

ZERO WASTE; ENERGY RECOVERY FROM NON-RECYCLABLE MIXED MUNICIPAL WASTE

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Abstract

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Zero Waste is a strategy offering waste management solutions for today's businesses. The Zero Waste strategy has been created with the objective of stimulating sustainable utilisation of resources, production and consumption with the highest possible level of recycling of generated waste. Due to the fact that currently there is very little information and only few relevant data available as a base for the implementation of the Zero Waste strategy, waste management specialists approach and apply such a strategy in different manners. On the other hand, there are areas of waste management where such a strategy has already been applied on a long-term basis in spite of non-existing relevant legislative tools. Indicators determined in the Zero Waste strategy may be achieved only if the individual countries clearly define legislative environment and adopt a national Zero Waste strategy with achievable objectives unambiguously determined. The area of waste separation, or handling of fractions of waste non-utilisable as secondary materials after separation, is one of the areas directly connected to the Zero Waste strategy. The objective of this paper is the evaluation of the usage of fractions of waste non-utilisable as secondary materials for energy recovery, providing thus valuable knowledge and information for the implementation of the Zero Waste strategy.

Keywords: Zero Waste, municipal waste, waste utilization

INTRODUCTION

Population growth connected to the growth of standards of living has very important impacts on a quantity of generated waste (Minghua *et al.*, 2009). The growing quantity of waste creates enormous pressure on a sustainable waste management, creating opportunities for the implementation of new approaches and strategies. For the first time, the Zero Waste term was used in 1973 in the chemical industry in connection with the recovery of utilisable components from chemical compounds (Palmer, 2004). Zero Waste is a waste management system. This strategy has been presented as a possible solution to waste management problems in the upcoming decades (Bartl, 2011; Connet, 2013a,b). The Zero Waste strategy is characterised by a circular material flow, which means the same material is repeatedly used. Within the Zero Waste

system, no material is left unused (Connet, 2013a; Murphy and Pincetl, 2013). One of the principal goals of the Zero Waste strategy is the reduction of landfills and no waste incineration without energy recovery (Wen *et al.*, 2009). Energy recovery from waste is considered a possible solution (Björk, 2012).

Zero Waste represents a divergence from traditional models applied in the area of waste management, as it stands for integrated systems in which each material (waste) is utilised. The Zero Waste strategy also includes already implemented approaches, such as the 3R rule (reduce, reuse, recycle), which, without any doubt, leads towards a waste minimising and material and energy savings. On the other hand, however, it is worth mentioning that the implementation of Zero Waste systems may go together with certain specific problems (Phillips *et al.*, 2011). The Zero Waste strategy has been

implemented in many countries (New Zealand, China, India), and also in many companies (Toyota, DuPont, Fuji Xerox) (Greyson, 2007). In July 2014, the European Commission adopted declaration 398/2014, defining the Zero Waste Programme for Europe. Previous guidelines are amended in such a manner so that the 7th EU Environment Action Programme is strictly adhered to and the following aspects are emphasized:

- Waste generation prevention and reduction of specific production of waste;
- Reduction of consumption of primary raw materials;
- Maximum utilisation of waste as a substitute for primary sources;
- Circulation of products and materials within their useful life.

On the basis of such new requirements and a system of adherence to environmental standards, fundamental decisions are taken regarding the manner of inclusion of raw materials into the material cycle, or the best possible utilisation and type of input materials for each individual technology. On the basis of several factors, it is possible to predict that in the Czech Republic, crucial changes in municipal waste management will occur.

The legislation factor is the first factor related to the adoption of a new waste management plan to be applied between 2015 and 2024. The most important aspect included in the waste management plan is the prohibition of depositing municipal waste, recyclable and biologically decomposable types of waste in landfills since 2014. The second factor is the manner of waste processing, and technologies applied for such a processing. Possibilities are assessed of waste management in a specific time and place. If waste is used for energy recovery, there are several problems, especially low numbers of waste-to-energy facilities, and quantity of homogeneous input materials both for energy recovery from waste and technology of recycling. The third factor is a material-wise composition of waste; within the fulfilment of the condition requiring the circulation of the maximum quantity of waste, a pressure will grow on the separation of a larger number of commodities out of a large quantity of municipal waste. Unfortunately, besides today-utilisable waste fractions such as biologically decomposable materials and single-component materials, multi-component materials will result from the separation. Composition and characteristics of such materials currently do not enable the re-utilisation or recycling of these. Nowadays, such materials are usually deposited in landfills, which is not compatible with the upcoming changes in the waste management. However, multi-component materials may be utilised very well for energy recovery. This paper focuses precisely on such materials.

