

CIRCULAR ECONOMY: ENERGY AND FUELS

5





The International Solid Waste Association (ISWA) is a global, independent and non-profit making association, working in the public interest to promote and develop sustainable waste management.

ISWA has members in more than 60 countries and is the only worldwide association promoting sustainable, comprehensive and professional waste management

ISWA's objective is the worldwide exchange of information and experience on all aspects of waste management. The association promotes the adoption of acceptable systems of professional waste management through technological development and improvement of practices for the protection of human life, health and the environment as well as the conservation of materials and energy resources.

ISWA's vision is an Earth where no waste exists. Waste should be reused and reduced to a minimum, then collected, recycled and treated properly. Residual matter should be disposed of in a safely engineered way, ensuring a clean and healthy environment. All people on Earth should have the right to enjoy an environment with clean air, earth, seas and soils. To be able to achieve this, we need to work together.

Executive summary



Image by Sysav

In June 2014 the ISWA Board established the ISWA Task Force on Resource Management to outline the waste sectors growing contribution to resource management and the circular economy.

This report is one of six reports prepared by the Task Force and describes the value in using waste to generate energy and fuels and the savings made in the use of fossil fuels and other energy resources.

The principles outlined are valid on a global scale but data and discussed technologies are focused on the OECD countries.

A range of methods exists to produce energy and fuels from waste. The most common are:

- combustion processes to generate electricity and heat;
- anaerobic digestion (AD) processes to produce biogas; and
- collection and treatment of biogas emitted from landfill sites.

Biogas can be further refined and added to the natural gas distribution network; used as a vehicle fuel; or used to generate electricity.

Energy recovery and material recycling supplement each other. There are many examples, such as:

- in biogas-plants organic matter is converted to biogas and the residue (digestate) is used to improve soil structure and fertility through its content of nutrients.
- Waste-to-Energy (WtE) plants which dispose of residues from recycling processes, contaminated waste and materials that can no longer be recycled (due to quality deterioration through many recycling steps). Metals (that are difficult to recycle from composite products) are recovered from the bottom ash which itself can be used in construction.

Energy recovery serves the same high level objective as many material recycling activities. For instance one objective of recycling plastic is saving oil or natural gas, which are normally used for energy purposes. In a similar manner oil, gas, or other primary energy resources are saved through energy recovery of plastics in WtE facilities producing electricity. Which process system to use depends on the outputs, processing efficiencies and local circumstances.

OUTPUTS IN OECD	CURRENT	POTENTIALS	
	TWh PER YEAR*	TWh PER YEAR*	VALUE B€ PER YEAR
● Electricity from WtE	75	300	15
● Heat from WtE	70	400	8
● Biogas/ methane from AD**	-	40	1.2 - 1.6
● Landfill gas**	50	20***	0.6 - 0.8
● Recovered metals from bottom ash, WtE	-	-	4

*: 1 TWh is the energy content of around 90 million m³ of natural gas, or around 300,000 households' annual electricity consumption for lighting and appliances.

**: from MSW, only

***: after diversion of waste for WtE and AD. 130 TWh assuming improved gas collection and no change in landfilled amounts.

The energy consumption of OECD countries is huge, and more than 60% of that energy is provided by fossil fuels. Waste, currently contributes around 1% of that energy supply, but has the potential to increase more than three fold. To reduce the use of fossil fuels and mitigate the associated climate effects, all other energy resources must be employed to their maximum potential, including waste.

Climate change is not only about replacing fossil fuels. It is also about mitigating other climate gases such as methane emissions from landfill sites. The main climate impact of the waste sector is substantially reduced when landfill gas is collected and used for energy recovery. Greater environmental gains are delivered however, when material recovery and energy resource utilisation are used together to divert waste to AD-plants, WtE facilities and back into manufacturing activities, as part of integrated waste management programmes.

This report concludes that feedstock for WtE could be more than doubled, taking another 200 million tonnes per year (Mtpy) of waste from landfill, and a further 40 Mtpy for biogas generation without disrupting dedicated recycling activities. The current and potential outputs in energy, fuels and metals from waste

treatment are listed in the table above, along with an indication of their economic value.

The technologies for WtE, AD-plants and landfill gas recovery are fully developed. The markets for the outputs of electricity and/or biogas are readily available. Many installations already operate as combined heat and power plants, whenever the heat infrastructure is present. Future coordination between district-heating development and energy recovery systems from waste can boost the efficiency of energy outputs and take advantage of the cooling opportunity when the heat demand is low or non-existent.

This report has also evaluated other forms of energy recovery, such as gas from pyrolysis and gasification. This technology is not seen as a major solution for most OECD countries for the management of heterogeneous municipal solid waste, during the next 30 years due to the technical and financial challenges that remain.

The diversion of waste from landfill is urgently required to minimise methane emissions to the atmosphere as part of efforts to reduce climate change gases. The production of energy and fuels from waste is a solution that will lower

demand for fossil fuels and provide nutrients and carbon for our soils. Effective legislative and fiscal frameworks are required across OECD countries to deliver on the outcomes identified in this report. Early pioneers have shown how such change can be achieved using a range of legal targets, support for new infrastructure and fiscal incentives, such as landfill taxes. Urgent action is required if these opportunities are to be taken.

Key messages

Energy recovery from waste goes hand in hand with recycling and as such it is an integrated part of the circular economy

- energy recovery supplements recycling by increasing the total achievable recovery, and both serve the same purpose of saving natural resources.
- residue from recycling processes can be utilised for energy recovery.
- when the quality of recycled products deteriorates in the course of several recycling circles and recycling no longer is feasible they can still be used for energy recovery.
- metals which are not captured in the collection system, e.g. because they are trapped in combined products, can be recovered from the inert residues after combustion.
- waste contains contaminated materials and substances with for instance sanitary and health hazards and should therefore be taken out of circulation. Such materials can be safely destroyed by combustion while recovering energy.
- countries with distinct and ambitious environmental targets for their waste management all have a combination of material and energy recovery. The countries with the highest degree of material recovery are mostly also those with highest degree of energy recovery.

Energy recovery through anaerobic digestion of wastes of biological origin is an important means of utilising easily degradable materials for energy production

- nutrients valuable for replacing fertilizer may be recovered when waste is digested in biogas plants.
- landfill gas recovery is important to limit the emission of the climate gas, methane, and to make it available as energy source.

Energy recovery from waste is an important contributor in saving fossil fuels and reducing climate impact

- the OECD countries and similar countries will all have a potential for utilising energy from waste.
- it requires a well organised waste management sector and energy infrastructure to utilise the output to its maximum potential.
- while the electricity infrastructure is usually in place, further development of the infrastructures for gas, heating and cooling will provide opportunities for increasing the efficiency of energy recovery and use.

Energy recovery from waste has the potential of expanding thereby increasing its share of the supply of gas, electricity and heat and being an important contributor to abatement of fossil fuels

- the waste potential for energy recovery from MSW and MSW-like waste in Waste-to-Energy facilities in OECD is estimated as 400-500 million tonnes per year (Mtpy), of which barely half is used currently, leaving an unused potential of around 200 million tonnes.
- Waste-to-Energy facilities are continuously pushing towards higher efficiency, making future new facilities more efficient when it comes to replacement of fossil fuels.
- local conditions may affect the value of the generated energy. For instance, supplementing the generation of electricity with production of heating, cooling or process steam will increase the value of waste as an energy resource.
- biogas has the potential of being used for peak load power generation or transportation fuel depending on local infrastructure opportunities.

Prepared by the ISWA task force on resource management

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With over 20 years' experience in advising on energy recovery systems from waste worldwide, Tore Hulgaard has a long track record of dealing with technical and environmental issues relating to waste-to-energy (WtE) systems, resource recovery and biological treatment of organic wastes.

He has a chemical engineering background and holds a PhD from the Technical University of Denmark (1991) providing the technical basis for dealing with process systems with a particular focus on the control of harmful emissions from energy conversion systems. After gathering industry experience at a boiler manufacturing company (Alfa Laval Aalborg), in 1995 he joined Ramboll providing independent consultancy worldwide.

As one of the leading authorities on waste treatment technologies in Denmark, he has provided specialist consultancy services to a wide range of public and private clients within the waste sector. He is now holding a position as Technical Manager in Ramboll.

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Introduction

Scope

Resource management within the waste sector has the high level objective of saving natural resources. Natural resources range from primary energy resources such as coal, natural gas, oil, and wood/biofuels through water, minerals and metals to rare earth elements. Some are critical because their appearance is limited or for geopolitical reasons, and some natural resources are associated with environmental impacts from their extraction or use.

The challenge is to generate value from waste in terms of saved natural resources. Material recovery is better than energy recovery in this respect when it comes to sorted, pure and homogenous high-value materials that are easily recovered such as plastic from industry, newsprint and where energy processes add no value such as pure glass and metals.

Energy recovery has, however, its place when it comes to materials that are not easily recycled such as soiled or contaminated materials, composite materials and materials with a quality not suited for recovery for instance due to deterioration of quality through cascading in the course of several recycling sequences. Energy recovery may also be the better choice for low-value materials such as wood and materials that require disproportionate resources to collect, handle and recover in a separate process system.

This study investigates, describes and analyses the potentials for recovery of energy and fuels from waste. The energy markets and market conditions for trade in the energy and fuels are investigated, and benefits and disadvantages related to recovering and using the energy and fuels are described (hereunder technical, financial, environmental and societal).

The aim of the report is to emphasize the contribution that energy recovery from waste brings to the circular economy.

The study is one part of the ISWA task force on resource management and should be seen together with the other parts conducted in parallel with this study.

The report will address the following forms of energy and fuels as they are the predominant forms of energy output from waste:

- electricity
- steam, heating, cooling
- biogas (methane)

Waste-to-Energy (WtE), where waste is thermally converted with energy recovery, generates primarily electricity and heat. Biogas plants generate biogas by anaerobic digestion (AD), and biogas is also the product from landfills. The biogas can be used for production of electricity (and heat) on site or distributed for use elsewhere e.g. for process energy, chemical processes or used as transportation fuel.

A common benefit of energy and fuels from waste is that these outputs replace other energy resources, particularly fossil fuels and thereby their emissions of carbon dioxide. The report will quantify the current and potential contributions.

Plants for energy recovery from waste are thus dual purpose; replacing other energy resources and being part of the waste management system. The report will describe how the plants provide other contributions to resource recovery such as nutrients from organic waste and metals from bottom ash.

The geographical and primary market scope of the study is the OECD countries, representing countries with a certain development level and an established waste management system. Other priorities and initiatives may be relevant for developing countries, refer for instance to report on Globalisation and Waste Management, (ISWA, 2012) and ISWA guideline on Waste-to-Energy in Low and Middle Income Countries (ISWA, 2013). Where OECD data appear scarce or where it is important to include other countries to obtain the full picture, other geographical areas may be addressed.

The time frame for the outlined perspectives is chosen to be around 30 years from today, which is comparable to the technical lifetime of common process systems and the time span which realistically can be considered. Focus is on technologies that are the predominant ones being operated at full scale and commercially available today. Pilot scale plants and process systems that are not foreseen to be widely used over the timeframe are only briefly described.

Waste-to-Energy (or WtE) is used with the same meaning as 'incineration with energy recovery' in this report. 'Energy recovery from waste' is used as a general expression for WtE, biogas generation and other types of recovery of energy or fuels from waste. 'Anaerobic digestion' (AD) is used for a biological process by which organic matter is converted into biogas. AD could happen in dedicated biogas plants or in landfills, and the biogas generated in landfills is termed 'landfill gas' (LFG).



Feedstocks

Waste for treatment by Waste-to-Energy

The feedstock for production of energy and fuels is basically municipal solid waste (MSW) collected at households and commercial waste with a character similar to household waste. It may also include certain types of industrial, construction and demolition waste (C&D waste) although these fractions are not normally counted as MSW.

The generation of MSW is recorded by OECD at a level of around 530 kg per capita per year; Figure 1, and disposal varies between countries, Figure 2, indicating significant use of landfills in some countries with limited recycling and recovery of energy and fuels.

Figure 1 includes MSW only. The definitions behind the indicated distinction between household and non-household waste for the MSW may vary among countries depending on waste management system, and particularly the non-household part may be categorised as MSW in some countries and excluded from MSW in others.

The OECD-statistics reveal that the total production of MSW in OECD amounts to 658 million tonnes per year (Mtpy), and that the amount of manufacturing waste, industrial waste and C&D waste would typically be roughly equal to the amount of MSW, but with large variations among countries (OECD, 2015).

Five major non-OECD countries (Brazil, China, India, Indonesia and Russia) produce a total of 300 Mtpy of MSW. Other countries have MSW generation in approximately the same scale as the OECD-countries measured in kg per capita per year, e.g. Hong Kong, Singapore and other locations in the South East Asia.

Historically changes in waste amounts have correlated with economic growth. Political initiatives are striving towards a decoupling of economic growth and waste generation. Hence, unchanged waste amounts are assumed in this report even though some economic growth is foreseen in the OECD countries.

From Figure 2 it appears that the share of MSW incinerated with energy recovery varies significantly between countries, ranging from 0 to more than 50 %, averaging around 19%. A small share of the MSW is incinerated without energy recovery, amounting to approximately 3% of the MSW in OECD, (OECD, 2013). The total incineration of MSW is therefore estimated as 22% of 658 Mtpy or 145 Mtpy, (OECD, 2013).

In addition to MSW some types of industrial waste and part of C&D waste are treated by WtE and will add considerably to the amount of waste used for energy recovery. The OECD statistics do not reveal details on how the industrial and C&D waste streams are managed. However, the average feedstock for WtE appears to be 70% MSW and 30% industrial and C&D waste, cf. Table 3 in section 5.1. With this share around 60 Mtpy industrial waste and C&D waste are treated by WtE, cf. Figure 3.

Figure 2 shows that countries with distinct and ambitious environmental targets for their waste management virtually all have a combination of material and energy recovery. The countries with the highest degree of material recovery are also often also those with highest degree of energy recovery. This applies for instance to Switzerland, the Netherlands, Sweden, Denmark, Japan and Norway which all have virtually done away with landfilling, and around 50% of the household waste is used for energy recovery in WtE facilities. In this perspective material recovery, energy recovery and biological treatment do not rule each other out. Rather, the different methods can be seen as complementary and together they create an efficient waste management system. The maximum potential for WtE may be assessed from the situation in these countries.

In case that all OECD countries installed sufficient WtE capacity and reached 50% WtE of MSW this would more than double

the waste throughput for energy recovery, from around 145 Mtpy to around 330 Mtpy of MSW, and hence, more than double the energy production from this source.

With the share 70:30 between MSW and industrial/C&D waste the potential for industrial/C&D waste suitable for WtE is estimated to around 140 Mtpy.

The total potential for WtE from municipal and industrial/C&D waste is summing to 470 Mtpy, recovering an unused potential of around 265 Mtpy, which currently is landfilled.

