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Deviations between wind speed data measured with nacelle-mounted anemometers on small wind turbines and anemometers mounted on measuring masts

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Abstract: This article focuses on the readings received from two different types of nacelle-mounted anemometers and their comparison with reference measurements on-site. The aim of the article was to evaluate the influence of the wind turbine rotors on the wind data measured with the nacelle-mounted anemometers. The measurements were made during a case study of two existing small wind turbines. The framework conditions in the analysed cases were similar: both analysed anemometers were mounted on small, 10 kW horizontal axis type wind turbines (HAWT-s) with active yaw and pitch control, and although the wind turbines were situated at different locations, the wind conditions of the measurement sites were relatively similar. The comparative wind speed data for the analysis was acquired in both cases from measurement masts that were installed in the proximity of the analysed anemometers on the basis of the standard EN 61400-12-1:2006. The anemometer readings were logged during measuring periods of two months and saved as 10 minute averages. Three anemometers and a wind direction sensor were used for the reference measurements on both sites. It was found that in both cases the operating state of the wind turbines (presumably the rotation of the rotor blades of the turbine) influenced the readings received from the nacelle-mounted anemometers to a statistically significant extent. The 10 minute average wind speeds of the nacelle-mounted anemometers were significantly lower than the means of the data acquired from the measuring mast anemometers. Despite the fact that the means did not coincide the correlations between the reference wind data and the nacelle-mounted anemometer readings were strong. In the analysed cases the readings from the ultrasonic anemometer were more similar to the reference measurements than the readings from the mechanical cup-anemometer.

Key words: wind measurements, anemometers, accuracy, wind turbines.

INTRODUCTION

Modern wind turbines with active yaw and pitch control rely in their operation on real-time wind speed data, which is used for the automatic control operations. This requires constant wind speed measurements in the proximity of the wind turbine. Normally anemometers that are mounted on the nacelle of the wind turbine are used for acquisition of the necessary data. This occurs due to the fact that the anemometer has to be approximately on the same height with the wind turbine hub and installing a separate mast just for measurements is not reasonable. The problem lies in the fact that the wind turbine and especially the rotating rotor blades of the turbine influence the air flow that has to be measured. And thereby influence the results of the measurements.

Precise measuring results about weather conditions are especially important when evaluating the performance of autonomous or semi-autonomous renewable energy systems (Osadcuks et al., 2013).

MATERIALS AND METHODS

This analysis was based on two small (P_n = 10 kW) wind turbines. Wind Turbine 1 (WT 1) has a hub height of 18 meters and a rotor diameter of 7.2 meters. Wind Turbine 2 (WT 2) has a hub height of 16 meters and a rotor diameter of 8 meters.

Two measuring masts were installed in order to collect data about the wind conditions on the site of each wind turbine. The placement of the measuring masts was chosen on the basis of the standard EN 61400-12-1:2006. The main factors for the correct placement of the measuring mast were:

1) distance from the wind turbine;
2) direction in relation to the main wind direction and wind turbine.

The positioning of the mast is illustrated on Fig. 1.

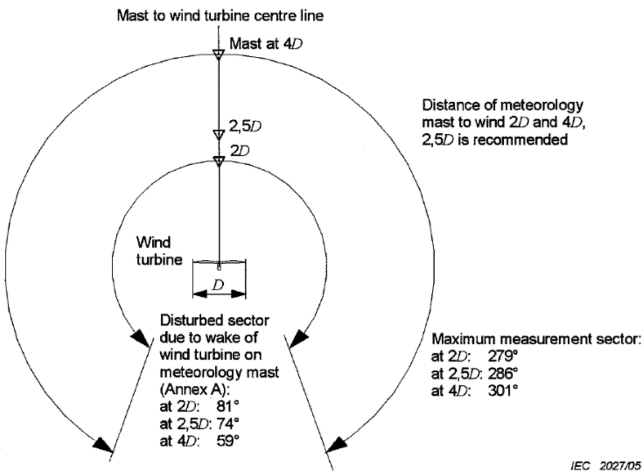

Figure 1. Placement of the measuring mast in relation to the wind turbine (European Committee for Standardisation, 2006).

The measuring masts were placed according to the wind measurement standard (European Committee for Standardisation, 2006) at a distance of 2…4 times the diameter of the wind turbine. The preferred distance is 2.5 times the diameter.The anemometers used for the measurements are described in Table 1.

A 40 meter high wind measurement mast was used for mounting the Thies Clima anemometers. Three anemometers were used on both masts: one on the height equal to respective wind turbine nacelle, one on 26 meters and another on 40 meters height. Also a Thies Clima wind direction sensor on height 40 m was installed on both measuring masts. Wilmers Messtechnik GmbH Wilog 306 loggers were installed on the foot of the mast for the data acquisition.The validity of the reference data from the measuring masts was verified using measurements made on multiple heights. The wind speeds on different heights may be different, because of the ground roughness (Bañuelos-Ruedas et al., 2010; Sen et al., 2012), but nevertheless there should be strong correlations between the data.

Table 1. The main parameters of used anemometers

Anemometer	Thies Clima cup-anemometer, type 4.3303.22.000 (measuring mast)	AirMar 150WX (Wind turbine 1)	SMA Wind Sensor (Wind turbine 2)
Measuring range	0.3 – 50 m s^{-1}	0–40 m s^{-1}	0.8–40 m s^{-1}
Accuracy	± 0.3 m s^{-1} / ± 2 % of m.v.	0 m s^{-1} to 5 m s^{-1}; 0.5 m s^{-1} + 10 % of reading 5 m s^{-1} to 40 m s^{-1}; 1 m s^{-1} or 5 %, dependant which is greater	± 5%
Electrical output	3–1042 Hz 4–18 V DC	9 – 40 V DC	n a^{-1}

The data was at first compared with a T-test, to test the similarity of the results from the nacelle anemometers with the reference data. The following hypotheses were made:

1. H1: The means of the data from the wind turbine anemometer and the reference anemometer on the same height are significantly different (but there may be a correlation between the data).
2. H0: The means of the data are similar.

For the initial comparison a T-test was applied to the data from the wind turbine anemometer and the reference data. The pairwise comparison was used because the time of each measurement was important (Kaart, 2012). The software package R was used for the statistical analysis.

The time steps where the nacelle anemometer or reference anemometer data was not available were neglected. Also the data from time steps when the wind direction was from the disturbed sector was neglected.

The T-test analyses the data on the hypothesis whether the mean nacelle anemometer results and reference anemometer results are significantly different, but it does not give an estimation about the correlation of the results.

Pearson and Spearman correlation coefficients were calculated in order to analyse the strength of relations between the nacelle-anemometer data and reference anemometer data. The Pearson correlation analyses the linear correlation of the results and the Spearman correlation analyses the rank correlation of the named parameters. The rank correlation describes the monotony of the relation.

The categorisation between the correlation coefficients can vary to some extent by approach. For the present analysis the approach shown in Table 2 is used (Dancey & Reidy, 2004).

