

## Report for IEA Bioenergy Task 36 Topic 2

### Integration of processes for optimizing resource recovery from waste streams

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## **Abstract**

### **Integration of processes for optimizing resource recovery from waste streams**

This report describes the current situation and optimization potential for energy recovery in waste management facilities. Various thermal and biological conversion technologies have been analyzed for their potential for an improved production of high quality energy and products. The status of these technologies has been determined as well as the challenges and limitations that will occur when implementing these processes into waste management systems.

Based on the technology survey a concept for an Integrated Advanced Waste Refinery (IAWARE) is presented which provides the opportunity to maximize production of high quality products and minimizes generation of unused heat. IAWARE key technologies thereby are gasification and anaerobic digestion for source specific conversion of waste. To demonstrate the potential of the concept two example scenarios – one state-of-the-art and one possible near future configuration – have been designed and evaluated for their energy recovery rate by conducting energy balance calculations.

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## List of abbreviations

AD	Anaerobic Digestion
BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
CGE	Cold Gas Efficiency
CHP	Combined Heat and Power
DME	Dimethyl Ether
DMS	Direct Melting System
FT	Fischer-Tropsch
GCV	Gross Calorific Value; equals HHV
HHV	Higher Heating Value; equals GCV
IWARE	Integrated Advanced Waste Refinery
LHV	Lower Heating Value; equals NCV
MBT	Mechanical Biological Treatment
MSW	Municipal Solid Waste
NCV	Net Calorific Value; equals LHV
ORC	Organic Rankine Cycle
PSA	Pressure Swing Adsorption
RDF	Refuse Derived Fuels
SNG	Substitute Natural Gas
SRF	Solid Recovered Fuels
WtE	Waste-to-Energy

## Summary

This report presents the results of a modeling exercise on the potential to optimize energy recovery in waste management facilities using current and future technologies. Various thermal and biological conversion technologies were analyzed for their potential to improve the production of high quality energy and products.

Waste-to-Energy (WtE) plants based on conventional grate or fluidized bed incineration already make an important contribution to the current energy system. Energy recovery from waste therefore saves fossil fuels and reduces fossil CO<sub>2</sub> emissions. However, maximization of energy recovery through the use of current technology is dependent on efficient heat utilization, since power generation efficiency is limited. Sufficient heat utilization would, however, require a district heating network or a local industrial customer, which is not always available, particularly in countries with warmer climates. The power generation is limited on the one hand by the nature of heat cycles, where the efficiency is determined by the difference and the level of heat input and removal temperatures. On the other hand it is also limited by the characteristics of waste fuel, which prevent WtE incineration plants reaching the same electrical efficiencies as fossil fuel power plants using the same technology (combustion with connected steam cycle). This is predominantly a result of the high chlorine and alkali content in waste, which increases corrosion risk and therefore forces to lower live steam parameters. It is also caused by efforts to control combustion and by the need for flue gas cleaning to avoid and minimize harmful emissions.

An improvement in electrical efficiency could be achieved through fuel pretreatment processes or by the use of different thermal waste conversion and heat cycle technologies. One example of the latter could be a waste treatment plant based on gasification with downstream combustion of product gas, connected to a steam cycle or a combined cycle including a gas turbine. Of course it is very important that such a plant includes sufficient product gas cleaning before combustion. Otherwise neither advanced live steam parameters are achievable, nor could the product gas itself even be burned in a gas turbine. Sufficient gas cleaning is therefore a crucial requirement, together with increased fuel pretreatment when aiming for use of gasification technology; and even more so when the aim is for gas reforming to produce high quality fuels or products, since the catalysts used for gas reforming require much higher gas purities than heat cycle processes. Despite the importance of this issue, sufficient cleaning processes for product gas from waste gasification are not yet proven technology. They still require research and practical testing, especially for larger scale applications and long-term commercial plant development.

As well as thermal waste treatment technologies there are biological treatment technologies (composting and anaerobic digestion), which can be used to treat biodegradable waste fractions. These processes are already proven technology in waste management systems. Both also enable material recovery (in the form of nutrients in digestate or compost), while anaerobic digestion further enables energy recovery or production of high quality fuels. This is achieved through the use of the biogas produced by AD in CHP plants or through biogas upgrade into SNG that can substitute natural gas. Due to the potential for material and energy recovery AD is a natural first choice for digestible waste fractions.

Even when applying advanced biological and thermal treatment processes in combination with heat cycles sufficient heat utilization is still the key for maximizing energy recovery from waste as power generation will always be limited. The production of high quality fuels that can be stored or transported and then used in high efficient CHP operation could therefore result in better recovery

factors; of course this is true only if the waste conversion into fuel is conducted with good efficiencies. Alternatively the fuel produced can be used in industry or transport sector as a product or fuel to substitute other sources. This is the basic idea behind the concept of an Integrated Advanced Waste Refinery or IAWARE. In this concept an optimal combination of waste treatment technologies based on local boundary conditions enables source specific treatment, and internal and external material and energy exchange to maximize the production of high quality products, while minimizing unused heat. The key technologies in this concept are gasification for thermal treatment and anaerobic digestion for biological treatment.

To demonstrate the potential of the concept two example configurations for an IAWARE facility were developed, including a state-of-the-art scenario using proven technologies and a possible near future scenario. The first scenario comprised waste incineration and anaerobic digestion. In this scenario the combustible waste fraction is burned with heat utilization in a steam cycle and the digestible fraction is converted into biogas, which is further upgraded to SNG. The heat and power required for digestion and upgrading is provided by the thermal treatment path. The second scenario uses waste gasification for part of the waste (the high quality waste fraction), with gas utilization through a methanation process for SNG production. The remaining waste – about 65 percent of the energy – is incinerated while the biological treatment path stays unchanged. Both scenarios have been evaluated for their energy recovery efficiency by conducting energy balance calculations. The input data for the simulation was based on actual performance data for existing plants, as well as research results and proposed projects regarding boundary conditions for the gasification and methanation process. The results showed that the IAWARE concept has the ability to improve the recovery efficiency for the high quality products power and SNG. When combining the energy values for power generation and SNG production – based on the net calorific value of the SNG – the recovery efficiency increased from about 22.5 percent (the electrical efficiency of the incineration plant alone) up to 26.8 percent for scenario 1 and 34.7 percent for scenario 2. Of course these values do not represent the final use, but if the SNG is used afterwards in high efficiency CHP plants the IAWARE concept would still provide a better recovery rate than ordinary incineration plants. Furthermore the AD residue could be used as fertilizer, which saves additional energy that would otherwise have been consumed in production of artificial fertilizer.

However, even with these results and assuming further improvements, WtE plants with the opportunity for complete heat utilization would still provide higher recovery rates. This is of course when only looking at the plain energy values and not considering energy quality or eventual use of products. This demonstrates the importance of heat utilization.

# 1 Background

Increasingly countries are aiming for a maximization of resource recovery from waste, either in the form of material or energy recovery. While material recycling is a common method for certain separated waste streams the treatment of mixed waste streams from residential areas (municipal solid waste MSW) is often conducted in waste incineration plants. Originally intended as a destruction method before landfill these waste incineration plants are nowadays run as energy recovery facilities by generating power and/or heat. But due to the nature of this technology and the requirements of waste management in general power generation is limited. A maximization of energy recovery therefore would require steady and sufficient heat consumption, e.g. through district heating or use by an industrial customer nearby. Figure 1 illustrates this point by showing an overview of energy recovery figures from MSW through incineration plant for certain European countries. These figures are not efficiencies since the actual calorific value of MSW is not taken into account but they nevertheless show the importance of heat utilization. By comparing the values it can be seen that the power generation rate from most countries could of course be improved but for a maximization of total energy recovery the heat utilization is crucial.

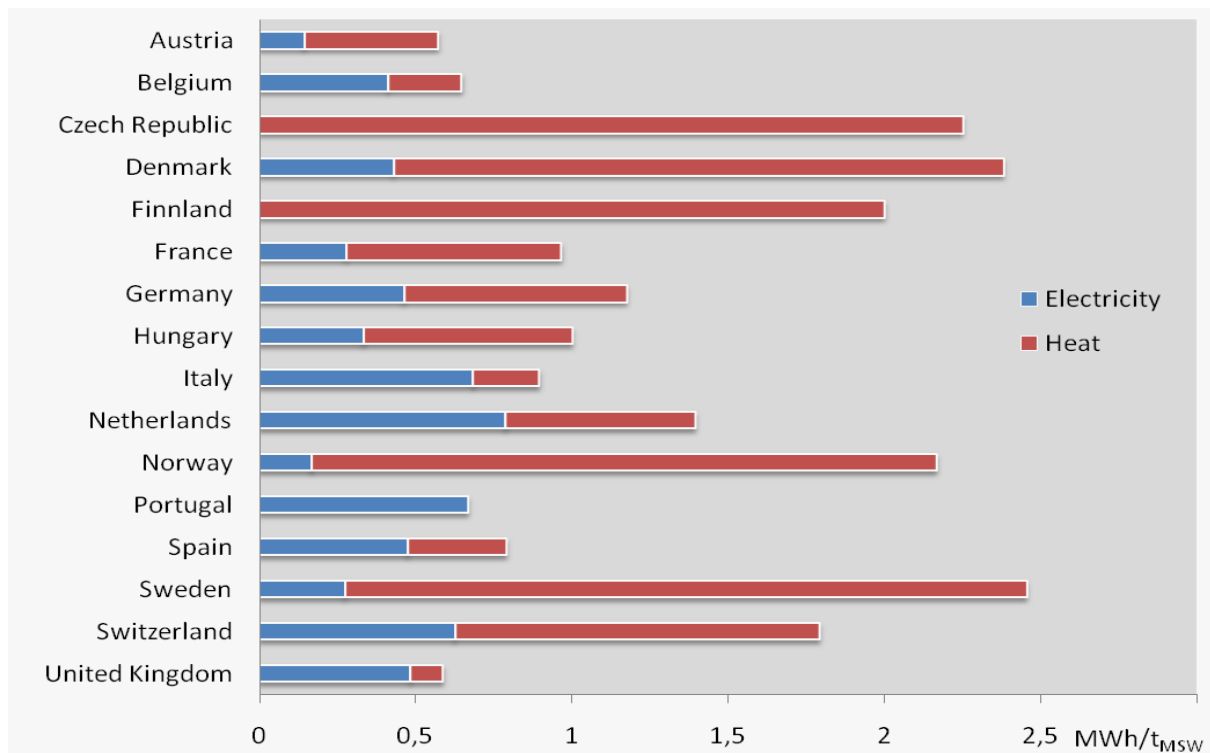


Figure 1 Energy Recovery from MSW in incineration plants for certain European Countries in 2005; source [Avfall Sverige, 2008]

But the necessary heat demand often cannot be guaranteed, especially for countries with warmer climate. Therefore there is an interest in alternative solutions for energy recovery from waste resulting in the production of high quality energy and products. The following report analyzes available technologies for that purpose including the determination of their current development status.