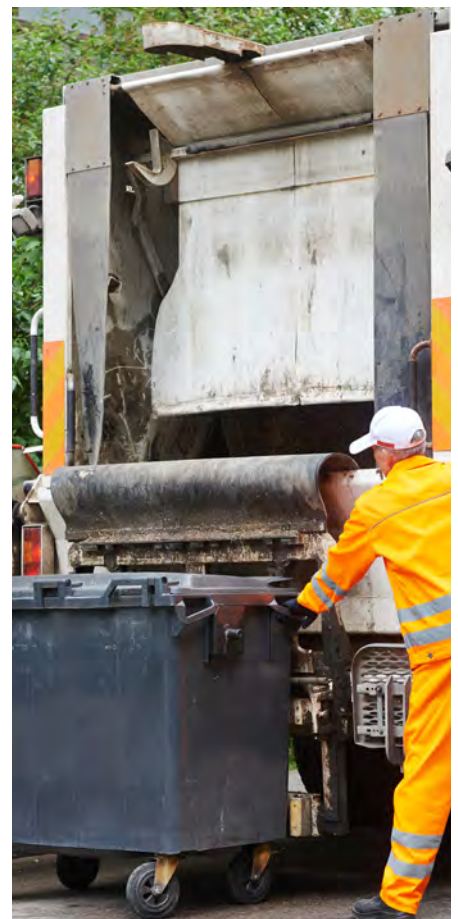
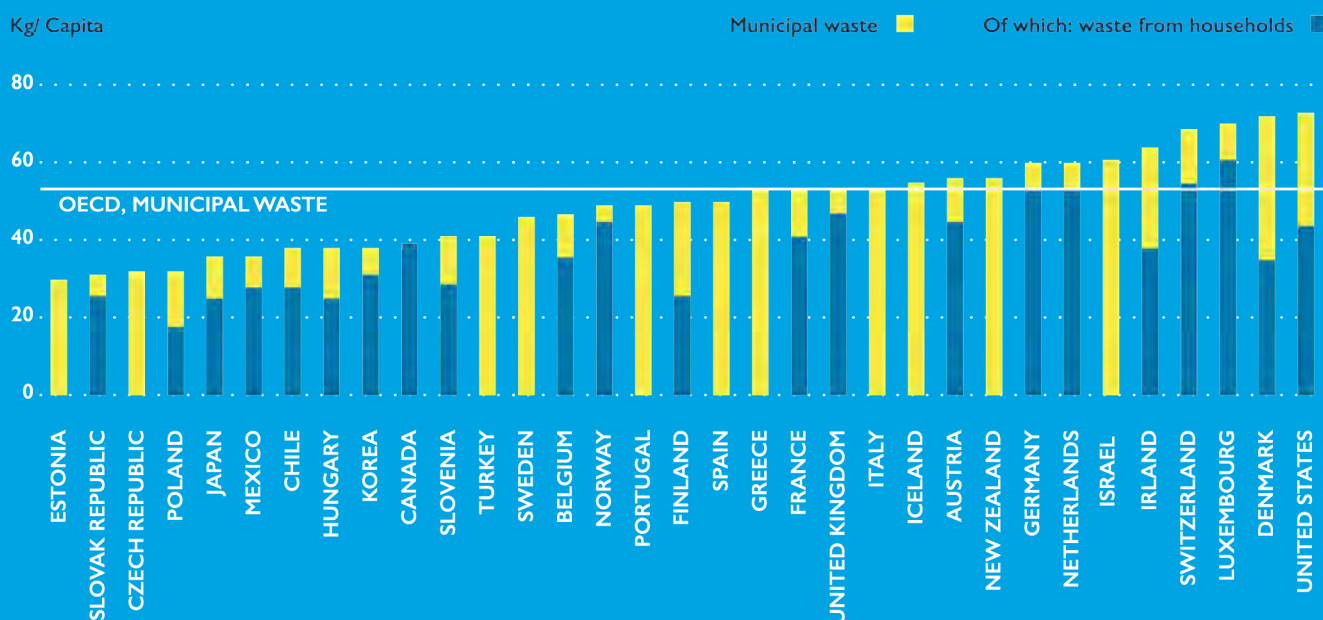
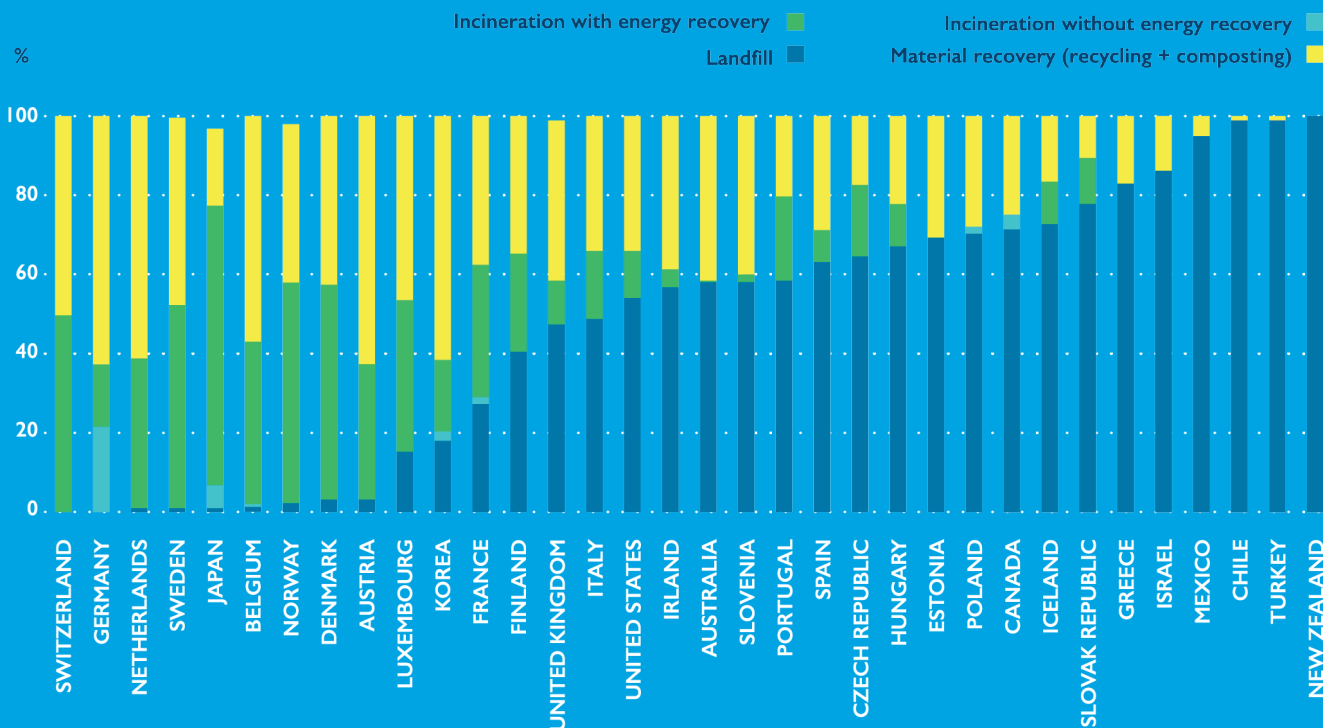


Fig. 1 **Municipal solid waste generation in OECD-countries, kg per capita in 2011**



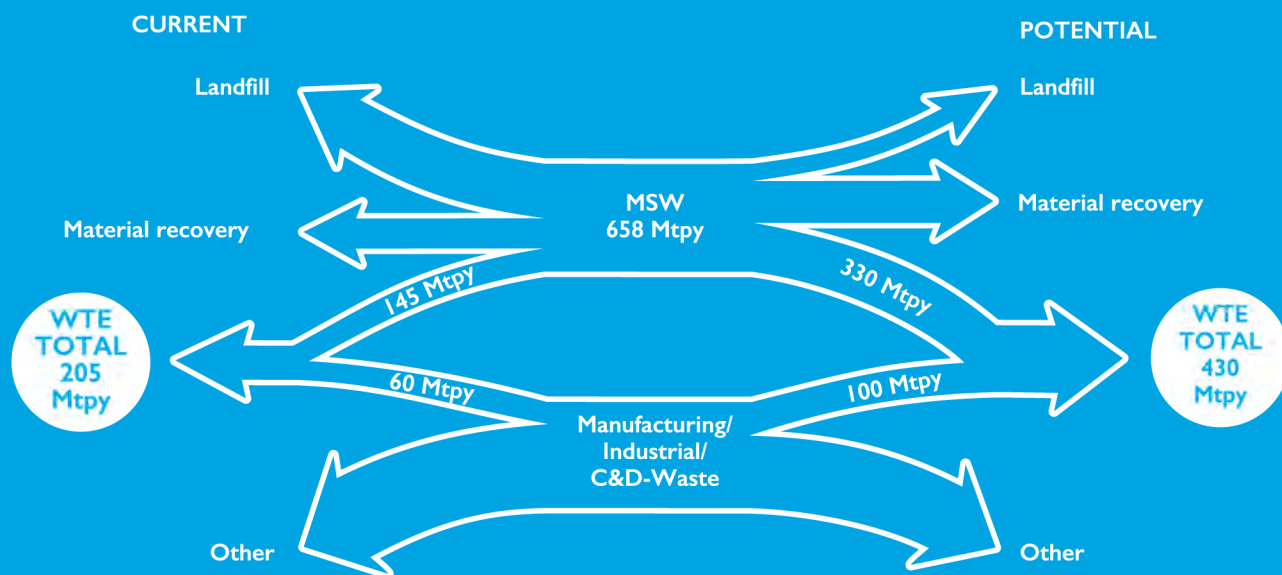
Source OECD, 2013

Fig. 2 **Municipal waste disposal and recovery shares, 2011**



Source OECD, 2013

Fig. 3 | Current and potential waste flows to WtE



Political initiatives for increased food waste collection as well as recycling initiatives direct waste from WtE to other waste treatment options as described in the sections below. Still it is considered that contaminated materials, composite materials, materials with a quality not suited for recovery, low-value materials and reject from recovery processes form a significant amount.

A recent Swedish report further describes the relations between material quality, material recovery and energy recovery, (Avfall Sverige, 2015). The report describes that in environmental system studies comparing material recovery and energy recovery, the calculations are often assuming a material recovery based on pure and homogenous fractions, and that in reality waste consists of a large variety of discarded goods with huge differences regarding potential for material recovery. Residual waste is in most cases made up of heterogeneous products for which there is little realistic and economically viable material recovery potential.

The report also addresses contaminated goods, 'For some kinds of waste there is a need to destroy the material through combustion, as material recovery process-

es may expose health risks due to e.g. high bacteria content or if the material by other means contain hazardous substances which should not reach society.'

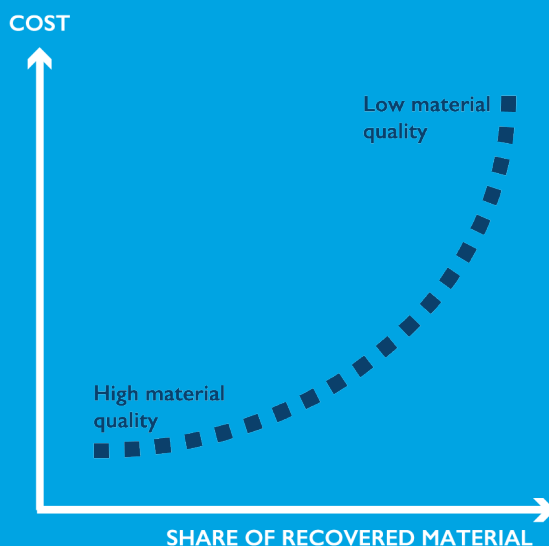
The author finds it right to give priority to material recovery over energy recovery, as in the waste hierarchy and that there are ways to create conditions for better material recovery by improved separation and a product development towards more recyclable goods. The products that are simple and of high quality will be the first to be separated for material recovery. A low material quality means that the environmental benefit from the recovery also will be lower. As illustrated in Figure 4 the cost of recovery increases with the share of recovered materials, while the material quality drops. There will therefore always be a breakeven point for a certain waste category, where an increased degree of material recovery is no longer justified from a cost and resource perspective and energy recovery will be a better solution. The report from Avfall Sverige also points to the discarded materials from recycling, 'One factor is related to the quality of recovered material. For every time a material is recycled, the quality is deteriorated and when the material quality eventually is poor it has

no market. Another factor that should be mentioned is that material recovery processes themselves might result in residues or rejects which cannot be recovered. This is particularly the case for plastics and paper. This also suggests that material and energy recovery are complimentary to each other.'

For the subsequent assessment it is assumed that the potential of 470 million tonnes per year suitable for WtE will be reduced over time to around 430 million tonnes per year due to increased material recovery and improved recycling options. This assumed increased availability of waste for WtE is thus 225 Mtpy.

The unused potential does not include waste from the agriculture, e.g. straw, forest residues, manure and poultry litter. These may be considered biofuels, which are outside the scope of this study (although thermal treatment of some agricultural residues may be under the waste incineration regulations).

Fig. 4 | **Relation between material recovery cost and quality of feedstock**



The recovery cost increase with the share of recovered material, while the quality of recovered materials drops.

Waste for biogas production through anaerobic digestion

Waste for anaerobic digestion (AD) in dedicated AD plants is usually counted as part of recycled waste, which is listed as 24% for OECD countries in average (160 Mtpy). Composted waste including AD is counted separately as 9% average (60 Mtpy) for OECD and 14% for OECD countries in Europe, (OECD, 2013).

The total generation of organic household waste for potential segregation and digestion is listed at around 80 kg/person on annual basis in Sweden, applicable for food waste only (NATURVÅRDSVERKET, 2014). This corresponds to roughly 15% of the total generation of MSW. Some commercial and industrial waste, particularly discarded goods from supermarkets and restaurants and residues from the food industry add to the potential. The report estimates the total food waste in the Swedish food supply chain (except in the primary production) to 127 kg per capita per year.

The actual feedstock available for biogas plants will be lower. This is particularly caused by the segregation efficiency. A part of the food waste will be mixed with other waste and will not be possible to sort out and be collected by the separate food waste collection. Secondly, separately collected food waste contains a certain amount of foreign substances and needs to undergo pre-treatment. The reject after pre-treatment may typically constitute 25-40% of the incoming waste.

For the subsequent assessments we assume that the exploitable potential for biogas production in dedicated AD plants amounts to half of the arising from households. By assuming 40 kg per year per capita and 1,250 million inhabitants in OECD this amounts to approx. 50 Mtpy in the OECD countries.

