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Prediction of Heating Value of Waste and Its Importance for Conceptual Development of New Waste-to-Energy Plants

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The article deals with the prediction of lower heating value (LHV) of residual municipal solid waste (MSW). LHV indicates the energy potential contained in the waste, which can be later effectively utilized during its thermal treatment, therefore it also affects the economy of a waste-to-energy plant. Heating value of MSW varies according to location and time. It is influenced by socio-economic factors, citizens' standard of living or the overall effectiveness of waste management. Over time, it changes due to the development of these parameters. Its prediction is crucial for the design of the key equipment parts of a waste-to-energy plant (e.g. specification of operating range for the furnace) and significantly influences the plant economy.

Concurrently, average heating value reported for each plant is influenced by the area, from which the waste is collected. Therefore, a concept of a new comprehensive tool which creates a predictive model based on data from various sources is introduced. These are the results of waste composition analysis carried out in different typologically selected locations and times, LHV reported at several existing plants and available waste management statistics at regional level. These sources are further discussed in the paper through examples.

1. Introduction

A waste incinerator with an up-to-date heat recovery system and highly efficient flue gas treatment system (waste-to-energy, WtE) is an integral part of well-developed waste management systems. Thermal treatment of municipal solid waste (MSW) represents a safe and clean technology due the very strict environmental regulations (e.g. 2000/76/EC directive on the incineration of waste and 2010/75/EU on industrial emissions). Moreover, all used equipment has to be in accordance to the Best Available Techniques stated in reference documents (European IPPC Bureau, 2006).

Production of heat and power is an important part of MSW incinerators design and operation. Potential for energy production is based on calorific value of incinerated waste and it is indicated by lower heating value (LHV). Importance of LHV on plant economy and LHV prediction is the focus of this paper.

The authors currently have worked on LHV estimation using operational data from real WtE plants. Benáčková et al.(2012) compared different methods of LHV estimation from operational data and showed its effect on the boiler efficiency. Touš et al. (2013) extended the previously mentioned work and suggested the LHV and efficiency evaluation improvement by applying data reconciliation principle. There are also papers describing LHV analysis based on local MSW composition examination. Methodology or procedure for analysis of MSW calorific value for larger geographical areas was not described yet. Assessment of representative LHV value for different levels of regional and administrative units is necessary for effective integration of energy recovery to the waste management system. These issues are solved by optimization tool NERUDA, which is developed in-house (Šomplák et al., 2013) in order to model a competitive environment among WtE plants, mechanical-biological treatment (MBT) plants and landfills based on minimizing costs of MSW treatment for waste producers.

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1.1 LHV and its importance for conceptual design

The former research related to WTE aimed mainly on minimization of its negative impact on the environment as a consequence of more and more sweeping emissions limit. Today, maximum heat recovery, financial profit and focus on electricity generation are the most important drivers for further development. LHV represents a key parameter influencing performance and economy of any combustion process. In this way it is a crucial parameter for WtE plant energy balancing and new plants capacity and technology design.

One of the key points in the design of WtE plant technology is power-throughput diagram (Figure 1). It is used for dimensioning of plant apparatuses and technologies according to the processing throughput and calorific value of incinerated waste. If the LHV of incinerated waste is incorrectly estimated during WtE plant design, it may result e.g. in reduced steaming rates, reduced efficiency of the steam turbine, in insufficient energy output parameters and consequently in unsustainable economy of the whole project. Problems with the grate burning may also occur.

1.2 State of the art

There are papers devoted to this field of research. Komilis et al (2012) developed empirical equations which describe the LHV of MSW as empirical functions of its elemental composition. Lin et al (2013) devised equations which enable to calculate the LHV by the content of different MSW components. Cucchiella et al. (2014) identified waste generation and its composition as a significant input data for new waste management plant planning. Subsequently, waste LHV is considered as a subject to change in financial sensitivity analysis.