## 2 Waste treatment technologies

In this section an overview of possible waste treatment technologies will be given with focus on the generation of high quality energy and/or products.

To keep a better view above the large number of possible treatment technologies they have been divided into three main categories: technologies for waste pretreatment, waste conversion and energy conversion. The single technologies are sometimes unique for waste treatment but often similar to technologies used for standard fossil or biomass fuels. The categories and some example technologies are shown in Figure 2.

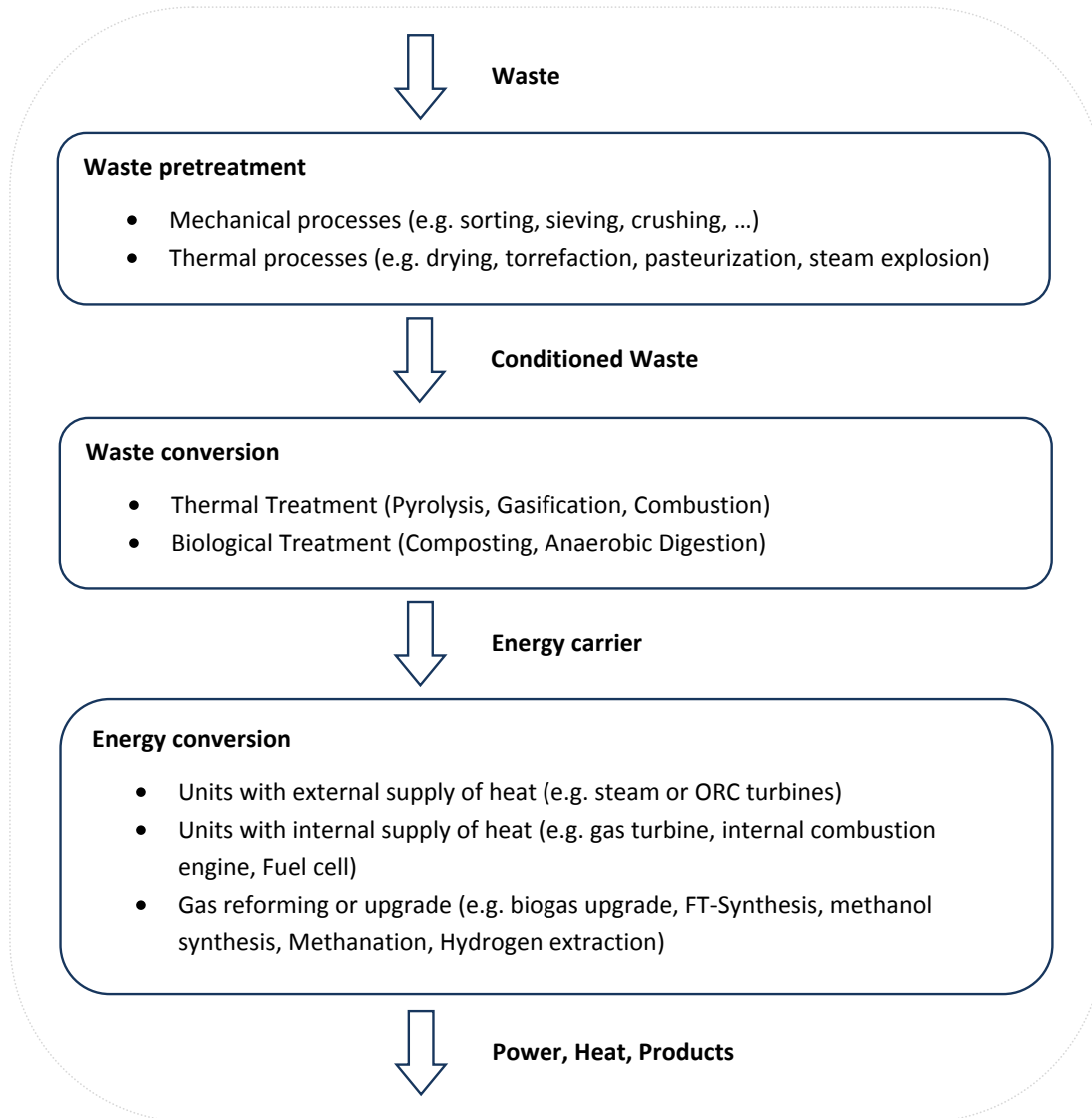


Figure 2 Classification of waste treatment technologies

### 2.1 Waste pretreatment

The waste pretreatment stage in general includes all actions for preparing the waste or waste fractions before they can be used in the respective conversion processes. The necessity and extent of waste pretreatment is determined by the requirements of the chosen conversion process but also by other



pretreatment technologies. Depending on the type of energy consumption – mainly power or heat – they can be divided into mechanical and thermal processes.

### 2.1.1 Mechanical processes

Though mechanical pretreatment processes the heterogeneous waste will be sized and sorted. Various crushing, shredding, sieving and sorting processes are used to achieve the following aims:

- Separation and collection of valuable materials for material recycling, e.g. metals or certain plastics
- Separation of biodegradable waste to enable biological conversion
- Homogenization of waste to meet requirements by waste conversion or other pretreatment processes

The sorting of waste can be done automatically or manually (although automatic sorting should be preferred in order to decrease the impacts on health and safety for personal). However manual sorting cannot be fully eliminated, for example for removing large pieces or for a final examination of presorted material.

Apart from sorting at central facilities the waste can also be sorted directly at source. Source separated collection of waste can make a useful contribution to minimizing energy consumption in pretreatment, increasing material recovery and improving opportunities for the use of advanced conversion technologies. Some technologies used for sorting and separating are:

- Metal recovery through magnetic systems for ferrous metals and eddy-current systems for non-ferrous metals. Both technologies are already proven technologies and are used commonly as post-treatment processes for incineration ashes. But these technologies can of course also be applied to waste pretreatment, as already done for waste fuels before entering fluidized bed incinerators.
- Optical sorting can be used for separation of valuable waste fractions as for example for certain types of plastics
- Extruders are commonly used to separate unwanted materials from the biodegradable fraction to guarantee the conformance with waste purity requirements for biological treatment processes.

### 2.1.2 Thermal processes

**Drying** reduces the moisture content of the waste by supplying heat in order to evaporate part of the water that is contained in the waste. By reducing the moisture content the waste calorific value also increases. When using the concept of net calorific value as a reference, the result of reducing the moisture content due to drying increases the chemical energy in the fuel as a result of conversion of thermal energy into chemical energy. The difference between the gross and net calorific values is an obvious point that has to be considered and discussed when talking about efficiency values and recovery rates. Drying will most likely be necessary when aiming for gasification since most gasifiers require a certain moisture content and calorific value that ordinary waste usually does not have. But even if not required drying will have an impact on the conversion process operation and efficiency. Since heat is used drying will also act as an internal heat consumer thus reducing the amount of required external heat utilization.

**Torrefaction** is a technology which is similar to pyrolysis. The fuel is heated up to temperatures around 250-350°C at which the moisture and part of the volatile content will be removed. Ideally the torrefied material has changed in structure and characteristic, remaining as a hydrophobic and more homogenous fuel with high calorific value. Therefore torrefaction can enable the use of more advanced waste conversion technologies which have stricter requirements for fuel quality. But since it is not a proven technology yet – at least not at large scale – it is hard to predict what benefit the technology could have in waste treatment. At the same time it has to be noted that torrefaction will reduce the total chemical fuel energy compared to dried fuel, since some energy carrying volatiles are removed. The amount of energy reduction depends on the process management and the integration within the whole system.

**Pasteurization, Sanitization or Hygenisation** are terms that are usually used for the same process when discussing biodegradable waste pretreatment. The intention of pasteurization is the reduction of pathogenic micro-organisms to nonhazardous limits. In the European Union by law pasteurization is required for certain waste streams, e.g. animal-by-products. However the requirements differ for individual countries. A typical pasteurization process requires keeping the waste at a temperature of 70°C for at least one hour, though other methods that operate at lower temperatures but longer times – e.g. in a thermophilic digester – are known and accepted as well. Apart from the primary function for hazardous control pasteurization can also be used for certain waste fractions to improve gas yield in the downstream anaerobic digestion process. Pasteurization is a proven technology in biological waste treatment and can furthermore act as an internal heat consumer.

Further thermal and chemical pretreatment technologies - as for example **Steam explosion** or **Hydrolysis** - can be used for pretreatment of otherwise hard to digest waste fractions, enabling their use in anaerobic digestion. The aim of these technologies is to break down the structure of lignocellulosic materials, weaken and remove the lignin protection layer and make the cellulose and hemicellulose accessible for digestion. Since the processes are often carried out at higher temperatures they could therefore also act as internal heat consumers.

## 2.2 Waste conversion

In this stage the unconditioned or conditioned waste will be converted into an energy carrier. This energy carrier contains the energy in form of thermal energy (defined by temperature) or chemical energy (defined by calorific value). In general the different processes can be classified into biological and thermal conversion.

### 2.2.1 Thermal conversion

The thermal treatment technologies Pyrolysis, Gasification and Combustion are all based on the same principles, a thermo-chemical conversion of waste at elevated temperatures. They differ in temperature level and in the amount of supplied oxygen which results in different products and residues.

**Pyrolysis** refers to fuel conversion at high temperatures without external oxygen supply. As mentioned for torrefaction the pyrolysis process is characterized through release of moisture and volatiles caused by external heat supply. The process products are pyrolysis char, pyrolysis oil and pyrolysis gas. While carbon is the main component in the char the pyrolysis gas contains mainly CO, CO<sub>2</sub>, H<sub>2</sub> and short-chained hydrocarbons. When released at operation temperatures the gas furthermore contains a fraction of long-chained hydrocarbons and water. These components condensate at lower temperatures forming the pyrolysis oil. The exact composition and distribution of solid, gaseous and condensable fraction depends on the process conditions (particularly temperature level and residence

time), but also on the chemical composition of the input fuel. In general high pyrolysis temperatures will lead to a decrease in char amount while high temperatures in combination with high residence times will increase the gaseous fraction at the expense of the condensable fraction. This is because more long-chained hydrocarbons are cracked into shorter ones. Therefore the boundary conditions for the pyrolysis process have to be set with regard to the desired product: char, oil or gas. Common products are char, the pyrolysis oil in liquid phase or the combined fraction of condensable and non-condensable components at elevated temperatures. The pyrolysis gas alone is usually not a product which is aimed for. The heat for the pyrolysis process can be either generated through combustion of part of the products or fuel or supplied by independent external heat sources. All products could be used in combustion plants as single or additional fuel while the pyrolysis oil could also be used in combustion engines or gas turbines if an adequate post-treatment of the oil ensures conformance with the required parameters.