MATERIAL AND METHODS

Locality Selection

A suitable locality has been selected for the purposes of the evaluation of energy recovery from fractions of municipal waste non-utilisable as secondary materials. Such a locality has been selected having in mind several partial goals, such as the most accurate definition of the structure of municipal waste, respecting different types of urbanisation in the area of interest, and respecting different behaviour of the inhabitants. Having carefully reviewed the data, a locality with 75 thousand inhabitants was selected. Samples of municipal waste were taken from waste hauled from the evaluated area, which were then treated and identified as Samples 1 to 3 and used for laboratory experiments and operational tests. Such samples may be characterised as follows:

Sample 1 – non-separated municipal waste 100% – 61.02 Mg.

Sample 2 – non-separated municipal waste enriched with 1/5 of plastic waste (plastic waste composition Tab. I) – 63.32 Mg.

Sample 3 – oversize fraction from treated municipal waste – 69.32 Mg.

Operational Test

The operational test was carried out in the waste incineration plant SAKO Brno, a.s., Brno, Czech Republic. Before the test was initiated, a polyp grab was used to take away previously filled waste from the determined space in the waste bunker. In such a manner, it was guaranteed that only waste supplied for the test was filled in K3 boiler selected for the test. Supplied waste was weighted and stored in the waste bunker in a determined place. The structure of non-recyclable plastic waste added in municipal waste is given in Tab. I.

At the beginning of a measurement, a weight of the polyp grab was determined used for filling waste in the K3 boiler, the situation of which is convenient for a direct filling of waste from the determined area of the waste bunker. When waste was filled into the boiler, weight of the grab and waste was always recorded individually per each filling operation. During the waste filling operation, the grab always stopped over the K3 boiler hopper, and when the weight measurement of the grab and waste became stable and visualised in the crane cabin, such a weight was recorded in the incineration

I: Percentage of non-recyclable mixed municipal waste hauled from municipalities

Content description	Percentage out of a total quantity [%]
Hard plastic, polystyrene	30
Soiled film	30
Municipal waste	30
Soiled PET	10

plant control system and in the operation logbook. When the weight of the grab was deducted from the weight of the grab with waste, the quantity of filled waste was determined. The measurement started one hour after the beginning of the filling of tested waste. During the measurement, all the operating parameters of K3 boiler and emissions values were stored. The measurement was discontinued after 2–3 hours, when a different type of waste (which was not objective of the testing) was filled. During the course of the test, the boiler was set for an output capacity of 45 Mg of steam per hour and it was kept in a capacity-control regime. A maximum deviation ± 2 Mg per hour was kept throughout the testing period. Values for the purposes of the lower calorific value calculation were taken from the incineration plant control system in ten-minute intervals. A calculation was performed using one-hour average of such values. In order to determine the lower calorific value of waste, a method of direct efficiency was applied, which stands for a ratio of heat input and output of equipment.

1. Lower calorific value calculation was performed as per the following equation:

$$Q_i^r = \frac{i_s \cdot m_s - i_{fw} \cdot m_{fw} - Q_{hpa}}{\eta} [MJ/kg],$$

where

- Q_i^r lower calorific value of waste [MJ/kg],
- i_s enthalpy of water steam [MJ/kg],
- i_{fw} enthalpy of feeding water [MJ/kg],
- m_s quantity of steam per hour [kg],
- m_{fw} quantity of feeding water per hour [kg],
- Q_{hpa} heat transferred to primary air [MJ/kg],
- m_{wst} quantity of incinerated waste per hour [kg],
- η equipment efficiency [-].

The efficiency of equipment was defined as the last measured value in equipment in 2014; such a value was 81.36%. When performing the calculation, first the length of the experiment was determined depending on the quantity of waste in the waste hopper. On the basis of long-term experience it is known that it takes from 45 to 60 minutes for the waste to get from the hopper to the boiler grate. In this manner, the beginning of the three tests was determined. The length of the test period was determined considering the quantity of waste in the boiler hopper after the last filling, and the development and subsequent filling. The length of the testing period was used for the determination of hourly averages, used for the calculation of efficiency.