1.3 Determination of waste LHV

The basic procedure for LHV determination of homogeneous fuels is thermal decomposition of tested materials in the calorimeter. Other way for LHV evaluation is its computation from the elemental (chemical) composition. Nevertheless, tthese methods are difficult and unsuitable under operating conditions due to the MSW inhomogeneity and variability of its composition. These laboratory based procedures are considerably time and work consuming too.

Therefore, preferred methods in case of WtE rely on backward calculation from operational data (e.g. steam production, flue gas temperature at boiler outlet). Methodology proposed by Reimann (European IPPC Bureau, 2006) is usually used for this purpose. Thorough statistical analysis of the resulting LHV data is necessary, as shown in Figure 2. The methods based on backward calculation provide LHV data for real WtE plants and their collection areas. This data can be used for analyses described in the paper.

Other applicable way for LHV evaluation is its estimation from the main component composition – paper, plastics, inert minerals, biodegradables, etc. There could be estate methods and tools for values conversion among component composition, elemental composition and fuel LHV. This procedure involves above mentioned laboratory methods.

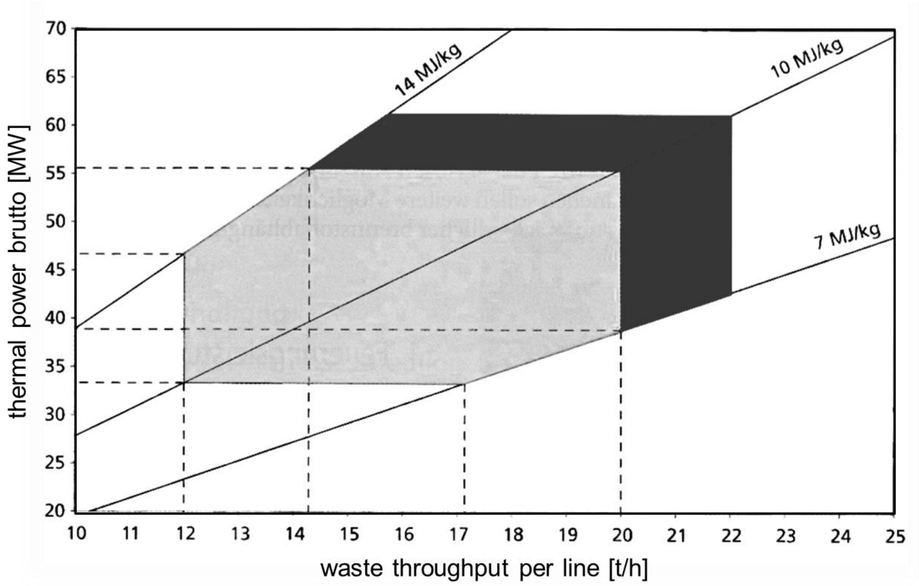


Figure 1: Power-throughput diagram (after Aleßio, 2002)

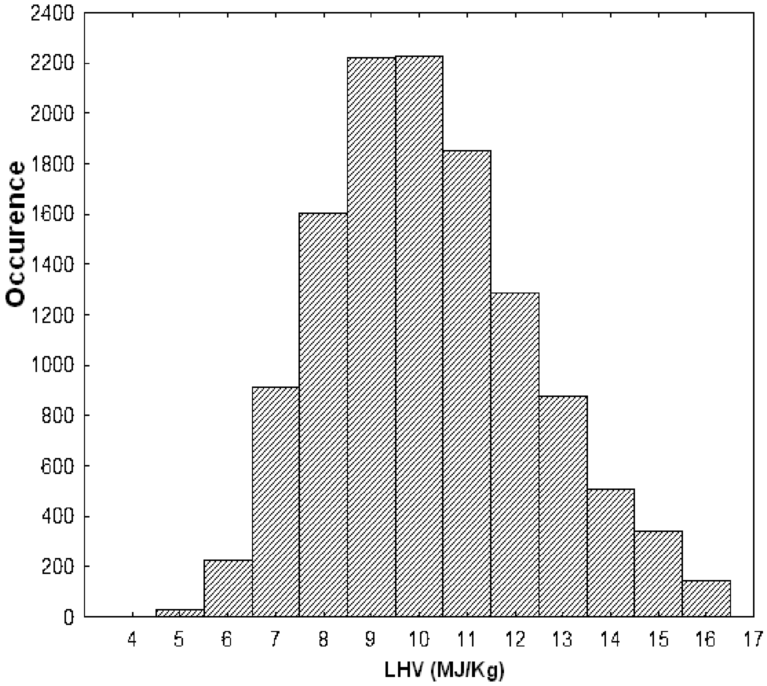


Figure 2: Example of operational data statistical analysis – distribution of fuel LHV