On the other hand there are of course also challenges when considering the use of the pyrolysis products. Unwanted and hazardous components as heavy metals or chlorine contained in the waste will still be found both in the char and the oil. The actual distribution of these components to char and oil is again depending on the process conditions and the characteristics of the single components which are either highly volatile or more persistence. Nevertheless when for example the use of pyrolysis product in a combustion plant is considered it will either require – if possible – a sufficient cleaning before further use or dealing with the same obstacles as in ordinary waste incineration plants.

**Gasification** refers to fuel conversion with a sub-stoichiometric oxygen supply. The gasification agent – which is responsible for the oxygen supply – is usually normal or enriched air, pure oxygen or steam; but other compounds would be possible as well. The aim of gasification is to convert the fuel completely into an energy-rich gas. Therefore preferably no char residue should remain. This energy-rich gas is often called product gas, gasification gas or syngas. It contains the main components CO, CO<sub>2</sub>, H<sub>2</sub>, N<sub>2</sub> (at air gasification) and short-chained hydrocarbons with methane as the main representative. Apart from these permanent gas components it also contains a condensable fraction of water and further hydrocarbons, usually referred to as tar. Further components depend mainly on the fuel composition. This means for waste fuels the product gas would also contain H<sub>2</sub>S, chlorine components, heavy metals and other components. Apart from the dependence on fuel characteristics the product gas composition also depends on the chosen gasification technology and its operation conditions.

There are a lot of different gasification technologies available or proposed. But in general all of these technologies can be classified by a few design parameters, which will define the requirements for input fuel and process conditions, as well as the general product gas composition. One important design parameter is the choice of gasification agent, another one is the type of gasifier and a third one is the gasification temperature.

When choosing steam as the only gasification agent an external heat supply will be required to enable the steam consuming conversion of carbon and hydrocarbons since these are mainly endothermic (heat consuming) reactions. This is therefore often called indirect or allothermal gasification. By using oxygen as gasification agent (either pure or as part of (enriched) air) the required heat for the gasification process can in contrast be generated internally through partly oxidation of the fuel. This is called direct or autothermal gasification.

Since the product gas always contains sensible heat when leaving the gasifier the conversion efficiency from input energy to chemical gas energy is limited. But often the gasification efficiency is reported as cold gas efficiency (CGE) which describes the ratio of chemical product gas energy to chemical fuel energy, both usually based on the net calorific value. And by using the CGE the efficiency for allothermal gasification is usually higher than for autothermal gasification. This is due to the fact that in pure autothermal gasification the only energy input is the fuel, while in allothermal gasification there is an additional external heat supply. The external heat could thereby even be partly converted into chemical energy.

Another important issue in choosing the gasification agent is the impact on product gas composition. By using steam the product gas will most likely contain high hydrogen ratios and even more importantly it will not be diluted with nitrogen, resulting in high calorific values. This opens for a number of product gas utilization choices, e.g. gas reforming, hydrogen extraction or just improved conversion efficiency in power generation units. At the same time there will be less energy tied to the sensible heat since due to the absence of  $N_2$  the volume of undiluted product gas is lower.

The same advantages – undiluted product gas, ability for fuel conversion, high calorific values – would also apply for gasification with pure oxygen. In contrast to steam gasification the resulting product gas will contain less hydrogen but more carbon monoxide. This could be advantageous for some gas utilization processes.

Air gasification on the contrary will result in a low calorific, nitrogen diluted product gas which is not suitable for fuel conversion. But when aiming for other gas utilization processes air gasification could also be advantageous since the process does neither need an air separation unit nor a unit for generation of the external heat and opens therefore for a wider and simpler gasifier design.

The gasification temperature affects the gas composition and therefore the gasification efficiency. The higher the gasification temperatures the higher the conversion of hydrocarbons which means the carbon monoxide content will increase while the methane content decreases. But the most important point is that tar components are also converted which enables for a more simplified cleaning stage before gas utilization. Gasifiers that operate at very high temperatures can even achieve a so called tar-free product gas.

A downside of high gasification temperatures is that an increasing amount of energy is contained in the sensible heat of the product gas and at least for cases autothermal gasification is used it also means that a higher ratio of fuel energy cannot be transferred into chemical gas energy.

When comparing different gasifier designs they can be divided into three main types; fixed bed, fluidized bed and entrained flow gasifiers. Sometimes two additionally types are reported: grate and plasma gasifiers. But grate gasifiers are usually quite similar to fixed-bed gasifiers while plasma gasification actually only describes a special way to supply heat.

Entrained flow gasifiers are usually applied to large scale applications. They run autothermally at very high temperatures above the ash melting point with ash removal as melted slag. The gasification agent is oxygen or air. Additional steam injection is possible as long as the required temperature levels are still achieved. The fuel is fed into the gasifier through the gasification agent itself. Therefore entrained flow gasifiers require an elaborate fuel pretreatment. The high gasification temperatures will provide a clean, tar-free product gas.

Fluidized bed gasifiers can be designed for autothermal or allothermal operation and for various gasification agents. The bed material ensures a good heat transfer inside the gasifier resulting in a homogenized and good controllable temperature zone. Since fluidized bed gasifiers are operated at lower temperatures than entrained flow gasifiers the product gas contains a significant amount of gaseous hydrocarbons, mainly  $CH_4$  and  $C_2$  components. It will therefore also contain relevant tar components if no specific catalytic bed material or additive is used. The lower temperature level is chosen to avoid sintering and bed agglomeration.

Fixed-bed gasifiers are usually autothermal gasifiers with air or oxygen as gasification agent. The two main design types differ in the flow direction of the resulting gas. If the gas passes the high temperature char conversion zone before exit it is called a co-current or downstream gasifier. With an adequate temperature in this zone remaining hydrocarbons are converted resulting in a product gas with low tar content. Securing the homogeneity of the zone is crucial for the process and the product gas quality. Therefore co-current fixed-bed gasifiers require certain fuel parameters and are also limited regarding size scaling. In counter-current or upstream gasifiers the resulting gas passes the

pyrolysis zone before exit. The raw gas contains a large amount of tar which has to be removed when aiming for more advanced gas utilization. Counter-current gasifiers are less demanding on fuel conditions – fuel size, moisture content – and enable for a simpler scaling than co-current gasifiers. However fixed-bed gasifiers are usually only applied to small applications.

In general – with exceptions – gasifiers require a homogenized fuel at specific size and low moisture content, at least when they are designed as single stage units. Therefore extensive fuel pretreatment has to be conducted when considering municipal solid waste as fuel, since MSW is anything but homogenized and dry. Staged gasification with an upstream drying and pyrolysis step would broaden the fuel choice.

The attraction of gasification is based on the large variety in gas utilization opportunities. In general there is nearly no limitation. The product gas could be burned directly in boilers or after sufficient cleaning in combustion engines or gas turbines. It could even be converted into standard fuels and products or be used in fuel cells. But this variety is actually limited to the design phase. By choosing a gas utilization process several design parameters will already be set.

An important point is the necessity for implementing a sufficient gas cleaning stage. This cleaning step is crucial, but the actual effort depends on the choice of utilization.

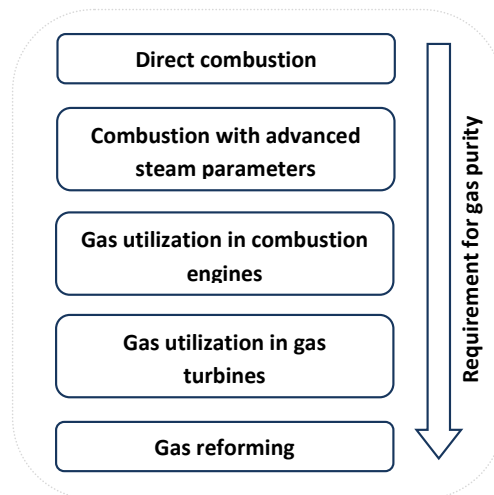


Figure 3 Requirement for gas purity with regard to utilization choice

**Combustion** refers to fuel conversion with excess oxygen supply. Air is usually used as oxygen supplier, but enriched air or pure oxygen would also be possible. The combustion process is aiming for a complete conversion of chemical fuel energy into sensible heat. In a line with pyrolysis and gasification the combustion process represents therefore the final step in the thermal treatment hierarchy which means complete oxidation of carbon and hydrogen. The resulting flue gas contains mainly  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$  (from air combustion) and  $\text{O}_2$  (excess oxygen). The actual ratios of minor components, such as CO, unburned hydrocarbons,  $\text{NO}_x$ , metals or chlorine compounds, are depending on the fuel composition and the process conditions. The formation and release of these unwanted and harmful components has to be prevented or eliminated by primary and secondary measures before releasing the flue gas into ambient air.

The sensible heat of the flue gas can be used for transferring energy to a heating grid, for generating steam for industrial processes or for running power generation units. The combustion efficiency should be close to maximum when securing sufficient combustion operation. Small losses occur from incomplete combustion, which is indicated by CO and hydrocarbons in the flue gas as well as through unburned carbon in the ash. Another commonly used parameter for describing the combustion efficiency is the boiler efficiency, but this is actually an efficiency describing the ratio of heat which is

transferred to a heat utilization process to fuel energy. The boiler efficiency is affected by energy losses from incomplete combustion, convection and radiation losses as well as unused sensible heat of ash and flue gas. The main source thereby is the flue gas loss which is determined by the flue gas temperature at exhaust.

Common boiler designs for combustion of waste include grate combustors and fluidized bed combustors. Grate combustion does not need a special pretreatment stage, while the waste intended for fluidized bed combustion needs to be pretreated to secure the size and homogeneity requirements of the fluidized bed reactor. In general waste typically meets the minimal requirements for calorific values to be burned in waste incinerators. If the calorific value is nevertheless very low – caused by large moisture and/or inert material content – additional standard fuel is usually injected to reach required temperatures inside the combustion chamber to secure complete combustion and to meet legal requirements, i.e. for dioxin destruction.

## 2.2.2 Biological conversion

The biological conversion technologies ethanol fermentation, anaerobic and aerobic digestion convert the biodegradable waste fraction at low temperatures with the help of micro-organism. Since the processes are more or less vulnerable to impurities, it is important that a sorting and controlling stage is conducted at the very least, to guarantee and secure adequate waste characteristics.

**Ethanol fermentation** (also called alcoholic fermentation) describes the transformation of sugars into ethanol (liquid fluid) through a biological process with the use of microorganisms such as yeasts. Usually the process takes place in the absence of oxygen (anaerobic conditions) and the byproduct is carbon dioxide. Non sugar carbohydrates (starch) have to be converted into sugar prior the actual fermentation process, which is also done by a biological processes. The fermentation yield increases with the sugar content of the organic material, therefore the feedstock should be a sugar-rich material. Fermentation is widely used nowadays but mostly using agricultural crops as feedstock. Using biodegradable waste would therefore require an extended pretreatment either to secure a sufficient sorting or to perform superior pretreatment steps to enable other waste fractions for fermentation.

