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Waste to Energy – An Evaluation of the Environmental Impact

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The thermal treatment of waste with the heat recovery belongs to preferred sources of renewable energy. We can state that waste stops to be a problem and becomes an available fuel. It brings two advantages – waste is treated and at the same time energy is produced. In this case we speak about Waste to Energy – WTE). Due to more and more sweeping environmental requirements on quality of by-products in all states (flue gas, waste water as well as solid residues) produced by the process WTE provides us with clean and reliable energy in the form of heat as well as power. This has been contributing to primary energy savings in conventional utility systems.
In this paper impact of WTE regarding the environment is quantified. The evaluation focuses on the calculation of the primary energy savings. A general methodology is proposed. Than an assessment of the emission rate is made and results discussed. Real up-to-date municipal solid waste incinerator is involved in a case study. Benefit of its operation has been compared with some other up-to-date utility concepts.

1. Introduction

The quantity of waste produced either by inhabitants (MSW) or by industrial companies has significantly grown during last decades. Thermal treatment with heat recovery represents one of the preferred options of waste disposal within the EU. Originally simple incineration facilities have developed into complex processes meeting strict emission limits. Simultaneously, the requirement on effective recovery of heat released is constantly growing. A new generation phase of thermal treatment process called Waste Fired Power Plants are being discussed (Van Berlo 2006). Due to more and more sweeping legislation related to the WTE plant operation, it provides us with one of the cleanest and reliable energy in the form of heat as well as power.
However, this trend also has an important side effect. The overall energy demand of the process is increasing. Since a portion of produced energy is consumed on-site (e.g. for driving electrical appliances) the potential of its export outside the process is reduced. Together with some constraints given by specific features of waste used as a fuel (reduction of maximum output steam pressure due to corrosion risk) this reflects in overall efficiency of energy production, which is much lower than in conventional plants utilizing fossil fuels. The average net efficiency of power production in an incineration plant reaches around 18 %; heat production efficiency is 63 %. In the case of a cogeneration overall efficiency around 43 % can be expected (Reimann 2006).

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2. WTE and its contribution to primary energy savings

A number of criteria to compare the effectiveness of energy recovery and utilization in incineration plants have been proposed recently. Their overview can be found in (Pavlas and Touš). Their common feature can be seen in an effort to describe relation between energy outputs (produced or exported energy) on one side and energy demand on the other. However, these criteria can only be used for comparison of energy effectiveness in similar facilities, in this case municipal solid waste incineration plant (MSWI) plants. An example of analysis set on one of the often used criteria can be found in (Pavlas and Touš). In the following text a simple methodology for comparing environmental impact of WTE systems and other up-to-date systems (cogeneration units, biomass fired technologies, etc.) is proposed.

The amount of primary energy saved (PES) due to export of energy from WTE can be defined as the difference between primary energy consumed in conventional (reference) utility systems corresponding to the same amount of energy which is supplied by the WTE plant and primary energy necessary for the operation of the incineration process itself:

$$PES = PE^{Ref} - PE^{WTE} \quad (1)$$

If we know the efficiency of heat and power production in reference plants (η^{Ref}_{th}, η^{Ref}_{el}) equation (1) can be transformed into:

$$PES = \left(\frac{Q_{\exp,th}}{\eta^{Ref}_{th}} + \frac{Q_{\exp,el}}{\eta^{Ref}_{el}} \right) - \left(\frac{I_{imp,th}}{\eta^{Ref}_{th}} + \frac{I_{imp,el}}{\eta^{Ref}_{el}} + E_f \right) \quad (2)$$

where Q_{exp} denotes total amount of exported energy from WTE (thermal and electrical); I_{imp} is imported energy not used for heat production and E_f is imported energy to the combustion process (e.g. supplementary fuel). Efficiencies used can differ according to location or region. At present typical given values can be 0.91 for heat production and 0.38 for electricity production. Once we are comparing together different forms of energy (i.e. heat and power; electricity is considered as a more valuable form of energy) we can then write the following symbolic equation:

$$PES = (Q_{\exp}) - (I_{imp} + E_f). \quad (3)$$

3. Comparison of various concepts

3.1 Wate-to-Energy Plant

The following example demonstrates the calculation of achievable PES for a real up-to-date MSWI plant with a daily capacity of 300 t. The output released in the combustion chamber by waste combustion is about 33 MW. Availability reaches 8000 h/y. In the heat recovery steam generator (HRSG) sensitive heat of flue gas is used for steam production (temperature 400°C, pressure 40 bar). This superheated steam subsequently flows onto the backpressure turbine, where it expands down to pressure of 1,2 MPa. Most of this low-pressure steam is exported; a small part is consumed by the process itself. Regarding power, about 60% is consumed on-site and the rest is exported. Performance data summarized in Tab. 1 were gained from annual reports and balance calculations. By using equation (3) considering the real annual capacity it can be obtained that the plant has contributed due to energy export to primary energy saving of 741,848 GJ per annum.