2. The calculation of an hourly quantity of waste filled in the boiler depending on an average value of steam generated in the incineration plant in 2014, and an hourly production of steam during the individual tests:

$$m_{wtst} = \frac{m_{s2014} \cdot m_{wtst}}{m_{stst}} [kg],$$

where

- m_{wtst} converted hourly quantity of waste incinerated during the test [kg],
- m_{s2014} hourly quantity of steam generated in the incineration plant in 2014 [kg],
- m_{wtst} hourly quantity of waste incinerated during the test [kg],
- m_{stst} hourly quantity of steam generated during the test [kg].

3. Conversion of a theoretical annual quantity of waste in kg processed in the incineration process to the production of an equal annual quantity of steam produced in the incineration plant in 2014:

$$m_{wtst} = \frac{m_{wa2014} \cdot m_{wtst}}{m_{wh2014}} [kg],$$

where

- m_{wtst} converted annual quantity of waste incinerated during the test [kg],
- m_{wa2014} annual quantity of waste incinerated in the incineration plant in 2014 [kg],
- m_{wtst} converted hourly quantity of waste incinerated during the test [kg],
- m_{wh2014} hourly quantity of waste incinerated in the incineration plant in 2014 [kg].

4. Conversion of the quantity of recovered heat energy depending on the lower calorific value and quantity of incinerated waste:

$$Q_{hea} = (Q_{wlc} \cdot m_{wtst} \cdot \eta) - Q_{air} [J],$$

where

- Q_{hea} annual production of heat energy [J],
- Q_{wlc} waste lower calorific value [J/kg],
- m_{wtst} converted annual quantity of waste incinerated during the test [kg],
- η boiler efficiency [-],
- Q_{air} heat energy supplied in the primary air per year [J].

5. Economics of heat energy produced from waste incinerated during the individual tests, compared to heat recovered in the incineration plant in 2014. For the purposes of the comparison of results of the tests, two modes were selected which enable the utilisation of recovered heat energy:

- a) Cogeneration mode – produced steam passes through a steam turbine generating electrical energy; steam, having passed through the turbine, is fed in a central heating distribution system.
- b) Condensation mode – steam passes through a condensing turbine without a possibility to supply steam to external consumers; only electrical energy is generated.

Quantity of recovered heat energy can be calculated applying the following formula:

$$Q_{he} = \frac{Q_{inc2014} - Q_{he\max}}{Q_{he\text{tst}}} \quad [J],$$

where

Q_{he} heat energy recovered in the cogeneration mode [J],

$Q_{inc2014}$ heat energy recovered from waste incineration in 2014 [J],

$Q_{he\max}$ maximum heat energy supplied in the system by the incineration plant [J],

$Q_{he\text{tst}}$ heat energy recovered from waste sample incineration [J].

Quantity of electrical energy recovered both in cogeneration and condensing modes can be calculated applying the following formula:

$$Q_{ee} = \frac{Q_{inc2014} - Q_{ee\max}}{Q_{ee\text{tst}}} \quad [J],$$

where

Q_{ee} electrical energy recovered in cogeneration or condensing mode [J],

$Q_{inc2014}$ heat energy recovered from waste incineration in 2014 [J],

$Q_{ee\max}$ maximum electrical energy supplied in the grid by the incineration plant [J],

$Q_{ee\text{tst}}$ heat energy recovered from waste sample incineration [J].

MEASUREMENT RESULTS AND DISCUSSION

1. Calculation of Lower Calorific Value:

Values determined during operation test carried out 18.05.2014 for Sample 1 are shown in Tab. II:

$$Q_i^r = \frac{i_s \cdot m_s - i_{fw} \cdot m_{fw} - Q_{hpa}}{\eta \cdot m_{\text{tst}}} =$$

$$= \frac{3.21 \cdot 45.61 - 0.56 \cdot 47.71}{0.8136} - 6.22 = 7.58 \text{ [MJ/kg]}.$$

Values determined during operation test carried out 25.05.2014 for Sample 2 are shown in Tab. III:

$$Q_i^r = \frac{i_s \cdot m_s - i_{fw} \cdot m_{fw} - Q_{hpa}}{\eta \cdot m_{\text{tst}}} =$$

$$= \frac{3.21 \cdot 45.21 - 0.56 \cdot 47.58}{0.8136} - 5.95 = 13.09 \text{ [MJ/kg]}.$$