Table 2. Strength of Correlation (Dancey & Reidy, 2004)

Value of the Correlation Coefficient	Strength of Correlation
$\lvert r \rvert = 1$	Perfect
$0.7 < \lvert r \rvert \leq 0.9$	Strong
$0.3 < \lvert r \rvert < 0.7$	Moderate
$0.1 < \lvert r \rvert \leq 0.3$	Weak
$r = 0$	Zero

As the number of measurements was relatively high (8000+ measurements at WT 1 and 4000+ measurements at WT 2), some of the graphic illustrations (Figs 3 and 7) of the data were compiled using the method of bins described in the standard EN 61400-12-1:2006 in annex K: In situ comparison of anemometer. The data sets were averaged using 1 m s^{-1} bins. (European Committee for Standardisation, 2006).

RESULTS AND DISCUSSION

Wind Turbine 1

Measurements at the location of WT 1 were made from 20.10.2013 to 21.12.2013. The readings were registered as 10 minute averages in 8811 time steps. From this data set 8,345 time steps were used for the further analysis, the other time steps had to be neglected because of the criterion that were described in the previous chapter.

The location of wind WT 1 is in North-Estonia, 42 kilometres away from the coast. The wind roses that were created on the basis of the data measured at different heights of the measuring mast are shown on the following Fig. 2.

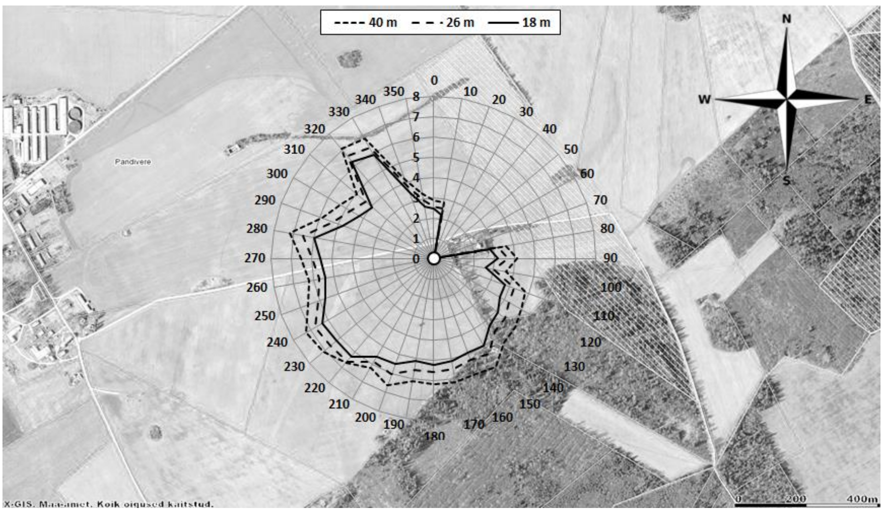

Figure 2. Wind roses on three different heights at the location of WT 1 (Estonian Land Board, 2014).

Fig. 2 shows, that as expected, the main wind direction is from the south-west, as it is common for this part of Estonia (Kull, 1996). The similarity of the wind roses on different heights indicates a strong correlation of the measuring mast anemometer readings and the validity of the reference anemometer measurement results. The excision in the north-east sector of the wind roses (Fig. 2) is caused by the positioning of the measuring mast in relation to the wind turbine (Fig. 1). The wind roses on different height give also indication about the ground roughness of different directions. The lines representing the average wind speed are more away from each other on the directions were the ground roughness is higher – like the forest area to the south of the measuring location (Fig. 2).

The parameters of the wind speed measured at the location of WT 1 are summarized in Table 3.

Table 3. Summary of measurement results at the location of WT 1

Parameter	WT anemometer 18 m	Measuring mast anemometers 18 m	26 m	40 m
Mean wind speed, m s^{-1}	3.72	5.17	5.58	6.01
Median wind speed, m s^{-1}	3.40	5.02	5.41	5.94

The T-test results of the collected data on Wind Turbine 1 (WT 1) showed that the mean difference of the nacelle anemometer reading and the reference anemometer is 1.455 m s^{-1}. The p-value found in the test is smaller than 0.05%, this gives a basis for the assumption that the wind turbine had a statistically significant influence on the results measured with the nacelle-anemometer.

It was found that the wind turbines (presumably the transient rotor blades of the turbine) influence the measuring results of the nacelle-mounted anemometers to a significant extent in both cases.

The test results showed also, that the confidence interval on a 95% significance level is 1.426 to 1.484 m s^{-1}. It means, that with a 95% confidence can be said that the mean difference between the nacelle anemometer and reference anemometer readings is in the range of 1.426 to 1.484 m s^{-1}, when the framework conditions remain the same.

The linear and rank correlation coefficients of the data from wind turbine 1 are shown in Table 4 and Table 5 respectively.

Table 4. Pearson correlations between the data measured on WT 1 and the reference data

-		WT anemometer 18 m	Measuring mast anemometers 18 m	26 m	40 m
WT anemometer	18 m	1.000	0.874	0.874	0.871
Measuring tower anemometers	18 m	0.874	1.000	0.996	0.985
	26 m	0.875	0.996	1.000	0.993
	40 m	0.871	0.985	0.993	1.000

From Table 5 it can be concluded that the linear correlation between the nacelle anemometer and reference anemometer on the same height is strong (the correlation coefficient is 0.874).

The coefficients between the different heights of the measuring mast were in the range of 0.985 to 0.993, which refers to an almost ideal relation. This gives ground to conclude that the reference anemometers were calibrated correctly and there were only little wind turbulences at the measuring site.

The Spearman rank correlation coefficients in Table 5 show the monotony of the relation. The monotone relation shows, that if the reading of one anemometer grows, then also the reading of the other compared anemometer increases, and this relation is relevant for the entire measuring range.

Table 5. Spearman rank correlations between the data measured on WT 1 and the reference data

-		WT anemometer 18 m	Measuring mast anemometers 18 m	26 m	40 m
WT anemometer 18 m		1.000	0.906	0.905	0.900
Measuring tower anemometers	18 m	0.906	1.000	0.997	0.986
	26 m	0.905	0.997	1.000	0.993
	40 m	0.900	0.986	0.993	1.000

The Spearman rank correlations are slightly higher than the linear correlation coefficients. This gives ground to conclude that the differences between the nacelle anemometer and reference anemometer are not even during the entire measuring range. The relation of nacelle anemometer and reference anemometer readings in the most relevant range for the wind turbine (from 3 to 12 m s^{-1}) is shown in Fig. 3.

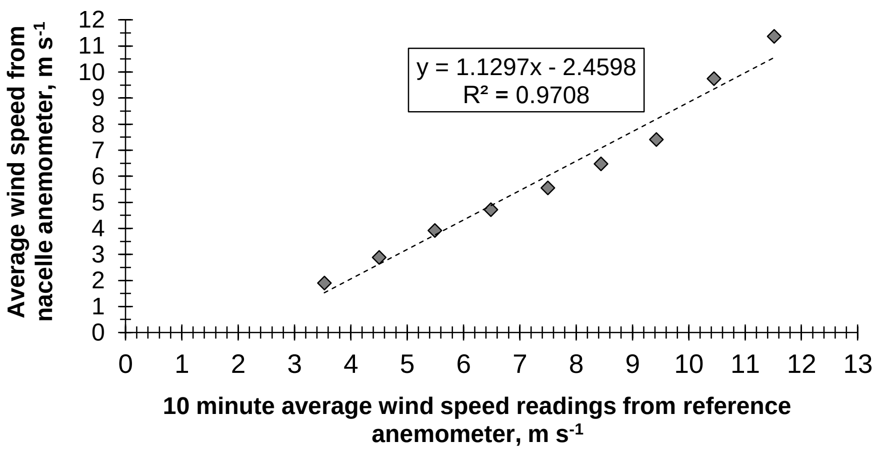

Figure 3. Relation of WT 1 nacelle anemometer and reference anemometer readings.

