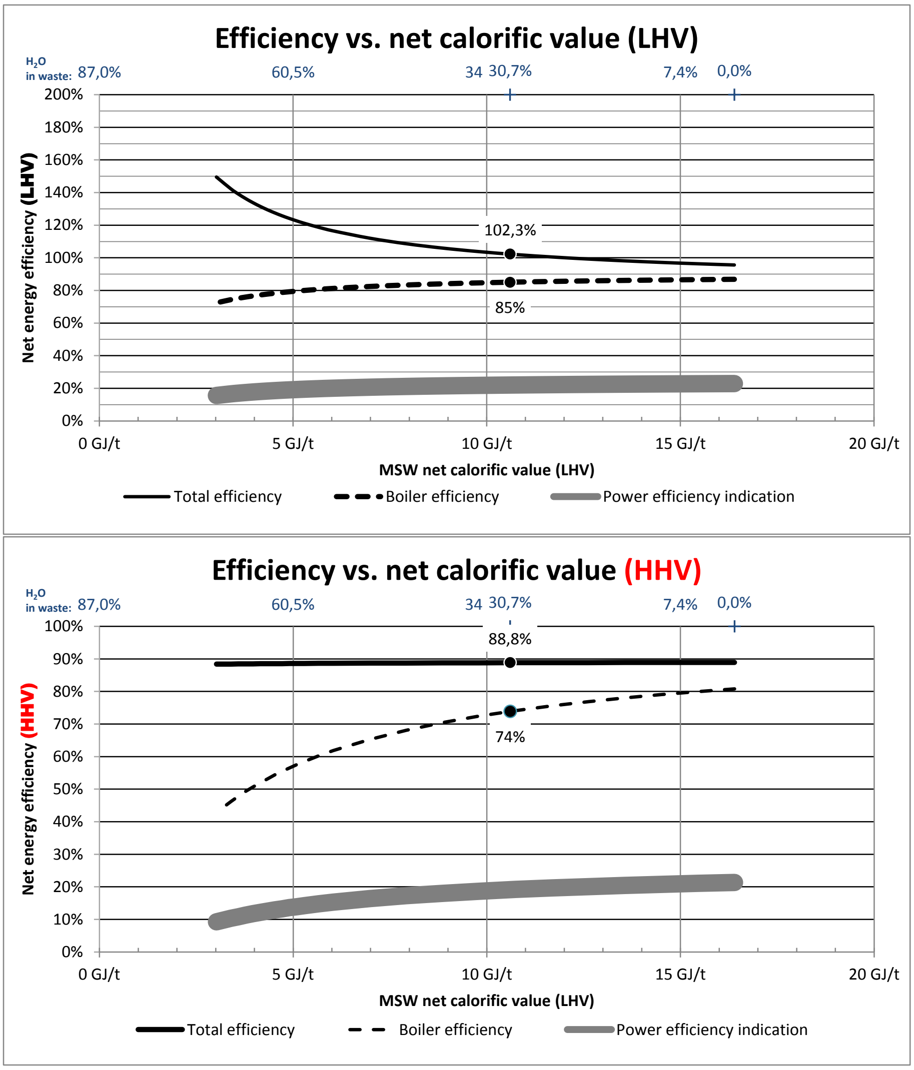


*Figure 1.Total energy efficiencies for WtE plant with flue gas condensation given 40°C district heating return temperature and varying heating values of the waste (energy recovery by flue gas condensation through the use of heat pumps is not included). In the top graph, curves are based on the usual lower heating value (LHV). The lower graph shows the same efficiencies based on the higher heating value (HHV). (Ref. 13)*[1].

The top diagram in Figure 1 is based on the normally referred "lower heating value" (LHV)[2]. In this diagram it can be seen that the WtE boiler efficiency is almost constant, at around 85% (dashed line), while the total efficiency increases with increasing moisture content (decreasing LHV) and far exceeds 100% as heating values fall below 10 GJ/t.

The y-axis on the lower diagram in Figure 1 is based on the higher heating value (HHV), illustrating that the boiler efficiency drops significantly with decreasing LHV. The power efficiency follows the boiler efficiency, as the power production is based on the steam produced by the boiler. The total efficiency on the other hand is almost constant when based on HHV, at around 89 % in the exam-

[1] Assumptions: District heating return temperature 40 °C. Excess air ratio λ=1.6 (with λ=1.3, efficiencies increase by roughly 1.5 % points). Ash content 25% of dry matter. Flue gas from boiler 170 °C. Own power consumption 40 kWh/t + 1% of HHV).

[2] In Europe, heating values of solid fuels are almost always stated on LHV basis. Higher heating values (HHV) include the energy contribution from condensation energy of water vapor from the flue gases, and are relevant when flue gases are condensed for heat recovery.

ple. The actual level of the total efficiency depends almost entirely on the temperature that the flue gas is cooled to by the condenser, determined by the district heating return temperature. Figure 2 shows the estimated total efficiency based on HHV of a WtE plant as a function of the district heating return temperature. Variations in the excess air ratio of the boiler will affect the moisture percentage of the flue gas, and hence affect the operating conditions of the condensation. However, it may shift the total efficiency only slightly (within ±1.5% points).

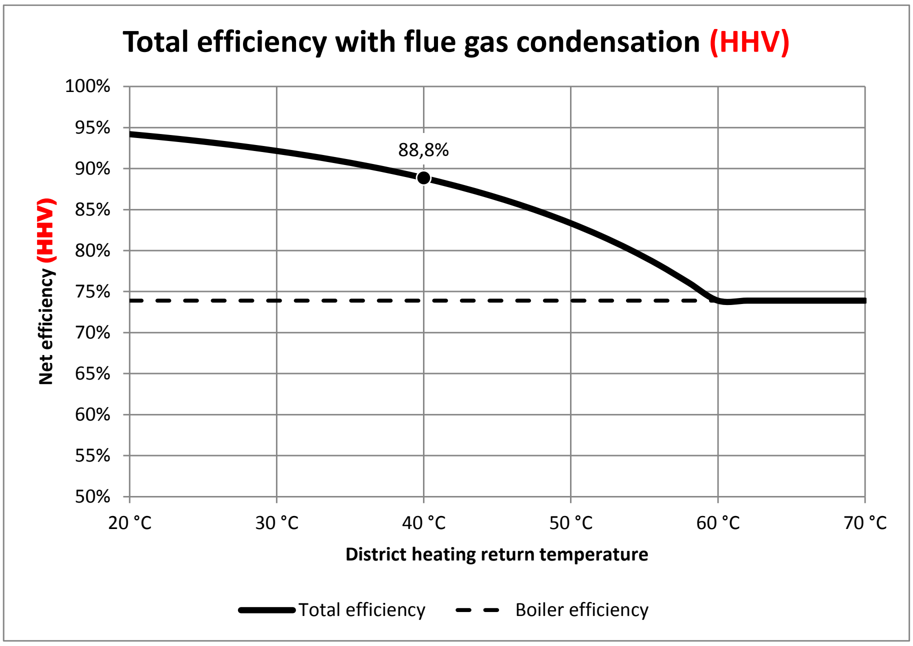


*Figure 2.Total efficiency estimate based on HHV for WtE and biomass plants given varying district heating return temperatures.(ref.13) – or temperature of the cold media of a heat pump.*

Thus Figure 2 can be used generally with good accuracy to estimate the total efficiency (based on HHV) of a WtE or solid biomass plant equipped with flue gas condensation, based only on the available district heating return temperature. The estimate is even valid for marginal efficiencies of single waste fractions such as organic waste, paper, plastics etc. The conversion to the usual LHV-based total efficiency is straight-forward. As an example, typical municipal solid waste with a LHV of 10.6 GJ/t and a HHV of 12.2 GJ/t treated at a plant with flue gas condensation fed with 40 °C DH water would according to Figure 2 have a total efficiency of 88.8% based on HHV. This can be calculated to the LHV-based total energy efficiency as: $88.8\% \cdot \frac{12.2\ \mathrm{GJ/t}}{10.6\ \mathrm{GJ/t}} = 102.2\%$, which corresponds to the WtE CHP "2015" tables. For organic waste with a HHV of 6.8 GJ/t and LHV of 4.7 GJ/t treated at the same plant, total energy efficiency would be $88.8\% \cdot \frac{6.8\ \mathrm{GJ/t}}{4.7\ \mathrm{GJ/t}} = 128\%$.