Utilising organic waste for energy recovery through AD could reduce the use of composting, which converts basically the same waste types and suffers from having no energy recovery. However, the feedstock for composting is often garden/park waste of which large parts are not particularly suited for biogas production because

they do not degrade easily. Food waste collected from households, commercial and industrial waste and other easily degradable waste of biological origin are potential feedstocks for anaerobic digestion and hereby raw materials for production of biogas.

Landfill waste for gas production

It appears from Figure 2 that in many countries landfilling is the predominant destination for waste, and in average landfilling constitutes almost 50%, totalling around 300 Mtpy of MSW as total for OECD, (OECD, 2013).

Waste for landfill gas (LFG) production through anaerobic digestion in the landfill does not appear to be counted separately in OECD. It will constitute a large share of the landfilled waste, whenever the biodegradable content will, depending on the design and operation of the landfill, have a potential for energy recovery generation in the form of methane.

Based on data from the OECD countries with the highest material and energy recovery rate the amount of waste for landfilling is less than 5% for MSW. It is expected that together with implementation of improved waste management systems and increased material and energy recovery in all OECD countries the amount of waste for landfilling will be reduced significantly over the next 30 years. EU required the landfilling of biodegradable waste to be reduced by 2005, so a range of initiatives have been undertaken to reduce landfilling. The speed of diversion from landfills depends on a range of political factors, cf. 3.4.. With the development in several European countries landfilling only a few percent (the mineral part) of the MSW, it appears realistic to assume the landfilling of MSW to be reduced to a third of the current level over the considered timeframe of 30 years. 100 Mtpy landfilling is therefore used later in the report to assess LFG generation.

While energy from LFG may not be a significant source of energy in EU and OECD countries, there is considerable opportunity to use this energy in many other countries. This is especially true in countries with developing economies that will continue to landfill significant amounts of waste and will for economic reasons not consider WtE in the foreseeable future. In those countries energy from LFG can provide a renewable, local source of energy.

What may affect the future availability of waste for recovery of energy and fuels

In the future, a range of factors will affect the possibilities of reaching the potentials for recovery of energy and fuels from waste as illustrated in table I where the main drivers and barriers are summarised for WtE, AD-plants and landfill gas extraction.

As landfill gas is generated from biodegradable waste in landfills, factors that promote use of landfills will also support landfill gas production, but its generation relies also on proper use of technology in landfill construction and use of recovered biogas.

It appears that there are many issues affecting the future availability of waste for energy and fuels. It is likely that the diversion of waste from landfills will continue and the incentive of abolishing fossil fuels will make WtE and AD important contributors in the future waste management and energy systems.



Image by Ramboll

Tab. I | Factors affecting the future use of WtE, AD and landfill with gas recovery

WASTE-TO-ENERGY	
Pushing towards wte	Diverting waste from wte
<ul style="list-style-type: none"> energy policies favouring non-fossil energy to reduce climate impact and reduce the dependency of imported energy resources. generation of electricity and heat in WtE as a means of replacing fossil fuel. ambitions of diverting waste from landfills. recycling activities will generate a reject of non-recyclables that is best used for WtE. recycling in repeated cycles gradually reduces the quality of the recycled products (cascading effect) necessitating an output in order to maintain the quality, and such outputs are likely inputs to WtE. economic development may increase the amounts of waste and the associated infrastructure needed. 	<ul style="list-style-type: none"> waste management policies; Extensive ambitions for recycling. This includes changes in production methods of new consumer goods that make disassembly easy facilitating reuse or recycling of different components. segregated collection of food waste. landfill may be preferred if economy is the main criterion for selection of waste management option.
ANAEROBIC DIGESTION	
Pushing towards ad	Diverting waste from ad
<ul style="list-style-type: none"> energy policies favouring non-fossil energy to reduce climate impact and reduce the dependency of imported energy; biogas generation as a means of replacing fossil fuel for e.g. power generation or transport. policies diverting biodegradable waste from landfills (binding targets/ban/taxation). policies diverting food waste from WtE. ambitions of recycling the digested food waste for soil enrichment by organic matter and nutrients (particularly phosphorous and nitrogen). 	<ul style="list-style-type: none"> landfill may be preferred if economy is the main criterion for selection of waste management opportunity. cost of separate collection and challenges in reaching proper quality. difficulty of making use of generated digestate as fertilizer.
LANDFILL WITH GAS RECOVERY	
Pushing towards landfills and gas recovery	Diverting waste from landfill
<ul style="list-style-type: none"> space available for landfills at a manageable distance. policies favouring low cost solutions for waste management. 	<ul style="list-style-type: none"> energy policies favouring energy generation from waste. limited energy efficiency of gas generation. no material recovery.

Energy extraction methods

Waste-to-Energy



Image by Ramboll

Waste-to-Energy (WtE) facilities have the primary objective of treating waste particularly with regard to sanitation, odour, avoiding spread of disease and other contamination, the secondary objective is to recover as much energy from the waste as possible.

WtE is used worldwide, Figure 5. In total around 2,000 plants are in operation in the OECD countries. In the 28 EU countries (plus Norway and Switzerland) approx. 460 WtE facilities are registered treating approx. 65 Mtpy of waste. In North America 85 WtE facilities are in operation treating approx. 16 Mtpy. Numbers refer to the listing of WtE facilities in most of the European countries and North America in (ISWA, 2012).

In South Korea 35 WtE facilities are in operation (cf. WTERT) treating around 3 million tonnes per year.

Japan has a slightly different structure with around 1,100 WtE plants in operation treating approx. 35 Mtpy which gives an average throughput of less than 30,000 tpy per plant. In Europe the average capacity is 150,000 tpy per WtE facility. Even though many WtE plants in Japan are of same size as in Europe far the most plants

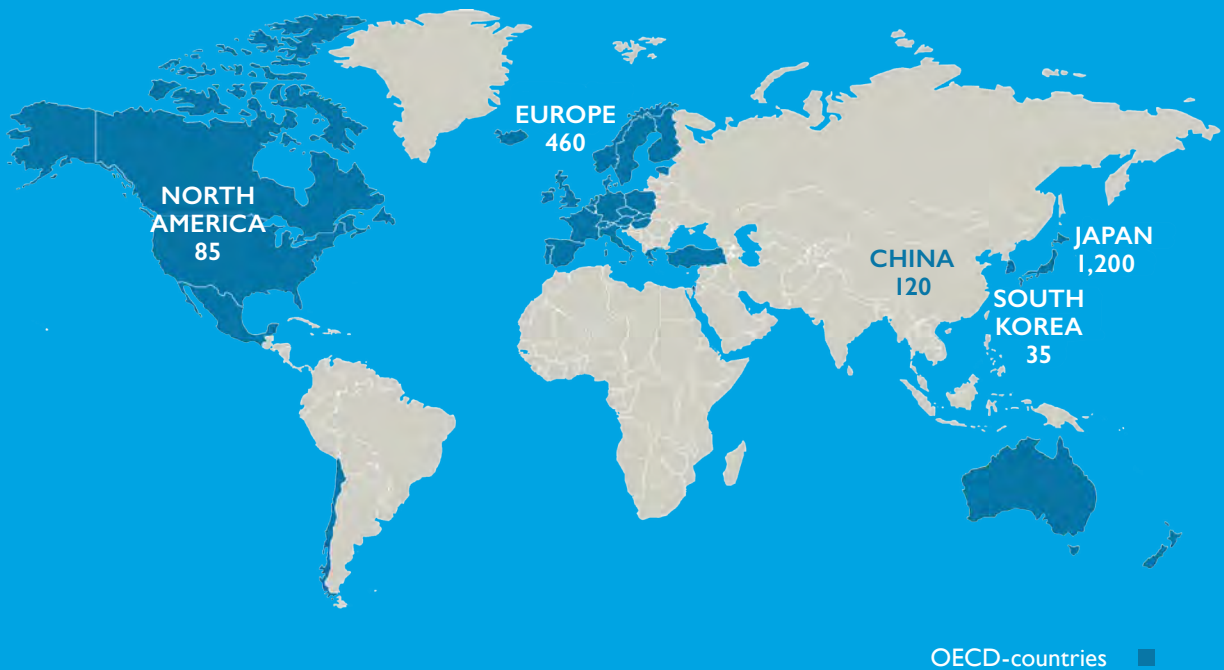
are very small. Furthermore only 26% of the Japanese facilities generate power.

WtE facilities are commercially available in different sizes ranging from typically 200 tpd up to 1,000 tpd for one WtE unit, and up to 4,000 tpd for facilities having several WtE units. With typically around 330 operational days per year the capacity can be more than 1 Mtpy for one facility.

WtE facilities are usually based on furnaces equipped with a boiler for energy recovery and a flue gas cleaning system to ensure that emission requirements are met, Figure 6. WtE plants with a capacity lower than 200 tpd are typically generating heat only as electricity production is normally not economically viable.

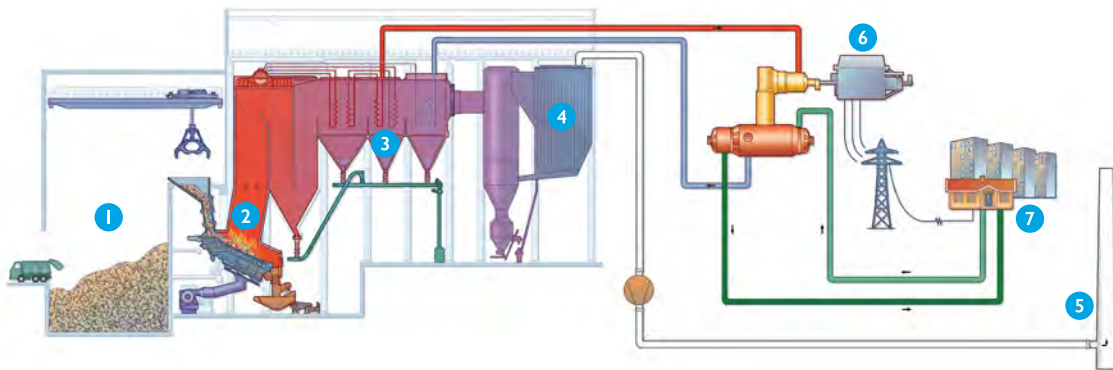
A WtE facility is specifically designed, dimensioned and operated to meet the emission requirements for a large range of waste types with their large variations in physical appearance, heating value and content of potentially polluting substances. The ability of coping with variations and the strict emission requirements are what make WtE facilities different from conventional combustors for e.g. power plants using natural gas, coal or biomass.

Fig. 5 | WtE facilities in OECD



Numbers are approximate values

Fig. 6 | Typical Waste-to-Energy facility (without flue gas condensation)



Main functions:

- | | |
|--------------------------------------|--|
| 1. Waste bunker | 4. Flue gas treatment |
| 2. Furnace | 5. Stack |
| 3. Energy recovery in a steam boiler | 6. Electricity generation in turbine/generator set |
| | 7. Heat sale by district-heating. |

In order to produce electricity the energy content of the flue gas is transferred to high pressure steam in the boiler from which is led to the steam turbine driving an electricity generator. The low pressure steam output from the turbine is condensed in an air or water cooled condenser. If there is a possibility of utilising heat from the plant the cooling water is district-heating water, which is heated in the process thereby recovering significant amounts of additional energy and boosting the total energy efficiency. The combination is termed co-generation or combined heat and power (CHP). As alternative to heat sale, some plants export steam to nearby industries.

In case of production of cooling the low pressure steam is led to an absorption chiller, which cools water running in a closed circuit.

In heat-only plants, the recovered energy in the boiler is transferred to the district-heating network. The boiler shall therefore not be designed for delivering high pressure steam, and no turbine/generator set is necessary.

Over the last decades several facilities have been equipped with further energy recovery through flue gas condensation, by which technique the heat production is boosted through recovery of the heat of condensation of the water vapour in the flue gas.

Further details on energy production from incineration of waste appear in a long range of references, e.g. CEWEP (Reiman, 2012), Eurostat, International Energy Association (IEA), (IEA, 2015) and OECD (OECD, 2013).

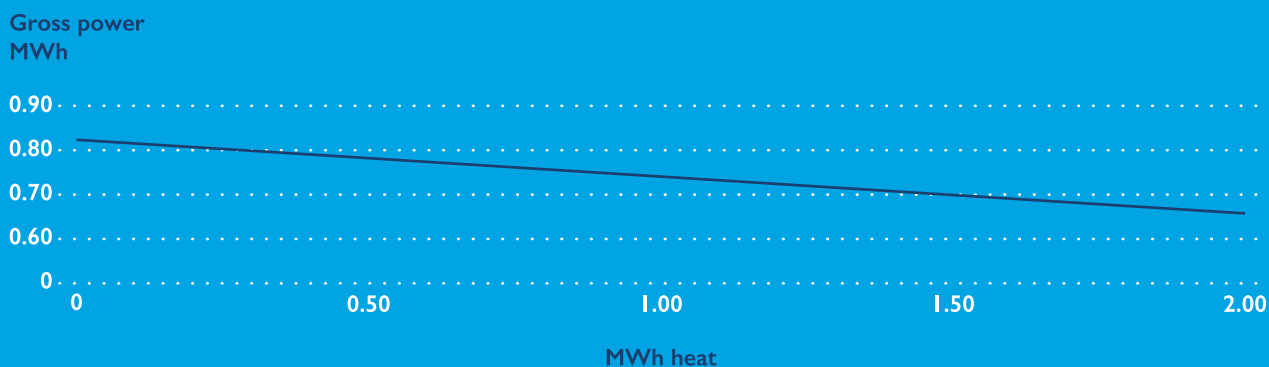
The typical net output of new WtE-facilities is 25-30% for electricity-only-plants (i.e. after subtraction of parasitic consumption).

Use of CHP will significantly increase the energy output, totalling 85% or more, and use of flue gas condensation may add more than 10% to the total efficiency. By extracting heat the electrical efficiency will slightly decrease as illustrated in Figure 7. The decrease is typically 0.05-0.2 MW electricity for 1 MW of heat, depending on turbine/condenser configuration and district-heating temperatures, among other things.

More details on efficiency can be found in Appendix.

When constructing a new WtE-facility its technology and energy optimisation is the result of financial optimisation, being based on a range of criteria, which are different from conventional energy systems, because other properties are also important, not least the ability to treat waste at almost all times through high plant availability.

Fig. 7 | **Example of relation between heat and power production from one tonne of waste in an optimised CHP-plant**



E.g. 2 MWh heat output reduces the electricity production with around 0.15 MWh

Material recovery from WtE facilities

MSW and similar waste types contain metals which can be recovered from the bottom ash. A large part of the metal content of the waste is contained in composite products where metals constitute a relatively small fraction. Such metals would to a large extent not be recoverable unless the waste component is exposed to a process that removes the matter surrounding the metal. An incineration process is well suited for the purpose and therefore provides access to a resource that is otherwise difficult to recover.

Recovery of metal from bottom ash happens through the use of sieves, magnets, Eddy Current separators, x-ray separators, induction sorting and other separators. The development is fast these years.