Fig. 3 shows 10 minute averages, which can be used to assess the real wind speed on the basis of the nacelle anemometer speed. It has to be noted that this figure can only be used for assessing the actual wind speed when the specific wind turbine is working. The measurement range of 3 to 12 m s^{-1} is given due to the fact that a simple dependence could not be given outside this range. Most of the measured wind speeds fell in that range as well (Fig. 4).

The frequency distribution and Weibull function of the reference anemometer of WT 1 are shown in Fig. 4.

A Weibull distribution curve with a shape parameter of k = 2.24 and a scale parameter of λ = 5.87 was fitted to the frequency distribution. A shape parameter of 2 (which results in a Rayleigh distribution) is considered as the most common value for a wind speed distribution in the Baltic area (Bisenieks et al., 2013).

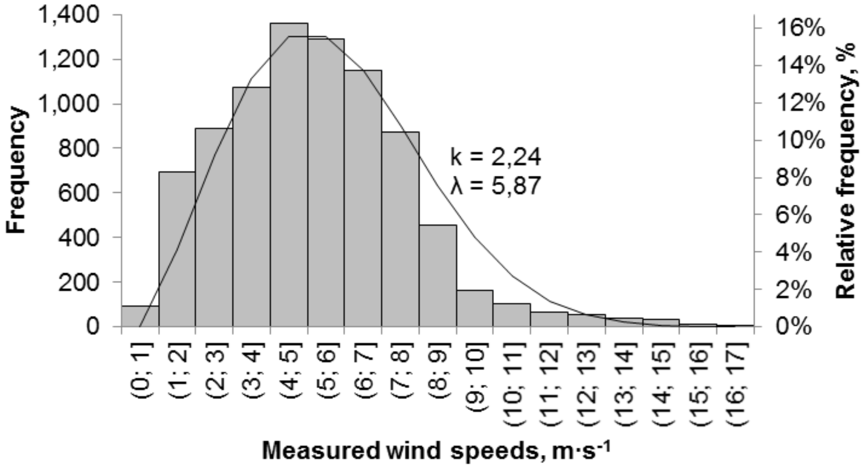

Figure 4. Frequency distribution and approximated Weibull distribution of the wind speed measurement results from the reference anemometer of WT 1.

For comparison, the nacelle anemometer results of WT 1 are presented on the following Fig. 5.

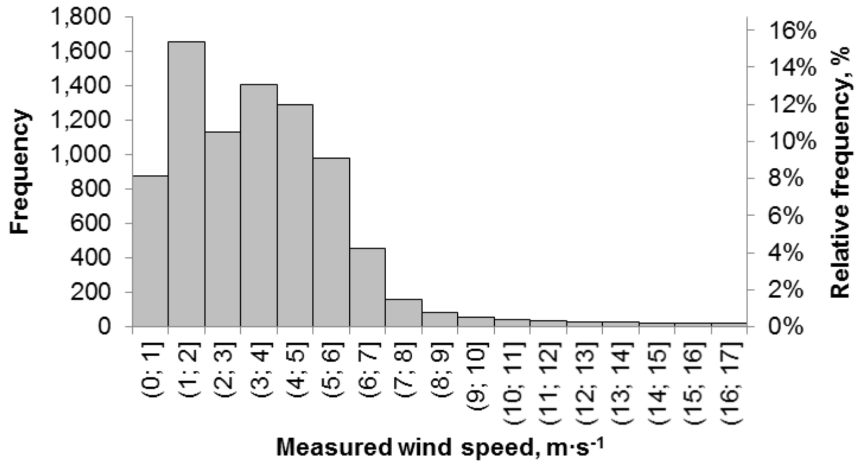

Figure 5. Frequency distribution of the wind speed measurement results from the nacelle anemometer of WT 1.

From Fig. 5 can be seen, that the nacelle anemometer results do not follow a Weibull distribution and their frequency distribution is significantly different from the frequency distribution of the reference anemometer results. The distribution is shifted to lower wind speeds. The discrepancies are especially in the range of the lowest wind speeds. The cut-in speed of WT 1 is in the range of 3 m s^{-1} and this causes that many of the nacelle anemometer results fall into the ranges of 0 to 1 and 1 to 2 m s^{-1} in time steps where the reference (actual) wind speed is from 3 to 5 m s^{-1}.

Wind Turbine 2

The location of wind WT 2 is on the Estonian island of Saaremaa, 5 kilometres away from the sea. For the Wind Turbine 2 (WT 2) the measurement period was also 2 months long. The measurements were made from 09.11.2013 to 11.01.2014. The readings were registered as 10 minute averages in 9060 time steps.

For the current analysis only the data from time steps was used, when the wind direction was not from the disturbed sector (Fig 1) and the data from wind turbine and measuring mast both were available. There were 4,872 time steps, were the data met those criterion.

The wind roses from different heights of the measuring mast at the location of WT 2 are shown on the following Fig. 6.

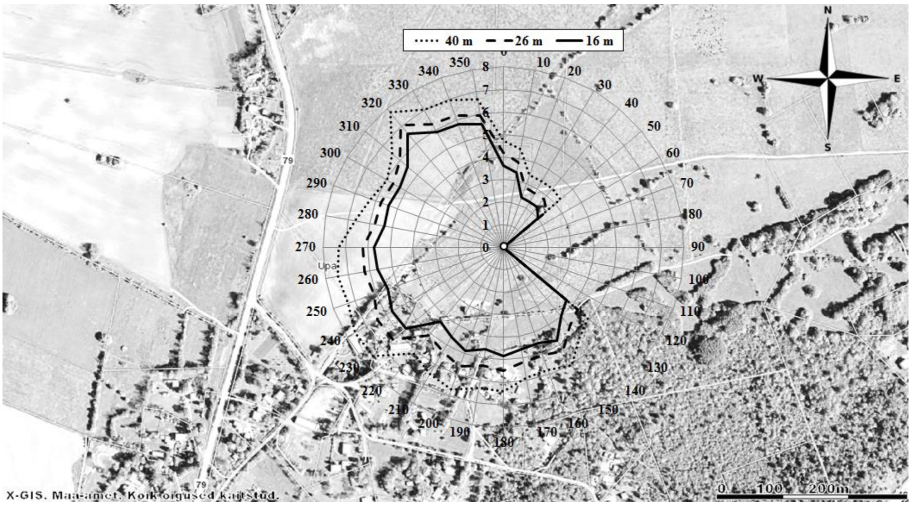

Figure 6. Wind roses on three different heights at the location of WT 2 (Estonian Land Board, 2014).

On Fig. 6 can be seen that the main wind direction on the site of WT 2 is from south-west. The influence of nearby buildings can also be seen on the wind roses. It can be said that the wind conditions at the site of WT 2 are because of the surrounding landscape more turbulent than on the site of WT1. The excision in the eastern side of the wind roses is caused by the positioning of the measuring mast in relation to the wind turbine.

The summary of the wind data described above is shown in Table 6.

