SELECTED PROPERTIES OF ALTERNATIVE FUEL MANUFACTURED FROM MUNICIPAL SOLID WASTE

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Summary

Successive closing down of filled-up large municipal landfill sites or those which no longer fulfil the legal regulations, compel local governments and enterprises dealing with waste disposal, to undertake activities aimed at designing and construction of new waste management plants. One of these is a municipal solid waste sorting plant where the waste stream is divided into sub-screen and screen fraction. The screen fraction after removing ferrous and non-ferrous metals, glass and other impurities and crushing to an appropriate particle size constitutes an alternative fuel. The most frequently alternative fuel is manufactured from selectively collected plastics, rubber, textiles and waste paper. Alternative fuel is also manufactured from municipal solid waste in mechanical waste treatment plants. Municipal solid waste is characterized by a non-uniform morphological composition (depending on many factors), which may result in variable parameters of the manufactured fuel. If the waste fuel manufactured in this way and supplied to cement plants does not reach certain quality standards, its price is low, or the product is not accepted for energy recovery. The work presents results of analyses of selected properties of alternative fuels generated from solid municipal waste stream with regard to the type of communes from which the waste originated (urban commune area or rural communes). Statistical analysis was conducted using Bayesian Networks.

As it results from the investigations, alternative fuel manufactured from municipal solid waste is characterized by high values of variation coefficient for such parameters as: ash content, moisture and calorific value. The content of carbon, sulphur and incineration heat revealed low values of variance coefficient. The analyses have demonstrated that

technological values of alternative fuel do not depend on the administrative type of the communes where the waste used for their production was collected.

Key words: municipal solid waste, alternative fuel.

INTRODUCTION

In 2010 only 80% of households in Poland signed contracts for municipal waste collection, whereas in 2011 the number was only 1% higher [Ochrona środowiska, 2012]. A new system of municipal waste management has been obligatory in Poland since 1 July, 2013. Its main objective is to include all inhabitants of Poland into the waste collection system (mixed and segregated waste). The applied solutions are meant to guarantee collection and processing of all generated solid waste stream, increasing the share of segregated waste in the structure of collected waste and put an end to illegal dumping sites. As stated by Malinowski [2011], after the introducing of the new system, e.g., in the Małopolska voivodship the mass of collected municipal waste may increase even by 50% in comparison with the amount collected in 2010.

In compliance with both Polish and EU legislation, waste should be recycled prior to the processes of its final disposal (including incineration and depositing). Unfortunately, Poland still lacks municipal waste disposal installations, which causes that a considerable part of the waste is deposited in landfills. One of the alternatives enabling solving this problem is the use of combustible properties of the waste in cement industry [Pawlak *et al.*,2011]. For this purpose mechanical waste disposal plants (sorting plants), where high-caloric waste fractions would be separated from municipal solid waste stream, should be constructed. These plants could be a part of Regional Waste Treatment Facilities.

Processing of municipal solid waste to alternative fuel has many advantages. Manufacturing alternative fuels from waste combustible fraction immediately contributes to diminishing the amount of waste deposited in landfills [Malinowski, 2012]. The use of alternative fuels in rotary kilns of cement plants is also very important for reducing cost, saving fossil fuels and eliminating waste materials, accumulated during production or after using these materials. Cement industries have important potential for supplying preferable solutions to waste management. Energy recovery from waste is also important for the reduction of CO_2 emissions [Madlool et al., 2011]. Slags (about 20-30% of the input mass),

which form during the process of thermal municipal waste disposal in a traditional waste incineration plant, should be deposited on a landfill, whereas during the co-incineration process of alternative fuels in a cement kiln, the problem of slag management does not exist because the incineration residue becomes clinker component. Moreover, also other wastes, arduous for the environment, are used for manufacturing alternative fuel (as the basic component or substrate). These include sewage sludge, used tyres, animal waste, agricultural biomass, wood shavings, sawdust and other substances [Celińska, Marek, 2009; Karcz *et al*., 2009; Oleniacz, 2011; Wzorek, 2009].

Fuels from waste are used in cement plants in many European countries such as France or the United Kingdom, as well as in Canada, the United States and Japan [Mokrzycki *et al*., 2003]. Currently, even 70% of heat in cement plants of the Western Europe is produced by burning alternative fuels. Annually, 40 million Mg of alternative fuel is incinerated in these plants [Zyśk, 2011]. In 2008 about 25% of heat produced in cement plants in Poland originated from burning alternative fuels [Lepucki, Duda, 2009]. In 2009 the amount grew to 36% [Oleniacz, 2012]. The indicator of alternative fuel use in Polish cement plants is still growing.