The recovered metal is sold for production of new metal products and thereby it replaces virgin resources, closing the cycle in the circular economy.

The recovery of metal from bottom ash will vary depending on the character of inciner-

ated waste, particularly source segregation tasks. Typical recovery of ferrous metal is around 7% and non-ferrous around 2% of the bottom ash, /Allegrini/, where the non-ferrous part carries the highest value.

The metal recovery from bottom ash may exceed 90% of its metal content if the most modern techniques are used. With approximately 200 kg boiler ash per tonne waste, and considering the potential for WtE of 430 Mtpy (cf. Figure 3), the total metal recovery potential is estimated to around 7 Mtpy of metal.

The resource value of the recovered metal is not easily quantified, but the economic value of the metals could be around 10 € per tonne of input waste, which provides short pay-back times for the investment in sorting systems. For the potential for WtE of 430 Mtpy of waste this corresponds to a potential value around 4 billion € per year.

The bottom ash itself, making up around 20% of the mass of input waste, may be used for construction purposes, particularly road construction or land reclamation. The regulations within OECD are not aligned, so large variations exist among countries. Some countries encourage the use for construction under regulations based on e.g.

leaching properties of heavy metals, and in other countries such activities are restricted, why the bottom ash is landfilled.

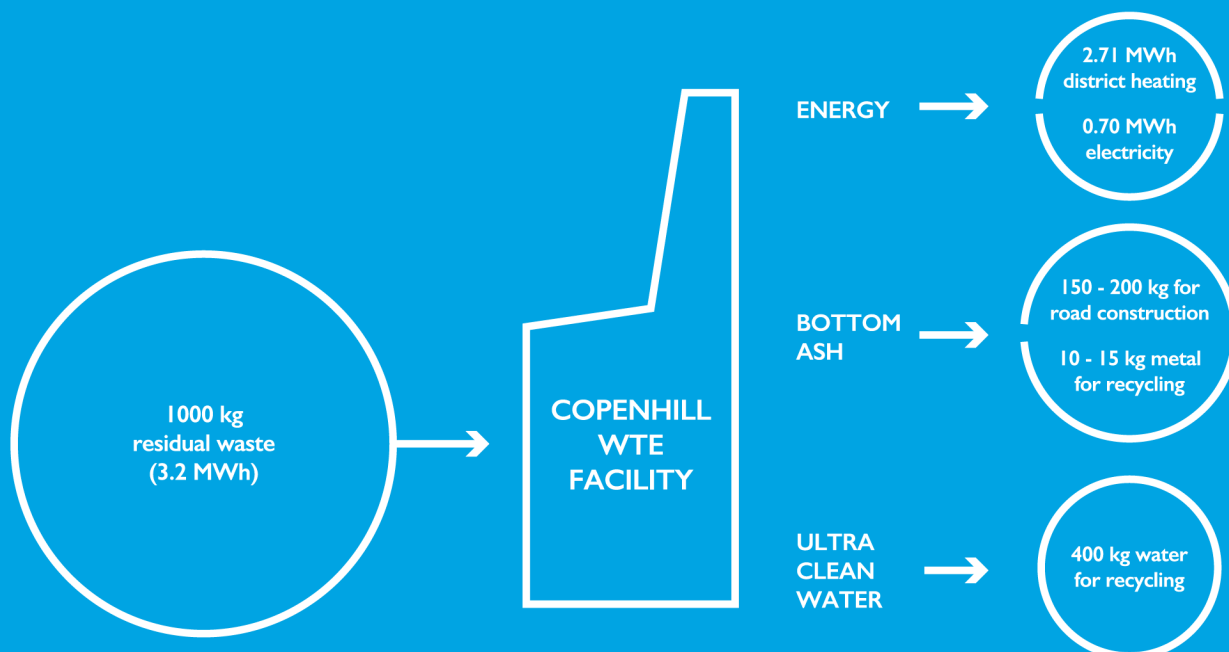
Fly ash may also be used for recovery of metals. At one plant in Switzerland high purity metallic zinc is extracted at a rate up to 1 kg per tonne of incinerated waste. (Kebag, Emmenspitzz KVA, 2015). A range of other plants wash fly ash to recover zinc-containing sludge which subsequently is sent for zinc-recovery at industrial melting facilities.

In case of flue gas condensation for recovery of heat, the water content of the flue gas is condensed, in principle as distilled water. After further purification it can be used for technical purposes, thereby replacing other water resources.

Figure 8 below illustrates the overall recovery process for a new WtE facility in Copenhagen which is under construction and planned to be in operation from 2016.

As WtE replaces fossil fuels and other materials are recovered it serves the same high level purpose as many recycling activities. It should therefore be regarded as an integrated part of the circular economy as illustrated in Figure 9.

Fig. 8 | Expected material and energy recovery in a new high-efficient WtE facility



AD of organic household waste

Anaerobic digestion may be applied to a range of organic materials which are bio-degradable by methane producing micro-organisms. Most types of organic materials will be partly bio-degradable, so that some matter is degraded and other remains in the digestate (residue/compost from the digestion process).

Source separated organic household waste contains both highly and less degradable organic matter together with some foreign matter. The pre-treatment step will remove foreign matter and other components that may impact the digestion process by causing sedimentation, flotation, blockages, increased wear and tear etc. They include materials such as plastic bags from the waste collection, packaging, bones, grit, metal pieces etc. This so called 'reject' is removed and sent to a WtE facility. Depending on collection and pre-treatment systems the reject share may be significant, i.e. 25-40%, but in source segregation from single family houses the reject share may be down to a few percent (Christensen, 2003).

The biomass is transferred to the reactor, which is heated to a temperature between 32 and 55°C. The residence time would typically be around 20 days and biogas is generated by microorganism in the reactor. The digestate is removed and often post-composted in order to mitigate odour. Dewatering after digestion is desirable for energy efficient plants because the dry solids percentage becomes low when a large share of the dry solids content is transformed into biogas.

The biogas typically contains around 55-60%(v/v) methane, 30% carbon dioxide and some nitrogen, so the generation

is best expressed by the production of methane, being the energy carrying constituent.

The methane production from organic household waste is usually estimated at around 70-90 m³/tonne, e.g. 90 m³/tonne as found in pilot scale by (Christensen, 2003). In well optimised plants, the methane yield represents approximately 50% of the energy content of the dry matter in the input biomass depending on the degradability of the constituents, residence time and other design and operational parameters.

The low methane content of biogas is a limitation for its use as alternative to natural gas in certain applications, where it would need upgrade to almost pure methane to be a substitute for natural gas. When upgraded it could for instance be used in a local industrial process, transferred to a local natural gas network or transported in high pressure containers to distribution centres for vehicle filling use, whereby it replaces transportation fuels.

It could also be used on site for production of electricity in a gas engine or for production of heat and power in which case purification is necessary but no upgrade. Other energy recovery systems producing electricity and heat could be used such as gas turbine, combined cycle systems or a steam boiler with a steam turbine.

In case the produced biogas is distributed for external use, upgrading biogas and pressurising methane come with a loss of methane and an electricity consumption, totalling around 10% of the energy content of the generated methane.



The net energy outputs of Table 2 of electricity-only facilities are of similar magnitude or lower than that of conventional Waste-to-Energy systems based on combustion of MSW or typical organic household waste, and for CHP-systems the output from biogas plants is roughly half of the WtE output. The main reason is that the digestion process leaves a carbon containing digestate, representing an energy loss. AD may, however, become energetically attractive for electricity-only plants at very low dry solids contents (below some 20-25%) as the efficiency of conventional WtE systems (without flue gas condensation) drops the wetter the waste.

Other activities in the chain from collection to electricity generation will affect the total efficiency of AD-systems. This includes the energy impact of source separation, including packaging in the kitchen, and activities related to separate collection of organic waste which are not considered in this report.

Resource recovery in AD apart from energy refers mainly to the content of fibrous carbon and nutrients in the digestate, particularly nitrogen, phosphorous

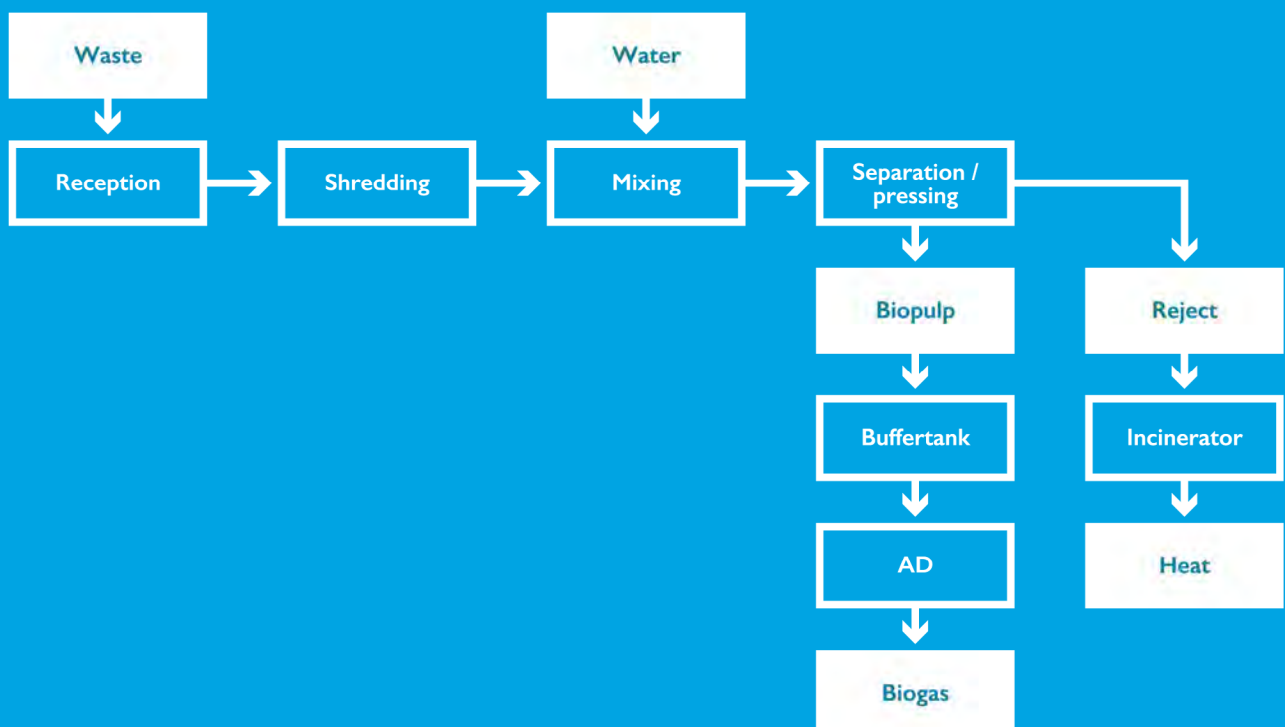
and potassium, being useful for soil improvement and fertilizer. The nitrogen content of the feedstock amounts to around 8 kg per tonne (at around 30 % dry solids content), being valuable because production of nitrogen fertilizer requires energy. The energy requirement for production of the same amount of nitrogen fertilizer corresponds to 4% of the energy content of the organic waste, which comes in addition to energy balance of Table 2. Phosphorous is considered a critical resource and therefore of particular interest for recovery. The content of phosphorous in organic household waste is typically around 1.2 kg per tonne, (Christensen, 2003).

If the organic household waste is collected at 40 kg per capita per year (cf. section 3.2) the phosphorous in the waste amounts to around 50 g per person per year which is made available for use on farmland to replace fertilizer. With around 1,250 million inhabitants in the OECD countries it makes up around 60.000 tpy phosphorous. Its resource value is not easily quantified, but reference to the economic value could provide an indication. The economic value lies around 0.1 € per capita per year

with the current phosphorous pricing or around 100 million € per year for OECD. Its importance shall be seen in a geopolitical and the long perspective as the access to phosphorous resources may be challenged with phosphorous mining being confined in limited geographical areas, which in turn has potential consequences for phosphorous pricing.

There is more on nutrients and carbon in the report on Carbon, Nutrients and Soil.

Fig. 10 | Main processes in a typical digestion facility for organic household waste



Tab. 2 | **Energy efficiency of anaerobic digestion of organic household waste, 3 cases**

PARAMETER	METHANE OUTPUT	ELECTRICITY OUTPUT, ONLY	ELECTRICITY AND HEAT OUTPUT
Methane output	50%	50%	50%
Upgrading and pressurising	-5%	0%	0%
Electricity consumption (parasitic)	-2%	-2%	-2%
Heat consumption for reactor heating	-2%	0%	-2%
Gas engine electricity output, gross production		20%	20%
Heat output		0%	25%
Total net energy (without regard to the form of energy)	41%	18%	41%

Typical output from an energy optimised system in % of the energy content in input waste represented by net calorific value of dry matter

Landfill gas extraction and use

Landfill gas is generated by microorganisms as it occurs in the AD-plants. Gas generation starts shortly after the waste is landfilled and ingress of oxygen is prevented by overlying waste, promoting the development of anaerobic microorganisms. Like the biogas from AD-plants the energy carrying constituent of LFG is methane which occurs at typically around 50%, but the gas composition from the individual landfill cell varies over time, (Christensen, 2011).

The remaining gas is mostly carbon dioxide and some nitrogen, but the gas can also include small amounts of hydrogen and hazardous substances such as hydrogen sulphide, vinyl chloride, ethyl benzene, toluene, and benzene, (Christensen, 2011), (USEPA, 2003).

The landfills must be designed and operated particularly for gas recovery, otherwise the generated gas will diffuse to the atmosphere through the deposited waste or through the surrounding soil, if

the landfill is not equipped with gas tight bottom liner. Therefore the gas collection efficiency is usually low for non-sanitary landfills common in developing countries.

Gas extraction is done through a large number of wells with gas collection pipes throughout the landfill. Also horizontal collection systems may be used in the early stages during filling. The landfill is closed with a cover that shall have low permeability towards escape of LFG, but still allows infiltration of moisture, that is necessary for gas generation (Willumsen, 2011). For optimum gas yield, to ensure waste decay and to limit the emissions of methane the landfill should be designed, surveyed and operated like a process system, and there are in fact particular reactor landfill designs e.g. as described in (Christensen, 2011).

Gas extraction may be assisted by suction providing a negative pressure in the gas collection pipes in a balanced way to prevent that the negative pressure causes ingress of air.

Gas generation rates depend on the content and nature of landfilled biogenic materials, the temperature and the moisture

content among other things. Modelling of the generation rates from mixed MSW can therefore only be done with large uncertainty, and in turn this also applies to the gas collection efficiency, because the base-line is unknown. Some waste fractions such as food waste have high decay rates whereas others such as wood has low decay rate. The food waste also has high gas production potential, one reason why the gas release is typically peaking in the early stages of a landfill life.