Large heat pumps have been installed at some plants to supply condenser cooling water at lower temperatures than the DH return temperature in order to further increase the heat recovery. In these cases the total efficiency can still be read from Figure 2 by replacing the district heating return temperature on the x-axis by the (lower) chilled water temperature from the heat pump.

Slightly higher total efficiencies can be achieved by recovering the heat from component cooling at the plant, which is usually cooled away. This would require the use of heat pumps. Recovery of component cooling energy is being implemented both at Amager Bakke and Fjernvarme Fyn in Odense during 2017, both reaching total net efficiencies around 105-110 %.

**Development perspectives and future demand**

The electrical efficiency may be increased with higher steam temperature and pressure. However, this may reduce the lifetime of the super-heater, due to corrosion by chloride and other aggressive ingredients in the flue gas, thereby increasing super-heater replacement rates and/or decreasing the operational availability. Simple solutions, which are common in the US, are to replace the super-heater regularly, and to protect the super-heater with a layer of Inconel, a corrosion resistant alloy. Another solution is to use a clean fuel (e.g. natural gas or self-produced gas) for heating an external super-heater, as implemented at Maabjerg Kraftvarmeværk, Holstebro.

A novel proposed solution ("Steamboost" being developed by company Babcock & Wilcox Vølund) is to segregate out a less corrosive part of the flue gas from the last part of the furnace. An additional high temperature superheater installed in this flue gas can increase the steam temperature from the usual 400-440 °C to 480 °C. Operating at a higher temperature the new superheater will increase the electricity efficiency by 3-6 percentage points (Ref. 12).

Combustion air humidification is a method to increase the energy recovery by flue gas condensation without using a heat pump. In the process, water is evaporated into the combustion air on one side generating high moisture content of the flue gas and hence, a high (adiabatic saturation) temperature in the flue gas condenser stage and on the other side the evaporation of water generates very cool cooling water for the heat recovery in the condenser. This technology is in successful use in several biomass plants in particularly Sweden and Finland. Combustion air humidification is expected to be introduced at the first WtE plant in Denmark within a few years.

Technology with net power efficiency 25% is available now (up to 30% for power-only) but the future development is depending on the price on electrical power, which is currently low and decreasing in Denmark. New plants are optimised for best net present value over the planning period which currently makes it unattractive to strive for very high power efficiency considering the increased capital cost and risk of corrosion. Optimisation may even question the concept of CHP compared to heat only boilers, depending on forecast of electricity prices and heat market availability and pricing. In Denmark, Scandinavia and other countries having district heating systems we expect the total energy efficiency to increase in the future due to increased penetration of flue gas condensation possibly augmented by combustion air humidification, and decreasing return temperatures from the district heating. (please, refer to Examples of best available technology).

Other energy conversion technologies may find its place such as organic rankine cycle (ORC), the use of which may significantly reduce the capital cost of a plant at the expense of some percent points of power generation efficiency.

Similarly, the amount of hazardous waste (fly ash and flue gas cleaning residue) may be reduced by optimisation of the overall process. In addition, treatment of residues may be further developed for recovery of salts and metals, Zinc in particular. Treatment may also render the residue non-hazardous easing the landfilling and possibly over time and development allowing use for construction purposes.

Advances in the metal recovery from the bottom ashes may increase the recycling rate. Dry bottom ash extraction systems are demonstrated at plants in Switzerland, and allow increased metal recovery rates as sub-millimetre metal particles can be extracted and mechanically sorted in a noncorroded form. Even for wet extracted bottom ash metals recovery is expected to increase significantly through further development of sorting systems.

A new World Bank study projects a 70% global increase in urban solid waste – with developing countries facing the greatest challenges. The projected rise in the amount of waste, from 1.3 billion tonnes per year today to 2.2 billion tonnes per year by 2025, is expected to raise the annual global costs from $205 billion to $375 billion (Ref. 5).

Even in Europe, the potential for WtE is huge. Only 6 states have reduced the amount of municipal waste landfilled to a minimum: Austria, Belgium, Denmark, Germany, the Netherlands and Sweden landfill only 4% of municipal waste or less. They have all introduced landfill bans of combustible waste and worked towards a complementary waste management system where both recycling and waste-to-energy play a role in diverting waste from landfills (diagram below).

In a Danish perspective this may provide an opportunity of offering waste treatment at high resource efficiency by WtE-facilities from which virtually all energy is used. At the same time waste would replace the import of other fuels in the energy system. And with payment following the waste import, the treatment and energy recovery effectively becomes an export activity with a potentially advantageous business case.

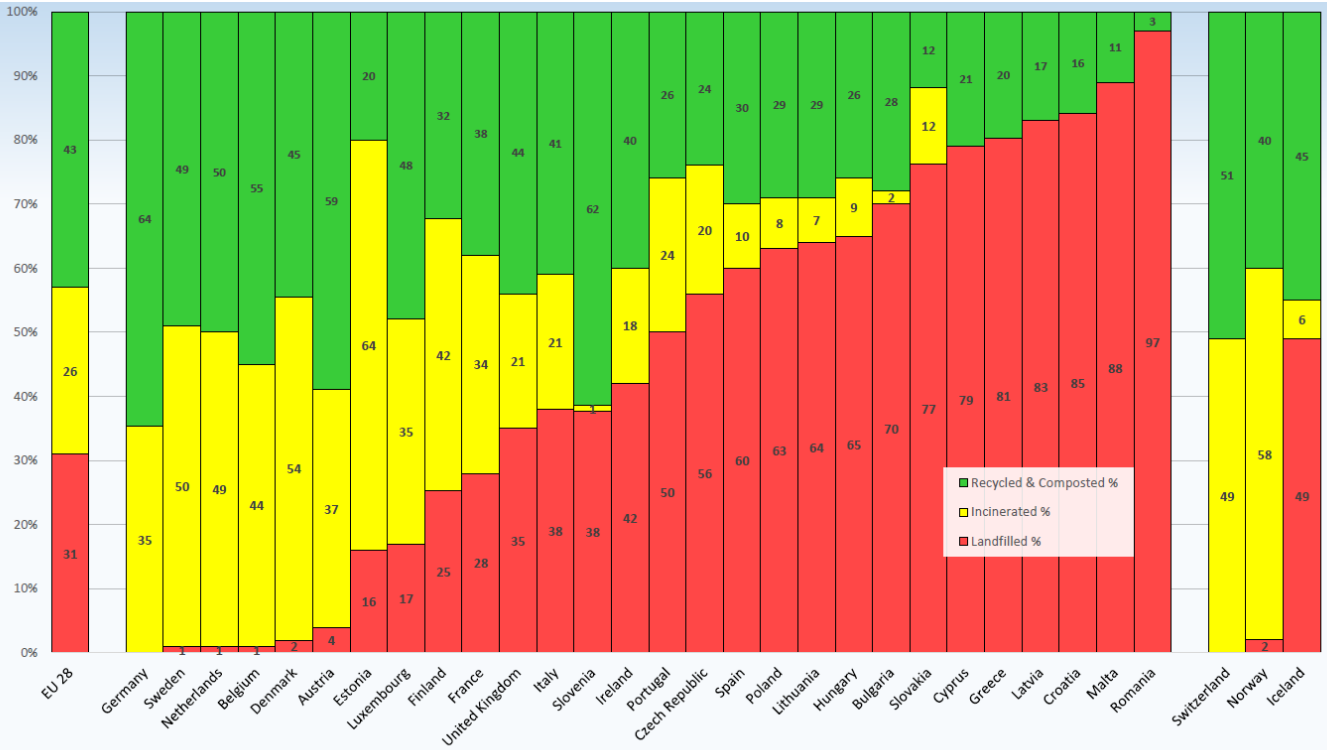


*Figure 3.Waste management in Europe, Graph by CEWEP (Ref. 4). Source: EUROSTAT.*

On the WWW interest groups, plant manufacturers and World Bank publish relevant information on development perspectives and future demand, for example:

- www.cewep.eu
- www.eswet.eu

- www.worldbank.org
- www.iswa.org

It is in discussion how the $CO_2$ content of the waste shall be distributed between the waste treatment and the energy recovery.