According to the data from the Polish Cement Association [PCA], currently the cement industry in Poland consists of 13 plants (in 9 major cement groups) with the production of cement at around 15–19 million Mg·year^{-1} in the last few years.

In case of municipal solid waste, separation of so-called combustible fraction does not predispose it for use in a cement kiln. Alternative fuels are a mixture of various wastes and therefore these fuels must fulfill certain criteria. The chemical contents of the fuel must meet regulatory standards to ensure environmental protection [Mokrzycki et al., 2003]. The fuel should be also characterized by homogeneity in all its mass, low moisture, content and high calorific value. The limitations associated with fuel manufacturing apply also to the content of chlorine and sulphur, which negatively affect calcination process and the elements of cement kiln. It should be economically viable along with its availability [Mokrzycki et al., 2003; Pawlak et al., 2011]. Figure 1 illustrates finished alternative fuel manufactured from municipal solid waste. The fuel produced in this way is no longer subjected to agglomeration process and is transported to a cement plant within 48 hours.

Figure 1. Alternative fuel from MIKI Ltd. Installation

The key parameters of alternative fuel which determine its usefulness for incineration in cement kilns are: calorific value (>14 MJkg^{-1}), moisture (<15%), the content of chlorine (<0.8% or <0.2%) and ash (<15%), PCB content – less than 50 ppm, heavy-metal content – less than 2500 ppm [out of which: mercury (Hg) – less than 10 ppm, and total cadmium (Cd), thallium (Tl) and mercury (Hg) – less than 100 ppm] [Sarna *et al.*, 2003; SPC, 2008; Trezza, Scian, 2005]. In some Polish cement plants the criteria admitting an alternative fuel for co-incineration are even more rigorous [Bogacka *et al.*, 2013].

Alternative fuels with lower calorific value are burnt in the calciner at temperatures of 1000–1100°C. More caloric fuels are fed with the carbon to the burner of the main kiln and incinerated in the area of the highest temperatures, which in the gas phase reach 2000°C [Oleniacz, 2012].

Malinowski [2012] states that despite a considerable non-uniformity of the municipal solid waste stream (in view of its fractional and morphological composition), about 500 kg of alternative fuel may be produced from each ton

of municipal solid waste generated in urban areas characterized by a considerable saturation with the facilities of socio-economic infrastructure. Approximately 380 kg of alternative fuel is obtained from 1 Mg of municipal solid waste generated in the urban areas with single family housing, whereas about 270 kg from typical rural areas. The greatest amount of alternative fuel is sorted out in the spring and summer quarters (on average by 4% more than in the autumn and winter quarters). The mass of generated fuel reveals seasonal fluctuations correlated with the changes in municipal waste morphological composition. The highest determination coefficient ($R^2 = 0.72$) was obtained for the relationship between the percentage of alternative fuel obtained from the urban areas and the total share of plastics and paper from these areas (Malinowski 2013). The data for the analyses originated from the research conducted on the installation of MIKI Recykling Ltd. in Krakow.

The mass of alternative fuel obtained from municipal solid waste depends on the place of the waste origin and its technological properties (particularly morphological composition). The question arises whether the place of origin of the waste from which the fuel was manufactured may influence also its quality. The problem emerges from the results of preliminary research on technological properties of alternative fuel manufactured from municipal solid waste by MIKI Recykling Enterprise. The research revealed very high values of the coefficient of variance for water content (total moisture) in the analyzed fuel from waste.

MIKI Recykling Enterprise has been manufacturing alternative fuel since 2011. Annually about 24 000 Mg of fuel for cement industry is manufactured by this enterprise. After separating metals, glass and subscreen fraction (at present this fraction granulation is 0-80 mm) on a sieve drum, the screen fraction remaining on the installation, containing mainly high caloric waste is divided into two streams using pneumatic separator):

- Light waste – dry paper, cardboard, plastics, rubber and textiles, which after crushing to particles of below 10cm^2 constitute alternative fuel with code 191210 (because the fuel is manufactured from municipal solid waste, it may contain some amounts of organic waste);
- Heavy waste – glass bottles (not separated on a sieve drum), large organic waste, wet paper, plastic containers filled with liquids, pampers and many other. Due to high content of biodegradable fractions (over 40%) they are destined for organic recycling.