**Aerobic digestion or Composting** describes a process where biodegradable material is converted by micro-organism in the present of oxygen. The process results in the formation and release of carbon dioxide, water and low temperature heat in the range of 50-70°C. The remaining residue is called compost and can be used for soil improvement or fertilizer. The composting process is usable for a wide range of biodegradable waste, but the ability to use the compost as soil improvement depends on the nutrient content and on the level of contamination with hazardous components. A disadvantage of the process is the missed opportunity to use the heat released to any degree due to the low temperature level. That means energy recovery is not the aim of composting, rather it is a process for treating biodegradable waste and for recovery of nutrients.

**Anaerobic digestion (AD)** enables on the contrary for energy and material recovery. Micro-organisms convert the biodegradable material in the absence of oxygen, resulting in the release of a gas in which the main components are methane and carbon dioxide. This gas is called biogas and can either be directly used for heat and/or power generation or it can be further upgraded to SNG to substitute natural gas. The remaining digestate enables recovery of nutrients and can therefore be used as a fertilizer, if contamination limits for hazardous components are met.

AD requires a more thorough pretreatment compared to composting and it is also more limited regarding the input material. Due to the limited residence time in the reactor only easily degradable fuel can be used. Primarily this digestible waste will be food waste or similar fractions. However other waste fractions could be used as well when sufficient pretreated is applied, e.g. through steam explosion or similar processes.

The AD process itself can be characterized by operation conditions regarding temperature level and dry matter content in the reactor. Regarding the latter AD processes are divided into wet and “dry” digestion. In wet digestion the common dry matter content in the digester is below 10 percent per weight while in “dry” conditions the dry matter content is around 20-35 percent per weight. While “dry” digestion has its advantages compared to the wet process – as for example lower water and heat consumption and a drier digestate – it has higher demands on the digester design and the process management to ensure homogeneity in the digester.

Regarding the temperature settings AD processes are divided into mesophilic and thermophilic digestion. Mesophilic micro-organisms work at temperature around 37°C while thermophilic micro-organisms require elevated temperature levels around 55-60 °C. That means the latter process has a higher heat consumption to maintain the required temperatures. Additionally the process is stated to be less stable than mesophilic digestion when it comes to tolerance against changes in environmental conditions. On the other hand higher temperatures enable faster digestion or result in a higher biogas yield over the same time periods compared to mesophilic digestion.

## 2.3 Energy conversion

In this stage the energy carrier from the waste conversion stage will be transformed into a finally usable form, which is mechanical or electrical energy, warm water, steam, fuels or other products.

### 2.3.1 Heat cycles

Heat cycles convert thermal energy into mechanical energy which can be used directly or as electrical energy after transformation in a generator. According to the laws of thermodynamics the conversion ratio of heat into mechanical energy is limited. Therefore in every heat cycle there is a heat input and a heat removal. The efficiency limit is set by the theoretical Carnot cycle efficiency with the same temperature range as the described heat cycle. In general the efficiency of every heat cycle increases with an increase in temperature difference between the average heat input temperature and the average heat removal temperature.

The heat input itself can be supplied by external sources or internal generation. The latter usually requires air as a working fluid to burn the added fuel. This results in an open cycle with a continuous exchange of working fluid due to the oxygen consumption. Therefore the outlet pressure is limited by ambient conditions. Additionally the range of possible fuels is limited, usually to liquid or gaseous fluids.

On the other hand cycles with external supply of heat enable implementation of closed cycles with special working fluids and wide pressure ranges. They also allow for utilization of nearly every heat source, e.g. solid fuels, geothermal or solar heat. However due to the necessity of heat exchangers the maximum cycle temperature is limited and remains at lower values when compared to heat cycles with internal heat generation.

**Gas turbines** are open cycle processes with air as working fluid. At first the air is compressed by a compressor. Then fuel is added and burned in the combustion chamber. The flue gas expands inside the turbine stages, providing the mechanical energy (partly used to compress the air), before it is expelled into the ambient environment. Gas turbines are commonly used nowadays and available in a wide power range. The common fuel is natural gas or oil, but facilities also exist where gas turbines run on product gas from gasification. The high exhaust temperatures additionally provide the opportunity for a combined cycle, using the heat to generate steam subsequently in a steam cycle.

Apart from the combined cycle opportunity the sensible heat of the flue gas at exhaust could also be directly used for heating.

**Internal combustion engines** are open cycle processes using air as the working fluid, usually built as a reciprocating engine. The air or air/fuel mixture is compressed with the combustion taking place at the top dead centre. The flue gas expands, providing mechanical energy. Internal combustion engines are usually used at small scale energy plants where they offer better efficiencies than gas turbines. The sensible heat from engine cooling and the exhaust gas could be used for heating or even for small scale combined cycles.

**Steam turbines** are one part of a so called Rankine cycle, a closed cycle with water as a working fluid. The water is pressurized through pumps and transferred into superheated steam by the steam generator, followed by expansion inside a steam turbine and condensation inside a condenser. The condensation temperature and pressure thereby are depending on the available cooling temperature level (ambient air, water or heating temperature level). Steam turbines are the primary units used in the power industry and waste management facilities; they are available in a wide power range. The efficiency improves with higher live steam parameters and low cooling temperatures. Additionally large units provide further advantages due to scaling effects and the possibility to use improvements like steam reheating and feed water heating. Using the condensation energy for heating is possible and common.

The **Organic Rankine Cycle (ORC)** process is only one example for an alternative turbine system. The ORC is similar to a steam turbine cycle, only with different working fluid. Instead of water the ORC uses refrigerants or other hydrocarbons. ORC turbines are usually used at small scale facilities and when only low temperature heat is available as input source. In these conditions the ORC offers a more feasible working pressure range than a water based system.

As mentioned there are several alternative heat cycle systems which also could be considered. Usually they are based on the same principles as the combustion engines or gas and steam turbines but with a different system for heat input and/or a different working fluid. Examples for these systems are Stirling engines, air turbines or the Kalina cycle. The systems have their advantages in special conditions but limitations in other areas. In general they are not that common or developed nowadays and do not seem to offer a significant advantage in terms of efficiency or handling.

### 2.3.2 Gas reforming and upgrade

The gas reforming and upgrade processes convert gases from the thermal and biological waste treatment stage into fuels or products similar to existing standard sources. This way they can substitute these fuels without changing the consumer systems. Usually gas upgrading processes consume additional energy and have high requirements regarding the gas purity.

The **Biogas upgrade** removes  $\text{CO}_2$  and further trace elements such as  $\text{H}_2\text{S}$  from the biogas leaving practically only  $\text{CH}_4$  remaining. The gas is therefore often called biomethane or Bio-SNG (SNG substitute natural gas). The SNG can be used directly for transportation or fed into the natural gas grid as a substitute natural gas at consumer level (heat, power, transportation, refining). Depending on the natural gas quality in the grid an addition of further hydrocarbons could be required to achieve the required Wobbe-Index. There are several upgrading technologies available based on adsorption, absorption or other principles, e.g. the membrane technology or cryogenic upgrading. The latter for example requires indeed a lot of energy but also provides an opportunity to upgrade landfill gas or deliver liquefied SNG that could be more easily transported and stored when no grid connection is available nearby. However the most commonly used methods are water scrubbing, pressure swing adsorption (PSA) and chemical absorption.



PSA uses the different adsorption behavior of  $\text{CO}_2$  and  $\text{CH}_4$  in porous solids such as zeolites or activated charcoal (adsorbent). When the biogas flows through the reactor column  $\text{CO}_2$  is adsorbed from the compressed biogas at the adsorbent while  $\text{CH}_4$  is not. The regeneration of the adsorbent is done afterwards by gradually lowering the pressure in the reactor column. The use of multiple columns allows for continuous operation and the generation of  $\text{CH}_4$  within the required purity range.

The water scrubbing method uses the pressure and temperature dependence for the solubility of  $\text{CO}_2$  in water. The compressed and cooled biogas flows through an absorber column filled with packing material while water in a counter-current flow removes  $\text{CO}_2$  from the gas. The regeneration of water afterwards is typically done in two pressure stages. With the water scrubbing method  $\text{H}_2\text{S}$  is also removed from the gas, so an additionally stand-alone cleaning process is not needed.

In upgrading plants with chemical scrubbing the biogas flows through the absorber column, while instead of water an amine solution flows in counter-current direction. The amine solution removes the  $\text{CO}_2$  from the biogas by so called 'chemical absorption'. The regeneration of the amine solution is done by heating the solution, whereby  $\text{CO}_2$  and amine solution are separated again. In contrast to the other two upgrading technologies works chemical scrubbing non-pressurized but requires a significant heat input for regeneration.

**Product gas reforming** technologies convert product gas from gasification into fuels or products that are able to substitute their fossil counterparts. The conversion processes are usually carried out at elevated temperatures with the use of catalysts.  $\text{H}_2$  and  $\text{CO}$  will be converted into the desired hydrocarbons while other components as carbon dioxide and water are removed. Usually a water-gas shift reaction has to be carried out before conversion to match the hydrogen-carbon ratio of the end product. Examples of product gas reforming technologies are Methanation, Methanol/DME conversion or Fischer-Tropsch-Synthesis.

Methanation requires the highest hydrogen-carbon ratio when compared to other technologies. The result of the process is  $\text{CH}_4$ , which (as mentioned for biogas upgrade) can be used for transportation or fed into the grid to substitute natural gas.

The Methanol/DME conversion generates either methanol or DME (dimethyl ether) that is for example considered to serve as fuel for transportation. Usually the DME production is a two step process with methanol as intermediate substance (methanol synthesis and dehydration) but one stage direct synthesis of DME is also possible.

The FT-Synthesis converts the gas into synthetic fuel and lubrication oil. These products can be used for transportation, local cogeneration or in the chemical industry.

While methanation results in a gas both latter technologies provide a liquid fuel which has advantages when considering storage or transport, at least in cases a natural grid feeding is not available.

### 2.3.3 Further technologies

Apart from heat cycles or gas reforming there are also other technologies available for utilizing the energy carriers from the waste conversion stage. Most notable are Fuel Cells. The conversion of chemical fuel energy into electricity is conducted without the intermediate step of heat production and therefore the Carnot efficiency limitation does not apply. Fuel cells are run directly with hydrogen while other fuels can also be used through an integrated or upstream located reformer.