Some major cities have visions to become $CO_2$-neutral - Copenhagen in 2025. Implementation of these visions may eventually affect the amount of fossil waste (mainly plastics) to be treated locally. Currently Danish WtE plants are importing some of their fuel as RDF from other parts of Europe, where waste treatment capacities are insufficient.

Such ambitions may render $CO_2$ capture attractive despite the relatively high cost of constructing and operating the system.

**Uncertainty**
The amount and the heating value of the available waste are dynamic properties, which change with time. Waste sorting (at source and central) and liberalization of commercial waste in DK are factors that might reduce the amount of residual waste and change its properties. In Sweden relatively high recycling rates have not significantly changed the heating value of waste sent to WtE.

Other more exotic processes such as thermal gasification may in a distant future develop and take over specific fractions from WtE.

**Economy of scale effects**
The initial costs for WtE CHP plants are so high that smaller plants (< 5-10 t waste/h) are seldom economical. The typical production line has a capacity of 10-35 t waste/h. More lines are installed if required. In Scandinavia WtE plants are typically located close to larger cities with a district heat system and they are designed to treat the waste amounts produced in the vicinity. During periods where local waste generation is below the treatment capacity, it is possible to supplement with waste from other regions, including imported waste (as RDF). The size of the moving grate defines the upper limit waste mass capacity for each boiler line (approx. 40 t waste/h).

**Examples of best available technology**
Amager Bakke at ARC under commissioning in 2017 will have a capacity of 2 x 35 tonnes/hour, steam data 440°C and 70 bar. It is equipped with flue gas condensation augmented by large heat pumps that cool the flue gas to 22 °C. The net power efficiency and total energy efficiency based on a lower heating value of 11.5 MJ/kg depends on the selected operation:

CHP-operation without heat pumps: $\eta_{el}$: 25%, $\eta_{total:}$ 95%
CHP-operation with heat pumps: $\eta_{el}$: 22%, $\eta_{total:}$ 107%
(Ref.: 11).

Amager Bakke is expected to be one of the WtE plants with the highest total energy efficiency in the world. Only Fjernvarme Fyn in Odense will achieve a similar total efficiency when heat pump assisted flue gas condensation cooling the flue gas to 24 °C is implemented here during 2017.

The Afval Energie Bedrijf in Amsterdam is the largest incineration plant in the world (1.5 million tonnes per year). The most recent extension (2007) involved 2 units of 34 tonnes/hour, steam data

440 $^{o}$C and 130 bar and river cooled condensers, which together with steam re-heating results in a net electricity efficiency of 30% when producing power-only (Ref. 2). This is the current world record power efficiency for WtE plants.

Comparing the two, power-only record efficiency of 30% is 5%-points higher than Amager Bakke without heat pump operation, but the total energy efficiency is 65%-points lower than Amager Bakke.

**Additional remarks**

Contrary to other fuels used for energy generation, waste has a negative price and is received at a gate fee. The primary objective of a waste-to-energy plant is the treatment of waste. Produced energy may be considered a useful by-product although with increasing importance for the future Danish energy system with extensive use of district-heating and high power production from wind. The total energy production from a WtE boiler can be varied by varying the fuel feed, although WtE facilities run at full load most of the time if the district-heating demand allows together with additional cooling opportunities. Operation of WtE CHP-unit as power-only may not be financially attractive, and often CHP facilities are constructed so that operation at power-only is not physically possible, as the necessary cooling facilities are not in place. The heat production can be changed also by starting or stopping the flue gas condensation. The electricity production is usually fully flexible from CHP plants because the turbine can be by-passed fully or partly at short notice and the rate of change may be as high as the turbine allows. The heat generation is thus changed corresponding to the change in electricity generation.

By condensing most of the water vapour content of the flue gas in the flue gas condensation system, a thermal efficiency (based on the net calorific value) exceeding 100% is achievable. At the same time, the plant produces excess amounts of clean condensate, which in essence is distilled water. This may be considered a secondary raw material recycled for replacing water for technical purposes such as covering losses of district-heating networks to which the energy system is attached. The flue gas condensation system is usually located downstream the flue gas treatment system, making the condensate low in salts and pollutants when leaving the condenser. The condensate could be treated further by EDI and reverse osmosis to reach the quality required for its subsequent use or discharge to sensitive water recipients.

**The energy model for the technology tables**

The energy efficiency estimates in the technology tables were calculated using a model of flue gas energy recovery to steam and district heating, including flue gas condensation (Ref. 14). A steam cycle model estimated the steam-to-power efficiency based on the steam parameters and turbine sizes. The same models were used to estimate efficiencies for the tables covering heat only and CHP plants for WtE as well as biomass plant types at all size ranges. The different performances in the tables are thus a consequence of different plant design data assumed in each case and the fuel properties.

Table 2 shows the basis plant design assumptions made for the “2015” scenarios for different feed stocks. Conservative and optimistic variations of these assumptions were made to produce the future, “Upper” and “Lower” performance data. For example, “Lower” WtE models would assume combustion air humidification and steam at 400°C/40bar, while “Upper 2050” assume 500°C/90bar, which will require advances in the technology such as Steam Boost described above. For small-to-medium biomass plants, “Upper” models assume the lower excess air offered by the Dall boiler already today etc.

*Table 2 Base assumptions for “2015” model CHP plants for energy performance estimation. ”Upper” means that the feature is only assumed in the optimistic “Upper” scenarios.*

| Fuel | Waste | Wood chips | Wood pellets | Straw |
|---|---|---|---|---|
| **Firing system** | Grate | Grate | Suspension | Grate |
| **Live steam, CHP** | 425°C/50bar | 540°C/90bar | 560°C/90bar | 540°C/90bar |
| **Flue gas T after steam boiler** | 160°C | 130°C | 130°C | 130°C |
| **Excess air ratio** | 1,5 | 1,3 | 1,3 | 1,3 |
| **Boiler losses other than flue gas (% of LHV)** | 2% | 2% | 2% | 2% |
| **Turbine losses (gear/generator) (% of gross power), CHP** | 3% | 3% | 3% | 3% |
| **Flue gas condensation** | Yes | Yes | "Upper" | "Upper" |
| **Combustion air humidification** | "Upper" | "Upper" | "Upper" | None |
| **Flue gas cleaning type** | Wet | Dry | Dry | Dry |
| **NOx abatement (small and medium size)** | SNCR | SNCR | SNCR | SNCR |
| **NOx abatement (large facilities)** | SNCR | SCR | SCR | SCR |

The total efficiency of plants with flue gas condensation is calculated assuming “direct condensation”, where the condensation heat is recovered directly with the available district heating water without the use of heat pumps.

DH plants share base assumptions with the CHP plants, except that live steam parameters are not applicable, and the turbine losses do not exist for these plants.

At some plants, condensation heat recovery is augmented by cooling the flue gas further, typically to 30 °C using heat pumps. In the tables, the row “Additional heat potential for heat pump (%)” contains the additional heat energy that a heat pump would recover from the flue gas by cooling it further to 30 °C. The so produced additional heat is the sum of this energy amount and any external driving energy (electricity or steam) supplied to drive the heat pump.

As an example, the plant Amager Bakke would belong to the “Large WtE” plants with high DH temperature levels of 50/100°C. The 2015 data from the tables provide name plate values of 22.5% for power and 73.6% for heat, summing up to 96.1%. The additional heat from heat pumps is given as 10.0%, increasing the sum to 106.1%. The steam driven heat pumps are driven by steam produced at the plant, which does thus not add to the net energy production.

Without heat pumps, the actual design power efficiency of 25% is higher than the 22.5% that the tables suggest. This is mainly due to the high steam parameters (440°C/70bar), and the lower forward temperature of the actual district heating water (85°C instead of the 100°C assumed in the tables). The total design efficiency is 95% without using heat pumps, which is on level with the 96.1% from the tables.

With heat pumps activated, the total efficiency reaches 107%. This is slightly higher than the 106.1 % in the tables, which is due to the flue gas being cooled to 20 °C instead of 30 °C, and some additional component cooling heat recovery is performed by the actual heat pumps as well. The power efficiency is reduced to 22.5% when using the heat pumps, mainly due to the transfer of driving steam for the heat pumps.