2. Waste composition and waste LHV analysis

Data on the waste composition, or directly its LHV in various regions may be available from several sources, which is illustrated in Figure 3. For example, in case of the Czech Republic these sources include:

- Non-profit authorized packaging company which provides sorting, recycling and recovery of packaging waste. This company collects data on the composition and LHV of the waste treated at a regional and national basis.
- The Ministry of the Environment of the Czech Republic gathers data on the component composition of the waste in smaller territorial units.
- The operational data of existing WtE plants are available as well, if provided by the operator. It can be used to determine the average LHV within their waste collection areas. Methodology for determination of MSW LHV by processing set of operational data from a real WtE plant is presented by Benáčková et al. (2012) or Touš et al. (2013).
- Also long-term waste composition analysis in a few selected locations were realized. These analyses were carried out during whole year, they provide information of waste composition on a monthly basis.

Available data on LHV are shown in Figure 3. The data from the above mentioned sources, however, can never match exactly with each other and there are some variations among them – inaccuracies. To minimize these variations a LHV prediction tool (see chapter 4) is created.

3. LHV prediction in localities as an input for complex optimization

In-house developed optimisation tool NERUDA (Šomplák et al., 2013) represents a powerful tool supporting decision making process related to new WtE plants (location, capacity, technology and heat recovery strategy). The analysed area (e.g. country) is divided in several sub-areas (regions, county level cities, municipalities) and a simulation of a competitive environment is performed, where flow of waste between producers and plants is evaluated. The main input data for such calculation consists of predicted LHV in each single sub-area included in the calculation. Because the data may be not available, nor accurate enough, or its value is source-dependent, a comprehensive computational tool for LHV estimation was created. The tool, which serves as an external data generator for subsequent calculation in NERUDA, is introduced in the paper.

Theoretical approach (transportation problem, supply chain problem) and experience from real waste management systems (incineration plants operation, waste collection systems, etc.) are combined in the NERUDA tool.

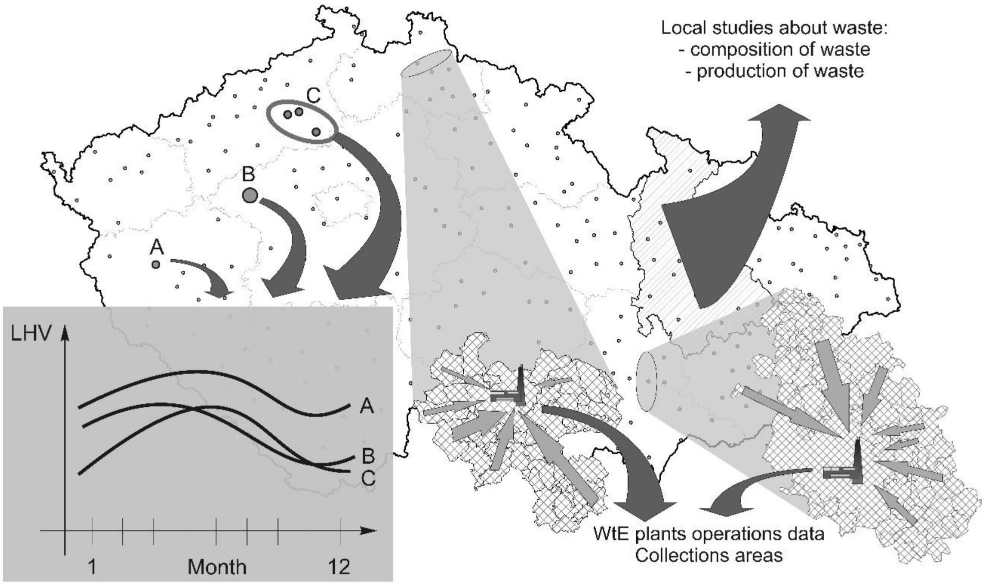


Figure 3: Waste compositions and LHV in Czech Republic – illustration of available data sources