## 3 Technology status

### 3.1 Thermal waste treatment

The combustion of waste is a proven and well established technology. It has been used for more than 100 years with more than 450 WtE plants in Europe and several thousand facilities over the whole world. For historical reason the combustion of waste is often called incineration. Originally incinerators were intended as a destruction method before landfill, with the purpose of eliminating hazardous risks as well as minimizing the landfill volume. But over the years the purpose of energy recovery has grown significantly, with continuous improvements in energy recovery efficiencies. At the same time there has been a huge improvement concerning the purity of the released flue gas. New and better cleaning technologies have been implemented which has led to a distinct reduction of hazardous emissions. The improvements in efficiency and emissions have been to a great amount caused by national and multi-national legislation efforts but also due to growing public perception.

When looking at the actual status and the potential of energy recovery in a waste to energy (WtE) incineration plant several factors have to be considered. Apart from the age of the plant – as stated above newer plants have been designed and are operated with the aim of optimizing energy recovery – one main important factor is the type of energy recovery, either heat or power or combined heat and power (CHP). The two energy forms have completely different qualities (this is usually linked to the term exergy), which has to be pointed out when comparing or making statements. There is an attempt to make these energy forms comparable by using the R1 factor, which can be helpful when comparing different plants. But when aiming for a detailed analysis of a special plant or when looking at energy balances and optimization potential this is not a useful tool. When aiming for heat use only, the heat released in waste combustion can be directly transferred to a heat carrier in form of heated water or steam. This can be done with moderate wall temperatures, which will reduce the risk of corrosion but still allow for a nearly complete energy recovery. In contrast when aiming for electricity generation higher live steam parameters (incinerators are nearly exclusive connected to a steam turbine) will improve the steam cycle efficiency and therefore benefit the energy recovery rate. At the same time low condensing temperatures also benefit the efficiency, which makes places with the opportunity to use water directly as cooling medium advantageous compared to sites that use cooling towers with evaporation or just air cooling. When aiming for a CHP configuration the cold end of the steam cycle is defined by the flow temperature of the district heating grid. This temperature will limit the electrical efficiency of the plant. But since additional energy will be used through heat utilization, CHP operation will result in better overall energy recovery rates than power generation alone. Apart from these main parameters other boundary conditions that have an impact on the plant efficiency are the waste moisture content and heating value as well as the level of contamination. Therefore it is hard to state recovery factors in general since this very much depends on the actual plant side as well.

However typical recovery rates that can be expected for new WtE incineration plants in power only configuration should be in the range of 20 till 25 percent net electrical efficiency, based on the net calorific value. Live steam parameters in these cases are in the range of 400°C and 40 bar. But of course this is not the achievable limit as the AEB Amsterdam WtE plant shows. With high live steam parameters of 130 bar and 480°C including a reheating stage as well as further optimizations a recovery rate of around 30 percent net electric efficiency is claimed [Murer et al, 2011]. Typical recovery rates for WtE incineration plants in CHP configuration are in the range of 10 to 15 percent electrical and 75 to 85 percent overall efficiency, both based on NCV. Of course this is not a limitation either. Depending on live steam parameters and district heating flow temperatures the electrical efficiency could be higher. And when including a flue gas condensation process into heat utilization the overall efficiency could also be improved.

When looking at the other thermal treatment technologies the differentiation between pyrolysis and gasification is not always clear. Usually the focus is more on gasification where pyrolysis is of course also one part of the process. But plants or studies on pyrolysis alone are quite rare in comparison.

An example for an actual existing waste pyrolysis plant is the MPA Burgau, Germany. The facility treats municipal and similar industry waste as well as sewage sludge at temperatures between 470 and 500°C. The resulting pyrolysis gas is directly burned in a combustion chamber, which is connected to a steam cycle for power and heat generation. The remaining pyrolysis char is landfilled [MPA Burgau, 2008]. The facility is claimed to be working satisfactorily. But since the char is not used and the pyrolysis gas is not cooled down before combustion a proper conclusion concerning the ability and potential for alternative utilization apart from combustion and steam cycle cannot be drawn.

Apart from this commercial plant there are of course research and laboratory studies conducted regarding waste pyrolysis. He et al. [He et al, 2010] tested MSW from a China dump site in a fixed-bed pyrolysis reactor at 750-900°C with dolomite as the downstream catalyst and showed a significant influence of reaction temperature and catalyst on the distribution and composition of pyrolysis char, oil and gas. Temperature increase lowered the char ratio in favor of oil and gas production, while the use of a catalyst (applied in hot gas when the pyrolysis oil is not condensed yet) resulted in converting a higher share of oil into gaseous components. These results can help in determining design parameters when aiming for a pyrolysis plant and an intention to use pyrolysis gas, oil and char in a certain way.

As mentioned there is more activity in the area of waste gasification. Arena [Arena, 2012] performed a survey of waste gasification plants, based on data from 2001 to 2011. He listed several plants which are or were reported to be in operation or in construction; a summary is presented in Table 1. For gasification, which is regarded as still being an area in development, this is actually quite an impressive number and since the list is not complete the actual number would be even higher. But it has also to be mentioned that some of the plants are not in operation anymore and others have never been finished.

Company	Gasifier type	Oxygen Supply	No.
<b>AlterNRG (Canada), Westinghouse Plasma Corp., Hitachi Metals (Japan)</b>	Plasma		2 (+1)
<b>Ebara TIFG (Japan)</b>	ICFB	Air	12
<b>Ebara Co. and Ube Industries Ltd (Japan)</b>	ICFB	Oxygen	3
<b>Energos (Norway/UK)</b>	Moving Grate	Air	8 (+6)
<b>Hitachi Zosen (Japan)</b>	BFB	Air	9
<b>JFE (Japan); (Kawasaki Steel and NKK)</b>	Fixed Bed	Enriched air	10
<b>JFE (Japan); Thermoselect (Switzerland)</b>	Fixed bed	Oxygen	7
<b>Kobelco (Japan)</b>	BFB	Air	12 (+1)
<b>Mitsui (Japan)</b>	Rotary Kiln	Air	7 (+2)
<b>Nippon Steel Engineering (Japan)</b>	Fixed Bed	Enriched air	32 (+5)
<b>Plasco Energy Group (Canada)</b>	Plasma		2
<b>Takuma (Japan)</b>	Rotary Kiln	Air	2

Table 1 WtE gasification-based plants based on data 2001-2011, Source [Arena, 2012]

As can be seen in Table 1 these gasifier plants comprise all kinds of gasifier types, but are mainly (enriched) air gasifiers that were directly coupled to a combustion chamber and steam cycle. Arena reported plant efficiencies in the range of 15 to 24 percent for these kinds of gasifier plants. This is not higher than figures for incineration plants which raises the question of the benefit of gasification. Since the number of plants and the available data are not that comprehensive it is hard to draw clear conclusions on the eventual benefits for final emissions or for an efficiency potential after plant optimization. But when looking at the design of many of these plants they could also be classified as a two stage combustion design which would not give any advantage in efficiency if higher live steam parameters are not possible.

This is also confirmed by a study on two of over 30 commercially operated gasifier plants in Japan and South Korea equipped with the Direct Melting System (DMS). The study was done by Tanigaki et al. [Tanigaki et al, 2012]. The DMS system is a counter-current, enriched air blown, fixed-bed gasifier with molten discharge of the slag. The fuel was MSW, with an addition of limestone as catalytic material and coke in the range of 15-20 percent of total energy input. The gasifiers were connected to boiler/steam cycle systems with live steam parameters of 400°C and 39.2 bar, which resulted in electrical efficiencies at around 19-23 percent based on fuel NCV. The cold gas efficiency of the gasifier was stated to be 49-55 percent, based on fuel NCV, which is not a very high value when aiming for alternative product gas utilization. But they can partly be explained by the high temperatures required for forming the molten slag. The live steam parameters were still in the common range of ordinary incineration plants, since burning the product gas had the same limitations regarding corrosion risks as it has been stated that most of the low boiling metals as lead, zinc or chlorine as well as potassium or sulfur will nearly completely (or at least to a greater amount) migrate into the gas. Only the high boiling point metals such as iron or copper stayed in the melt.

Higher steam parameters would therefore most likely require product gas cleaning before final combustion. This is stated to be in place at the new Kymijärvi waste gasification plant, where steam parameters of 540°C, 121 bar and net efficiencies of 31 percent electrical and 87 percent in total are aimed for [Isaksson, 2012]. The old Kymijärvi gasification plant near Lahti comprised an air blown BFB gasifier directly connected to a larger coal fired boiler [Raskin et al, 2001]. The gasifier was running successfully for several years on wood residues, railway sleepers, shredded tyres, plastics and other recycled fuels but it contributed only a minor energy input to the boiler compared with the coal. Therefore variations in product gas quality could be easily adjusted by the main boiler fuel.

This is also an important point which has to be emphasized when aiming for waste gasification as a standalone facility. Variations in the fuel characteristics will lead to significant changes of gasification characteristics and product gas quality. This is not desirable for operating advanced gas utilization processes. Therefore a sufficient fuel pre-treatment to maintain stable and homogenous fuel characteristics is crucial.

When aiming for gas reforming it would additionally require a switch to oxygen or steam as gasification agent. Furthermore, since the catalysts used for reforming require very high gas purities, a sufficient gas cleaning would be necessary. This concept has not been shown in a large scale demonstration or commercial plant, but there have been several studies including laboratory and pilot plant tests on the subject of gasification potential and preferable boundary conditions.

The studies focused mainly on fluidized and fixed-bed gasifiers and the influence of temperature settings, gasification agent and catalysts. All kind of waste fuels were tested including mixed waste fractions such as actual MSW or SRF, and single waste streams, for example plastics, tyres or rubber, textiles, meat and bone meal, agricultural and forest residues or sewage sludge. The fuel was nearly exclusively dry at use with moisture content values – if stated – below 10 percent. Some exception were Dunnu et al. [Dunnu et al, 2012] who reported using SRF received from an MBT facility with 22 percent moisture content and Peng et al. [Peng et al, 2012] who used wet sewage sludge with a moisture content of 76 percent mixed with dry forest waste in different ratios (0-100 percent). This shows the importance of a sufficient waste drying process before entering the gasifier. Otherwise the

drying has to be conducted in the gasifier, which will require additional heat, either through more external heat supply or through more partial oxidation in autothermal gasification. If this does not happen the gasification temperature will decrease below design values with negative impact on product gas quality. Furthermore it must be ensured that the fuel residence time in the gasifier is still sufficient for gasification reactions in circumstances where drying has to occur first.

Most studies concentrated on one gasifier type and one gasification agent. One exception is Karatas et al. [Karatas et al, 2012], who compared the gasification characteristics of waste tyres in a fluidized bed reactor with 3 different gasification agents: air + CO<sub>2</sub>, air + steam and steam alone. The result showed high gas calorific values of 15 MJ/Nm<sup>3</sup> for steam gasification – an increase of more than 50 percent compared to the other gasification agents – with significant higher values of methane and hydrogen in the gas. This is of course not surprising since it is an allothermal process where the heat for steam generation and gasification is externally generated and transferred to the reactor. Furthermore neither is the product gas diluted with nitrogen as in the other cases nor is the gas calorific value alone the only sign for gasification efficiency. But on the other hand it shows a possible way when aiming for an energy-rich product gas and a high ratio of methane or hydrogen.