Values determined during operation test carried out 01.06.2014 for Sample 3 are shown in Tab. IV:

$$Q_i^r = \frac{i_s \cdot m_s - i_{fw} \cdot m_{fw} - Q_{hpa}}{\eta \cdot m_{\text{tst}}} =$$

$$= \frac{3.21 \cdot 41.72 - 0.56 \cdot 43.41}{0.8136} - 5.34 = 8.32 \text{ [MJ/kg]},$$

where

Q_i^r waste lower calorific value [MJ/kg],

i_s enthalpy of water steam [MJ/kg],

i_{fw} enthalpy of feeding water [MJ/kg],

m_s quantity of steam per hour [kg],

m_{fw} quantity of feeding water per hour [kg],

Q_{hpa} heat transferred to primary air [MJ/kg],

m_{tst} quantity of incinerated waste per hour [kg],

η equipment efficiency [-].

II: Values determined during the test carried out 18.05.2014

Feeding start	9:27
Test start	12:00
Test end	15:12
Total duration of the test [min]	192
Total quantity of waste [Mg]	59.57
Quantity of waste per hour [Mg]	18.58

III: Values determined during the test carried out 25.05.2014

Feeding start	08:30
Test start	09:30
Test end	14:10
Total duration of the test [min]	280
Total quantity of waste [Mg]	49.11
Quantity of waste per hour [Mg]	10.67

IV: Values determined during the test carried out 01.06.2014

Feeding start	09:35
Test start	10:40
Test end	14:57
Total duration of the test [min]	257
Total quantity of waste [Mg]	66.24
Quantity of waste per hour [Mg]	15.55

In order to perform an accurate determination of the lower calorific value by means of an indirect method, depending on the heat losses, another auxiliary measurement would have to be performed. The used method, however, proved the compliance with the direct data evaluated by the incineration plant control system and with the graphic development of the lower calorific value. Tab. V shows that Sample 2 had the highest lower calorific value; Sample 1, on the contrary, had the lowest lower calorific value.

V: Lower calorific value of waste achieved during the operation test

Waste Sample Identification	Calculated lower calorific value [MJ/kg]	Difference [%]
Sample 1	7.58	0
Sample 2	13.09	+57.91
Sample 3	8.32	+8.89

2. Calculation of an hourly quantity of waste fed in the boiler depending on an average value of steam production in the incineration plant in the year 2014, and on an hourly production of steam during the individual tests:

Operation test carried out 18. 05. 2014, Sample 1:

$$m_{whstst} = \frac{m_{sp2014} \cdot m_{wtst}}{m_{stst}} = \frac{42.55 \cdot 18.58}{45.61} = 17340 \text{ [kg]}.$$

Operation test carried out 25. 05. 2014, Sample 2:

$$m_{whstst} = \frac{m_{sp2014} \cdot m_{wtst}}{m_{stst}} = \frac{42.55 \cdot 10.67}{45.21} = 10040 \text{ [kg]}.$$

Operation test carried out 01. 06. 2014, Sample 3:

$$m_{whstst} = \frac{m_{sp2014} \cdot m_{wtst}}{m_{stst}} = \frac{42.55 \cdot 15.55}{41.72} = 1586 \text{ [kg]},$$

where

m_{whstst}calculated hourly quantity of waste incinerated in the test [kg],
 m_{sp2014} ... hourly quantity of steam produced in the incineration plant in 2014 [kg],
 m_{wtst} hourly quantity of waste incinerated in the test [kg],
 m_{stst} hourly quantity of steam produced in the test [kg].

The performed calculations show that for a production of 42,550 kg of steam, it would be necessary to incinerate 17,340 kg of waste (Sample 1) per hour with a lower calorific value of 7.58 MJ/kg; 10,040 kg of waste (Sample 2) per hour with a lower calorific value of 13.09 MJ/kg; and 15,860 kg of waste (Sample 3) per hour with a lower calorific value of 8.32 MJ/kg.