Tab. 1 Results of comparison of different technologies in terms of achievable primary energy savings and emission produced

		WTE plant with backpressure turbine	Cogeneration based on reciprocating combustion engine	Biomass-fired heating plant with medium capacity	Biomass-fired ORC power plant	Biomass-fired ORC cogeneration plant
Fuel		MSW	Natural gas	Biomass	Biomass	Biomass
No. of installations	[-]	1	1	1	1	1
Availability	[h/y]	8,000	8,000	8,000	8,000	8,000
Performance data						
E_w resp. E_{alt}	[GJ/y]	957,618	0	34,560	236,800	236,800
E_f	[GJ/y]	5,036	137,088	0	0	0
$I_{Imp,el}$	[GJ/y]	5,560	0	518	0	0
$I_{Imp,th}$	[GJ/y]	4,805	0	0	0	0
$Q_{exp,th}$	[GJ/y]	642,815	62,381	28,800	0	167,040
$Q_{exp,el}$	[GJ/y]	22,954	57,888	0	66,240	34,560
PES	[GJ/y]	**741,848**	**83,799**	**30,284**	**174,316**	**274,508**
pes	[GJ/GJ]	**0.76**	**0.61**	**0.84**	**0.74**	**1.16**
Emissions						
Carbon monoxide, CO	[kg/y]	22,272	18,684	8,915	61,087	61,087
Nitrogen oxides, NO_x	[kg/y]	87,840	240,477	3,269	22,398	22,398
Particulate matter, PM	[kg/y]	2,986	5	4,993	34,209	34,209
Sulphur oxides, SO_x	[kg/y]	26,592	35	371	2,545	2,545

Note: E_{Alt} and E_W is energy released by combustion of an alternative fuel and waste

The environmental benefit of this real WTE plant has been compared with other environmentally friendly technologies. These competitors (see Tab. 2, where short description is given as well) have reached high stage of development, are proven in operation, available in the market and have good potential of further development worldwide.

3.2 Performance data, emissions released and primary energy savings achieved by individual facilities

Important energy flows for each of involved technology were evaluated first. Typical operational regimes and performance data obtained from real operation were taken into consideration. .Later on obtained values were introduced into equation (3) and annual PES determined.

Tab. 1 shows the result obtained. It is necessary to emphasise that the availability of 8,000 h/y was assumed for each of technology involved. Regarding technologies producing heat (all except biomass-fired power plant) such high operating hours can be guaranteed only if the output is dispatched to corresponding networks (i.e. large district heating networks, industrial heating). In the opposite case the availability can decrease significantly. Since the capacity of the included technologies is not identical the absolute PES estimated using (3) differs significantly and cannot be compared directly.

Tab. 2 Description of technology concepts involved in the assessment

Technology concept	**Fuel/ Capacity/ Efficiency**	**Application**
Cogeneration unit based on reciprocating combustion engine	▪ Natural gas ▪ Power output 2 MW_e; thermal output 2.2 MW_{th}; fuel rate 500 m_N3/h ▪ Overall efficiency 88%	▪ Combined heat and power ▪ Operated in energy systems of bigger cities or as utility system of industrial processes
Biomass-fired heating plant with medium capacity	▪ Forestry residues; waste from wood-processing industry; energy crops ▪ Hot water boiler with output of 1 MW_{th} ▪ Efficiency 83 %	Heat production in ▪ small wood-processing enterprises ▪ decentralized heat supply systems ▪ industry or in large commercial buildings.
Biomass-fired ORC power plant	▪ Forestry residues; waste from wood-processing industry; energy crops ▪ Organic Rankine cycle with condensing turbine ▪ Boiler output of 7 MW_{th}; ; power output of 2.3 MW_e ▪ Boiler efficiency 85%; electrical efficiency 25%	▪ Power production only
Biomass-fired ORC cogeneration plant	▪ Forestry residues; waste from wood-processing industry; energy crops ▪ Organic Rankine cycle with Back pressure turbine ▪ Boiler output of 7 MW_{th}; ▪ Boiler efficiency 85%; electrical efficiency 15%	▪ Heat and Power production ▪ Integrated in district heating systems of large cities

For that reason, a criterion defining specific savings is proposed. Specific primary energy savings are related to total process energy input ($E_{alt} + E_f + I_{imp}$):

$$pes = \frac{Q_{\exp} - (E_f + I_{imp})}{(E_{Alt} + E_f + I_{imp})} \tag{6}$$

The highest specific PES in this comparison are reached by biomass-fired cogeneration plant. On the other side the lowest positive environmental impact is featured to cogeneration unit based on reciprocating combustion engine. The benefit of WTE plant is comparable with the positive impact of biomass-fired heat only plant and power plant.