The studies of Portofino et al. [Portofino et al, 2012] and Donatelli et al. [Donatelli et al, 2010] who used a fixed bed and a rotary kiln gasifier for their tests confirm these values for steam gasification of waste tyres, high gas calorific values with a high ratios of hydrogen. Of course this is also assisted by the use of high calorific waste tyres as input fuel. But even by using dried MSW from a Chinese landfill site Guan et al. [Guan et al., 2009], He et al. [He et al., 2009] and Wang et al. [Wang et al., 2012] could show the ability to generate high calorific product gases in a range of 9 to 13 MJ/Nm<sup>3</sup> with high ratios of hydrogen up to above 50 percent as well as high methane concentrations and low tar ratios. All used fixed bed gasifiers with a downstream catalyst of dolomite. This shows also the importance of the catalyst which helps to convert tar components into hydrogen, carbon monoxide and short chained hydrocarbons as methane.

The importance of a catalyst either located downstream or right inside the gasifier is also confirmed by studies that used air blown gasifiers. Arena et al. [Arena et al., 2010] could show that by using dolomite instead of quartz sand as bed material in an air blown fluidized bed gasifier the gas calorific value increased up to 11 MJ/Nm<sup>3</sup> with increase in hydrogen ratios from 8-10 up to 24-31 percent when using plastic waste as fuel. At the same time the tar content decreased from 160 g/Nm<sup>3</sup> down to nearly zero. Kim et al. [Kim, 2011] reported even gas calorific values up to 14 MJ/Nm<sup>3</sup> by using mixed plastic waste in a two stage air blown fluidized bed gasifier with a downstream catalytic stage filled with active carbon or dolomite. Again the high values were also abetted by using high calorific input streams. When using MSW as fuel and dolomite as bed material Arena et al. reported gas calorific values about 5 to 7 MJ/Nm<sup>3</sup> at gasification temperatures between 870 and 900°C and equivalence ratios between 0.23 and 0.34.

These are only some examples of laboratory and pilot plant tests that have been conducted for waste gasification. Other studies report similar values.

Reported or calculated values for cold gas efficiencies from autothermal gasification (calculated by using reported gas yield and calorific values) ranged from 25 up till 90 percent. The lower values derived from tests with low calorific fuels such as meat and bone meal, agricultural residues or MSW at suboptimal temperature conditions without catalysts while the higher values were achieved by using fuels with high calorific values at optimized temperatures with the use of catalytic bed materials or downstream catalysts.

Cold gas efficiencies reported and calculated for steam gasification experiments reached higher levels up to 115 percent which means the product gas had a higher chemical energy content than the input fuel. In these circumstances it has to be mentioned that these results derived from short-term or bench tests and include a high uncertainty in the actual values. Additionally the laboratory reactors are often heated electrical reactors, which could explain high efficiencies. But on the other hand this is not very

likely to be a design choice for real gasifiers in the field. From this point of view values and information from air blown gasifiers can be better transferred into real facilities. But even in that case there will be still many challenges when changing from laboratory and pilot scale to commercial facilities.

In general it can be stated that allothermal gasifiers using steam were reported to achieve higher cold gas efficiencies than air or oxygen blown gasifiers. An additional benefit when aiming for gas reforming is the already higher hydrogen ratio for these kind of gasifiers, which lowers the demand for extended shift reactions before gas utilization in order to achieve the required hydrogen-carbon ratio. Of course when looking at the overall balance even the external heat has to be generated somewhere.

A large focus in these studies have been set on the basic gasification characteristics to achieve low tar contents, high cold gas efficiencies etc. An important point that is still missing are studies on the gasification characteristics of minor components such as alkali or metal release since these components will also determine the requirement and amount for necessary cleaning stages before final gas utilization. This is a crucial point and much more research and studies are needed.

Little research has been done on alternative heat cycle processes in combination with product gas from waste gasification. There is knowledge of combining waste gasification with combustion engines, which has been done for example in Japan. But otherwise the feasibility for using waste gasification or pyrolysis units connected to gas turbines, fuel cells or gas reforming still has to be proven, at least in a bigger scale and over a longer time period.

On the other hand results from studies on waste gasification showed that the general product gas characteristic – that means major components and calorific value – has a good comparability to biomass gasification. Additionally even knowledge from existing coal or lignite gasification plants could be used as well. This circumstance increases available knowledge and the literature amount on studies, research projects and practical facilities were conclusions even for waste treatment can be drawn from. Of course a complete copy of design and operation figures is not feasible since, due to the feedstock, waste management systems have to deal with quite unique potential risks like corrosion, metal release or dioxin formation. But if adequate gas cleaning system can be established gas utilization technologies and solutions from biomass and coal gasification could also be used.

## 3.2 Biological waste treatment

The biological treatment technologies composting and anaerobic digestion are both already proven technologies that are used for a significant amount of waste and in a steadily increasing number of facilities. The ratio of biological treated MSW, for example, has in the European Union increased from 10 percent in 2001 to 15 percent in 2011 with highest ratios in Austria and the Netherlands with 34 and 28 percent, respectively [Eurostat 2013]. Biological treatment is still mainly conducted in composting plants but there is also a clear trend towards more AD plants. In Sweden, for example, a significant increase in AD treatment capacity could be observed over the last few years while the composting treatment capacity stagnated. The development between 2006 and 2010 is presented in Table 2 where the clear upward trend for AD capacity but also for treated food waste can be seen.

	2006	2007	2008	2009	2010
<b>Anaerobic digestion (t)</b>	283 730	356 090	405 580	535 930	661 620
<b>Composting (t)</b>	452 390	515 290	568 700	630 500	566 210
of which					
<b>Food waste (t)</b>	134 990	166 810	162 680	178 770	214 230
<b>Total biological treated household waste (t)</b>	469 880	561 300	597 280	617 680	587 170

Table 2 Development of Biological Treatment in Sweden, Source [Avfall Sverige, 2011]

There are several AD plants – with both mesophilic and thermophilic reactor types – in operation that uses food waste or other digestible MSW fractions as feedstock. Usually this fraction is only one part of the feedstock which may also comprise manure, waste from slaughterhouses and food industry, energy crops and others. A proper mixing of these substrates based on good knowledge of the digestion characteristics of each substrate will avoid potential operation problems, e.g. from foaming, too high nitrogen content or slow reaction time. At the same time the mixing of substrates will stabilize the overall biogas yield and reduces unnecessary resource consumption, e.g. through mixing moist with drier substances to receive the right moisture content and consistence for digestion and slurry transportation. Example figures for biogas/methane yields from different substrate types are shown in Table 3. These methane yields are obtained in batch digestion experiments with unlimited time. Therefore the achievable biogas yields in actual AD plant will be lower mainly due to the limited residence time within the digester.

Substrate	TS [%]	VS [% of TS]	Methane yield $\text{m}^3_{\text{CH}_4}/\text{t}_{\text{VS}}$
Source separated food waste – household	33	85	461
Source separated food waste – canteen	13	92	650
Source separated food waste – restaurants	27	87	506
Fruit and vegetable waste	15	95	666
Slaughterhouse waste –stomach/intestinal	16	83	434
Slaughterhouse waste – residual blood	10	95	547
Returned product (dairy)	20	95	520
Grease interceptor sludge	4	95	682

Table 3 Examples for measured methane yield in batch digestion experiments, Source [SGC, 2009]

Various biogas utilization processes are also already proven technologies with several units in operation. This is true for the direct biogas utilization in combustion engines for generating heat and power but also for biogas upgrade facilities for generating SNG.

The technology that is currently used the most for biogas upgrade is water scrubbing. But there are also a significant number of facilities that uses PSA or chemical absorption. According to Petersson and Wellinger [Petersson and Wellinger, 2009] there were already around 100 biogas upgrade plants in 2009 worldwide which were connected to AD processes based on various substrates such as sewage sludge, energy crops or digestible waste fractions. Since then the number has increased further. In Sweden for example the number of upgrading facilities has increased in 2010 alone by 9 units to reach a total of 47 units by the end of 2010, resulting in an increase of biogas upgrade to SNG from around 100 GWh in 2005 up to over 600 GWh in 2010 [Energigas Sverige, 2011]. The utilization of SNG is mainly depending on the ability to inject SNG into an existing gas grid. If this is the case the gas grid injection is usually the option – e.g. for countries like Germany, the Netherlands or Switzerland – while otherwise the SNG is mainly utilized in form of vehicle fuel, e.g. in Norway or Sweden.

Even the utilization of the digestate is a well-developed area. The digestate can be and is used as fertilizer in agriculture if the contamination ratio is within the required limits. In Sweden for example

over 90 percent of the digestate from co-digestion plants (these are the digestion plants where MSW is one of the substrates) is used as fertilizer while the amount from AD plants at waste water treatment facilities is less than 25 percent. Certification systems for digestate are available to assist plant operators and help potential customers.

Despite the already significant use of AD in waste treatment there are of course still quite a number of research projects ongoing dealing with several challenges and obstacles in AD for waste or biogas upgrade. Research topics include a better classification and post-treatment of digestate, various pretreatment technologies for increasing gas yields and enable for new substrates – e.g. lignin rich fractions through hydrolysis reaction – as well as new gas utilization possibilities, e.g. the use of non-upgraded biogas in fuel cells. Furthermore the improvement of knowledge on digestion characteristics for various substrates and in general a better process controlling including reducing the required power and heat consumption are also main research areas.



## 4 Integrated Advanced Waste Refinery (IAWARE) facilities

### 4.1 The IAWARE concept

When sufficient heat utilization is not an option the two ways to increase resource recovery from waste are increasing the power generation or implementing the production of fuels or other products which can be used with higher recovery rates at a different places or times. As stated in the former chapters the power generation efficiency can be increased either by improvements in the ordinary waste combustion steam cycle process or by switching to different waste and energy conversion technologies. But even in these cases recovery efficiency will be limited since a significant ratio of waste energy will always be converted into heat. A more promising way could be the conversion into products if they are used, for example as chemicals in industry by directly replacing other fossil sources, as nutrients in replacing artificial fertilizers or in high efficient CHP facilities. The choice of the most suitable treatment technology is also influenced by the waste characteristics including type and purity of the waste and by further boundary conditions, which are mainly dependent on the facility location. For example, the latter defines whether and where there is a market for fertilizer, which type of fuel should be generated (gas grid connection, other transportation or storage opportunities nearby) or whether there is an industry facility nearby that could use the product or fuel produced and it will also determine other energy or product streams that can be utilized in the waste treatment facility. Furthermore the size of the waste treatment facility – which usually depends on the generated waste amount in the area – is an important criterion since the gas reforming technologies for utilization of product gas from waste gasification in particular require a certain size for a practically and economically feasible operation. Lastly the combination of various treatment technologies opens for the opportunity to use excess heat or materials from one process for another.