3. Conversion of a theoretical annual quantity of waste (in kilograms) required for the incineration process to a production of corresponding annual quantity of steam generated in the incineration plant in 2014:

Operation test carried out 18. 05. 2014, Sample 1:

$$m_{uatst} = \frac{m_{ua2014} \cdot m_{whstst}}{m_{wh2014}} = \frac{237367 \cdot 10^3 \cdot 17340}{14750} = 279047 \cdot 10^3 \text{ [kg]}.$$

Operation test carried out 25. 05. 2014, Sample 2:

$$m_{uatst} = \frac{m_{ua2014} \cdot m_{whstst}}{m_{wh2014}} = \frac{237367 \cdot 10^3 \cdot 10040}{14750} = 161570 \cdot 10^3 \text{ [kg]}.$$

Operation test carried out 01. 06. 2014, Sample 3:

$$m_{uatst} = \frac{m_{ua2014} \cdot m_{whstst}}{m_{wh2014}} = \frac{237367 \cdot 10^3 \cdot 15860}{14750} = 255230 \cdot 10^3 \text{ [kg]},$$

where

m_{uatst}converted annual quantity of waste incinerated in the test [kg],
 m_{ua2014} ...annual quantity of waste incinerated in the incineration plant in 2014 [kg],
 m_{whstst}converted hourly quantity of waste incinerated in the test [kg],
 m_{wh2014} ...hourly quantity of waste incinerated in the incineration plant in 2014 [kg].

The calculation shows that in order to generate the corresponding quantity of steam featuring defined parameters (400 °C; 4 MPa) as that one generated in the incineration plant in 2014, the following is required:

Sample 1: Incineration of $279,047 \cdot 10^3$ kg of waste with a lower calorific value of 7.58 MJ/kg per year. In order to achieve such results, an extra annual quantity of $41,680 \cdot 10^3$ kg of waste would be necessary; this would require the modification of an annual approved quantity of incinerated waste, which is currently $248,000 \cdot 10^3$ kg.

Sample 2: Incineration of $161,570 \cdot 10^3$ kg of waste with a lower calorific value of 13.09 MJ/kg per year. In order to achieve such results, an annual quantity of incinerated waste should be reduced by $75,797 \cdot 10^3$ kg.

Sample 3: Incineration of $255,230 \cdot 10^3$ kg of waste with a lower calorific value of 8.32 MJ/kg per year. In order to achieve such results, an extra annual quantity of $17,863 \cdot 10^3$ kg of waste would be necessary; this would require the modification of an annual approved quantity of incinerated waste, which is currently $248,000 \cdot 10^3$ kg.

4. Conversion of recovered heat energy in dependence on a lower calorific value and quantity of incinerated waste:

Operation test carried out 18. 05. 2014, Sample 1:

$$Q_{hea} = (Q_{velce} \cdot m_{uatst} \cdot \eta) - Q_{air} =$$

$$= (7.58 \cdot 237367 \cdot 10^3 \cdot 0.8136) - 69448 \cdot 10^9 = 1394415 \cdot 10^9 \text{ [J]}.$$

Operation test carried out 25. 05. 2014, Sample 2:

$$Q_{hea} = (Q_{velce} \cdot m_{uatst} \cdot \eta) - Q_{air} =$$

$$= (13.09 \cdot 237367 \cdot 10^3 \cdot 0.8136) - 69448 \cdot 10^9 = 2458516 \cdot 10^9 \text{ [J]}.$$

Operation test carried out 01. 06. 2014, Sample 3:

$$Q_{\text{hea}} = (Q_{\text{wlc}} \cdot m_{\text{watst}} \cdot \eta) - Q_{\text{air}} = \\ = (8.32 \cdot 237367 \cdot 10^3 \cdot 0.8136) - 69448 \cdot 10^9 = 1537325 \cdot 10^9 \text{ [J]},$$

where

Q_{hea} annual production of heat energy [J],

Q_{wlc} lower calorific value of waste [J/kg],

m_{watst} converted annual quantity of waste incinerated in the test [kg],

η boiler efficiency [-],

Q_{air} heat energy fed annually in primary air [J].

The calculation shows that if the same quantity of waste were incinerated in the incineration plant as in 2014, an annual recovery of heat energy would be reduced by 330,238 GJ of heat energy when incinerating waste (Sample 1) with a lower calorific value of 7.58 MJ/kg; if waste (Sample 2) of a lower calorific value of 13.09 MJ/kg were incinerated, an annual recovery of heat energy would grow by 733,863 GJ; if waste (Sample 3) of a lower calorific value of 8.32 MJ/kg were incinerated, an annual recovery of heat energy would be reduced by 187,328 GJ.