The main objective of the research was testing a hypothesis assuming the existence of statistically significant differences between the selected technological properties of alternative fuel manufactured from municipal solid wastes originating from various environments (rural commune, urban area with single family housing and urban area saturated with objects of infrastructure).

METHODS

Samples for analyses were obtained from MIKI Recykling Ltd. in Krakow. The analyses of alternative fuel were conducted during the period from July 2012 to April 2013 to consider possible seasonal changes. The investigations comprised physicochemical analysis of 120 alternative fuel samples manufactured from municipal solid waste originating from various areas (60 samples from urban communes – Liszki and Mogilany, 30 samples from urban areas of Krakow with single family housing and 30 samples from the area of Krakow strongly saturated with infrastructural objects). The collected samples were analysed with respect to their density, heat of incineration, total moisture, calorific value, and the content of ash, carbon and sulphur. The analyses were conducted according to the following standards:

1. PN-EN 15443-2011 Solid recovered fuels – Methods for the preparation of the laboratory sample,
2. PN-EN 15400-2011 Solid recovered fuels – Determination of calorific value,
3. PN-EN 15403-2011 Solid recovered fuels – Determination of ash content,
4. PN-EN 15414-3-2011 Solid recovered fuels – Determination of moisture content using the oven dry method,
5. PN-G 04571-1998 Solid fuels – Determination of carbon, hydrogen and nitrogen content in automatic analyzers – Macro method,
6. PN-ISO 351-1999 Solid fuels – Determination of total sulphur content – combustion method at high temperature

Relative air humidity inside and outside the hall was monitored during sample collection. Fuel samples were collected only when relative air humidity outside the hall did not exceed 65%.

Statistical analysis of the research results was conducted using the Statistica 10 package (correlation analysis and ANOVA between means) and the GeNie 2.0 computer programme (*Bayesian networks analysis*) developed by Pittsburg University for scientific purposes. Bayesian networks (BNs), also called belief networks, Bayesian belief networks, Bayes nets, and sometimes also causal probabilistic networks, are an increasingly popular methods for modeling uncertain and complex domains such as ecosystems and environmental management [Uusitalo, 2007].

In Bayesian belief network, a prior probability distribution is assigned to each variable and then the strength of the dependence between each pair of variables is defined. A Bayesian network is a probabilistic model that represents a set of random variables and their conditional independencies via a directed acyclic graph. Formally, Bayesian networks are directed acyclic graphs whose nodes represent variables, and whose edges encode conditional interdependencies between the variables. A Bayesian network could represent the probabilistic relationships between reasons and effects [Gruszczyński, 2010]. The use of probabilistic measures in Bayesian networks results from the fact that the changes of the state may occur according to more or less predictable ambient effect [Bartnik *et al.* 2006].

In environmental research as well as in many other fields, data and parameters often have continuous values, therefore quantitative variable introduced to the GeNie programme before the construction and teaching of the network is subjected to discretization (the first stage of the network construction). The process relies on replacement of quantitative variables by qualitative variables, in result of which the data within each variable are classified into value groups (low, medium, high), so that the subsequent probability of occurrence of determined feature in another variable could be determined for specific classes (value intervals). The classes may generated automatically (3 available methods) or manually. The key problem involved in generating the BN cause-effect networks is the algorithm applied to reconstruct the form of relationships between the system variables. In general, two approaches are possible: construction of a BN only with participation of experts, based on their belief (expert may design graph of the network and parameters for its processing) and construction of the network as a whole – as a reflection of knowledge contained in the database

only [Gruszczyński, 2010]. Quite a serious problem in making adaptation models is defining their generalization properties. With a relatively small amount of data, there is a risk of adjusting a model to a concrete set, which then manifests in a disproportional growth of the error in the classification of the data outside the training set. A commonly applied way of the assessment of this risk is cross validation [Bishop, 2006]. Cross validation was also conducted in the GeNie 2.0 programme.