4. Comprehensive tool for LHV prediction

Let us shortly introduce the idea on an example related to specific country – Czech Republic, the geographical division of which is depicted in Figure 4 (left side). The largest territorial unit is the whole state – the Czech Republic represents level 1 in the subdivisions of countries for statistical purposes according to Nomenclature of Units for Territorial Statistics (NUTS). The smallest territorial unit is a municipality (LAU 2). There are intermediate levels between the highest and the lowest level – regions (NUTS 3), districts (LAU 1) and territories of municipalities with extended powers (without NUTS classification). Once we analyze the situation on the municipality with extended powers level, we need accurate values of LHV for approx. 200 subareas – nodes (see Figure 4).

Right side (branch) of the figure represents available data related to processing plants, where average LHV of waste coming from specific collection areas can be calculated from operational data.

Agregated data for some level have to correspond to superior and inferior data sets. Estimated LHV has to correspond one another on the various levels – country, regions, municipalities or collection areas in this case. This principle is expressed by indexes in the following equations – e.g. index “j,I” reflects that district “j“ belongs to a specific set of districts, which together constitute specific region “i“. The sum of information from specific inferior data sets “j“ has to correspond to specific data set “i“. This principle is applied for all interconnected data sets levels.

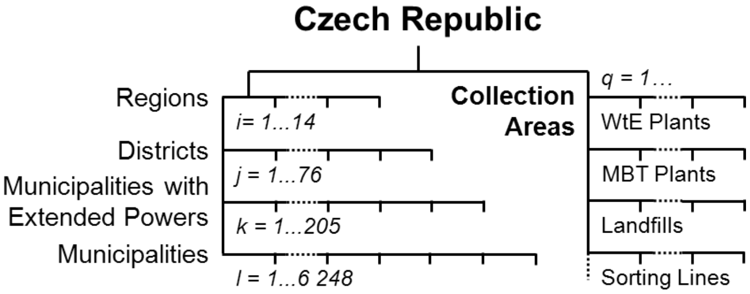
Waste mass production and its LHV belong to the desired parameters of the described model. The design of the comprehensive tool is based on the following assumptions Eqs(1-2).

$$LHV = LHV^{*} + \varepsilon^{LHV} \tag{1}$$

$$m = m^{*} + \varepsilon^{m} \tag{2}$$

where:

LHV	real lower heating value [GJ/t]
LHV^{*}	estimated lower heating value [GJ/t]
m	real amount of waste generated [t/y]



Note: data sets designation: $i \in I$ – regions, $j \in J$ – districts, $k \in K$ – municipalities with extended powers, $l \in L$ – municipalities, $q \in Q$ – collection areas

Figure 4: Tree of territorial units and areas – designation and interdependence of data sets

m^*	estimated amount of waste generated [t/y]
ε^{LHV}	inaccuracy of lower heating value [GJ/t]
ε^{m}	inaccuracy of amount of waste generated [t/y]

The optimizing aim is to find general mathematical model for LHV prediction with acceptable accuracy for majority of subareas. This can be achieved by minimizing of inaccuracies ε. Following equations Eqs(4-8) show the way in which these assumptions are implemented at different levels of territorial units, or for the plants' collection areas.