The loss of power production caused by the steam consumption of the heat pumps is system specific and cannot be tabulated here. If electrically driven heat pumps had been used instead, the power production loss would be avoided, but instead the heat pump would consume power themselves. Please refer to the heat pump technology sheets.

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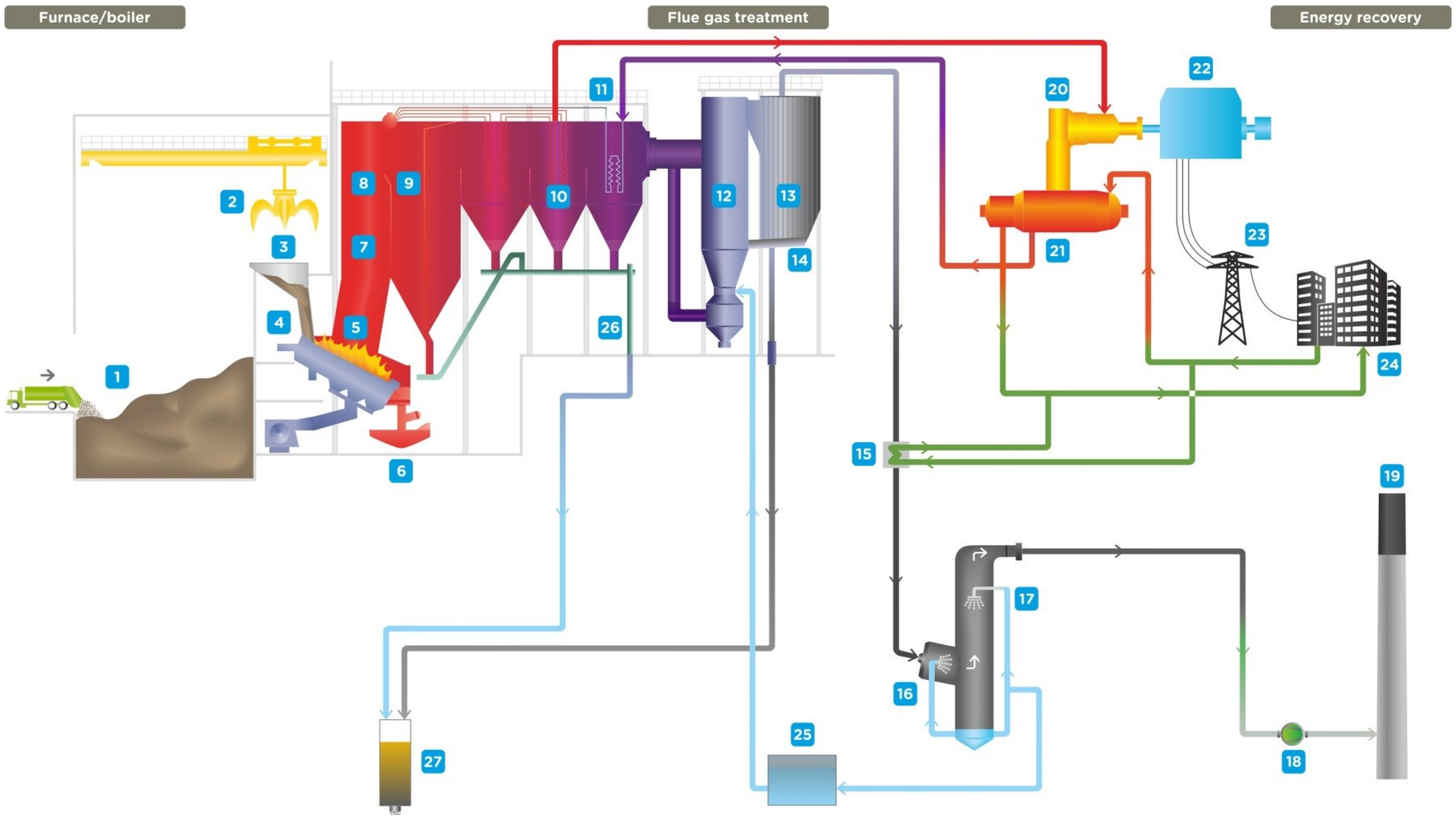
# Annex 1, Process flow of a WtE CHP-facility (example)



# 09 BIOMASS CHP, STEAM TURBINE – ORC PLANT LARGE - MEDIUM – SMALL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## Qualitative description

**Brief technology description**

Combined Heat and Power (CHP) production from biomass has been used in an increasing scale for many years in Denmark utilizing different technologies. The typical implementation is combustion in a biomass boiler feeding a steam turbine.

Biomass CHP plants based on steam turbines is today a well-known technology that have been erected in reasonable numbers. Improvements can still be expected, but only at an incremental level. Therefore the technology belongs to Category 4: *Commercial technologies, with large deployment*.

Combustion can in general be applied for biomass feedstock with average moisture contents up to 60% for wood chips and up to 25 % for straw dependent on combustion technology.

Plants firing wood chips are usually equipped with flue gas condensation as described in Section 43, DH boiler, Biomass fired. Flue gas condensation can significantly increase the heat production, but not the power production. Figure 1 shows the total efficiency estimate for a biomass plant based on its higher heating value (HHV). The diagram is equivalent to Figure 2 in technology sheet "08 WtE CHP plant", which includes a calculation example on how to derive the total efficiency based on the lower heating value.

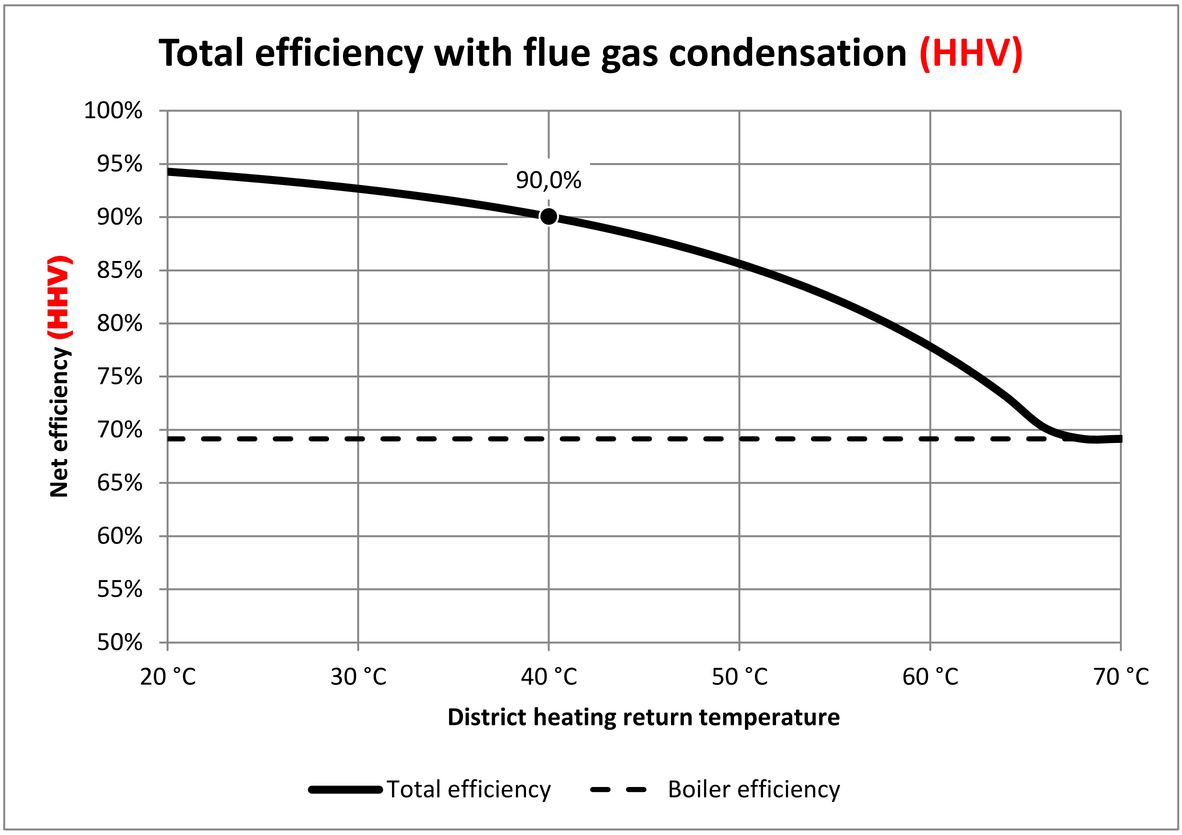


*Figure 1.Total efficiency estimate based on HHV for biomass plants[1] given varying district heating return temperatures.(ref.13) – or temperature of the cold media of a heat pump.*

Straw is usually delivered in rectangular bales with dimensions of 1.2 x 1.3 x 2.5 meter (W*H*L) and a weight of 300 to 800 kg each (for older plants ~500 kg). Hesston type big bales are most common but also bales with a height of only 0.9 meter (such as New Holland Midi bales and Class Big Square bales) are accepted at some CHP plants. The energy density of straw is about 9 times lower than that of coal. The bales are most commonly loosened/shredded and fed into the boiler by use of stoker screws.