This is the idea behind the IAWARE concept, an Integrated Advanced Waste Refinery, as outlined in Figure 4. It involves defining an optimal combination of waste treatment technologies based on the local boundary conditions, which enables for source specific treatment, internal and external material and energy exchange to maximize the production of high quality products while minimized the generation of unused heat.

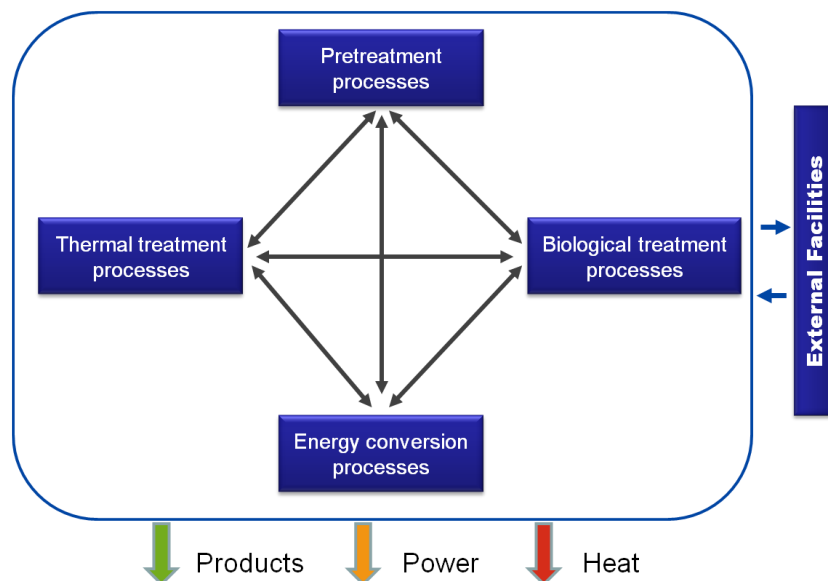


Figure 4 Outline of an IAWARE facility

## 4.2 IAWARE examples

Due to the amount of available treatment technologies, waste input characteristics and product possibilities there are a large variability of feasible IAWARE configurations. Of course there are also limitations: for example some technologies are hard to combine with each other; while some products are not likely to provide a promising choice. The production of Solid Recovered Fuels (SRF) or Refuse Derived Fuels (RDF) is not a preferable product of an IAWARE facility, since the fuel characteristics do not completely comply with standard fuels which means it is not possible to use SRF/RDF without restrictions simply by just substituting standard fuels. For the same reason a common Mechanical Biological Treatment (MBT) facility is not comparable to an IAWARE since it only comprises pre-treatment and biological treatment processes without dealing with the combustible residues.

Due to the large variety of possible IAWARE configurations ('scenarios') together with the importance on other boundary conditions the potential of IAWAREs have been evaluated for two example configurations. This has allowed us to use available efficiency data on proven technologies as well as "best" estimations on newer technologies. The scenarios shall represent examples for a current state-of-the-art and a possible near future facility.

### 4.2.1 Scenario 1

Scenario 1 is the current state-of-the-art example and comprises an anaerobic digestion process for the digestible waste fraction with a downstream biogas upgrade to SNG while the combustible waste fraction will be incinerated with energy recovery through a connected steam cycle. A simplified outline of the facility is shown in Figure 5. Unsorted or source separated MSW and similar commercial waste are split into the two treatment paths. The digestible waste stream is further pretreated by sieving processes to secure the required purity for use in the digester. The resulting reject of this pretreatment is added to the combustible waste fraction. Material recovery of valuable metals is also integrated into the thermal treatment path as a pre-combustion and/or an ash treatment process. The steam cycle process provides power to the grid and heat to an eventual existing district heating network. Parts of the generated power and heat will be used for running the digestion and biogas upgrade processes.

The recovery potential of this scenario was evaluated through energy balance calculations using actual performance data from waste treatment facilities in a midsize Swedish municipality [Amornvareesaman, 2012]. The key parameters for these processes were:

- The amount of 100,000 tons per year is incinerated with a net calorific value of 11 MJ/kg at used conditions.
- The net efficiency for the incineration plant (gross values minus own use of electricity and heat for running the plant) is about 15 percent electrical and 85 percent in total when the plant is running in CHP configuration, based on the net calorific value of the waste. If the plant is running without external heat utilization the net electrical efficiency increases to about 22.5 percent, based on NCV. Both values fit into the efficiency range presented in Chapter 3: Status of technologies.
- The amount of 30,000 tons per year is digested while the biogas yield is about 87 Nm<sup>3</sup> of methane per ton waste. This value corresponds also with the statements from Chapter 3.
- The yearly power and heat consumption of the biological treatment processes is about 7 GWh for heat and 4.2 GWh for electricity. These values include sorting and waste pretreatment, the digestion, the biogas upgrade and the post-treatment of the digestate. The heat consumption is

quite high which is due to the use of a thermophilic digestion and a biogas upgrade process based on chemical absorption. By using these technologies the internal heat utilization is maximized (although it is not that significant an amount when compared to the total heat generation), while the power consumption is lowered. Despite this the total power consumption is still noticeable with waste pretreatment (sorting, sieving) and post-treatment of the digestate (dewatering) as big power consuming processes.

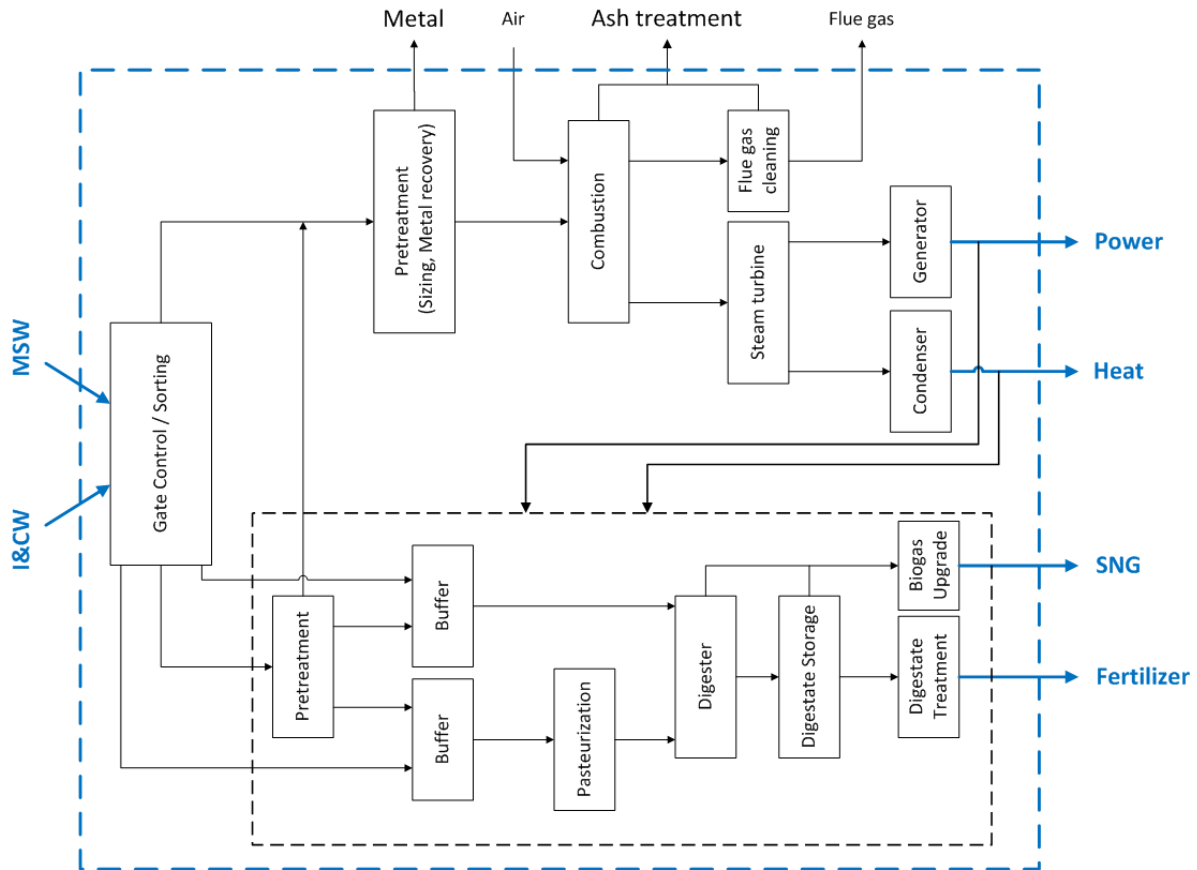


Figure 5 Scenario 1 configuration

- In consultation with Topic 4 the net calorific value of the digestible waste was set to 3.5 MJ/kg to comply with figures from the LCA tool WRATE for kitchen waste [Gandy, 2012]. This value differed slightly from the actual value in the reference plant; but the anomaly is due to the combination of wastes used in that plant (household waste, catering, slaughterhouse wastes etc). The calorific value of this waste is determined by the ratio of fat, carbohydrates and proteins. However, in WRATE, which was used for life cycle analysis of this scenario the closest waste was kitchen waste, with a slightly different composition of fat, carbohydrate and proteins. Since the calorific value is not used for the scenario evaluation – the biogas yield is based on the actual stated values and the input mass – this difference will not change the results of the scenario evaluation. But it will of course change the result of a comparison scenario where the whole waste amount is burned. This also has to be considered when we consider the final conclusions, although the impact will not be that critical, since most of the total waste energy is contained in the combustible waste fraction. Furthermore when considering the biogas yield used the digestion conversion efficiency into biogas would be nearly 90 percent based on the net calorific value of the waste. This is not impossible but quite high. Of course with stated and common values for dry matter content and hydrogen content the conversion efficiency based on the gross calorific value would be significantly lower, in the range of 50 percent. Available information about calorific values for digestible

waste and digestion conversion efficiencies with regards to the calorific value are quite rare and sometimes inconsistent. A more thorough survey should therefore be conducted to get better and more reliable data.

#### 4.2.2 Scenario 2

Scenario 2 represents a near future example and partly uses gasification. The incoming waste is this time split into three fractions: one digestible, one that is gasified and one that is incinerated. The gasifier fraction contains the high quality fuel: the combustible fraction with high calorific value and preferable with low content of components that can cause problems as agglomeration or corrosion. The sorted gasifier waste fraction is sufficiently pretreated using drying, sizing and sieving before entering the gasifier itself. The resulting product gas is also sufficiently cleaned, followed by a downstream gas reformation. Methanation was chosen as an example for reforming technologies, which means the waste is finally converted into SNG. This was chosen partly because of the better available data on process feasibility and conversion efficiency; and also because SNG is already produced through biogas upgrade. The biological treatment path consequently is unchanged compared to Scenario 1. The remaining combustible waste fraction (added to the reject fractions from digester and gasifier pretreatment) is incinerated with energy utilization through a connected steam cycle. A simplified facility outline is presented in Figure 6.