Table 6. Summary of measuring results in the proximity of WT 2

Parameter	WT anemometer 16 m	Measuring mast anemometers 16 m	26 m	40 m
Mean wind speed, m s^{-1}	2.96	5.21	5.84	6.83
Median wind speed, m s^{-1}	2.70	5.02	5.63	6.58

The T-test, which was made on the basis of the data from the nacelle anemometer of WT 2 and the reference anemometer in the proximity of wind turbine, showed that the mean difference of the comparable data pairs was 2.25 m s^{-1}.

The p-value found in the T-test was under 0.05, this means that the wind turbine influenced the nacelle anemometer results to a statistically significant amount. The test showed also that on the confidence interval on a 95% significance level was 2.22 to 2.28 m s^{-1}, which means that with a 95% confidence can be said that the mean difference between the readings on the nacelle anemometer and reference anemometer would remain in this range if the other framework conditions would remain the same.

The correlation coefficients for the data measured at WT 2 are shown in the following tables (Table 7 and Table).

Table 7. Pearson correlations between the data measured on WT 2 and the reference data

-		WT anemometer	Measuring mast anemometers		
		16 m	16 m	26 m	40 m
WT anemometer	16 m	1.000	0.812	0.797	0.772
Measuring mast anemometers	16 m	0.812	1.000	0.982	0.949
	26 m	0.797	0.982	1.000	0.979
	40 m	0.772	0.949	0.979	1.000

From Table 7 can be concluded, that the correlation coefficient between the nacelle anemometer and reference anemometer is strong, but not very strong, the correlation coefficient is 0.812. The linear correlations between the anemometers were in the range from 0.949 to 0.982, which lets conclude, that the correlation between the anemometers on the measurement mast was very strong.

The correlation coefficients were slightly lower than the correlations on the measuring mast in the proximity of Wind Turbine 1. This could be caused by more turbulent wind conditions.

Table 8. Spearman correlations between the data measured on WT 2 and the reference data

-		WT anemometer	Measuring mast anemometers		
		16 m	16 m	26 m	40 m
WT anemometer	16 m	1.000	0.929	0.920	0.896
Measuring mast anemometers	16 m	0.929	1.000	0.985	0.954
	26 m	0.920	0.985	1.000	0.981
	40 m	0.896	0.954	0.981	1.000

The Spearman rank correlations are also at the WT 2 slightly higher than the linear correlation coefficients. This gives ground to conclude that the differences between the nacelle anemometer and reference anemometer are not even during the entire measuring range.

The relation of nacelle anemometer and reference anemometer readings in the most relevant range for the wind turbine (from 3 to 12 m s^{-1}) is shown in Fig. 7.

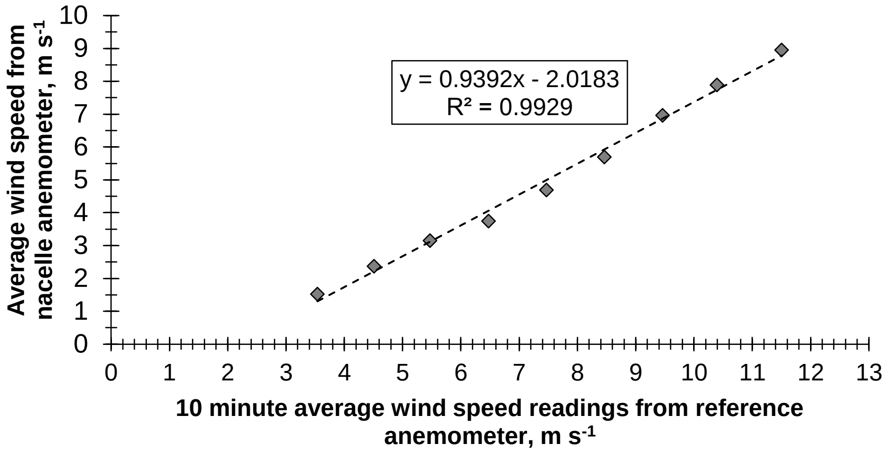

Figure 7. Relation of WT 2 nacelle anemometer and reference anemometer readings.

The frequency distribution and Weibull function of the reference anemometer of WT 2 are shown in Fig. 8. Weibull distribution curve with a shape parameter of $k = 2.24$ and a scale parameter of $\lambda = 5.87$ was fitted to the frequency distribution.

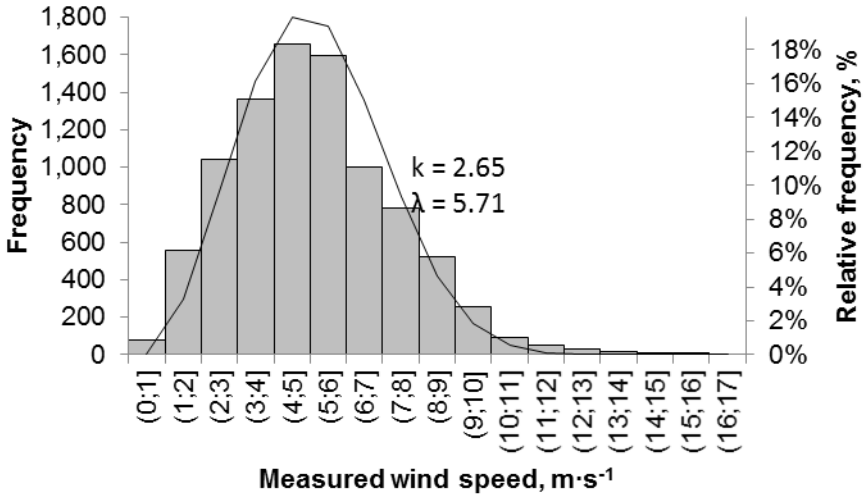

Figure 8. Frequency distribution and approximated Weibull distribution of the wind speed measurement results from the reference anemometer of WT 2.

For comparison, the nacelle anemometer results of WT 2 are presented on the following Fig. 9.

From Fig. 9 can be seen, that the WT 2 nacelle anemometer results can also not be approximated with the Weibull distribution, but they are more similar to a Weibull distribution than the results from WT 1 (Fig. 5).

The comparison of Fig. 8 with Fig. 9 shows the slowing down effect of the rotor blades to the wind measured with the nacelle anemometer. The most frequent wind speed range at the nacelle anemometer is 2 to 3 m s^{-1}. This is 2 m s^{-1} less (which is consistent with the T-test results) than the most frequent wind speed range at the reference anemometer, 4 to 5 m s^{-1}.

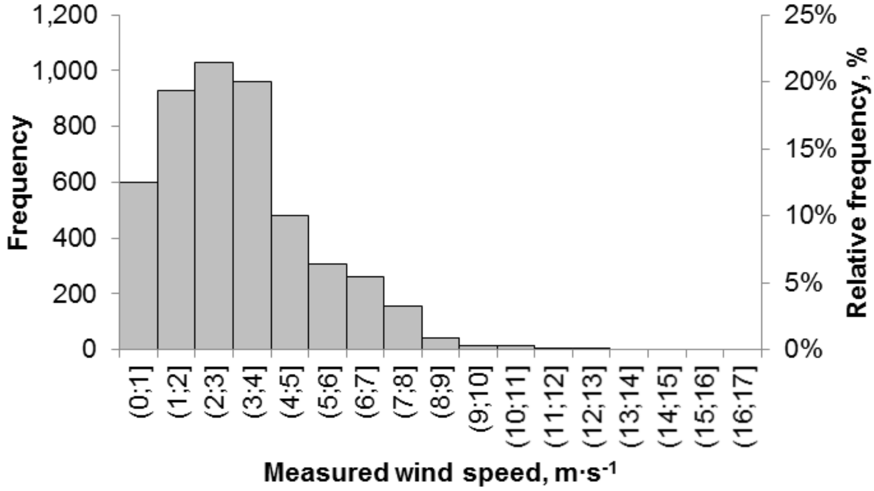

Figure 9. Frequency distribution of the wind speed measurement results from the nacelle anemometer of WT 2.