Forest residues are typically delivered as wood chips. Forrest residues may also be delivered as pellets. During pellet production the fuel is dried to moisture content below 10%.

The furnace technology can be of different nature: Grate firing, suspension firing (where the bio-mass is pulverized or chopped and blown into the furnace, optionally in combination with a fossil fuel) and different types of fluidised bed. Grate combustion is a well-established and robust technology with regard to using different types of biomass. There are examples of combination boiler technologies with both suspension- and grate firing. There is a limit to how big a grate fired plant can be constructed.

Only a few fluid bed boilers exist in Denmark and are typically used for CHP plants in situations where the plant size exceeds the maximum for grate firing. In particular wood chips are an excellent

[1] Assumptions: District heating return temperature 40 °C. Excess air ratio λ=1.3. Wood with an ash content of 2% of dry matter. Flue gas from boiler 170 °C. Own power consumption 40 kWh/t + 1% of HHV.

fuel for fluid bed boilers. Suspension firing is suitable for very large power plants (substantially above 200 MJ/s thermal heat input) and it requires a pulverisation of the fuel before it is fed into the furnace. Pulverisation of biomass is not an easy task but in particular pellets can be disintegrated into its finer particles using a (coal) mill. These particles are often adequate directly for combustion.

Another type of plant is the ORC plants; in this the (biomass-) boiler is used for heating (no evaporation) thermal oil to slightly above 300 C. This heated oil is then transferring the heat to an ORC plant which is similar to a steam cycle but it uses a refrigerant instead of water as working media. In all cases the major plant components are: Fuel treatment and feed system, high-pressure boiler (either water-steam or a refrigerant), (steam-) turbine, generator and flue-gas heat recovery (condenser/scrubber).

The reason for an interest in ORC plants is that such equipment is delivered in standardized complete modules at an attractive price and in combination with 'a boiler' that only is used for heating oil, the investment is relatively modest.

The ORC technology is a waste heat recovery technology developed for low temperature and low pressure power generation. The ORC unit is a factory assembled module – this makes them less flexible but cheap. The 'Rankine' part indicates that it is a technology with similarities to water-steam (Rankine) based systems. The main difference being the use of a media i.e. a refrigerant or silicone oil (an organic compound that can burn but does not explode) with thermodynamic properties that makes it more adequate than water for low temperature power generation. The data sheet describes different types of plants used for combined production of electricity and district heating. The smaller plants are grate fired boilers for the production of hot water (for district heat) possibly with an ORC for electricity production. The medium sized plants are typically grate fired plants with steam production and a steam turbine/generator of the back-pressure type for electricity and heat production. The larger plants are: 1. a suspension fired boiler for wood pellets, 2. a CFB boiler for wood chips and 3. a grate fired boiler (also) for straw.

The data sheets do not cover industrial plants, which typically deliver heat at higher temperatures than district heating plants, and therefore have lower electricity efficiencies. Industrial plants can have lower capital cost and operation & maintenance cost (O&M cost), among other things, because they are designed for shorter technical lifetimes with less redundancy, low-cost buildings etc.

**Input**

The fuel input can in general be described as biomass; e.g. residues from wood industries, wood chips (collected in forests), straw and energy crops. Sometimes it is possible to change fuel on a plant from one type of biomass to another but it needs to be explicitly guaranteed by the supplier of the plant. Below is a broad description of biomass fuels.

Wood (in particular in the form of chips) is usually the most favourable biomass for combustion due to its low content of ash, nitrogen and alkaline metals, however typically with 45 % moisture for chips and below 10 % for pellets. Herbaceous biomass like straw, miscanthus and other annual/fast growing crops have higher contents of K, N, Cl, S etc. that leads to higher primary emissions of $NO_x$ and particulates, increased ash, corrosion and slag deposits.

The amount of biomass available for energy production varies over time. From 2006 to 2014, the Danish straw production varied between 5.2 and 6.3 million tonnes per year (avg. 5.6 mil. t.), while the amount used for energy varied between 1.4 and 2 million tonnes (avg. 1.6 mil. t.).

Other exotic biomasses as empty fruit bunch pellets (EFB) and palm kernel shells (PKS) are available in the market; however, operation experience seems to be limited.

**Output**

The energy outputs from CHP facilities are electricity and heat. The heat may come as steam or hot water.

**Typical capacity ranges.**

| | |
|---|---|
| Large scale: | > 100 $MW_{th}$ (~25 $MW_e$) |
| Medium scale: | 25 - 100 $MW_{th}$ (~6-25 $MW_e$) |
| Small scale: | 1 – 25 $MW_{th}$ (~0.1-6 $MW_e$) |

It is noted that emission limit values (ELV) for biomass plants are linked to the thermal input to the boiler in MJ/s. More stringent requirements are valid for plants above 50 MJ/s according to the EU Industrial Emission Directive (IED), ref. 4, and air emission levels of the EU reference note on best available technique of large combustion plants, LCP BREF AEL, ref. 5.

The capacities of cogeneration plants supplying heat to district heating systems are primarily determined by the heat demands. Over the last many years there has been a serious change in the production philosophy of CHP plants primarily due to a change in in particular power prices in Denmark. Earlier (say more than 15 years ago), electricity was the most valuable product of the two. Currently the electricity prices on NordPool – the electricity exchange – are often below the prices obtained from selling district heat. This shift also has the consequence for future CHP projects, that it is no longer important with high electrical efficiency; in fact, for many projects it is attractive to avoid the current planning obligation to also produce electricity from heat plants above a certain size. Most plants are equipped with a facility to bypass the turbine temporarily to increase the heat production at the expense of losing the electricity production; this is in use more often than it was 10-20 years ago.

**Regulation ability**

The plants can be controlled for part load operation, but due to high initial investment costs, they should be operated in base load. In a future perspective with large amounts of renewable electricity (PV-solar and wind) in the grid it is important for the system balance that thermal (biomass fired) plants can operate in a large range (15 % to 100 % for once-through suspension fired boilers). Biomass plants with drum type boilers (typical for grate fired boilers) can be operated in the range from 40-100% load.

CHP plants are typically equipped with heat accumulators in order to decouple electricity production from heat consumption; in particular for minor plants with its own district heating grid this allows the plant to be stopped on a daily or weekly basis. Large plants may be designed for optional operation in pure electrical mode (condensing mode) with slightly higher electrical efficiency but without CHP-production. It is possible to sell electricity from biomass CHP plants when there is a need for supporting the grid with its increased amount of fluctuating renewable electricity as wind and solar on a market basis. The condensing mode option is mainly seen in large plants over 130 $MW_{th}$ and primarily used today for large Pulverized Fuel (PF) plants.

**Advantages/disadvantages**
Some biomass resources, in particular straw, contain highly corrosive components such as potassium, sodium and chlorine. In order to avoid or reduce the risk of slagging and corrosion, boiler manufacturers have traditionally abstained from using similar steam pressure/temperatures in biomass-fired plants as in coal-fired plants. However, advances in materials and boiler design have enabled the newest plants to deliver fairly high steam data and power efficiencies. Straw fired boilers can be operated up to 540 °C and wood fired boilers up to slightly above 560°C. In most cases the technical limits are somewhat above what is economically feasible. The availability of suited steam turbines might limit the steam temperature for smaller sized plants.

In the low capacity range (less than 25-30 $MW_{th}$) the scale of economics effect is quite considerable and there is a very significant economical difference between steam (and thereby electricity) producing boilers and hot water (DH only) producing boilers. In particular boilers for the latter type can be series produced and are thus much cheaper than a boiler for producing super-heated steam for power production of similar size.