Collection of generated LFG depends on the permeability of cover and bottom liner and the gas extraction system. As an efficient cover and extraction system cannot be in place during filling, the collection efficiency is generally low in the initial stages of a landfill, where the gas generation rate is usually high (Steger, 2013).

Also after several decades it a challenge to collect and utilise the gas because both the production rate and percentage of methane drop.

Alternative forms of energy and developments

There are alternative forms of energy and fuels from waste including for instance gas from gasification/pyrolysis (carbon monoxide and hydrogen, particularly), hydrogen from biological processes or electrolysis, ethanol from biogenic wastes and oil from plastic.

Biological processes are under development and few are used with household waste as base energy source. They will resemble AD to a large extent in terms of energy efficiency, why reference is made to Table 2. Liquid outputs such as ethanol will however, have a higher potential for use as transportation fuel because they are less demanding to store and transport than gas.

Electrolysis has as a starting point the drawback of transforming high value electricity to lower value fuels, cf. Figure 11. Electrolysis may, however, be relevant where abundant amounts of low value electricity are available, e.g. from hydropower in remote areas from which high voltage cabling to sufficient number of consumers is not feasible, and in peaks where excess wind turbine capacity is installed.

Only gasification is used in at any significant scale at present, why main focus is on thermal gasification. Gasification is a process by which a syngas is produced by heating a fuel and making it react with air or steam. The generated syngas mostly consists of carbon monoxide and hydrogen, but the process also generates tar and unwanted gases like hydrochloric acid and hydrogen sulphide, why gas treatment is necessary.

Thermal gasification is often discussed for energy recovery from waste because gas could in principle be distributed, stored and used in plants with high efficiency. While thermal gasification has been operated over many years on homogeneous fuels such as coal or wood chips, gasification of a heterogeneous material such as MSW has proven difficult particularly because of its heterogeneous nature when it comes to physical appearance and chemical composition.

Around 10% of the total waste generation in Japan, or 3.6 Mtpy, is treated by thermal gasification, pyrolysis or plasma gasification. Around 110 plants with an average capacity around 100 tpd are in



Image by Valorsul

operation using gasification or other thermal conversion technologies. The energy efficiency is usually modest (several below 5%) because of high own consumption for pre-treatment and heating the reactor and relatively large losses, e.g. for quenching of the crude gasification gas. The feedstock is in some cases RDF from source separated waste e.g. plastic and industrial waste which in other countries would be recycled. This makes the Japanese experience difficult to transfer to countries with another waste management structure and high value of generated energy.

Some gasification facilities for MSW have been built in Europe, but these all appear to have been closed down. On top of technical difficulties, one reason is the energy efficiency which has proven low or very low compared to conventional WtE systems, mostly because of high consumption for pre-treatment of waste, energy consumption for heating the waste, loss by cooling the syngas and energy for production of oxygen, if required. The potentially high efficiency of the gas usage has not proven to outweigh the parasitic consumptions of the gasification process to a sufficient extent. A technology screening revealed that the net electricity output for electricity-only plants is listed in the range 13-24%, which for the highest percentages does not include pre-treatment of waste (Fichtner, 2004). The reports summarised that 'In terms of energy efficiency of standalone plants when optimised for power generation, existing gasification and pyrolysis technologies are less efficient than modern combustion technology.'

ISWA has published a report describing alternative thermal conversion technologies, (ISWA, 2013a). Even though alternative thermal technologies provide inter-

esting perspective the report concludes that the quantity of readily available objective information about the performance of alternative thermal waste treatment technologies is limited, and it is found that the generated syngas in most cases is treated downstream by combustion and hereby the technology is rather staged combustion than gasification. ISWA's report is in line with the conclusions stated in SWANA's (the Solid Waste Association of North America) report on gasification, (SWANA, 2011):

- gasification is unproven on a commercial scale for MSW;
- gasification of MSW to produce electricity is technologically viable, however, MSW gasification is not a mature technology, and therefore, some risk mitigation strategies would need to be developed to limit risk; and
- process and equipment scale-up is needed to demonstrate reliable systems and define economics. Commercial applications on MSW will be very challenging and involves high costs.

Alternative thermal treatment technologies are mainly to be considered for specific waste streams and primarily if syngas can be used for upgrading to hydrogen for use in industrial processes or to ethanol or similar fuels. However, no reports are found of plants upgrading syngas from waste at commercial scale.

In conclusion the alternative recovery methods for energy and fuels production are not currently used to an appreciable extent, and for the reasons above they are not foreseen to play a significant role for treatment of MSW over the investigated time frame.

Yields of energy and fuels

Energy is a corner stone in modern society and is used for many purposes like heating, cooling, transport, industrial processes, lighting, running electrical equipment and electronics etc.

The energy needs of the society are covered by a range of different sources e.g. natural gas, gasoline/diesel, wind, sun, nuclear processes, hydropower, coal, wood and waste. The energy forms are not particularly comparable in terms of quality, but they can all be characterised by the energy content in kWh, GJ, Btu or similar. Some forms of energy can be converted into others – with a certain efficiency and loss. For instance coal is used to generate electricity with an efficiency of 30-50%.

It is therefore important to understand the main differences in quality and value as illustrated below.

Electricity is the highest ranking form of energy because it can be used to deliver mechanical work through an electric motor with virtually no loss. Electricity is the only form of energy that is multi-purpose and is used for many applications, e.g. electronics and household appliances.

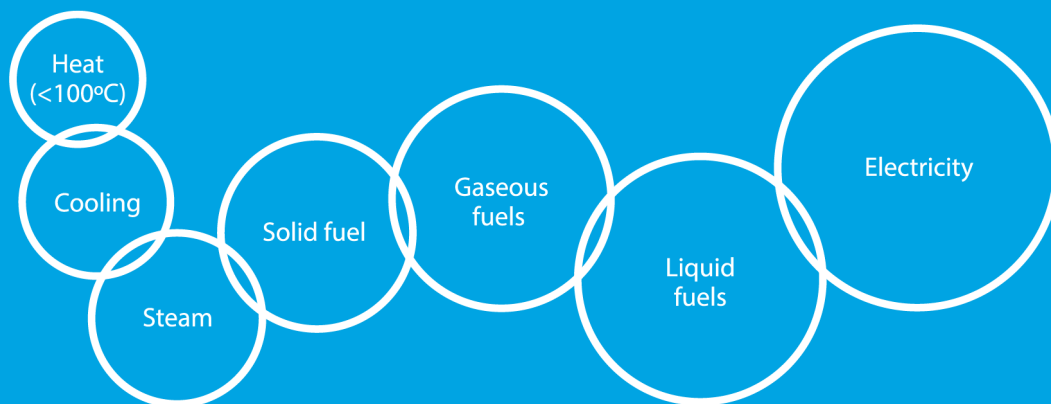
Electricity has the advantage of being easy to transport over long distances in high voltage power cables, but has the disadvantage of being difficult to store.

Heat is the lowest ranking form of energy because it possesses little potential for generating work, and heating of buildings is the predominant use. Heat in the shape of hot water has the advantage of being easy to store. The disadvantage is that sale of heat requires a heat demand, primarily governed by local climatic conditions, and a district-heating network to reach the consumers. Cooling is equivalent to heat having little capability of transforming to other energy forms, but its generation comes with slightly higher consumption of primary energy, and it is therefore valued higher.

Methane, being the energy carrying constituent of biogas, is an intermediate form of energy. Natural gas contains around 90% methane and biogas typically in the range 50-60%. Methane is not used to generate mechanical work directly, but has to be combusted in e.g. a gas turbine, engine or boiler to generate work or electricity. The conversion to electricity typically has an efficiency around 35-40% when used lo-

cally, and could be higher if used in large scale combined cycle systems. Methane may also be used as raw material in the process industry, e.g. for generating liquid fuels. Methane has the advantage of being relatively easy to transport in pipes and store in enclosed underground caverns made for the purpose, but a gas network is necessary to reach most customers. The gas infrastructure could also include tanker ships, lorries and a local gas station for vehicle use. In any case upgrading and pressurising (or liquefying) to natural gas quality requires energy, representing a parasitic consumption. The energy outputs of different usages are listed in Table 2.

Fig. 11 | Valuing energy and fuels



Indicative value from its ability to generate work (or high temperature), ease of transport and use in energy systems.

Electricity and heat

There are alternative forms of energy and fuels from waste including for instance gas from gasification/pyrolysis (carbon monoxide and hydrogen, particularly), hydrogen from biological processes or electrolysis, ethanol from biogenic wastes and oil from plastic.

Biological processes are under development and few are used with household waste as base energy source. They will resemble AD to a large extent in terms of energy efficiency, why reference is made to Table 2. Liquid outputs such as ethanol will however, have a higher potential for use as transportation fuel because they are less demanding to store and transport than gas.

Electrolysis has as a starting point the drawback of transforming high value electricity to lower value fuels, cf. Figure 11. Electrolysis may, however, be relevant where abundant amounts of low value electricity are available, e.g. from hydropower.

The share of waste is 1.2% of the total energy production of electricity and heat as illustrated in Figure 12, generated in more than 1000 WtE facilities. The WtE share of electricity production is 0.7%, and its share of heat production is around 8%. The figures are listed in Table 3.

Although the waste's contribution to the energy supply comes in small percentages, the energy production is still significant and its share is comparable in magnitude to solar photo voltaic - energy (from PV solar cells) and more than a third of the generation from conventional biofuels. The total energy input by waste corresponds for instance to around 130 Mtpy of wood chips, equivalent to the annual growth of a forest of the size of Great Britain.

It appears that more than 60% of the electricity is produced from fossil fuels, i.e. coal, oil and gas. The fossil fuels are currently so dominating that it is unlikely that they will be phased out over the considered time span of around 30 years. Minimising the use of fossil fuels therefore requires extensive optimisation of all other production sources, including waste. The contribution from Waste-to-Energy is important because the alternative energy source to waste would in most cases be fossil.

The OECD numbers indicate an electricity generation efficiency of 16% in average for MSW and industrial waste, and the heat sale is of similar magnitude, calculated from data in Table 3. As it appears from Appendix that new facilities are built with

higher efficiency, providing more electricity (and heat) than hitherto from a similar resource. Gradually the average electrical efficiency will increase over the considered time of around 30 years from 16% to 25-30%.

By increased efficiency and by using the full potential for WtE the contribution from waste will increase from 0.7% to around 3% of the current electricity production.

The potential electricity generation would thus be around 300 TWh per year, if the full waste potential of 430 Mtpy is used in modern WtE facilities with improved efficiency, Figure 3.

The use of waste for heat production already constitutes a significant share of 8% in OECD although only a minor part of the heat potential from WtE is currently used for heat sale, cf. Table 3.

The potential energy recovered by WtE is depending on the caloric value of waste as illustrated in Figure 13.

Tab. 3 | Energy production from waste in OECD, annual basis, 2012

ENERGY	MSW TWh	INDUSTRIAL WASTE TWh	SUM TWh	SHARE OF TOTAL PRODUCTION %
Electricity	61.4	13.4	74.8	0.7
Heat	60.2	10.2	70.4	8.1
Energy input by waste	319	148	467	-

1 TWh = 1000 GWh = 3600 TJ

Fig. 12 | Energy production

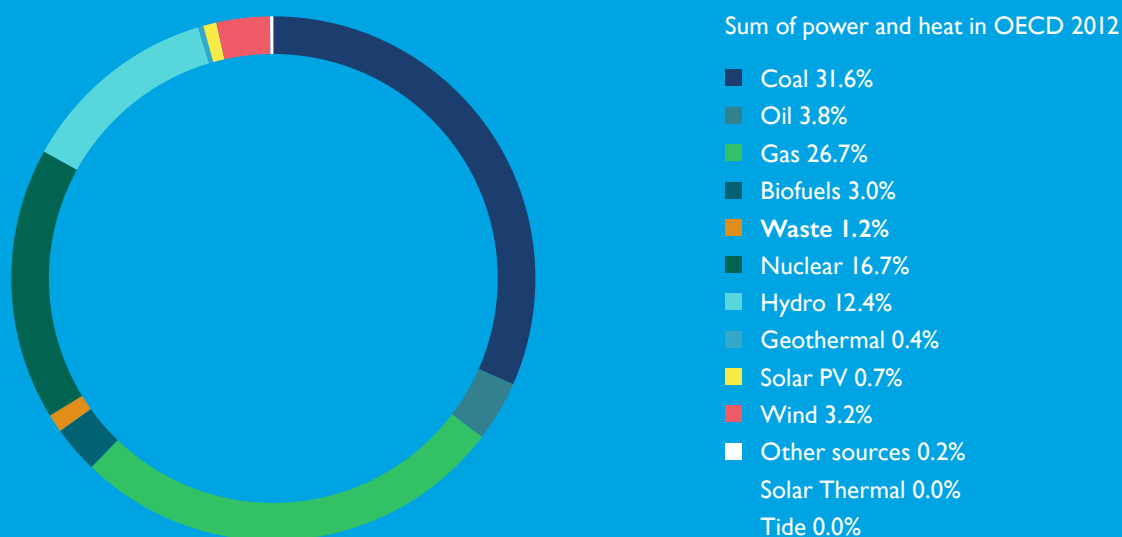
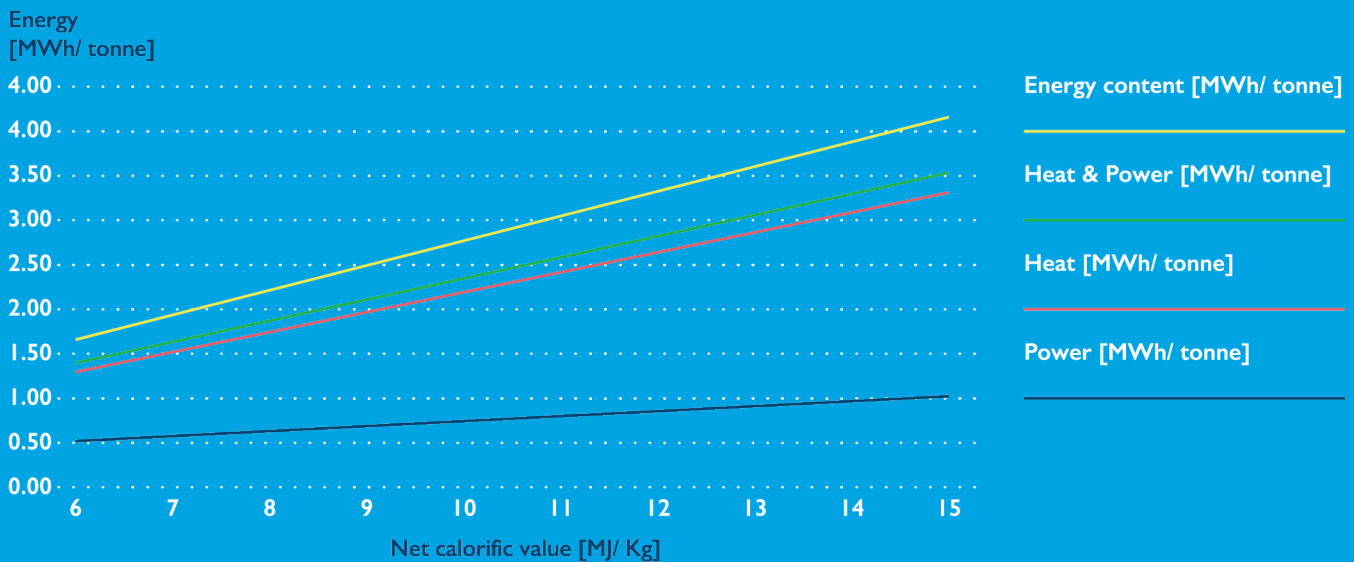
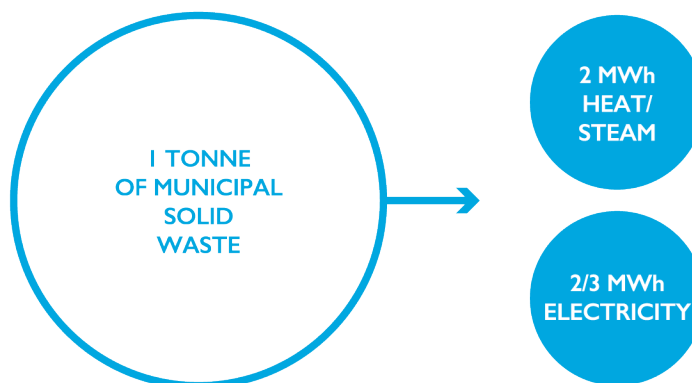


Fig. 13 | **Energy content and energy output depending on calorific value**



Source: ISWA, 2013

Fig. 14 | **Typical energy output from CHP-facility with input of MSW at 10 MJ/kg (2.8 MWh/tonne) net calorific value**



Typical energy output from CHP-facility with input of MSW at 10 MJ/kg (2.8 MWh/tonne) net calorific value. The heat generation of flue gas condensation is not included. Steam may be transformed to heat with insignificant loss. With no steam output, the electricity production would increase.