Table 1. Properties of alternative fuel manufactured from municipal solid fuel originating from various researched areas

Item	Index	Parameter	Units	Alternative fuel manufactured from waste from areas:		
				City – A	City – B	Rural areas
1.	Fuel density	mean	$kg \cdot m^{-3}$	**138**	**142**	**137**
		v_j	%	3.8	4.1	4.7
2.	Fuel moisture	mean	%	**23.2**	**22.8**	**21.7**
		v_j	%	23.1	33.1	35.8
3.	Incineration heat	mean	$kJ \cdot kg^{-1}$	**23755**	**24585**	**24474**
		v_j	%	7.6	6.7	7.4
4.	Calorific value	mean	$kJ \cdot kg^{-1}$	**17024**	**17771**	**17971**
		v_j	%	11.3	14.7	14.2
5.	Ash content in dry mass	mean	% d.m.	**11.9**	**11.9**	**11.5**
		v_j	%	19.8	21.7	18.6
6.	TOC content in dry mass	mean	% d.m.	**43.6**	**44.3**	**44.5**
		v_j	%	1.4	2.6	2.3
7.	Sulphur content in dry mass	mean	% d.m.	**0.257**	**0.277**	**0.299**
		v_j	%	8.4	4.2	8.7

Source: Author's own studies, 2013
(urban area A – single family housing, urban area B –high saturation with infrastructural objects,
v_j – variance coefficient).

RESULTS

During the period from June, 2011 until June 2012, initial analyses were conducted on alternative fuel moisture. Moisture is of crucial importance (beside chlorine content in the fuel) concerning its final assessment and acceptance by cement plant. Initial research revealed that fuel moisture ranged from 12 to 36%. One should remember that moisture of alternative fuel from waste exceeding 30% disqualifies it as energy carrier. The results of technological properties of alternative fuel manufactured from municipal solid waste originating from various areas were compiled in Table 1.

As it results from Table 1, the alternative fuel is characterized by the lowest variability of density (mean 140 kg·m^{-3}), calorific value (mean 24.3 MJ·kg^{-1}, ranging from 20.9 MJ· kg^{-1} to 26.9 MJ kg^{-1}) organic carbon content in dry mass (mean 44.1%) and sulphur in dry mass (mean 0.276%). Variance coefficient assumes the highest values for ash content in dry mass (mean 11.6%, ranging from 5.4% to 16.7%), calorific value (mean: 17.5 MJ kg^{-1}, ranging from 12.4 MJ kg^{-1} to 22.3 MJ kg^{-1}) and moisture (mean 22.6%, ranging from 11.2% to 38.1%).

Moisture of alternative fuel manufactured in MIKI Recykling is one of the parameters which do not meet the quality standards stated for fuels produced for cement industry. Statistical analysis did not reveal any relationship (a lack of significant difference between means) between values of moisture and the other analysed technological values of the fuel and the place of origin of the waste from which it was produced. Incineration heat, ash content and calorific value of the fuel from waste are much higher than the values characterizing a stream of municipal solid waste. On the other hand, the fuel moisture is lower than the moisture of municipal solid waste. On this basis it may be inferred that the installation in MIKI Recykling is working properly, separating very moist waste at the initial stage of the technological process and directing for crushing only the waste with high calorific value.

Alternative fuel moisture may depend on many parameters, both ambient (humidity, air temperature or season of the year) and the inside (morphological composition of the fuel, fuel properties, etc.). Cause-and-effect relationships between all analysed parameters were analysed using Bayesian Search function. Table 2 presents the rules for digitalization of variables.

Table 2. The criteria of discretization of the Bayesian model variables

Item	Original variable name	Units	Variable name in model	Values and limits of variables
1.	Area	-	AREA	City-A, City-B, Rural area
2.	Season	-	SEASON	Summer (July – October), Winter (November – April)
3.	Fuel density	%	DENSITY	LOW (<136), MEDIUM (136-144), HIGH (>144)
4.	Fuel moisture	%	FUEL MOISTURE	LOW (<18), MEDIUM (18-25), HIGH (>25)
5.	Incineration heat	MJ·kg⁻¹	HEAT	LOW (<23), MEDIUM (23-25), HIGH (>25)
6.	Calorific value	MJ·kg⁻¹	CALORIC VALUE	LOW (<16.5), MEDIUM (16.5-18.5), HIGH (>18.5)
7.	Ash content	%	ASH	LOW (<10), MEDIUM (10-13), HIGH (>13)
8.	TOC content	%	TOC	LOW (<43.5), MEDIUM (43.5-44.5), HIGH (>44.5)
9.	Sulphur content	%	SULPHUR	LOW (<0.24), MEDIUM (0.24-0.32), HIGH (>0.32)
10.	Air humidity	%	AIR HUMIDITY	LOW (<55), MEDIUM (55-65), HIGH (>65)

Source: Author's own studies, 2013
(urban area A – single family housing, urban area B –high saturation with infrastructural objects)