**Space requirements**
Generally, all the biomass plants are designed with a very small fuel storage facility. Typically it is sized to last for at most two days of full load operation. The size of the storage has for some fuels a major impact on the totally required space (area).

The area to be used for the buildings containing the process equipment is estimated in various ways. Very little additional area is added, say for administration, canteen, garages, work shop, etc. independent of the size of the plant. Further to this, some additional area to be used for other fuel handling, manoeuvring and weighing of trucks, parking of vehicles, roads and other free area. In total, it is ensured to have a reasonable 'bebyggelsesprocent'.

Despite that the largest plants (wood chips and pellets) are so large that a harbour facility is most appropriate, this is not included neither in space requirements nor in cost. Other facilities like a rail road for fuel transport are not considered.

**Environment**
The main ecological footprints from biomass combustion are persistent toxicity, climate change (GHG potential), and acidification. However, the footprints are considered small (ref. 1). It is, however, an area of both major concern and major discussion. Further to this is also added a concern on the sustainability of using in particular wood-like biomasses for power production. It is not the intent of this catalogue to initiate such a discussion but merely to mention that perhaps biomass fuelled plants can reduce GHG emissions considerably compared to fossil fuel fired plants but it is still to be determined if it resource-wise globally is a better solution.

Modern flue gas cleaning systems will typically include the following processes: $DeNO_x$ - ammonia injection (SNCR) or catalytic (SCR), $SO_2$ capture by injection of lime or the use of another $SO_2$ absorbing system, dust abatement by bag house filters. The described solutions are used as a precondition for the information in the data sheet.

$NO_x$ emissions may be reduced, by about 60-70%, by selective non-catalytic reduction (SNCR) on wood chips fired boilers and 30-40% on straw fired boilers. NOx emission may be reduced by 80-90% by selective catalyst (SCR). SNCR is a relatively cheap solution but it is not necessarily applicable for a boiler subject to high load variations. The SCR solution can be either a high dust, high temperature location near or in the boiler or it could be a much more expensive tail-end solution requiring re-heat of the flue gas.

The EU IED, ref. 4, determines the current emission limits in Denmark and it is expected that new, lower emission limits will be introduced with the future legislation initiated by the EU.
The emissions in the Data Sheets from 2020 and in the following years are based on proposed limits in the coming Best Available Technologies Air Emission Levels (BAT AELs) introduced by the EU BREF document for Large Combustion Plants, ref. 5, that is expected to come into force as of 2020. For small and medium scale plants, similar EU legislation is expected to come into force in the same timeframe.

The suggested solutions will comply with future emission limits suggested by BREF; that is, the cost of a tail-end DeNOx is added to the medium (and larger) plants at a certain point in the future.

Biomass CHP boilers produce four sorts of residues: Flue gas, fly ash, bottom ash and possibly condensate from flue gas condensation. In case of flue gas condensation there will be a surplus of distilled water to be recycled or discharged from the plant.

All bottom ash and most fly ash from straw firing is recycled to farmland as a fertilizer.
Almost all ash from wood firing is deposited in landfills. Research is ongoing on how to meet the environmental acceptance limits for recycling the ash to the forests.

The condensate water from wood firing is usually treated to remove heavy metals, particularly cadmium, so that its content reaches 3 – 10 milligrams per $m^3$, or the level required for its discharge, which is usually the local municipal sewage system . The treatment residue must be deposited in a safe landfill.

Condensate from straw-firing can be expelled without cleaning, since almost all cadmium is withheld with the fly ash in the bag filter.

Future plants above a certain capacity are required to have monitoring of air emissions of mercury, Hg. Generally, Hg is not a problem in straw fired units since Hg is oxidized by the chlorine in fuel and captured in the bag filter. Wood fired units might have a challenge with Hg if fired with woodchips from certain regions and only cleaning the flue gases with an electrostatic precipitator , ESP.

**Research and development**
Research is ongoing in many areas relevant for bio mass CHP boilers, e.g.:
- Reduce the cost of fuel, by improved collection and pre-treatment, better characterisation and measurement methods.
- Improve control ability against fuel variations
- Improve combustion process for reduction of CO (and other unburned components e.g. PAH), $NO_x$, particles and $SO_2$

- Further development of secondary technics for reduction of particles, aerosols, cadmium, $NO_x$ $SO_2$ and PAH
- Reduce corrosion, in particular high-temperature corrosion
- Reduce slagging
- Recycling of ashes for agricultural use
- Improved trouble-shooting
- Improve steam cycle by introduction of steam reheat (>75 $MW_{th}$)

**Predicting performance and cost**
The development within this area is driven by possible prospects for being able to earn money and therefore also by the expected future prices on heat and power. Twenty years ago electric power was a valuable product (high exergy content) and thus it was beneficial to aim at as high an electrical efficiency that could possibly be achieved. Today, the power prices are in periods below prices on heat and this has a big impact on investment decisions; it is no longer a given thing that the electrical efficiency should be as high as possible. In the years to come this will also give a larger difference between the most efficient solutions ever developed and made commercially available and the most economically preferred solutions actually bought.

The cost (CAPEX) of the different technologies and scaling of the plants is given in the tables both as Mio. EURO per installed MW electricity production capacity and also as Mio. EURO per installed MJ/s heat production capacity. Notice that it is in both cases the total cost either divided by installed power capacity or divided by installed heat production capacity. Do not add the two numbers! This approach has been chosen in order to accommodate for the fact that due to the above mentioned situation with power prices we have seen a tendency of deliberately designing new plants with a reduced electrical power capacity; this only has a modest (but not less important) effect on the total plant cost but the effect is definitely not as serious as could be indicated in an economic model only based on one product (electric power).

In economics, it is traditional to use a scale of economy model based on raising the scale size to a particular power (often around 0.7) to scale the cost. In this work an exponent of 0.7 has been chosen throughout and the size of scaling is based on thermal heat input to the plant. For each of the examples treated a more detailed basic plant model based on the major components (buildings, boiler, flue gas treatment, turbine, DCS and electrical work, fuel storage, contingency and other project costs) has been built. The costs from the different sub-parts have been estimated using the scaling model from known examples (actual projects, supplier budget offers, study/feasibility projects or other traceable cost). From this, the total cost is calculated and scaled with performance data.

One serious experience from this and other similar investigations is that the scale of economics does not work well in case of larger differences in technology. For example a 100 MW thermal heat input grate fired steam producing boiler cannot be used as basis for pricing a 20 MW thermal heat input grate fired hot water producing boiler. The latter is produced almost in series whereas the 100 MW unit is erected in place, the latter is not subject to the pressure vessel directive, and it is not subject to the same emission requirements either. Therefore it is much cheaper than would be found by scaling the cost from the 100 MW plant.

**Uncertainty**
CHP plants for biomass are fully commercial (Category 4) with small uncertainties for performances and costs. The trend of the recent years towards building large plants (>110 $MW_{th}$) including steam reheat, humidification of combustion air, more advanced flue gas cleaning etc., introduces a moderate increase of uncertainty. These advanced solutions are expected to be in Category 4 within a few years.

Further tightening of emission data requires development of more efficient combustions processes in the boiler and secondary flue gas cleaning systems. This will increase the capital costs and O&M cost. It will add a limited uncertainty, but the real cost uncertainty is to what extent the emission limits will be tightened.