Natural gas and biogas

For a MSW with a typical net calorific value around 10 MJ/kg the generation of electricity from 1 tonne of waste is around 0.7 MWh and a potential heat production around 2 MWh and up to 2.5 MWh if flue gas condensation is installed.

Sale of heat requires presence of a local market for heat, which is governed by the local climatic conditions and the existence of a district-heating network. Where there is a heat demand use of combined heat and power (CHP) may increase the production by a factor 4, or even factor 5 by use of flue gas condensation (cf. Appendix) compared with power, only. It should be borne in mind that the current use of district-heating is small, and for instance only constitutes 13% of the market of supplying buildings and industry with heat in the European Union, EU27, (Connolly, 2013). The same study finds it realistic to increase the share of district-heating to 50% by 2050, thereby reducing the dependency of fossil fuels and the carbon dioxide contribution of the heat supply of buildings and industry, because fossil fuels are currently the predominant energy sources for heat.

The heat from WtE can be a significant contributor to the increased district-heating sale, if the waste potential of 430 Mtpy is used, cf. section 3.1. The

heat sale from WtE has the potential of increasing from the current level of 70 TWh (cf. Table 3) to 400 TWh per year provided the use of district-heating is increased so that 40% of the heat potential is sold, where the increase in turn could save the equivalent of around 30 billion m³ of natural gas.

Similarly to heat, sale of cooling requires a market for cooling and a district-cooling network. Such networks are not as widespread as district-heating, but the potential remains large. District-heating networks may also be used as energy supply for generating cooling at local cooling installations.

The low pressure steam remaining from the turbine can also be used for industrial purposes or desalination where sea water is made into fresh water. Such usage is depending on the possibilities locally.

The total annual consumption of natural gas in OECD countries represents an energy content of around 16,000 TWh (OECD, 2015).

As mentioned previously biogas may be used locally for electricity generation, upgraded to natural gas quality as for transfer to central power plants through existing gas networks or used as substitute for transport fuel.

When it is assumed that all of the estimated potential of 50 Mtpy of food waste per year (cf. section 3.2) could be made available for generation of methane at 80 m³ methane per tonne, it would represent an energy content in methane of around 40 TWh per year, corresponding to almost 4 billion m³ natural gas per year (methane has almost the same energy content as natural gas per m³).

The potential from household biological waste is therefore estimated as 0.3% of the current natural gas consumption.

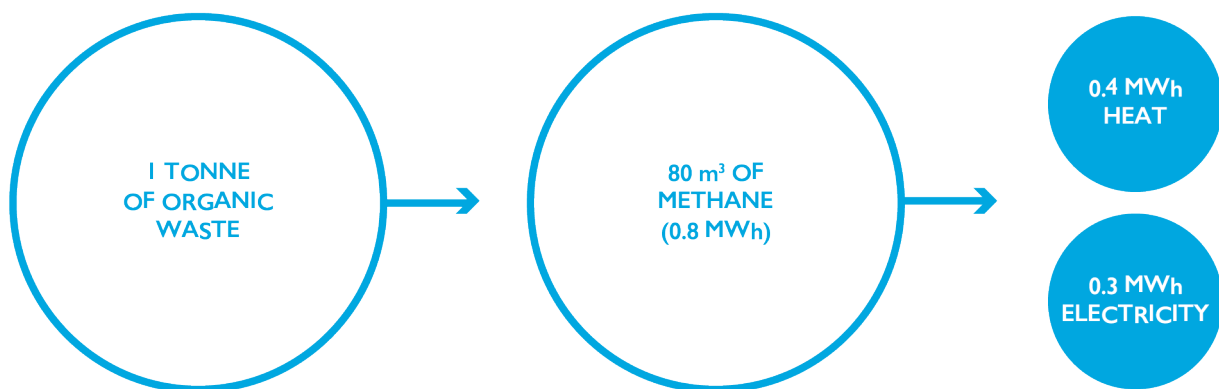
Al together the methane production from municipal wastes could fit into the current natural gas system, and thereby contribute to saving fossil fuel. It may play a role locally, particularly with other biogas sources (such as manure and sewage sludge).

Tab. 4 | Methane production potential from waste in OECD, 2012

ENERGY	METHANE ENERGY, TWh/ YEAR	PERCENTAGE OF NATURAL GAS CONSUMPTION
Food waste from households	40	0.3%
Natural gas, OECD total	16,000	100%



Fig. 15 | Typical energy output from an optimised biogas facility for organic household waste



Typical energy output from an optimised biogas facility for organic household waste with input at 30% dry solids content corresponding to a dry matter energy content of 6 MJ/kg (1.7 MWh/tonne) low calorific value.

Landfill gas

No collection of data have been found on the current generation, collection and use of landfill gas (LFG) at OECD level. The order of magnitude could be roughly estimated by combining landfilled amounts with estimated gas generation per tonne and gas collection efficiency. As mentioned in section 4.4 there is large uncertainty in estimating the gas generation rates and collection efficiency not least because gas generation happens over many decades. The average generation is assumed from an experience of ultimate gas generation at 60 m³ methane per tonne wet MSW (total accumulated potential over time (Barlaz, 2010) The experience of 60 m³ per tonne seems to deviate from the standard figure used of 100 m³ per tonne (Willumsen, 2011). The difference may be caused by incomplete decay of biogenic matter even over long time.

For the rough assessment an average gas current collection efficiency of 30% of landfills is assumed. Although many land-

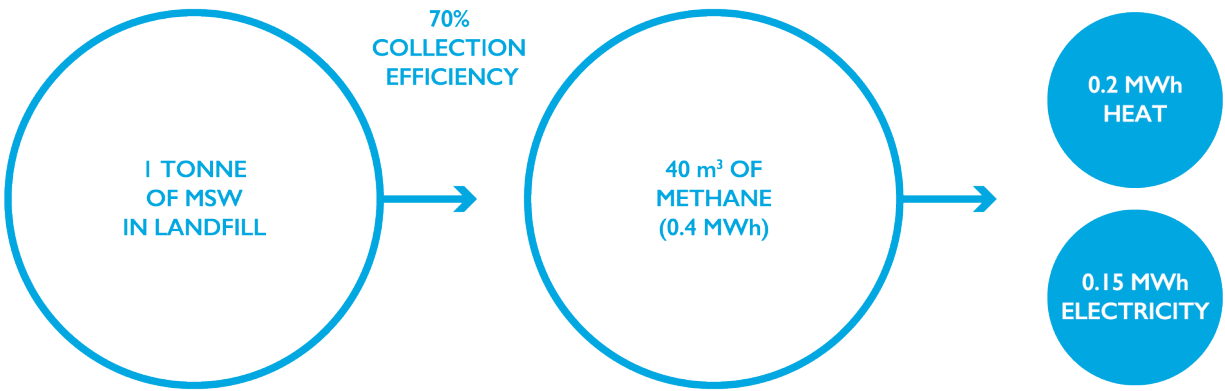
fills are equipped with efficient gas collection, the majority of landfills would have none or inefficient gas collection. The total current LFG recovery from 300 Mtpy MSW landfilled in OECD is thus roughly estimated as around $300 \times 60 \times 30\% \times 0.001 = 5$ billion m³ of methane per year equivalent to an energy content of 50 TWh per year. Used in electricity-only engines or similar the gross electricity production would be around 20 TWh per year. This rough estimate does not include the contribution of landfilled industrial waste and other waste types than MSW. The gas generation from these sources will depend on an assessment of the biodegradable content, background data of which have not been available.

The majority of the recovered LFG is used for electricity production in reciprocating engines, gas turbines or boilers with steam turbines as judged from the US LMOP database summarising more than 600 LFG recovery projects in the USA (US EPA, 2015). Occasionally LFG is

used for combined heat and power, heat only or process energy, and there are several projects with upgrade to natural gas quality (including liquefied gas) for vehicle used or other purposes.

There are efforts for increasing the LFG collection efficiency driven not only by the energy yield but also by intentions of reducing the emissions of hazardous air pollutants and methane, being a powerful greenhouse gas. There is little evidence on achievable collection efficiencies. Modelling of optimised gas recovery system find that up to around 80% recovery would be realistic (Stege, 2013), and new large scale landfills may designed and operated to achieve such collection efficiencies. Over the considered time frame of 30 years there will still be a large number of existing landfills with low collection efficiency considering that landfills generate gas over many decades. For this reason an average collection efficiency of 70% is assumed for the projections of potentials below and in Figure 16.

Fig. 16 | **Rough indication of energy output from a landfill of mixed MSW**



Rough indication of energy output from a landfill of mixed MSW from which the LFG is used in a CHP-plant.

Climate effects of energy forms

With 70% collection efficiency, the LFG potential could be estimated as 130 TWh per year assuming unchanged landfilling of 300 Mtpy, and assuming that the composition of landfilled MSW does not change significantly. This corresponds to the equivalent of roughly 12 billion m³ of natural gas.

The gas energy yield would drop over the considered time frame of 30 years to around 20 m³ methane per tonne MSW or around 20 TWh per year in case the average percentage of biogenic matter is halved, landfilling of MSW is reduced to 100 Mtpy, and the average gas collection efficiency is increased to 70%. This is equivalent to around 2 billion m³ natural gas per year.

No collection of data have been found on the current generation, collection and use of landfill gas (LFG) at OECD level. The order of magnitude could be roughly estimated by combining landfilled amounts with estimated gas generation per tonne and gas collection efficiency. As mentioned in section 4.4 there is large uncertainty in estimating the gas generation rates and collection efficiency not least because gas generation happens over many decades. The average generation is assumed from an experience of ultimate gas generation at 60 m³ methane per tonne wet MSW (total accumulated potential over time (Barlaz, 2010)). The experience of 60 m³ per tonne seems to deviate from the standard figure used of 100 m³ per tonne (Willumsen, 2011). The difference may be caused by incomplete decay of biogenic matter even over long time.

For the rough assessment an average gas current collection efficiency of 30% of landfills is assumed. Although many landEnergy and fuels recovered from waste will replace other primary energy resources, of which a large part is fossil, and therefore the energy from waste will generally be associated with reduction of CO₂-emissions.

The CO₂-reduction will depend on the local energy system, that the energy is delivered to, i.e. which primary energy resources are replaced and which share fossil fuel makes up of the replaced primary energy. With the current use of more than 60% fossil fuel in the total energy system in the OECD countries the vast majority of energy from waste will replace fossil fuels.

This may be explained because the fossil share is so high that it is unrealistic to completely phase out fossil fuels over the considered time frame. The reduction primarily comes from increased use of alternatives (hydro, nuclear, bio mass, wind, tide, solar), but expansion in these is limited for technical, environmental or economic reasons. Any increase in energy recovery from waste will therefore most likely be a significant contributor in replacing fossil fuels.

Any energy form, electricity, heat, cooling or gas will have a CO₂-reduction potential, but there will be differences between the energy forms. Electricity production will have high potential because a large part of the electricity is generated from fossil fuels, and for reasons governed by physical laws electricity is produced with limited efficiency from fossil fuels causing relatively high CO₂-emission when measured in kg per MWh electricity.