By comparing the results from WT 1 and WT 2 can be seen that the differences between the nacelle and reference anemometer readings were smaller on WT 1. This could be caused by less turbulent wind conditions, more advanced anemometer technology (ultrasonic anemometer) and more stable wind turbine operation.

CONCLUSIONS

It was found that, when the wind turbines are operational, the rotation of the rotor blades influences significantly the measurement results of the nacelle-mounted anemometers in both analysed cases. The wind roses compiled on the basis of the reference measurement data were as expected. The means of the 10 minute wind data from wind turbine nacelle´s anemometers were significantly lower than the means of the data acquired from the reference measuring mast anemometers. The average difference of nacelle and reference anemometer readings at Wind turbine 1 was 1.45 m s^{-1} and at Wind turbine 2 was 2.25 m s^{-1}. One of the reasons for the smaller difference at Wind turbine 1 can the less turbulent wind conditions on the site of Wind turbine 1.

Despite the fact that the means were different the correlations between the reference wind data and the nacelle-mounted anemometer readings were strong. In the analysed cases the reading from the ultrasonic anemometer was more accurate (smaller difference and stronger correlation) than the reading from the mechanical cup-anemometer. It has to be noted the numerical relations and specific findings are based on the specific cases where the measurements were done. In practice the results from nacelle anemometers can be used for indication. When the data has to be used for more exacting purposes, like for the automatic control of the turbine, then an individual correction algorithm should be found for the specific wind turbine and anemometer combination. Future work could concentrate on the differences between anemometer readings when the rotor is in the cut-out regime (the rotor stands still) and the situation right before the cut-out wind speed.

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REFERENCES

AIRMAR WX Series Ultrasonic Weather Station Instruments, Available at: http://www.airmartechnology.com/uploads/Brochures/WX%20Series%206%20page%20Brochure%20FINAL%20printer.pdf [online][viewed 15.01.2014].

Bisenieks, L., Vinnikov, D. & Galkin, I. 2013. PMSG based residential wind turbines: possibilities and challenges. *Agronomy research* **11**, 295–554.

Bañuelos-Ruedas, F., Angeles-Camacho, C. & Rios-Marcuello, S. 2010. Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights, *Renewable and Sustainable Energy Reviews* **14**, 2383–2391

Estonian Land Board, Geoportal, Web Map Server, Available at: http://xgis.maaamet.ee/xGIS/XGis [online][viewed 15.01.2014].

European Committee for Standardisation, Standard EN 61400-12-1:2006, Wind turbines Part 12-1: Power performance measurements of electricity producing wind turbines

Kaart, T., Matemaatiline statistika ja modelleerimine (Mathematical Statistics and Modelling) Available at: http://www.eau.ee/~ktanel/DK_0007/loengud.php (30.12.2013) (in Estonian)

Kull, A., *Eesti Tuuleatlas* (Estonian Wind Atlas) 2003. (in Estonian)

Osadcuks, V., Pecka, A. & Selegovskis, R. 2013. Energetic balance of autonomous hybrid renewable energy based EV charging station in winter conditions. *Agronomy research* **11**, 357–366.

SMA Solar Technology AG, SMA Sunny Sensorbox Manual, available at: http://www.affordablesolar.com/site/doc/Doc_Sunny%20SensorBox%20Manual_20080311124256.pdf [online][viewed 15.01.2014].

Sen, Z., Altunkaynak, A., & Erdik, T. 2012 Wind Velocity Vertical Extrapolation by Extended Power Law, *Advances in Meteorology* **2012**. Article ID 178623, 6 p.

Wilmers Messtechnik GMBH, Data Loggers by Wilmers Messtechnik, Available at: www.wilmers.com/html_en/html/dataloggers_en.html [online][viewed 15.01.2014].

Thies Clima, Measurement and Documentation: Thies' range of service for meteorology, environmental protection and industry, Available at: http://www.nerc.gov.jo/Wind/instruments/THIES%20catalog%20wind_compact%20sensor.pdf [online][viewed 30.12.2013].

University of Strathclyde, Correlations: Direction and Strength, available at: http://www.strath.ac.uk/aer/materials/4dataanalysisineducationalresearch/unit4/correlationsdirectionandstrength/ [online][viewed 30.12.2013].

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Application of high temperature catalysis to abate emissions from a small scale combustion system

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Abstract. A newly designed downdraft wood stove achieved low-emission heating by integrating an alumina-supported mixed metal oxide catalyst in the combustion chamber operated under high temperature conditions. Since the mixed metal oxide catalysts have been the center of attention regarding their applicability at high temperatures, a novel idea has been put into practice by integrating them in a small scale combustion system in order to mitigate the emissions. The alumina-supported mixed metal oxide catalyst reduced the volatile hydrocarbons, carbon monoxide and carbonaceous aerosols by more than 60%.

Key words: Small scale biomass combustion, Mixed metal oxide, Catalysts, Emission reduction, Pressure drop.

INTRODUCTION

The use of biomass or bioenergy can be traced back to the beginning of human civilization when people started to burn wood for heating and cooking purposes. Ironically, after so many years have gone by, wood still remains the largest biomass resource in the world (Demirbas, 2009). However, one major difference which has occurred over this period of time is the introduction of the concept 'modern biomass' which states the usage of traditional biomass resources in highly efficient systems. This concept has been put into practice with more conviction and determination during the last decade, particularly in Europe, due to ever rising CO_2 levels in our environment. By now, it is an established fact that about 10–30% of total energy demand for hot water supply and domestic heating in European countries like, Austria, Germany, Sweden and Finland is provided by small scale biomass combustion systems (Junginger et el., 2011). Moreover, it has been also concluded that despite the vast spread of technologically advanced small scale combustion devices in European countries (like countries mentioned above) during the recent years, still the old biomass combustion systems (stoves and boilers) occupy more consumers (Jokiniemi et al., 2008). These conventional systems which are based on natural draft play a pivotal role in contributing to the high emission levels of particulate matter (PM), carbon monoxide (CO), organic gaseous compounds (OGC) and polycyclic aromatic hydrocarbons (PAH). These facts and figures have triggered an enormous understanding and awareness among the researchers as well as local population concerning harmful pollutants emitted by residential biomass combustion systems. For this reason inefficient small scale biomass combustion systems have been heavily criticized and demanded to be replaced by new efficient technologies.