**Examples of market standard available technology**

- Fyn Power Plant (DK), Unit 8; commissioned in 2009; 120 MJ/s thermal input, 35 MW electricity; 84 MJ/s district heat. 170,000 tonnes of straw per year. Equipped with flue gas condenser. Retrofitted with SCR tail end.
- Sleaford (UK) commissioned 2014, 115 MJ/s thermal input (straw/wood chips), 38.5 MWe, net electrical efficiency 33%. 240,000 tonnes of straw per year.
- Lisbjerg (DK) 110 MWth. Commissioning year 2016. Energy efficiency 103% at CHP mode. Equipped with tail end SCR, combustion air humidification and flue gas condenser.
- Snetterton (UK), commission year 2017, 130 MJ/s thermal input (straw/wood chips), 44 MWe, net electrical efficiency 34%. 270,000 tonnes of straw per year.
- Avedøre Power Plant (DK) Unit 2 is a multi-fuel CHP power plant that can operate on wood pellets, straw, oil (HFO), and natural gas. It was commissioned in 1999. It has a 100 MJ/s separate biomass-fired boiler (ultra-super critical stream data – 290 bar, 540 °C) supplying steam in parallel with the main boiler; 170,000 tonnes of straw per year. When the plant is running 100 % on wood pellets in the main boiler and 100 % straw, it is producing 425 MW electricity in condensing mode, and 355 MW electricity and 485 MJ/s district heat in back pressure CHP mode.
- In Denmark the plants Studstrup 3 and Avedøre 1 have recently been converted from coal firing into wood pellets firing. In Skærbæk a gas fired unit is converted into firing wood chips by installing 2 new grate fired boilers supplying steam to the existing turbine
- There are a few new large CHP plants expected to be built in the coming years. The currently known projects are Amager 4 and Asnæs 6.

**Additional remarks**
Despite the observation that straw is a much more difficult fuel than wood (chips/pellets) the electricity efficiencies are almost equal. This reflects the fact that the development of straw-fired plants for many years was driven by power utilities focusing on high efficiencies.
The deployment of small and medium-sized biomass fired CHP plants in DK was largely inactive for some years after 2000, but changed conditions for DH is changing the situation. There are several trends in the area of new biomass CHP plants:

1. They are being built in large sizes, mainly because of a better plant economy, but also to accommodate for an increase in the DH market
2. The electrical efficiency is not in focus due to low electricity prices.

3. Wood chips heat only boilers (hot water) up to 20 MJ/s thermal input have become very popular; they are produced in a more or less serial production and this lowers both capital and O&M cost.

The size classification has been changed from previous editions. The boundary between small and medium-sized plants of 25 $MW_{th}$ is selected based on the suppliers' experience.

The fuel efficiency for CHP is increased through introduction of a flue gas condenser. The humidity in the flue gas is condensed just before the stack. The condensing heat is used to preheat district heating water. In case fuel with low humidity such as straw is used, the combustion air can be humidified in order to increase the heat output from flue gas condensation. (ref. 3). In particular for straw the flue gas condensation also has the function of scrubbing (cleaning) the flue gas.

In the sheets the cost of the fuel store has been included but only a small storage capacity has been considered (corresponding to a few days' of operation). In some power plant projects it will be necessary to include larger stores and this must be accommodated for.

Also, the foot print of the plants does include a limited amount of space around the plant for transportation to/from the store, other forms of access roads, parking, minimum store, and other necessary equipment.

**Energy model**

The energy model used for the different types and sizes of plants in this section of the catalogue is described in the chapter "*08 WASTE-TO-ENERGY CHP PLANT*".

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# 42 WASTE-TO-ENERGY HEATING PLANT

## Qualitative description

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**Brief technology description**

The waste-to-energy (WtE) heating plant is very similar to the WtE CHP plant described in part 08, WtE CHP plant, and reference is made to the descriptions therein. The main difference is the absence of a steam cycle, and that the boiler produces hot water instead of high pressure steam[1]. The hot water is subsequently used to deliver district heat via heat exchangers.

The absence of a steam cycle means that WtE heating plants are not equipped with steam turbines and its auxiliaries. The hot water boiler is simpler and less expensive than the steam boiler, as it does not include evaporation and superheating parts, and heating surface temperatures are significantly lower, reducing the corrosive impact of the flue gas.

The flue gas cleaning part of a heating WtE plant is identical to a similar (size and waste feed) CHP plant.

**Input**

See part 08, WtE CHP plant.

**Output**

The outputs are identical to the outputs from a similar WtE CHP plant, except for the energy quality. The total energy efficiency is identical for heat and CHP plants, except that some minor heat losses in the generator and turbine gearbox of the CHP plant are avoided. The heat production form a heat only WtE plant is thus identical (or very slightly higher) than sum of produced electricity and heat form an equivalent CHP plant

**Typical capacities**

The waste capacities of heat only WtE plants are typically relatively small plants with 5-15 tonnes of waste per hour, corresponding to a thermal input in the range 15-50 MJ/s. Plants larger than approx. 15 tonnes/hour waste input are currently designed for combined heat and power. Legislative/planning requirements push towards CHP. Disregarding potential legislative/planning requirements, the decision between CHP and heat-only is based on a range of parameters, of which the important ones include so-

[1] Heat-only WtE plants can also be designed to produce low pressure steam for industrial purposes or steam based district heating networks, but these are of limited relevance in Denmark and thus not considered here.

cio economic value and net present value over planning period (including forecasts of electricity price), heat market and its seasonal variation, available waste amounts, strategic considerations of the plant owner and financing opportunities.

**Regulation ability**

See part 08, WtE CHP plant.

**Advantages/disadvantages**

See part 08, WtE CHP plant.

The main advantage of a heat WtE plant compared to a CHP plant is lower investment, maintenance costs and footprint. The main disadvantages of heat WtE plants is the lack of electricity export and thus lower energy sales revenue and higher dependence on the sale of energy at the local heat market.

**Environmental aspects**

See part 08, WtE CHP plant. It should be borne in mind that the ecological footprint of a CHP-plant includes the reduced emissions from the electricity production replaced by WtE, and the footprint of electricity production is usually higher than that of the same amount of energy supplied as heat.

**Development perspectives and future demand**

See part 08, WtE CHP plant.

**Uncertainty**

See part 08, WtE CHP plant.

The choice between erecting CHP or heat only plants is mainly driven by the local heat market, expected energy prices (in particular the ratio between power and heat price) and legislative requirements.

**Economy of scale effects**

The investment in a WtE district-heating plant is considerable lower than for a WtE CHP plant with the same capacity. In addition, operation and maintenance cost are lower. While the total cost (per tonne waste or per MJ output) for a CHP facility increases considerably for small size plants, the relatively simple district-heating plants may be built in small scale with reasonable economy. This may render the plants attractive particularly in remote communities treating locally produced waste, and waste management alternatives entail large transportation cost.

**Examples of best available technology**

See part 08, WtE CHP plant.

**References**

# 43 DISTRICT HEATING BOILER, BIOMASS FIRED

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## Qualitative description

**Brief technology description**
Boiler fired by wood-chips from forestry and/or from wood industry, wood pellets or straw.

If the moisture content of the fuel is above 30-35%, as with forest wood-chips, flue gas condensation should be employed. Thereby the thermal efficiency can exceed 100 % (based on lower heating value). The efficiency is primarily determined by the return temperature from the district heating network. In well-designed district-heating systems, this return temperature is below 40 °C, yielding efficiencies above 105 %. For plants firing wood-chips with 45 – 55 % moisture content, the thermal efficiency exceeds 110 %. Some plants are equipped with heat pumps for full flue gas condensation and thermal efficiencies of more than 120 % are reached (ref. 3). A procedure to estimate the total efficiency of biomass and WtE with flue gas condensation is shown in Figure 2 in part 08, WtE CHP plant.

Flue gas condensation would not be financially attractive at plants below 1 - 2 MJ/s due to the additional capital and O&M costs. Such plants without flue gas condensation should only use fuels drier than 30 % moisture content (ref. 3).

Straw fired boilers are normally equipped with a bag filter for flue gas cleaning. Electro filters do not work so efficiently with straw firing as they do with wood firing.

Flue gas condensation is now available also for straw firing but must be combined with a bag filter to hold back ash and calcium chloride particles from the scrubber. The flue gas condensation raises the efficiency with 5-10 % (ref. 3).

**Input**
Wood chips are wood pieces of 5-50 mm in the fibre direction, longer twigs (slivers), and a fine fraction (fines). The quality description is based on three types of wood chips: Fine, coarse, and extra coarse. The names refer to the size distribution only, not to the quality.

Existing district heating boilers in Denmark can burn wood-chips with up to 45-63 % moisture content, depending on technology. In 2014-2015, the actual moisture content was 40 % in average, varying between 25 and 55 % (ref. 1).