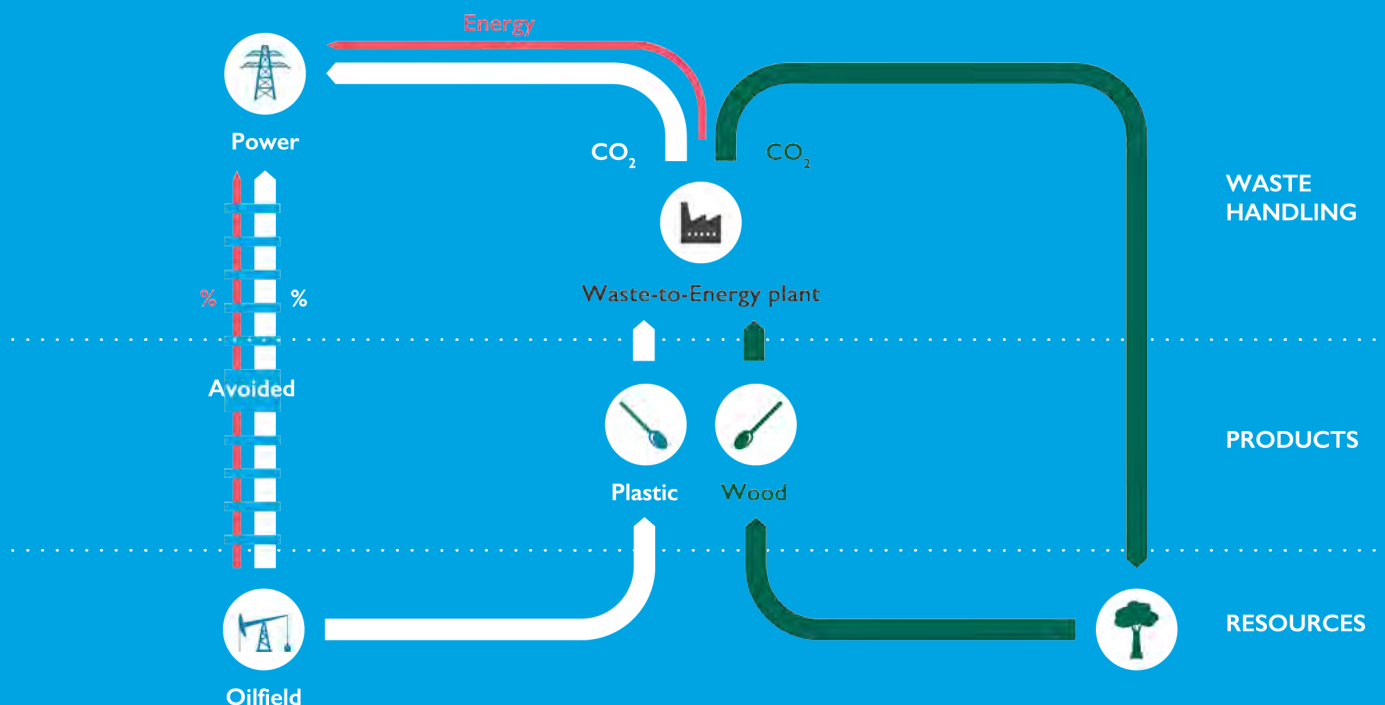
Specific for WtE, by increased implementation of WtE facilities in the OECD countries from currently 200 Mtpy to the estimated 430 Mtpy the CO₂-reduction potential is significant.

Plastic in waste for energy production is usually ascribed a certain CO₂-emission in the CO₂-accounting system because plastic typically originates from oil and natural gas and, hence, of fossil origin. This affects the CO₂-balance of energy recovery, and the CO₂-emission must be distributed between a fossil part, which is counted, and a biogenic part, which is not counted as emission.



Image by Kjeld Madsen - Dragør Luftfoto

Fig. 17 | Circular systems for biogenic and non-biogenic materials



The spoon represents a constituent of the waste stream and it is made of either wood or plastic. In both cases, electrical power is the output of the WtE facility, thereby replacing the same amount of power produced by other power plants. In turn, oil or other fossil fuels is saved because the vast majority of marginal power production is of fossil origin. If the spoon is made of wood the CO₂-emission is considered neutral as it is part of the biogenic circle. In case it is of plastic the emitted CO₂ replaces CO₂ emitted from power generation using fossil fuels.

To illustrate the order of magnitude of CO₂ reduction by increased implementation of high efficient WtE facilities with power production and hereby substitution of fossil fuel and avoidance of landfilling, a simple environmental balance can be setup as illustrated below, Figure 18.

As Figure 18 shows, incineration of one tonne of waste ultimately saves emissions of 100 kg of CO₂ per tonne of waste when comparing with natural gas.

Implementing WtE facilities incinerating additional 225 Mtpy (430-205 Mtpy) of waste, amounts to significant CO₂ savings as shown on the right.

The calculation above is based on offsetting natural gas. If the calculation is done by offsetting coal the CO₂ saving would be around 3 times higher because coal has higher CO₂-emission per MWh electricity output than natural gas as illustrated Figure 19.

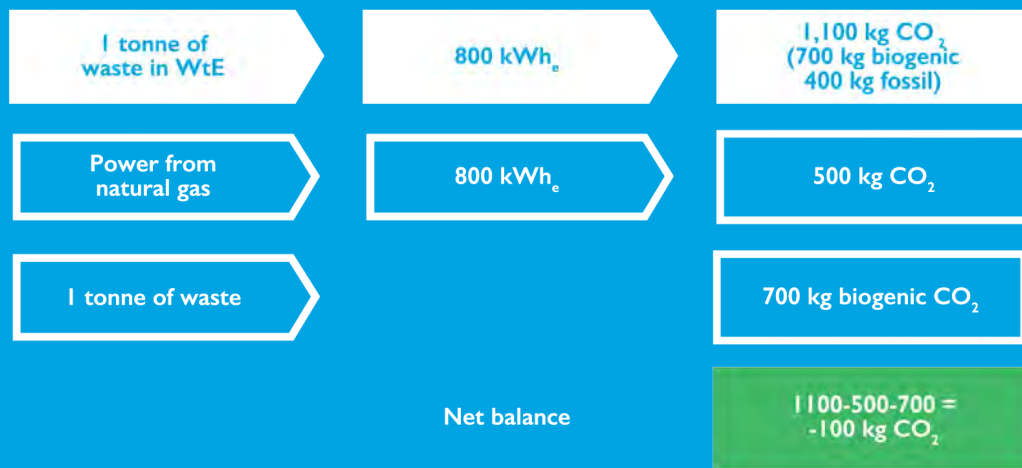
In anaerobic digestion of waste the generated methane can replace the same amount of natural gas or another fossil fuel and thereby the associated CO₂-emissions, because the CO₂ from conversion of biogenic matter is not considered as CO₂-emission. The multiple uses of methane allows for seeking the best opportunities locally. It will have high CO₂-reduction potential when it replaces natural gas, replaces petrol as transport fuel or when it is used to produce electricity (and heat). While the CO₂-reduction potential will depend on local opportunities, it will often be higher for natural gas replacement or transport usage than for electricity because natural gas and petrol in themselves are fossil, and electricity may only partly be of fossil origin. With 50 Mtpy of organic household waste potential, the methane generation is estimated at around 4 billion m³ per year, and the CO₂-offset is estimated to 8 Mtpy, assuming natural gas is replaced. This corresponds to replacing

the emission from driving some 70 billion kilometers per year in passenger cars.

It should be borne in mind that methane in itself is a powerful climate gas, 34 times more powerful than CO₂ (on mass basis on 100 years' time scale) (Myhre, 2013). Any leak will significantly affect the balance of climate gases, and the escape of 1% of the generated methane takes more than 10% of the CO₂-offset potential. Therefore care is taken to minimize emission of unburnt methane during its production and use, ranging from selection of process combination in planning to the daily maintenance at the biogas plants. For instance the use of biogas in gas engines is associated with emission of unburnt methane (typically around 2% of the input). Care should be taken to avoid diffuse emission of methane because biogas systems must be kept at positive pressure to prevent ingress of oxygen, but the positive pressure will cause emission of methane from any minor leak.

Fig. 18

Simple CO₂ balance for handling of one tonne of waste and generation of 0.8 MWh of electricity in electricity-only plants in two alternative systems



The WtE plant treats 1 tonne of waste, generates 800 kWh of electricity and emits 1,100 kg CO₂. The alternative system also produces 800 kWh electricity but by use of natural gas, causing emission of 500 kg CO₂ and the waste is landfilled causing emission of 700 kg biogenic CO₂. Any emission of methane (being a strong greenhouse gas) from landfilling has not been considered in the CO₂-balance.

- 100 Kg CO₂
per tonne waste

X

225,000,000
tonnes per year

=

- 22,500,000 CO₂
per year

CO₂ saving by additional WtE potential equivalent the emission from 10 billion m³ of natural gas per year or the emission from driving 180 billion kilometers per year in passenger cars, based on 123.4 g/km for passenger cars in 2014 (European Commission, 2015)

The use of digestate from the AD-process as soil improver/fertilizer is often considered a carbon sink because the carbon content of digestate is deposited in the soil and only slowly released as CO₂. The immediate carbon sink is around 70 kg per tonne of organic household waste, amounting to 3.5 Mtpy carbon assuming 50 Mtpy of waste, but this is counteracted by the gradual release of CO₂ and the generation of the powerful greenhouse gas, nitrous oxide, by the biological processes in the soil.

One of the major challenges of landfills from a climate gas perspective is the emission of methane. On a global scale IPCC (Fischedick M., 2014) has estimated that more than 600 Mtpy of CO₂ equivalents is emitted as methane from landfilled solid waste, which is remarkable compared to the savings estimated for the use of energy from WtE and AD. Although only a certain fraction of this originates from OECD (no OECD-data on methane emissions from landfills were available), it is clear that diversion of biodegradable waste from landfills to energy recovery or recycling will have a noticeable positive climate effect solely from the reduction of methane emissions from

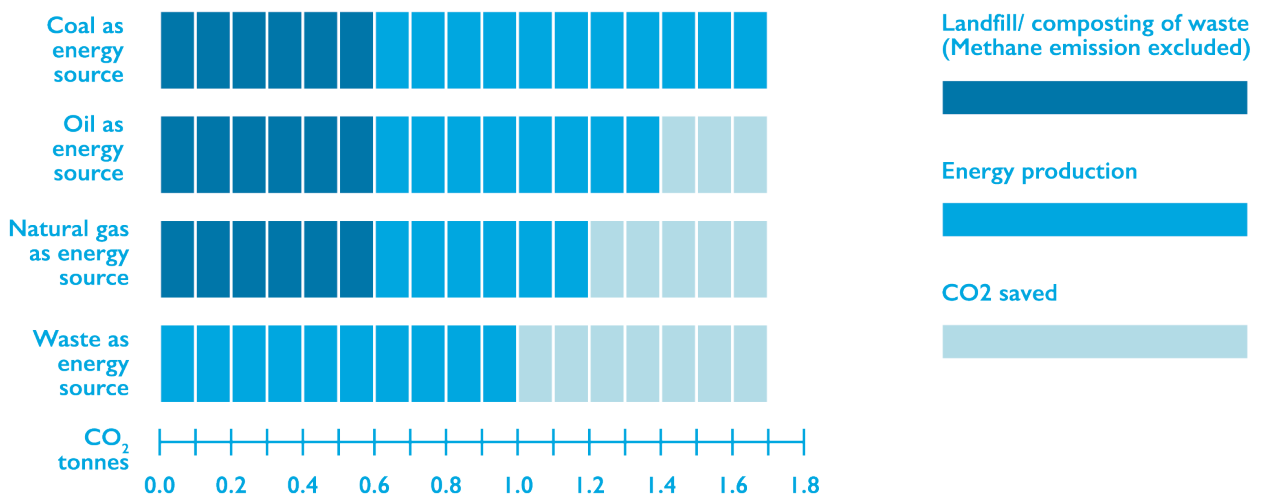
landfills as it is pointed out in (ISWA, 2009).

Improving the collection efficiency of LFG will also reduce the emission of methane and increase the replacement of fossil fuels through the use of the LFG. However, the LFG collection efficiency shall exceed 90% to make the LFG generation and use have a positive climate impact, if the non-collected LFG is emitted as methane.



Image by Ramboll

Fig. 19 | **CO₂ balance of waste treatment and generation of energy**



CO₂ emission by producing 10 GJ (2.8 MWh) heat/power and treatment of 1 tonne of waste

Markets and distribution

Electricity

Energy prices may be affected by taxes or subsidies, typically on a country by country basis. The economic value of energy from waste is best judged by the socio-economic value of the form of energy that is replaced without the effects of subsidies, taxes and levies.



Image by Ramboll

Electricity is easily transferred from the energy recovery facility to the local power grid, making it available for all types of customers, even at a distance through trans boundary connections.

Waste produced electricity therefore replaces other production and its value is reflected in the value of the replaced production. This includes its value in terms of environmental footprint, associated air emissions and carbon dioxide emissions, and its economic value. Within a period of around 30 years energy recovery from waste will primarily replace fossil fuels and the CO₂ reduction is considered significant as described in section 5.3.

In some areas (e.g. USA and parts of Europe) there is a separate market for green electricity, including electricity from AD and WtE, comprising at least parts of the produced electricity. The market platform is used to document that a certain share of the consumed electricity comes from renewable sources.

Electricity is typically sold at market price based on short or long term contracts or a combination hereof.

This selling price is much lower than the household electricity price consisting of a range of additional price elements such as network cost, subscription fees, green electricity fee, energy specific tax and sales tax. The EU-average cost of “energy and supply” (not including network) is listed as around 70-80 €/MWh in 2012, (EURELECTRIC, 2013) and (EUROPEAN COMMISSION, 2014). The selling price of waste generated electricity may be somewhat lower than the “energy and supply”-indication because other price elements could be

included under this heading. For instance, in the Nordic countries of Europe the annual average system price is listed in the range 30-47 €/MWh for the years 2011-2014 (Nordpool spot, 2015). The relatively low prices in the Nordics shall be seen in the light of an efficient market platform, increased electricity trans-boundary transport capacity and introduction of large additional production from wind turbines, which is sold at whatever price the market brings.

The potential sale of electricity from WtE has a value of around 15 billion €/year, assuming the potential for electricity sale to be 300 TWh/year and a typical price of 50 €/MWh.

If biogas from AD-plants is used for electricity production, the value of the potential of 50 Mtpy organic household waste amounts to around 700 million € per year, assuming the same price of 50 €/MWh.

Heating/cooling

The perspective of heating/cooling production from waste is first of all that it supplements electricity in combined heat and power plants by recovering the energy that cannot be converted into electricity for reasons given by physical laws.

While the typical net output would be around 25-30% from an electricity-only plant the total energy recovery could be increased significantly by use of combined heat and power (CHP) even though it will caused a slight reduction of power production as described in section 4.1,

Sale of heat/cooling requires the existence of local demand, and that a transmission network is established. Heat could be supplied from heat-only WtE-plants or combined heat and power (CHP) plants.

As for electricity the value of the generated heat/cooling is expressed by the value of the energy sources it will replace. The heat price is usually somewhat lower than the electricity price, reflecting its lower energetic value, cf. Figure 11. There are large variations between different district-heating areas depending on the nature of local heat sources, amongst other things.

In the low price end, the heat price could be the marginal cost of CHP-generated heat from a conventional fuel, which may be below 10 €/MWh, because little fuel input is necessary to generate the heat. In the high end for instance, the resulting price of for instance investment in and operation of a natural gas fired boiler could yield a heat production price above 50 €/MWh (not including taxes). The potential sale of heat from WtE based CHP has a value of around 8 billion €/year, assuming the potential for heat sale to be 400 TWh/year and an average price of 20 €/MWh.

There could be taxation issues related to the sale of heat affecting market and pricing, e.g. tax on the heat delivered from the Waste-to-Energy plant and/or tax on the alternative fuel for heat supply.

If heat is generated from biogas CHP-units installed as part of AD-plants, the potential generation amounts to 18 TWh per year at a value of 180 million € per year, considering the potential of 50 Mtpy of organic household waste and assuming that 50% of the heat is sold.

Methane

The advantage of producing methane is first of all that it could replace natural gas or other fossil fuels, and their associated emission of carbon dioxide, because use of waste generated methane is considered bio-genic with zero carbon dioxide emission.