5. Heat and electrical energy recovered in the cogeneration and condensing modes:

Cogeneration mode

Operation test carried out 18. 05. 2014, Sample 1:

$$Q_{\text{he}} = \frac{Q_{\text{inc2014}} - Q_{\text{he max}}}{Q_{\text{hetst}}} = \\ = \frac{1394415 \cdot 10^9 \cdot 1338570 \cdot 10^9}{1724653 \cdot 10^9} = 1082259 \cdot 10^9 \text{ [J]},$$

$$Q_{\text{ee}} = \frac{Q_{\text{inc2014}} - Q_{\text{ee max}}}{Q_{\text{hetst}}} = \frac{1394415 \cdot 10^9 \cdot 126714 \cdot 10^9}{1724653 \cdot 10^9} = \\ = 102450 \cdot 10^9 \text{ [J]} = 28458 \text{ [MWh]}.$$

Operation test carried out 25. 05. 2014, Sample 2:

$$Q_{\text{he}} = \frac{Q_{\text{inc2014}} - Q_{\text{he max}}}{Q_{\text{hetst}}} = \\ = \frac{2458516 \cdot 10^9 \cdot 1338570 \cdot 10^9}{1724653 \cdot 10^9} = 1908149 \cdot 10^9 \text{ [J]},$$

$$Q_{\text{ee}} = \frac{Q_{\text{inc2014}} - Q_{\text{ee max}}}{Q_{\text{hetst}}} = \frac{2458516 \cdot 10^9 \cdot 126714 \cdot 10^9}{1724653 \cdot 10^9} = \\ = 180632 \cdot 10^9 \text{ [J]} = 50175 \text{ [MWh]}.$$

Operation test carried out 01. 06. 2014, Sample 3:

$$Q_{\text{he}} = \frac{Q_{\text{inc2014}} - Q_{\text{he max}}}{Q_{\text{hetst}}} = \\ = \frac{1537325 \cdot 10^9 \cdot 1338570 \cdot 10^9}{1724653 \cdot 10^9} = 1193177 \cdot 10^9 \text{ [J]},$$

$$Q_{\text{ee}} = \frac{Q_{\text{inc2014}} - Q_{\text{ee max}}}{Q_{\text{hetst}}} = \frac{1537325 \cdot 10^9 \cdot 126714 \cdot 10^9}{1724653 \cdot 10^9} = \\ = 112950 \cdot 10^9 \text{ [J]} = 31375 \text{ [MWh]},$$

where

Q_{he} heat energy recovered in cogeneration mode [J],

Q_{ee} electrical energy recovered in cogeneration mode [J],

Q_{inc2014} heat energy recovered from waste incineration in the plant in 2014 [J],

$Q_{\text{he max}}$ maximum heat energy supplied by the plant in the distribution system [J],

$Q_{\text{ee max}}$ maximum electrical energy supplied by the incineration plant in the grid [J],

Q_{hetst} heat energy recovered from incineration of waste samples [J].

The calculation shows that if the same quantity of waste were incinerated in the incineration plant as in 2014, an annual recovery of heat energy would be reduced by 256,311 GJ, and electrical energy recovery would be reduced by 6,739 MWh when incinerating waste (Sample 1) with a lower calorific value of 7.58 MJ/kg; if waste (Sample 2) with a lower calorific value of 13.09 MJ/kg were incinerated, an annual recovery of heat energy would grow by 569,579,863. GJ, and electrical energy recovery would grow by 14,977 MWh; if waste (Sample 3) with a lower calorific value of 8.32 MJ/kg were incinerated, an annual production of heat energy would be reduced by 145,393 GJ, and electrical energy by 31,375 MWh.