Figures 1, 2 and 3 show the distribution of cause-and-effect relationships between the analysed variables and probability distribution of the occurrence of particular state of the analysed variables in regard to the fuel moisture. Figures demonstrate that fuel density, total sulphur content in dry mass, season of the year in which the sample was collected and the area from which the waste originated do not influence any of the analysed factors. Probability distribution does not change either for the incineration heat or the content of carbon and sulphur in dry mass at changing ranges of fuel moisture. Cause-and-effect relationships exist between:

1. incineration heat of alternative fuel and ash content in dry mass and organic carbon content in dry mass,

2. calorific value of alternative fuel and incineration heat and moisture of fuel (the relationship is obvious because calorific value is computed from incineration heat and moisture),

3. Moisture of alternative fuel and air humidity in the production hall and calorific value of the fuel.

A change of fuel moisture value (e.g. from low to medium) causes that probability distribution of obtaining specified ranges of air humidity values in the hall and fuel calorific value change. Obviously, the lower fuel moisture, the higher its calorific value.

However, a connection between air humidity in the production hall (which was always higher than the ambient humidity) and fuel moisture is an interesting relationship. Low values of fuel moisture (Fuel moisture = LOW = 100%) is accompanied by a high probability (70%) that the air humidity in the hall was below 55% (Fig. 2). On the other hand, for fuel moisture over 25% (Fuel moisture – HIGH = 100%), there is a high probability (60%) that the relative air humidity in the hall is also high, exceeding 65% (Fig. 4). However, the assessment of this model concerning fuel moisture is not high. Its precision is 0.63 (on a 0-1 scale, the more the better).
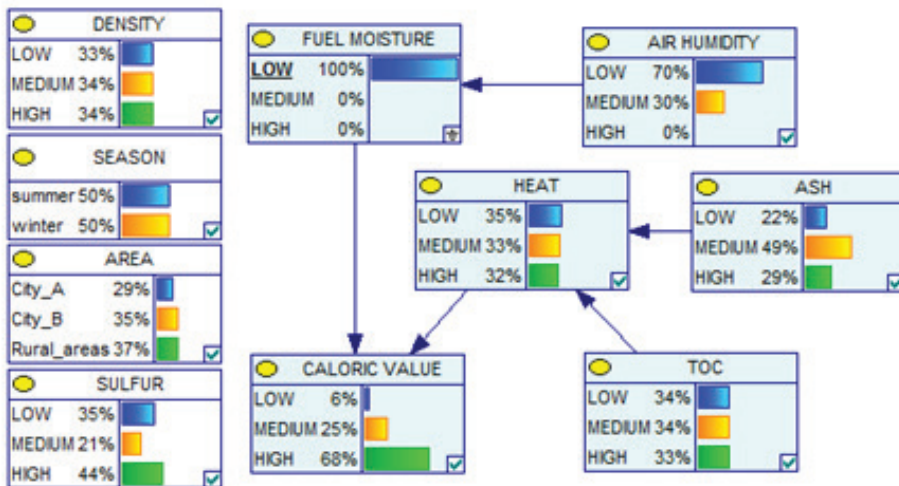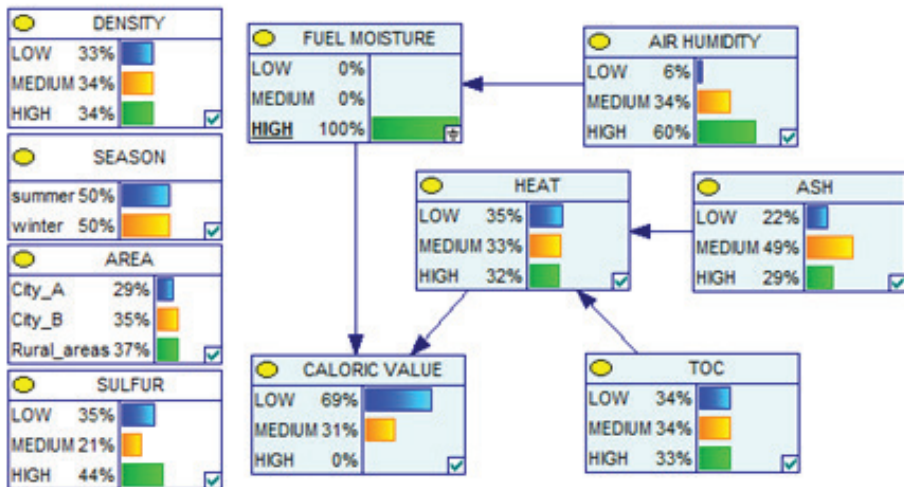