Speaking of older and newer technologies, it has to be mentioned here that two types of technologies exist concerning small scale biomass combustion systems. The old biomass combustion systems are based on 'up-burn' which is in a process of being rapidly replaced by 'down-firing' systems (new technologies). As mentioned above, these older systems are a main source of PM_1 (particles with diameter less than 1 μm) in European countries. It has been also concluded that such particles serve as a purpose of 'support' onto which carbonaceous particles (organic compounds and soot) are deposited which are primarily responsible for the adverse health effects (Kelz et al., 2010). So in order to counter such an undesired release of pollutants, particularly from small scale biomass systems, a concept has been conceived according to which 'down-firing' technology will be implemented in specially designed wood log stove in combination with catalytic treatment in order to abate harmful emissions to minimum possible values. It is noteworthy to mention here that the abatement of emissions through catalytic treatment from small scale biomass combustion systems has not been studied or implemented on a wide scale. So this novel concept of integrating catalytic components in different parts of the stove i.e. grate, walls of combustion chamber and the base will open more channels and schemes in order to accomplish the acceptable emission levels coming out of biomass combustion systems particularly, those used for residential purposes.

In the past, the process of catalysis has been strongly linked to chemical and refinery industries. However, recently the catalytic converters have been deployed and installed in automobiles, biomass fired boilers and power generation facilities in order to promote the environmentally friendly usage of technological devices. It has been estimated that the market of catalysis around the world worth around US $ 9 billion, out of which, one third is occupied by the environmental catalysis. So building on this ever growing trend of environmental catalysis, this article gives a further insight into the integration of catalytic components in a downdraft wood log stove to foresee the feasibility of this novel approach to resolve the problem of high emissions (e.g. carbon monoxide, volatile organic compounds, dust particles etc.) at small-scale furnaces for solid biomass

MATERIALS AND METHODS

Setup and description of the tested equipment along with measuring techniques

A test bench has been developed (as shown in the Fig. 1) in order to examine the emissions from a prototype downdraft stove. The test bench is designed in such a way that it can facilitate the analysis of dust composition.

For the determination of flue gas and combustion chamber temperature profiles, the thermocouples of Type K (manufactured by the company 'Newport Electronics GmbH') have been used. For this purpose, a set of various thermocouples has been inserted into the grate, in the middle of upper and lower combustion chambers as well as in the walls of the lower combustion chamber. Moreover, the pressure conditions were recorded with the help of pressure sensors, inserted into the combustion chambers (upper and lower) as well as into the exhaust pipe. The measurement of static and dynamic pressures in the flue gas has been done with the aid of Prandtl tube produced by the company ‘Testo AG’. The continuous transmission and data recording of Prandtl tube and pressure nozzles in the combustion chamber is carried out through data logging module provided by the company ‘Ahlborn’. The data of the thermocouples have been recorded through a data logger of the company ‘National Instruments’ along with the help of the software ‘Labview’.

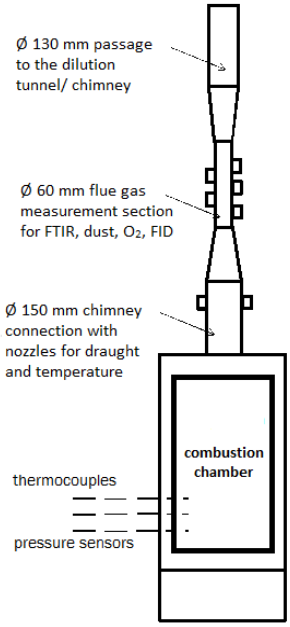

Figure 1. Illustration of the test bench with a flue gas measurement section (hot) for the emission measurement.

The emissions coming out of the stove are measured by means of a gas analyzer which consists of a Fourier Transform Infrared Spectrometer (FTIR, Manufacturer: Calcmet), a Flame Ionization Detector (FID, Manufacturer: Mess- & Analysentechnik GmbH, Typ: thermo-FID ES) and a paramagnetic oxygen analyzer (Manufacturer: M&C, Type: PMA 100). The infrared spectrum of FTIR can measure simultaneously organic as well as inorganic components. At the moment, about 44 different components can be recorded through FTIR.

The Volatile Organic Compounds (VOC) can be recorded by means of both FID and FTIR measuring devices. In case of VOC, the concentrations ranging under 50 mg m^{-3} (at standard conditions i.e. = 0°C, 1 atm) can be considered from the FID measuring device. On the other hand, the values above 50 mg m^{-3} (at standard conditions i.e. = 0°C, 1 atm) can be assumed from the FTIR measuring device. Following parameters can be measured simultaneously:

1. Oxygen O2 (paramagnetic analyzer).
2. Carbon dioxide (FTIR).
3. Moisture in the flue gas i.e.H2O (FTIR).
4. Carbon monoxide CO (FTIR).
5. Volatile organic compounds (VOC) as organic carbon (Org.-C) (FTIR and FID).
6. Nitrogen oxide as nitrogen dioxide equivalent (NO2equi) (FTIR).
7. Sulphur dioxide SO2 (FTIR).
8. Methane CH4 (FTIR).
9. Organic compounds like, alkanes, alkenes, aromatics, aldehydes as well as ketones (FTIR).
10. Flue gas temperature, gas velocity and draft conditions.

The recording of the above mentioned parameters took place on continuous time basis except for the dust measurement. During the evaluation of the data, the average values of the pollutants were calculated for each dust sampling cycle whereas each cycle lasts for 30 minutes. With the aid of a chimney fan, a constant negative pressure of 12 Pa has been maintained in the chimney stack in order to achieve a fuel thermal output from 8 to 9 kW.

The gravimetric analysis of total amount of dust was done in accordance with VDI guidelines 2066-1, according to which a partial volume flow must be taken in isokinetic manner out of the main flue gas stream. In this process, the accompanied particles can be deposited on the already weighed plane filter. Since the filter housing is located outside the flue gas pipe, this sampling procedure is termed as 'out-stack process'. The filter system was heated up with a heating jacket in order to prevent the falling down of temperature under saturation temperature of the flue gas. The temperature of the filter was maintained at 70°C so that the semi-volatile hydrocarbons could also be deposited on the filter. After the experiment, the deposited dust amount was determined gravimetrically and then can be specified by taking into consideration the measured partial volume and oxygen concentration. The plane filter was made of micro-glass fibers having a diameter of 45 mm.

Used fuel and its properties

The beech wood has been used as a fuel throughout the whole series of experiments due to its excellent firing properties. The composition of the fuel is listed under the Table 1.

Table 1. Fuel content of beech wood used during the experimental stage

Parameters	Result	Unit
Volatile substances	84.5	% (dry matter)
Ash content 550°C	1.91	% (dry matter)
Water content	9.55	% (fresh state)
C	49.2	% (dry matter)
S	0.207	% (dry matter)
N	0.55	% (dry matter)
H	6.24	% (dry matter)
Cl	0.003	% (dry matter)
F	0.001	% (dry matter)
Cd	0.017	mg kg^{-1} (dry matter)
Ca	9170	mg kg^{-1} (dry matter)
Fe	31.1	mg kg^{-1} (dry matter)
Cu	2.23	mg kg^{-1} (dry matter)
Mg	320	mg kg^{-1} (dry matter)
Mn	121	mg kg^{-1} (dry matter)
Lower heating value	17,700	kJ kg^{-1}
Higher heating value	19,020	kJ kg^{-1}

Catalyst synthesis techniques

In this work, two different synthesis routes have been developed in order to coat aluminium oxide foams with a mixed metal oxide active phase. These two respective techniques cannot be yet described in detail because of ongoing patent approval.