Condensing mode

Operation test carried out 18. 05. 2014, Sample 1:

$$Q_{\text{he}} = \frac{Q_{\text{he2014}} - Q_{\text{ee max}}}{Q_{\text{hetst}}} = \frac{1394415 \cdot 10^9 \cdot 386928 \cdot 10^9}{1724653 \cdot 10^9} = \\ = 312838 \cdot 10^9 \text{ [J]} = 86899 \text{ [MWh]}.$$

Operation test carried out 25. 05. 2014, Sample 2:

$$Q_{\text{he}} = \frac{Q_{\text{he2014}} - Q_{\text{ee max}}}{Q_{\text{hetst}}} = \frac{2458516 \cdot 10^9 \cdot 386928 \cdot 10^9}{1724653 \cdot 10^9} = \\ = 551571 \cdot 10^9 \text{ [J]} = 153214 \text{ [MWh]}.$$

Operation test carried out 01. 06. 2014, Sample 3:

$$Q_{\text{he}} = \frac{Q_{\text{he2014}} - Q_{\text{ee max}}}{Q_{\text{hetst}}} = \frac{1537325 \cdot 10^9 \cdot 386928 \cdot 10^9}{1724653 \cdot 10^9} = \\ = 344900 \cdot 10^9 \text{ [J]} = 95805 \text{ [MWh]},$$

where

Q_{he} heat energy recovered in the cogeneration or condensing mode [J],

Q_{he2014} heat energy recovered from waste incineration in the plant in 2014 [J],

$Q_{\text{ee max}}$ maximum electrical energy supplied by the incineration plant in the grid [J],

Q_{hetst} heat energy recovered from incineration of waste samples [J].

The calculations show that if the same quantity of waste were incinerated in the incineration plant as in 2014, an annual electrical energy recovery would be reduced by 20,580 MWh when incinerating waste (Sample 1) with a lower calorific value of 7.58 MJ/kg; if waste (Sample 2) with a lower calorific value of 13.09 MJ/kg were incinerated, an annual recovery of electrical energy would grow by 45 734 MWh; if waste (Sample 3) with a lower calorific value of 8.32 MJ/kg were incinerated, an annual recovery of electrical energy would be reduced by 11 674 MWh.

6. Effect of input-waste composition on the economy of incineration plant operation.

Determination of incineration plant earnings from energy sales in 2014

a) Incineration plant operated in cogeneration mode

- Earnings from heat energy sales.
 - Maximum annual quantity of heat energy supplied in the system – 1,338,570 GJ.
 - Earnings of the incineration plant per GJ of heat energy – 170 CZK.
 - Income from annual quantity of heat energy – 227,556,900 CZK.
- Earnings from electrical energy sales.
 - Maximum annual quantity of electrical energy supplied in the grid – 35,198 MWh.
 - Earnings of the incineration plant per MWh of electrical energy – 1,000 CZK.
 - Income from annual quantity of electrical energy – 35,198,000 CZK.

If a total of recovered heat and electrical energy were supplied in the heating system and the electric grid, earnings of an incineration plant operated in a cogeneration mode would be 262,754,900 CZK.

b) Incineration plant operated in condensing mode

- Earnings from electrical energy sales.
 - Maximum annual quantity of electrical energy supplied in the grid – 107,480 MWh.
 - Earnings of the incineration plant per MWh of electrical energy – 1,000 CZK.
 - Income from annual quantity of electrical energy – 107,480,000 CZK.

If a total production of electrical energy were supplied in the electric grid, earnings of an incineration plant operated in a condensing mode would be 107,480,000 CZK.

The difference between the cogeneration and condensing modes would be 155,275,200 CZK being the former the more advantageous.

If in the year 2014, tested samples were incinerated in quantities corresponding to the total quantity of waste incinerated in the plant in 2014, which means 237,367 Mg with a lower calorific value corresponding to the individual tests, and the total heat and electrical energy would be supplied in the heating system and electric grid, the financial impact of the individual modes of operation of the plant would be as shown in Tabs. VI–VIII.

Tabs. IX and X show the cost of conversion of 1 Mg of municipal waste to energy. Due to the fact that such information of the incineration plant is a business secret, only costs of processing incurred on 25. 05. 2014 and 01. 06. 2014 may be published.

The testing has shown that Sample 2 would generate the most interesting results for the incineration plant from the economical point of view. If such waste were incinerated, an added value of 471 CZK/Mg would be generated. When cost of treatment of Sample 2 is deducted (471–335), the earning is 136 CZK/Mg of incinerated waste. Having

VI: Comparison of incineration plant results achieved in 2014 to the results achieved when recovering heat energy from the tested waste samples in the cogeneration mode

Sample identification	Lower calorific value of waste	Required annual quantity of waste	Heat energy recovered	Difference in the heat energy recovered	Difference in the heat energy recovered
	[MJ/kg]	[Mg]	[GJ]	[GJ]	[CZK]
Incineration plant 2014	9.29	237,367	1,338,570	-	-
Sample 1	7.58	279,047	1,082,259	-256,311	-43,572,870
Sample 2	13.09	161,570	1,908,149	+569,579	+96,828,430
Sample 3	8.32	255,230	1,193,177	-145,393	-24,716,810