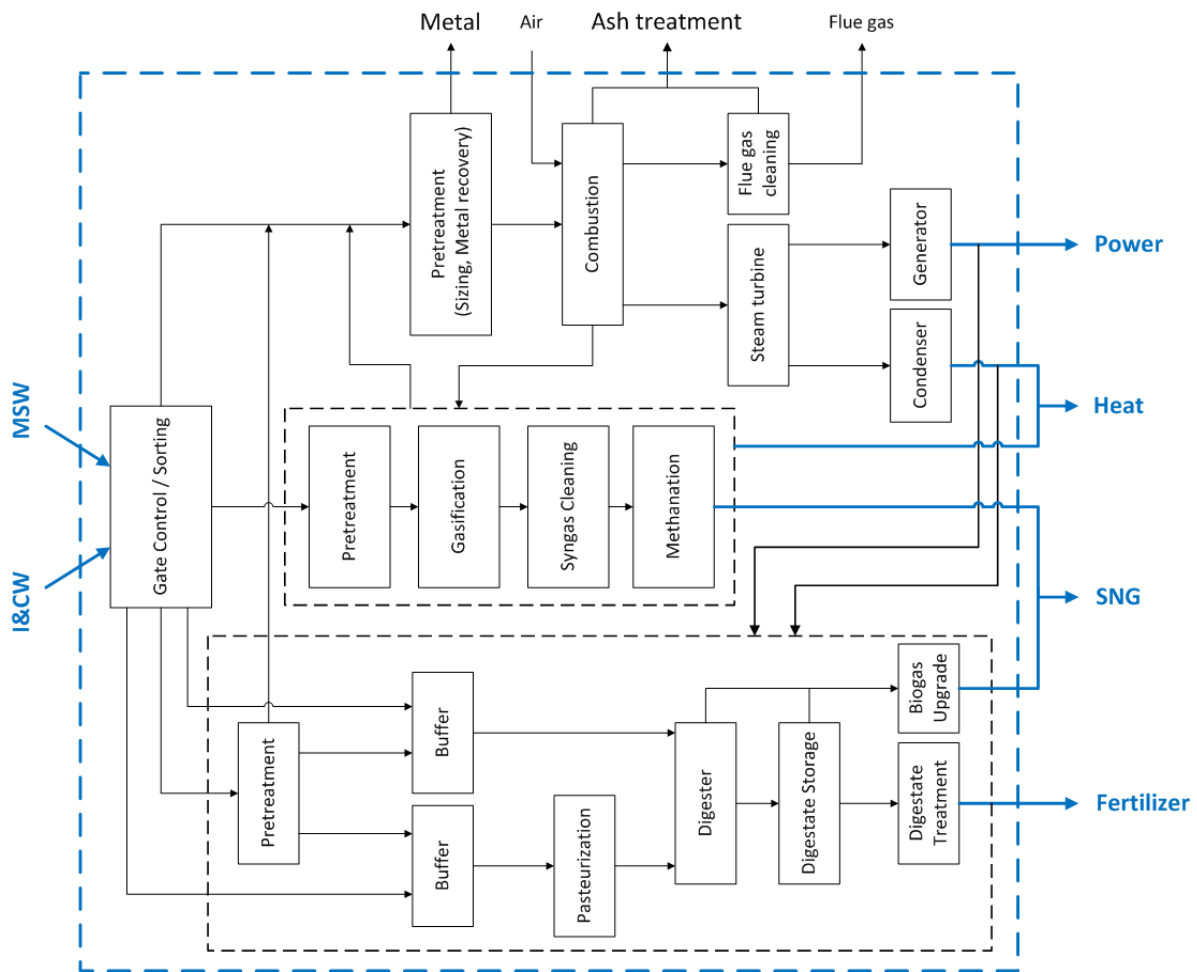


Figure 6 Scenario 2 configuration

The recovery potential of this scenario was evaluated through energy balance calculations using the same data as in scenario 1 for the corresponding technologies incineration and digestion, while data

from research studies and proposed projects is used for the gasification path. Therefore the results contain a higher uncertainty due to this. The key parameters were:

- An amount of 25,000 tons per year is gasified with a net calorific value of 15.5 MJ/kg at used conditions. This is about 35 percent of the combustible waste energy.
- The conversion efficiency for SNG production is set to 60 percent, based on the net calorific value of the gasified waste. An additional 20 percent of the waste energy will be used as heat when external heat utilization is possible. The SNG conversion efficiencies corresponds well with published figures for allothermal steam gasification and methanation research results, as well as with proposed figures for SNG production facilities based on biomass gasification.
- Other figures stay the same as stated in Scenario 1. That includes the incineration process efficiencies, despite the fact that the waste characteristics (moisture content, calorific value, ash content, etc) and the plant size is changed compared to scenario 1. To what extent this statement is true could be discussed.

### 4.3 Results from example evaluation

The results of the example evaluation using the stated boundary conditions are presented in Table 4. For both scenarios the results are given for CHP and power configuration mode which means with or without external heat utilization. The required heat for digestion and biogas upgrade in scenario 1 power mode is provided by combustion of biogas itself. If the combustion of high quality biogas shall be avoided the required heat could also be provided by steam extraction from the steam turbine or by the incineration process itself. For the case when the heat is taken directly from the incineration process the resulting recovery figures are presented in parentheses of scenario 1 power mode. For comparison of the IAWARE potential the results for the reference “Incineration” – which describes a process where the whole waste amount will be incinerated using the incineration process efficiencies from scenario 1 and 2 – and “Advanced Incineration” – which describes an incineration process with top-level recovery values of 30 percent net electrical efficiency – are presented as well. The values in parentheses for these references represent recovery figures when only the combustible fraction is incinerated while the digestible fraction is composted. In these cases the power consumption of the composting process is not considered.

Case	Electricity [GWh]	Heat [GWh]	SNG [GWh <sub>LHV</sub> ]	other	Notes
Scenario 1 (CHP)	41,9	206,0	25,8	Fertilizer	
Scenario 1 (Power)	66,7 (64,0)	0	18,8 (25,8)	Fertilizer	() Heat for Upgrade process from incineration
Scenario 2 (CHP)	16,9	152,1	90,4	Fertilizer	
Scenario 2 (Power)	32,9	0	90,4	Fertilizer	
Comparison A Incineration CHP	48,4 (46,3)	234,6 (214,1)	0	- (Compost)	() Digestible Waste composted, without consideration of power demand
Comparison B Incineration Power	75,3 (70,9)	0	0	- (Compost)	() Digestible Waste composted, without consideration of power demand
Comparison C Advanced Incineration	100,4 (91,7)	0	0	- (Compost)	() Digestible Waste composted, without consideration of power demand

Table 4 Results from evaluation of scenarios

Comparing the scenarios with the reference cases there is a clear trend both for CHP and power only facilities. A part of the energy which otherwise would be converted into power and heat will be saved

as SNG instead. When looking at facilities in power configuration mode the energy recovery efficiency of comparison B is 22.5 percent based on the waste net calorific value. For scenario 1 this increases to 25.6 percent in total when combining power with the SNG chemical energy based on net calorific values. The single values are 19.9 percent net electrical efficiency and 5.6 percent SNG conversion rate. When maximizing the SNG production by using heat from incineration for digestion and biogas upgrade the recovery factor would even increase to 26.8 percent in total with single values of 19.1 percent for power generation and 7.7 percent for SNG conversion. For scenario 2 the combined total recovery efficiency increases further to 34.7 percent with 9.2 percent net electrical efficiency and 25.4 percent SNG conversion rate. That is a significant increase despite the fact that actually only 35 percent of the fuel energy was used in gasification.

In comparison the advanced incineration reference – comparison C – has a net electrical efficiency of 30 percent when the total amount of waste is incinerated. When the digestible fraction is composted instead the net electrical efficiency figures for Comparison B and C based on the whole waste amount would be 21.2 and 27.4 percent, respectively.

Comparing the results for facilities in CHP configuration the same trend for increased recovery of high quality energy and products can be observed. It should be mentioned for these cases that the required heat utilization decreases from 234 GWh for the incineration reference Comparison A down to 206 GWh for Scenario 1 and to 152 GWh for Scenario 2. In relative figures that is a decrease in required heat utilization from 70 percent of the waste energy down to 61.5 and 42.8 percent, respectively. That means the chances for higher heat utilization would increase.

Apart from the increase in energy recovery there is also the benefit from production of fertilizer through the AD process which will reduce the need of artificial fertilizer and therefore saves additional energy that would be used in the production of this artificial fertilizer.

## 5 Conclusions

The results from the scenario evaluation have shown the potential of IAWARE's for increasing energy recovery when compared to current state-of-the-art WtE incineration plants. Of course, since the evaluation was based on assumed figures, there is still optimization potential in all processes, current incineration as well as IAWARE facilities. This is especially valid for the alternative thermal treatment technologies that are not proven technologies yet. But despite these uncertainties the general trend will not change and therefore the statement regarding the IAWARE potential for energy recovery will remain true.

Anaerobic digestion is a state-of-the-art treatment technology for biodegradable waste fractions already; and it provides higher energy and material recovery ratios than conventional incineration. Therefore, for the digestible fraction this should already be the first choice. For further biodegradable fractions there should be more thorough studies on whether incineration or composting is the better choice. This is not only a question of energy recovery, but also of material recovery as well as other boundary conditions. However through more extensive pre-treatment part of these fractions could be enabled for used in AD processes as well.

Final conclusive statements are not possible based on the waste treatment facility alone. It is important that there is also an evaluation of the whole waste management system, which means examination of alternative treatment possibilities (in line with the waste hierarchy) as well as the final use of the recovered energy. A good fuel conversion ratio in an IAWARE facility, for example, would be overturned by poor fuel use later, e.g. by use in a low efficiency conversion process.

However, this work has shown that efficient heat utilization still results in better energy recovery ratios when using the waste in a standard CHP or even heat only incineration plant than imposing an advanced IAWARE concept, which due to the nature of the technologies will always loose energy in conversion.

The biggest challenge for implementing more advanced IAWAREs will be the ability to set up successful commercially operating alternative thermal treatment processes that on one hand can handle the difficult fuel waste and on the other hand will secure sufficient gas cleaning before gas reforming. In general the development of the gasification technology has shown great progress in the past few years, but waste gasification is neither biomass gasification nor coal gasification. It has its own unique challenges that will need more focused research as well as commercial scale demonstration facilities.

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