RESULTS AND DISCUSSION

Reference experiment

At first, a reference experiment was carried on the downdraft stove in order to determine the emissions, temperature profiles and pressure conditions during the operation of the stove in an unmodified state. This reference test is vital in the context of evaluating the effect of different modifications and changes in the stove which will be done in upcoming experiments. In Fig. 2, the temperature profiles of different sections of the stove have been depicted. In addition, the emission values during the reference test can be found in the Table 2. For every burning cycle, the stove was operated for the first 30 s in 'up-draft' mode. After that, it was operated in downdraft (Twinfire mode) for the next 29.5 minutes. The average temperature in the grate was calculated to be around 750°C whereas, the temperature in the walls of the lower combustion chamber, where catalysts are planned to be installed in future experiments, was found to be ca. 650°C. The Table 3 provides information regarding average temperatures in different sections of the stove. These concentrations are recorded for four burning cycles of the reference test.

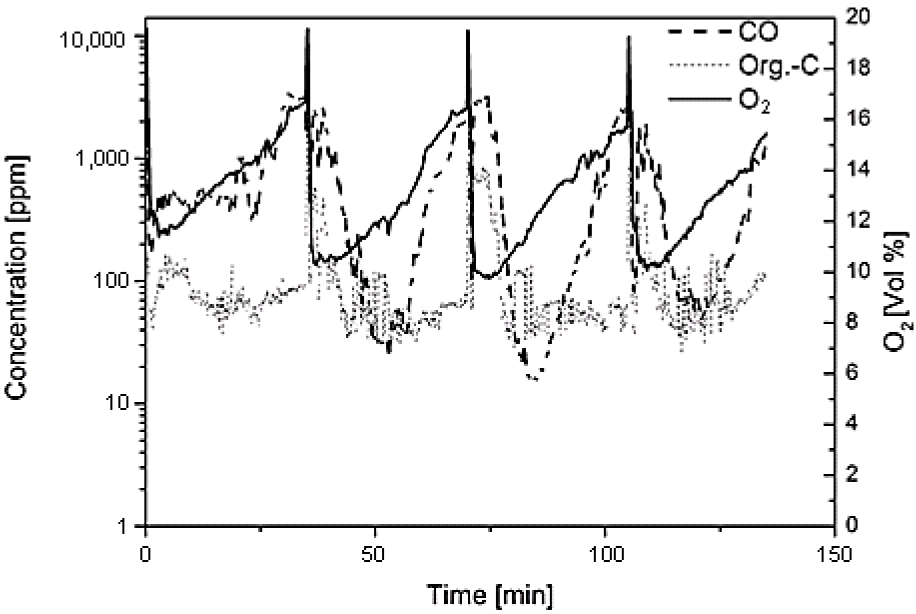

Figure 2. Time-dependent behavior of pollutants during the reference experiment.

Table 2. Emission values during the reference test

Pollutants	Emission values mg m^{-3} i.N., 13% O_2
CO	1,514
VOC	132
Aromatics (sum)*	26
Dust	37

* A total of 15 aromatic compounds, the important including benzene, naphthalene and toluene

Table 3. Average temperature calculated in different sections of the stove during multiple burning cycles

	Temperature (average)	Unit
Upper chamber	557	°C
Grate	834	°C
Lower chamber	841	°C

Integration of uncoated Al_2O_3-foams as a support material

Al_2O_3-foams were tested as a possible support material for a suitable catalyst at the start of the experimental stage. For this purpose, two such foams were inserted into the walls of the combustion chamber. However, first of all it was important to calculate the pressure drop across the monoliths in order to ascertain the smooth operation of the stove after installing the monoliths. The pressure drop across the monoliths was found to be lower than 0.5 Pa which is sufficiently low and shows the applicability of the foams.

As observed, there is no negative effect on the combustion behavior of the stove after installing the uncoated Al_2O_3-foams, so it leads to the testing of the monoliths in the combustion chamber with Mixed Metal Oxide (MMO) as an active phase.

Integration of the catalyst in the walls of lower combustion chamber

Wall catalyst based on MMO/Al_2O_3-foam

As evident from the Table 4, after the catalyst incorporation, the emissions of CO and VOC (Org.-C) were reduced by 21% and 42% respectively (in comparison to the reference test). Moreover, the dust emissions were also abated by 55%.

Table 4. Reduction in emissions after integrating MMO/Al_2O_3-foams

Experiment unit	Reference mg m^{-3} i.N., 13% O_2	MMO/α-Al_2O_3 mg m^{-3} i.N., 13% O_2	Reduction %
CO	1,514	1,201	21
VOC (Org.-C, FID)	109	63	42
VOC (Org.-C, FTIR)	132	83	37
dust with rinsing	37	17	55
dust without rinsing	33	14	57

Reduction of pollutants with the integration of wall catalysts and heat reflecting plate

In order to lower the emissions, the temperature of wall catalysts in the lower combustion chamber was increased by placing a heat reflecting plate (made of vermiculite) in front of the door in the lower combustion chamber. In Fig. 3, the time-dependent behavior of CO, VOC (Org.-C/THC) and aromatics (sum) has been depicted. The Table 5 shows the emissions values after installing the catalyst.

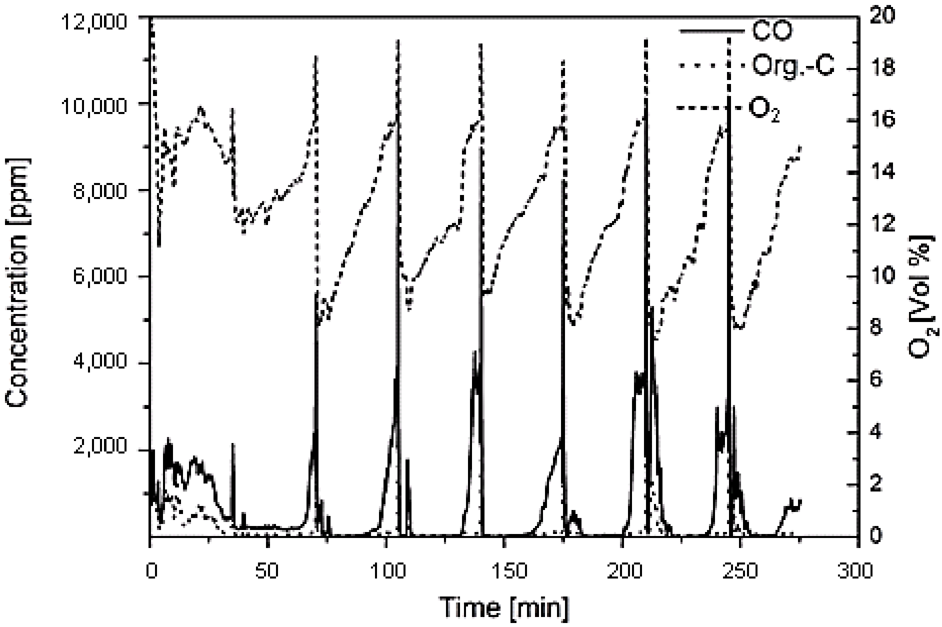

Figure 3. Time-dependent behavior of pollutants after catalytic oxidation in the stove.