Later on the emission rate of basic pollutants (i.e. carbon monoxide, nitrogen oxides, solid particulates and sulphur oxides) were estimated. The level of emissions released into the atmosphere was determined using emission factors. It is a standard tool for emission estimation in air quality management. Emission factors used for calculation were obtained from AP-42 (U.S. EPA 1995) and were supplemented by average efficiency of air pollution control systems found e.g. in (Niessen 1995). The amount of emissions released into atmosphere by each of the technology per annum is shown in Tab. 1 as well. There is no reason to compare the values at the moment since the technologies are of different capacities; nevertheless these results form the base for following calculations.

3.3 Energy and Environmental analysis applied for selected region

Previous calculations have revealed that the analyzed WTE plant with an annual throughput of 100 kt contributes to PES of 741,848 GJ. Reflecting values presented in Tab. 1 for other technology concepts it can be stated that the same amount of primary energy would be saved at an annual operation of:

- 9 CHP units fired by natural gas or (later in the text denoted as 9-0-0-0)
- 25 heat only boilers running on biomass or (0-25-0-0)
- 4 biomass- fired power plants or (0-0-4-0)

  3 cogeneration plants producing heat and power from biomass (0-0-0-3).

Once complex analysis the aim of which is the evaluation of global environmental impact of WTE plant operated in a certain region is performed, combination of afore mentioned technology concepts have to be taken into account. The choice of 8 combinations involved in the study presented in this paper reflects conceptually different strategies of utilizing available energy sources (see Tab .3). Number of units in each alternative has been selected to provide comparable PES as is reached due to operation of one WTE plant with throughput of 100 kt/y. First six alternatives are based only on biomass utilization. In the next to the last biomass is partly supplemented by natural gas and the last option entirely concentrates on natural gas. As the number of installations of each technology in the alternatives changes, the heat and power produced change too.

Tab. 3 Results of an analysis applied for selected region

Alternative	Heat produced [GJ/y]	Power produced [GJ/y]	PES [GJ/y]	Emissions CO [t/y]	NO_x [t/y]	SO_x [t/y]	PM [t/y]
WTE	642 815	22 954	741 848	22	88	27	3
0-25-0-0	705 492	0	741 659	218	80	9	122
0-0-0-3	451 008	93 312	741 171	1 645	60	7	92
0-10-1-1	446 400	100 800	742 580	209	77	9	117
0-1-1-2	351 360	135 360	741 502	189	69	8	106
0-4-2-1	279 360	167 040	741 248	218	80	9	122
0-0-4-0	0	281 851	741 714	260	95	11	146
2-4-1-1	409 881	216 576	740 587	196	539	7	89
9-0-0-0	552 070	512 309	741 623	165	2 128	0.3	40

Note: Notation of alternatives involved – example 2-4-1-1 denotes 2 units A, 4 units B, 1 unit C and 1 unit D (A - Cogeneration based on reciprocating combustion engine; B – Biomass-fired heating plant with medium capacity; C- Biomass-fired ORC power plant; D- Biomass-fired ORC cogeneration plant)

On the base of presented figures for main pollutants (Tab. 3) it is possible to conclude that the WTE system provides one of the cleanest forms of the energy. Emissions of CO and particulate matter (PM) are several times lower that for the other evaluated technologies. NO_x emissions are comparable with those from biomass fired technologies and are by several orders lower compared with the CHP generation from the natural gas. The higher emission load is noticeable in the case of SO_x. This is caused by higher sulphur content in the incinerated waste.

4. Conclusions

Thermal treatment of solid municipal waste with heat recovery represents without any doubt one of most efficient way how to treat this specific waste. In this case the waste stops to be a problem and becomes a valuable alternative/renewable fuel. The energy generated in WTE units contributes to primary energy savings and consequently to the reduction of greenhouse gases emissions and the other pollutants in the extent comparable to the energy produced from the biomass. This has been in the paper objectively documented for a real WTE unit with annual throughput 100 kt. Once refusal attitudes to the putting into operation of new up-to-date WTE units are presented it is taken as granted that other competitive waste disposal methods are proposed. At the same time solutions for securing the energy supply with comparable contributions to the environment also should be provided. Presented results and methodology can be easily used for evaluation of the importance of WTE plants as a up-to-date utility systems.

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