On the basis of these equations, objective function Eq(3) was created. The inaccuracies in the estimates of LHV are minimized while to each inaccuracy is assigned a relevance depending on the credibility of the source, the number of measured values, etc.

$$z = \sum_{l \in L_q, q \in Q} \varepsilon_{l,q}^{LHV} \cdot \delta_{l,q}^{LHV} + \varepsilon_{l,q}^{m} \cdot \delta_{l,q}^{m} + \sum_{l \in L_k, k \in K} \varepsilon_{l,k}^{LHV} \cdot \delta_{l,k}^{LHV} + \varepsilon_{l,k}^{m} \cdot \delta_{l,k}^{m} + \sum_{k \in K} \varepsilon_{k}^{LHV} \cdot \delta_{k}^{LHV} + \varepsilon_{k}^{m} \cdot \delta_{k}^{m} + \sum_{j \in J} \varepsilon_{j}^{LHV} \cdot \delta_{j}^{LHV} + \varepsilon_{j}^{m} \cdot \delta_{j}^{m} + \sum_{l \in L} \varepsilon_{i}^{LHV} \cdot \delta_{i}^{LHV} + \varepsilon_{i}^{m} \cdot \delta_{i}^{m} \tag{3}$$

And

$$\sum_{i \in I} (LHV_i^* + \varepsilon_i^{LHV}) \cdot (m_i^* + \varepsilon_i^{m}) = (LHV_{CZE}^* + \varepsilon_{CZE}^{LHV}) \cdot (m_{CZE}^* + \varepsilon_{CZE}^{m}), \tag{4}$$

$$\sum_{j \in J_i} (LHV_{j,i}^* + \varepsilon_{j,i}^{LHV}) \cdot (m_{j,i}^* + \varepsilon_{j,i}^{m}) = (LHV_i^* + \varepsilon_i^{LHV}) \cdot (m_i^* + \varepsilon_i^{m}), \tag{5}$$

$$\sum_{k \in K_j} (LHV_{k,j,i}^* + \varepsilon_{k,j,i}^{LHV}) \cdot (m_{k,j,i}^* + \varepsilon_{k,j,i}^{m}) = (LHV_{j,i}^* + \varepsilon_{j,i}^{LHV}) \cdot (m_{j,i}^* + \varepsilon_{j,i}^{m}), \tag{6}$$

$$\sum_{l \in L_k} (LHV_{l.k,j,i}^* + \varepsilon_{l,k,j,i}^{LHV}) \cdot (m_{l,k,j,i}^* + \varepsilon_{l,k,j,i}^{m}) = (LHV_{k,j,i}^* + \varepsilon_{k,j,i}^{LHV}) \cdot (m_{k,j,i}^* + \varepsilon_{k,j,i}^{m}), \tag{7}$$

$$\sum_{l \in L_q} (LHV_{l.q}^* + \varepsilon_{l,q}^{LHV}) \cdot (m_{l,q}^* + \varepsilon_{l,q}^{m}) = (LHV_{k,q}^* + \varepsilon_{k,q}^{LHV}) \cdot (m_{k,q}^* + \varepsilon_{k,q}^{m}), \tag{8}$$

where:

δ^{LHV}	relevances of LHV value inaccuracies [-]
δ^{m}	relevances of MSW mass production value inaccuracies [-]

$$L_q, L_k \subset L, k \in K_j, K_j \subset K, j \in J_i, J_i \subset J, i \in I.$$

Note: $\mathrm{J_i}$ indicates the set of districts of the region i. A similar principle is used for the other territorial units.

5. Conclusions

The paper describes the methodology of inaccuracies estimation of key parameters for energy recovery of the MSW – its mass generation and LHV in a specific area. These parameters are crucial to the high quality design of new WtE plant subsystems. The principle consists in compliance with the essential quantitative and energy balances between various territorial units in a defined area – there is a Czech

Republic example in the paper. To obtain the resulting values for investigated parameters, inaccuracies for the existing estimates are minimized which ensures the validity of balance constraints.

The tool is open for further development – this is necessary to complement in relation with the collection of new data. Larger amount of data will result in a more accurate estimation of the calculated parameters. The next step is a better estimation of relevancies of the individual inaccuracies. To determine the sensitivity of the results due to different relevancies, it is possible to estimate intervals of the relevancies, possibly by a probability distribution, from which it is possible to generate random realizations δ and consequently to analyse the change of the result ε.

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