Other possible fuels are chipped energy crops (e.g. willow and poplar) and chipped park and garden waste. The fuel quality must be in focus. Small particles must be avoided. High moisture content of e.g. willow will increase the level of CO and PAH. Willow is known to take up Cadmium from the soil increasing the concentrations in ash and flue gas condensate. Poplar has been found to give problems in the boiler like "popcorn" in a combustion test. Chipped Park and garden waste must be of a good quality with low content of non-combustible materials, because of risks for blocking the grate (ref. 1).

Wood pellets are made from sawdust, wood shavings and other residues from sawmills and other wood manufacturers. Pellets are produced in several types and grades as fuels for electric power plants and district heating (low grade), and homes (high grade). Pellets are extremely dense (up to the double of the density of the basic material) and can be produced with a low humidity content (below 5 % for high grade products) that allows easy handling (incl. long-term storage) and to be burned with high combustion efficiencies. When humidified, pellets are prone to auto-ignition. When exposed to mechanical treatment like conveyer transportation the pellets may break (or disintegrate) and release dust; this dust is highly explosive and therefore constitute a serious hazard.

Straw is a by-product from the growing of commercial crops, in North Europe primarily cereal grain, rape and other seed-producing crops. Straw is often delivered as big rectangular bales, typically approx. 5-700 kg each, from storages at the farms to the district heating plants etc. during the year pursuant to concluded straw delivery contracts.

**Output**
District heat or heat for industrial processes typically in the form of hot water.

**Typical capacities**
1 - 50 MJ/s. The majority of district heating plants are below 15 MJ/s with an average size of 5 -6 MJ/s dependent of the fuel (ref. 5).

**Regulation ability**
Typical wood fired pants are regulated 25 - 100% of full capacity, without violating emission standards. The best technologies can be regulated 10 - 120% with fuel not exceeding 35 % moisture content.

Straw fired plants should not be operated below approx. 40 % of full load due to emission standards. Straw fired plants should accordingly be equipped with a heat accumulating tank allowing for optimal operational conditions.

**Space requirements**
Generally, all the biomass plants are designed with a very small fuel storage facility. Typically it is sized to last for at most two days of full load operation. The size of the storage has for some fuels a major impact on the totally required space (area).

The area to be used for the buildings containing the process equipment is estimated in various ways. Very little additional area is added, say for administration, canteen, garages, work shop, etc. independent of the size of the plant. Further to this, some additional area to be used for other fuel handling, manoeuvring and weighing of trucks, parking of vehicles, roads and other free area.

**Environment**
$NO_x$ emissions may be reduced, by about 60-70%, by selective non-catalytic reduction (SNCR). For a district heating plant size 4-8 MJ/s, this would cost about 0.1 M€ in investment and 0.4 € pr. kg removed $NO_x$ in operational cost (ref. 4).

Biomass fired boilers produce four sorts of residues: Flue gas, fly ash, bottom ash, and possibly condensate from flue gas condensation.

All bottom ash and most fly ash from straw firing is recycled to farmland as a fertilizer.
Almost all ash from wood firing is dumped in landfills. Research is ongoing on how to carbonize the ash for recycling to the forests.

The condensate water from wood firing is usually treated for heavy metals, particularly cadmium, so that the content reaches 3 – 10 milligrams per $m^3$ or the level required for its discharge, which is typically the local municipal sewage system. The sludge from heavy metals treatment must be deposited in a safe landfill.

Condensate from straw-firing can be discharged without cleaning, since almost all cadmium is withheld with the fly ash in the bag filter.

Flue gas condensation may also reduce the $SO_2$ emission to a minimum, when the pH value is kept above 6.5 – 7.0 in a wet scrubbing condenser. The $SO_2$ removal may add to the feasibility of condensation due to savings in $SO_2$-emission tax, which is currently at around 1.3 € per kg $SO_2$.

**Research and development**
There is still a need for R&D in the following areas:

- environmentally safe recycling of ashes to forestry; e.g. by pellets to ensure slow release of nutrients
- improved combustion process for reduction of CO (and other unburned components e.g. PAH), $NO_x$, particles and $SO_2$
- further development of secondary techniques for reduction of emissions of particles, aerosols, cadmium, $NO_x$ $SO_2$ and PAH
- handling and combustion of new types of fuels, such as energy crops and garden/park waste
- methods for limiting content of cadmium and PAH of the condensate for discharge
- upgrading flue gas condensate to a water quality suitable for addition in the district heating water system

<u>New technology:</u>
Instead of implementing the combustion process in the boiler vessel, an alternative Danish solution has been developed and demonstrated in three plants until now. The Dall Energy Biomass Furnace combines updraft gasification and gas combustion. Hereby several advantages are achieved: The plant becomes simpler and possibly cheaper, the reactor is fuel flexible, the emissions are reduced and the furnace can regulate between 10-100 % according to the supplier.

The Biomass Furnace delivers hot flue gas to a commercial boiler. This concept is promising and has already drawn attention in the energy sector. More plants will help getting the technology through the "learning curve".

**Uncertainty**
District heating plants for biomass are fully commercial (Category 4) with small uncertainties for performances and costs. Further tightening of emission data requires development of more efficient combustions processes in the boiler and secondary flue gas cleaning systems. This will increase the costs for investment and O&M. It will add a limited uncertainty, but the real cost uncertainty is to what extent the emission limits will be tightened.

**Predicting performance and cost**
The necessary investment (CAPEX) of the different technologies and scaling of the plants is given in the tables as mio. € per installed MJ/s heat production. In economics, it is traditional to use a scale of economy model based on raising the scale size to a particular power (often around 0.7) to scale the cost. In this work an exponent of 0.7 has been chosen throughout and the size of scaling is based on thermal heat input to the plant. For each of the examples treated a more detailed basic plant model based on the major components (buildings, boiler, flue gas treatment, DCS and electrical work, fuel storage, contingency and other project costs) has been built. The costs from the different sub-parts have been estimated using the scaling model from known examples (actual projects, supplier budget offers, study/feasibility projects or other traceable cost). From this, the total cost is estimated and scaled with performance data.

One serious experience from this and other similar investigations is that the scale of economics does not work well in case of larger differences in technology. For example a 100 MW thermal heat input grate fired steam producing boiler cannot be used as basis for pricing a 20 MW thermal heat input grate fired hot water producing boiler. The latter is produced almost in series whereas the 100 MW unit is erected in place, the hot water boiler is not subject to the pressure vessel directive, and it is not subject to the same emission requirements either. For these reasons the small scale facility is much cheaper than would be found by scaling the cost from the 100 MW plant.

**Uncertainty**
DH plants for biomass are fully commercial (Category 4) with small uncertainties for performances and costs. The trend of the recent years towards building large plants (>25 $MW_{th}$) including absorption heat pumps for enhanced flue gas condensation, humidification of combustion air, more advanced flue gas cleaning etc., introduces a moderate increase of uncertainty. These advanced solutions are expected to be in Category 4 within a few years.

Further tightening of emission limit values requires development of more efficient combustions processes in the boiler and secondary flue gas cleaning systems. This will increase the capital costs and O&M cost. It will add a limited uncertainty, but the real cost uncertainty depends on the level of tightening of the limit values.

**Examples of market standard technology**
Danish manufacturers of market standard for wood firing are e.g. Euro Therm A/S, Justsen A/S and Weiss A/S.
The newest operational plants can be visited in the cities of e.g. Brande, Ebeltoft, Fuglebjerg, Skjern, Slagelse and Sønderborg.
The Dall Energy Biomass Furnace can be visited in the cities of Sønderborg and Bogense.

Danish manufacturers of market standard technology for straw firing are e.g. Euro Therm A/S, Lin-Ka Energy A/S and Weiss A/S.

The newest operational plants can be visited in the cities of e.g. Billund, Borup, Vejen and Øster Toreby. Høng and Nexø which include flue gas condensation.

New filter technologies are being tested for cleaning of flue gas condensate. Among the promising types are drum, ceramic and PP filters. The aim is to develop solutions, which can definitely comply with the limits for connection to wastewater treatment, and further processing so that water can be used as make-up water for boilers and for district-heating networks (ref. 1).

**References**


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4. "En opdateret analyse af Danmarks muligheder for at reducere emissionerne af $NO_x$" (Updated analysis of Denmark's options to reduce $NO_x$ emissions; in Danish), Danish Environmental Protection Agency, 2009.
5. Energiproducenttællingen 2012, Danish Energy Agency


## Quantitative description

See data sheets in Excel format.