Source: Author's own studies, 2013

Figure 2. Probability distributions for variables of the *Bayesian Network* model variables at determined "fuel moisture – LOW (<18%)"
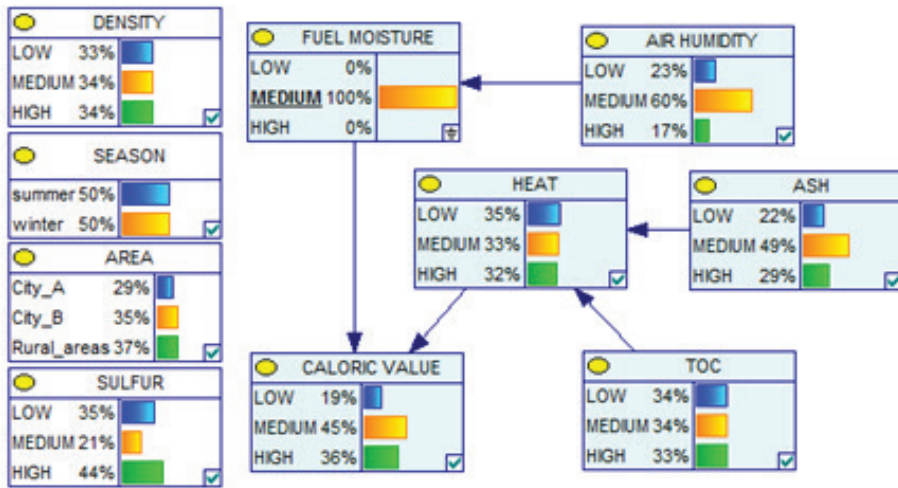
Source: Author's own studies, 2013

Figure 3. Probability distributions for variables of the *Bayesian Network* model variables at determined "fuel moisture – MEDIUM (18 – 25%)"

Source: Author's own studies, 2013

Figure 4. Probability distributions for variables of the *Bayesian Network* model variables at determined "fuel moisture – HIGH (>25%)"

Because the alternative fuel is stored in the hall for the period of between 12 and 48 hours before its transporting to a cement plant, relative air humidity may be one of the factors determining fuel moisture. Relative air humidity in the hall is higher than relative ambient air humidity because during production process also municipal solid waste (with about 40% moisture) is temporarily stored in the hall. The waste returns water in the evaporation process.

In result of conducted investigations it was suggested that the production hall should remain open all the time on dry days (3 gateways), which would ensure exchange of air. 3 additional ventilators and two fuel aerating devices were installed in the hall. Prior to its transportation, alternative fuel is also mixed by an excavator every three hours. Applied solutions caused that mean fuel moisture decreased to the level of 19.5%, while mean calorific value exceeds 18 MJ ·kg^{-1}. Post – implementation analyses were conducted on 20 fuel samples collected during May-June 2-13 period.

Further research on alternative fuel has been planned aiming at decreasing moisture content and improvement of the other fuel properties.

CONCLUSIONS

Fuel manufactured from municipal solid waste is characterized by very good fuel properties. Incineration heat is stabilised on the level of 24 MJ·kg^{-1}. Averaged calorific value of alternative fuel exceeds 17 MJ·kg^{-1}, thus it is higher than e.g. calorific value of agricultural biomass regarded as one of the best sources of renewable energy. Sulphur content in the fuel is very low. Alternative fuel manufactured from municipal solid waste reveals high values of variance coefficient for such parameters as: ash content, calorific value and moisture. The most serious problem of fuel produced from municipal solid wastes is its moisture which may depend on many factors, one of which is relative humidity of air in the production hall. A detailed analysis of the fuel morphological composition and determining the effect of, e.g., the content of biodegradable waste (including particularly organic waste and paper) on the fuel moisture and its other technological properties, is necessary to determine the other factors.

The analyses have demonstrated that the properties of alternative fuel (particularly concerning moisture) do not depend on the type of commune from which the waste used for its manufacturing was collected, therefore they are independent of physicochemical parameters of the waste. Moreover, the research

results allow stating that the installation used by MIKI Recykling enterprise operates correctly, separating very moist waste at the beginning of the technological process and directing only high calorie fractions to final crushing.

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