VII: Comparison of incineration plant results achieved in 2014 to the results achieved when recovering electrical energy from the tested waste samples in the cogeneration mode

Sample identification	Lower calorific value of waste	Required annual quantity of waste	Electrical energy recovered	Difference in the electrical energy recovered	Difference in the electrical energy recovered
	[MJ/kg]	[Mg]	[MWh]	[MWh]	[CZK]
Incineration plant 2014	9.29	237,367	35,198	-	-
Sample 1	7.58	279,047	28,458	-6,739	-6,739,800
Sample 2	13.09	161,570	50,175	+14,977	+14,977,350
Sample 3	8.32	255,230	31,375	-3,823	-3,823,160

VIII: Comparison of incineration plant results achieved in 2014 to the results achieved when recovering electrical energy from the tested waste samples in the condensing mode

Sample identification	Lower calorific value of waste	Required annual quantity of waste	Electrical energy recovered	Difference in the electrical energy recovered	Difference in the electrical energy recovered
	[MJ/kg]	[Mg]	[GJ]	[GJ]	[CZK]
Incineration plant 2014	9.29	237,367	107,480	-	-
Sample 1	7.58	279,047	86,899	-20,580	-20,580,400
Sample 2	13.09	161,570	153,214	+45,734	+45,734,180
Sample 3	8.32	255,230	95,805	-11,674	-11,674,240

IX: Costs of conversion of 1 Mg of municipal waste to energy, 25.05.2014

No. trucks	Total no. of Km to the plant and back	Price per Km	Transport total	Quantity of waste	Gate fee per Mg	Waste total	No. of hours of pressing
[-]	[km]	[CZK]	[CZK]	[Mg]	[CZK]	[CZK]	[h]
3	20	38	2,280	61.8	850	52,530	60
Hourly wage of the operator	No. of operators	Separation total	No. of hours of the loader	Hourly rate of the loader	Loader total	Total cost per 1 Mg of waste	
[CZK]	[-]	[CZK]	[h]	[CZK]	[CZK]	[CZK]	
111	2	13,320	10	510	5,100	1148.06	

X: Costs of conversion of 1 Mg of municipal waste to energy 01.06.2014

No. trucks	Total no. of Km to the plant and back	Price per Km	Transport total	Quantity of waste	Gate fee per Mg	Waste total	No. of hours of pressing
[pc]	[km]	[CZK]	[CZK]	[Mg]	[CZK]	[CZK]	[h]
3	20	38	2,280	61.8	850	52,530	40
Hourly wage of the operator	No. of operators	Separation total	No. of hours of the loader	Hourly rate of the loader	Loader total	Total cost per 1 Mg of waste	
[CZK]	[-]	[CZK]	[h]	[CZK]	[CZK]	[CZK]	
111	2	8,880	40	510	20,400	1360.67	

performed a comparison of all the samples, it can be concluded that Sample 2 waste generates a gross earnings of 136 CZK/Mg. Therefore, it is possible to assume that if the incineration plant incinerated 237.367 Mg of waste (Sample 2) with a lower calorific value of 13.09 MJ/kg, which means the same quantity as in 2014, the plant earnings would reach 32.28 million Czech crowns. Such a result would be achieved only if the complete production of

heat and electrical energy were sold to distribution networks. The incineration of Sample 2 waste would generate more benefits, such as reduced quantity of incinerated waste, which implies a lower frequency of outages of the plant and a lower wear and tear of technological equipment. However, unfortunately, such financial benefits cannot be accurately quantified.

CONCLUSION

Results of the tests performed in the incineration plant confirmed a hypothesis that it is possible to prepare high quality fuel from municipal waste with a high waste-to-energy conversion ratio. With such a fuel, plant equipment is capable of achieving the maximum lower calorific value required for the recovery of heat and electrical energy while meeting emission limits and fulfilling Zero Waste strategy objectives. However, indicators given in the Zero Waste strategy can be achieved only if legislation requirements for the individual technologies are clearly defined. Analysis performed by us may provide support for the assessment of the possibility to apply the Zero Waste strategy in incineration plants.

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