Methane from digestion of wastes would typically need upgrading and pressurising for transfer to a local natural gas network or for transport to a gas station for sale for road transport usage. The upgrading includes removal of carbon dioxide and other pollutants, e.g. siloxanes and hydrogen sulphide. In some areas (e.g. parts of Europe) a separate market for green gas is under development, particularly for biogas that has been upgraded to natural gas quality and transferred to the natural gas network. Certificates are issued for the produced green gas, allowing consumers to draw green gas from the common network through purchase of certificates. Such certificates may also document that a certain part of the consumed energy comes from renewable sources.

Pricing methane would as a starting point be market price for natural gas, but subsidies may apply making production and sale of waste generated methane economically attractive. There could also be an indirect subsidy by allowing tax free sale of methane (e.g. for road transport), where other fuels are taxed.

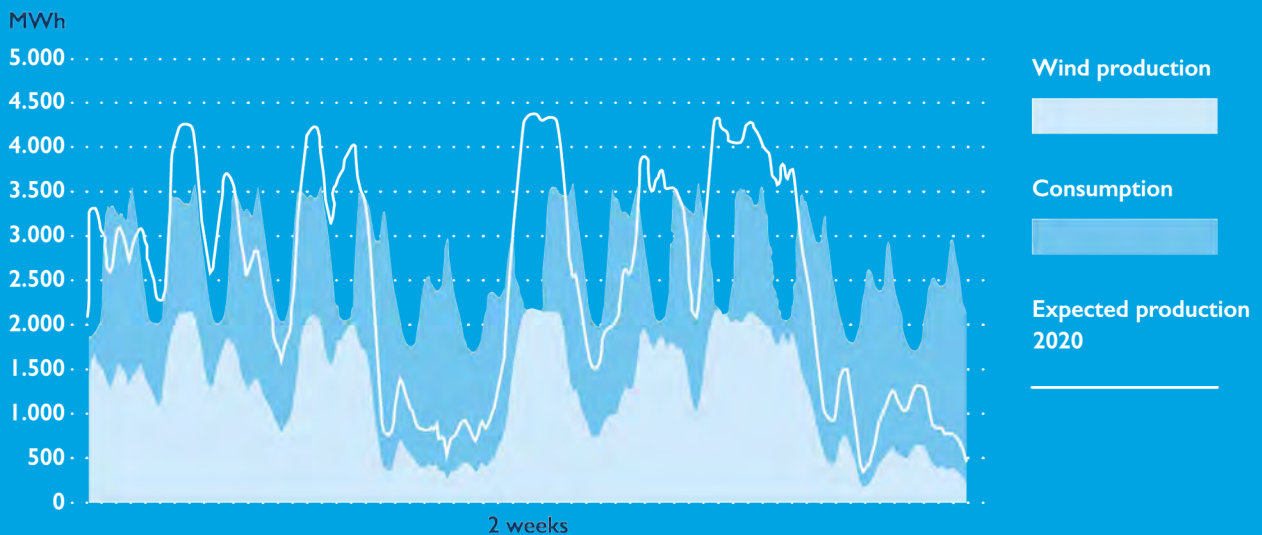
The average price of natural gas (energy and supply) in Europe is listed in the range 30-40 €/MWh in 2012 for industry and households (EUROPEAN COMMISSION, 2014). Hence, this could be considered the typical current value for upgraded methane from AD-plants excluding the effect of subsidies, taxes and levies.

With this price level, the potential biogas generation from AD-plants of 40 TWh per year has the value 1.2 to 1.6 billion €/year. It appears that the value of selling the methane could on average be higher than using it locally for electricity production in an electricity-only plant, allowing some expenses for upgrading, pressurising and transport of the gas to external consumers. It also appears that market opportunities and pricing are locally dependent, requiring individual assessment for each case.



Image by Valorsul

Fig. 20 **Illustration of current wind energy production and consumption of electricity over 2 weeks together with forecasted wind production in year 2020**



White area delimits current wind production, grey area the consumption, white line shows forecast for 2020, and blue areas between white lines and grey area indicates forecasted wind electricity generation in excess of the consumption.

Development in energy markets

The electricity market is already in some areas affected by large inputs of renewable energy that cannot easily be controlled, e.g. solar PV-systems and wind turbines as illustrated in Figure 20 above. This causes the other players in the electricity production system to behave differently because the demand, which is not covered by the renewables, will vary significantly, and pricing is expected to follow supply/demand.

The future electricity production should therefore be more flexible. Also Waste-to-Energy will face this challenge and will need to adjust operation accordingly to maximise the value of the energy production e.g. by establishing a larger treatment capacity but operating less hours to feed into the grid at times when other renewable energy sources cannot follow the market demands.

With the push towards a significant reduction in the use of fossil fuel and a world-wide increasing demand for energy, other

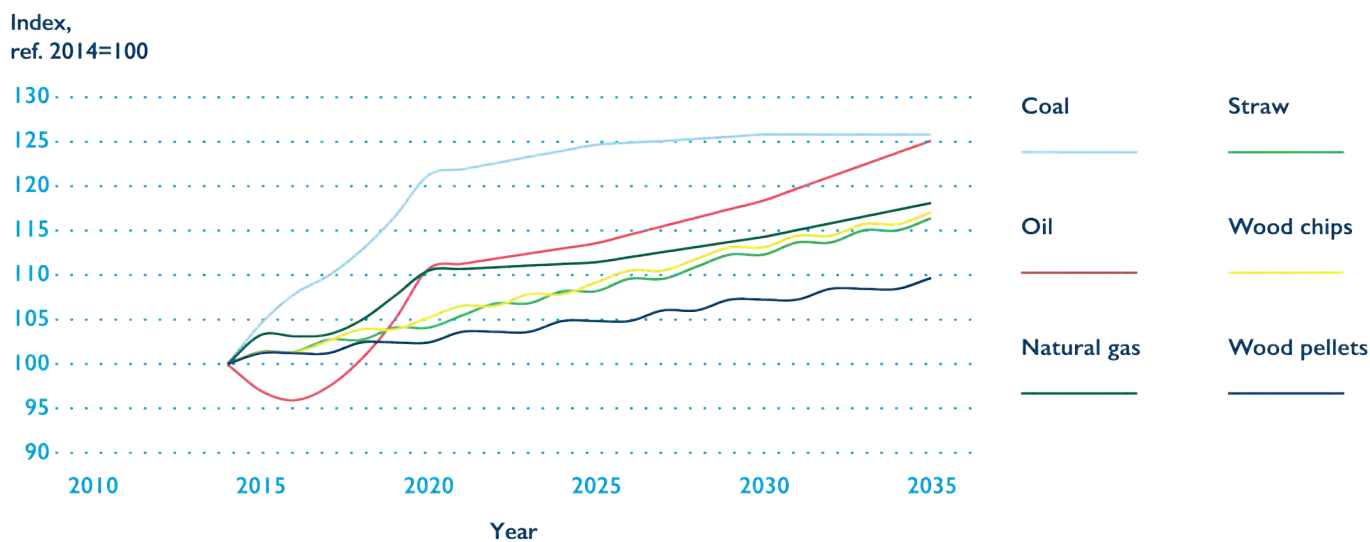
electricity sources will need to expand their production significantly. To exploit the primary energy resources to their maximum potential, maximising efficiency will be a key target, not least for the Waste-to-Energy facilities. Future WtE facilities are therefore expected to be developed with an outstanding energy efficiency and older plant with a low energy efficiency are within a foreseeable future expected to be replaced with modern and energy efficient plants.

CHP-plants that deliver heating or cooling will have an advantage in the future energy market because they can shift away from electricity production, when electricity prices are low. In addition the district-heating networks shall allow intermediate storage of the heat for complete decoupling of the operation of energy recovery systems and energy usage.

Valuing energy and fuels and market trends

Projections for future energy prices come with high uncertainty. The price may be influenced by global developments of fuel prices in addition to local or regional circumstances. However a price increase of electricity around 40-60% within the next 20 years is expected, Figure 22, in which case energy recovery from waste becomes even more attractive.

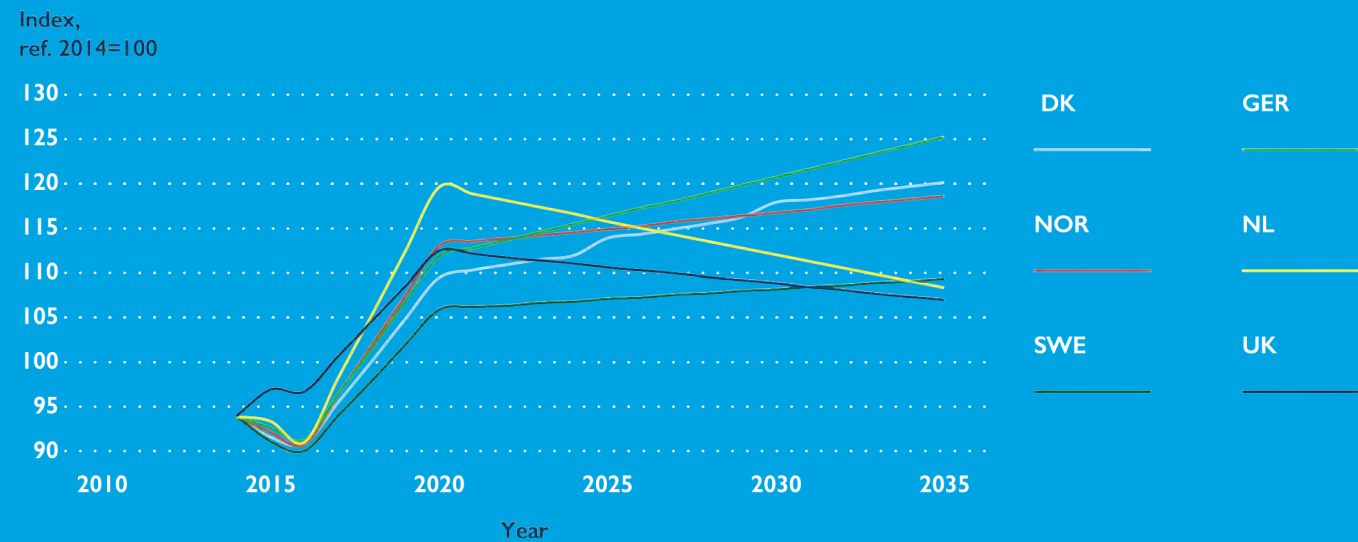
Fig. 21 | Fuel price projections



Fuel price projections, indexed constant prices with reference to year 2014. The index shows for each respective fuel, the fuel price (per MWh energy content) in percent of the price of the year 2014.

Source: Energinet.dk, 2014

Fig. 22 | Electricity price projections



Electricity price projections, indexed constant prices with reference to year 2014. The index shows electricity price (per MWh) in percent of the price of the year 2014.

Source: Energinet.dk, 2014

Investor attractiveness



Image by Ramboll

Facilities for recovery of energy and fuels are owned by municipal companies in some countries and in other they are privately owned. The ownership of municipal waste may be transferred from the public to the treatment facility through contracts often arising from a public tendering process. Regardless the ownership the public has an interest in ensuring long lasting stable and environmental friendly waste management capability, and treatment facilities like WtE and AD-plants can be part of this. Like other infrastructure projects there are many stakeholders when establishing such facilities, and it is important to address the questions and concerns raised to make the project successful.

The sale of gas, electricity and heat/cooling are usually activities, which play an important economic role in the business case, and the energy output is an important co-driver for a project in the treatment of waste.

With a financial lifetime of a plant of typically around 20 years, long term contracts for waste delivery is a high priority, and would usually be required to acquire external financing through banks. As described in section 3 the potential of waste for energy recovery is anticipated to increase significantly within the next 25-30 years and large amounts of waste are available globally. How this waste is made available locally should be considered in each case. Certainty of energy pricing and the existence of a market for the generated form of energy are also important for the business case.

Taxation and subsidies may play a large role, but both are susceptible to rapid changes making them difficult to use as basis for a long term business case.

Making an energy recovery project attractive to investors is therefore asso-

ciated with allocation of risk. The high efficient WtE technologies for treating waste and recovery of energy are, as illustrated in the report, well-proven technologies which have been optimized and improved over decades. Seen from investor perspective the technological risks are considered low for WtE projects.

Also AD-plants are considered well-proven, and the technological risk is considered low when efficient pre-treatment of waste is ensured together with odour mitigation. It remains a challenge to ensure disposal of the digestate for agricultural purposes because there is a risk of contamination or the perception that there is such a risk.

AD-plants are often dependent on a number of different feedstocks where organic household waste is just one. The risks include uncertainty of future energy pricing, existence of an efficient market for renewable energy, and the pricing and availability of supplementary feedstocks.

It shows that the public and the investor have mutual interest in mitigating risks for energy recovery facilities to become successful.



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Appendix

The output from Waste-to-Energy facilities is usually electricity and steam, which can be used for heating, cooling and other applications. From AD plants and landfills the output from the process is biogas, where the energy carrying constituent is methane.

Those forms of energy are quite different in quality and value as illustrated below.

Electricity is the highest ranking form of energy because it can be used to deliver mechanical work through an electric motor with virtually no loss, and electricity is the only form of energy that is used for many applications, e.g. electronics and household appliances.

Electricity has the advantage of being easy to transport over long distances in high

voltage power cables and the disadvantage of being difficult to store.

Heat is the lowest ranking form of energy because it possesses little potential for generating work, and heating of buildings is the predominant use. Heat in the shape of hot water has the advantage of being easy to store. The disadvantage is that sale of heat requires a heat demand and a district-heating network to reach the consumers.

Cooling is equivalent to heat, as an alternative for recovering the part of the energy the steam that cannot be converted into electricity. Cooling may be generated from steam in an absorption chiller.

The value of electricity relative to heat will depend on the circumstances locally,

particularly what would otherwise have supplied the electricity and heat. The typical pattern is that electricity is valued a factor 2-3 higher than heat. For instance, within EU, the so-called "RI-formula" used as a measure of plant energy efficiency attaches a weight to electricity of 2.6, whereas heat is only ascribed 1.1, cf. Annex II in the waste framework directive, (EU council, 2008).

Steam is an intermediate product of the WtE system (like in other boilers). It is generated in the boiler from which it is transferred to the steam turbine/generator system, generating electricity and potentially heat. Steam may be used directly for industrial purposes (heating, boiling, drying etc.). The conversion of energy in steam to electricity in a turbine is limited in efficiency governed by the laws of physics

Tab. 5 | Gross efficiency of WtE-facilities

EFFICIENCY (%)	TYPICAL, EXISTING	TYPICAL, NEW	HIGH EFFICIENT
Electricity-only	24	28	33
CHP			
Electricity	20	23	28
Heat	65	66	67
Total	85	89	95
CHP with flue gas condensation			
Electricity	20	23	27
Heat	77	77	83
Total	97	100	110

% of energy input by fuel represented by its lower heating value

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