Table 5. Emission reduction after integrating MMO/α-Al_2O_3-foams with heat reflecting plate

Experiment unit	Reference mg m^{-3} i.N., 13% O_2	MMO/α-Al_2O_3 mg m^{-3} i.N., 13% O_2	Reduction %
CO	1,514	578	62
VOC (Org.-C, FID)	109	16	85
VOC (Org.-C, FTIR)	132	35	74
dust with rinsing	37	11	71
dust without rinsing	33	10	70

<u>Integration of the MMO/α-Al_2O_3 catalyst synthesized through Technique 1</u>

After recording positive results concerning emission control by using a suitable catalyst, the active phase of mixed metal oxide (as used in previous experiments) was brought onto the aluminium oxide foam through an innovative technique, which is termed here as ‘Technique 1’. Unfortunately, nothing can be described here regarding this technique due to the ongoing patent application.

As can be seen from the Table 6, the emissions of CO and Org.-C were reduced by 58%, clearly indicating the suitability of both the active phase and the corresponding synthesis route.

Table 6. Reduction in the emissions after integrating the catalyst MMO/α-Al_2O_3 synthesized through Technique 1

Experiment unit	Reference* mg m^{-3} i.N., 13% O_2	MMO/α-Al_2O_3 mg m^{-3} i.N., 13% O_2	Reduction %
CO	1,718	725	58
VOC (Org.-C, FID)	156	65	58
VOC (Org.-C, FTIR)	202	92	54

* The reference experiment was performed again with the new batch of same fuel type

Integration of the mixed metal oxide/α-Al_2O_3 catalyst synthesized through Technique 2

On experimental basis, another technique, 'Technique 2' (described in the section 2.2), has been adopted to observe the suitability of the procedure regarding better oxidation activity of the catalyst.

As evident from the Table 7 and 8, the selected synthesis route was not proved to be fruitful, as emission values were higher than using 'Technique 1'.

Table 7. Emission values after fitting the catalyst (MMO/α-Al_2O_3) synthesized through Technique 2

Experiment unit	Reference mg m^{-3} i.N., 13% O_2	MMO/α-Al_2O_3 mg m^{-3} i.N., 13% O_2	Reduction %
CO	1,718	1,359	21
VOC (Org.-C, FID)	156	115	26
VOC (Org.-C, FTIR)	202	147	27

Table 8. Comparison between the two selected synthesis routes

Experiment unit	Technique 1 mg m^{-3} i.N., 13% O_2	Technique 2 mg m^{-3} i.N., 13% O_2
CO	725	1,359
VOC (Org.-C, FID)	65	115
VOC (Org.-C, FTIR)	92	147

Aging behavior of the wall catalyst MMO/α-Al_2O_3

For the determination of the thermal and chemical deactivation of the catalyst, it was aged by fitting into a downdraft stove and subjected to real operating conditions for 630 h (equal to one heating period). The long-term/aging experiments were planned in such a way that the catalyst was exposed to real operating conditions for three weeks (except the first aging cycle was 6 weeks) and after that immediately tested for its activity. Shortly after, the catalyst was again subjected to a long-term experiment for three weeks before being analyzed again for its stability. The results have indicated that, as shown in Table 9, the catalyst showed initially quite a promising oxidation of pollutants namely, carbon monoxide, volatile organic compounds and dust (particulate matter). This behavior can be attributed to the thermal activation of the catalyst caused by the diffusion of active phase species into the support material, resulting into the synthesis of more active catalytic phase (Tsybulya et al., 2003). However, as clear from Table 9, the activity of the catalyst dwindled with the passage of time. This can be possibly due to the poisoning of the active phase on the support material. However, there is so far no evidence for the provided assumptions as catalyst characterization (e.g. XRD, XPS) is planned to be done at the end of the aging experiments (after the fifth cycle).

Table 9. Emission values during the course of the aging experiments with MMO/α-Al_2O_3 catalyst

Experiment	Reference	After cycle-1	After cycle-2	After cycle-3
unit	mg m^{-3} i.N., 13% O_2	mg m^{-3} i.N., 13% O_2	mg m^{-3} i.N., 13% O_2	mg m^{-3} i.N., 13% O_2
CO	1718	586	222	837
VOC (Org.-C, FID)	156	36	8	64
dust (after rinsing)	37	11	9	16

Aging behavior of the wall catalyst synthesized through Technique 2

In order to get verification about thermal activation in case of mixed metal oxide catalyst, another long-term/aging experiment was performed with a selected wall catalyst, as tested earlier, where the catalyst was exposed to real conditions in the stove for about 4.5 h. As can be seen from the Table 10, there is quite a substantial amount of reduction in the emissions. The emissions of CO and VOC (Org.-C) were reduced by 62% and 77% respectively. Clearly, there is a thermal activation effect which can be observed in regard to the selected MMO/Al_2O_3 catalyst. However, like pointed out earlier, a catalyst characterization has to be done in order to support this assumption but it is very obvious that there exists quite a high probability of thermal activation, as can be observed from multiple experimental results.

Table 10. Reduction in the emissions after the catalytic treatment during the 'normal' and 'long-term' experiments

Experiment	During normal experiment	During long-term experiment	Reduction
unit	mg m^{-3} i.N., 13% O_2	mg m^{-3} i.N., 13% O_2	%
CO	1,359	518	62
VOC (Org.-C, FID)	115	27	77

FUTURE WORK AND CONCLUSIONS

The selected monoliths, primarily composed of aluminum oxide (Al_2O_3) were coated with mixed metal oxide as an active catalytic phase and later inserted into the walls of the stove in the lower combustion chamber. These Al_2O_3 foams (porosity of 10 ppi) consist of 92% α-Al_2O_3 along with the trace phases of mullite and cordierite. The results revealed that the catalyst was found to be quite active in terms of oxidation of harmful pollutants e.g. CO and VOC. In addition, two different synthesis routes for mixed metal oxides on the alumina foam were followed in order to make sure about the high activity of the selected mixed metal oxide. Furthermore, the aging experiments were performed with three different wall catalysts, each consisting of mixed metal oxides but synthesized via different methods. It is quite obvious that each of the three catalysts showed a 'thermal activation effect' during the long-term/aging experiments, but this assumption cannot be yet supported due to the lack of catalyst characterization, which is planned to be carried out as soon as possible. Due to the limitations posed by the ongoing patent application, it was not possible to disclose the precise synthesis route of the selected active phase. However, it is worth-mentioning that the concept of integrating the catalytic components in a downdraught stove yielded promising results. Since, the feasibility of high temperature catalysis has not been studied extensively so far in small scale combustion systems; this work can prove to be a 'catalyst' itself to facilitate further research and development in this field.

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REFERENCES

Demirbas, A. 2009. *Biofuels*. Springer, 336 pp.

Junginger, H., Jonker, J., Faaij, A., Cocchi, M., Hennig, C., Walter, A., Marchal, D., Hektor, B., Kranzl, L., Matzenberger, J., Nikolaisen, L., Rosillo-Calle, F., Schouwenberg, E. & Trømborg, E. 2011. Summary, synthesis and conclusions from IEA Bioenergy Task 40 country reports on international bioenergy trade. IEA Bioenergy.

Jokiniemi, J., Hytönen, K., Tissar, J., Obernberger, I., Hartmann, H. & Bellmann, B. 2008. Biomass combustion in residential heating: Particulate measurements, sampling, and physicochemical and toxicological characterization. Finland: University of Kuopio, Fine Particle and Aerosol Technology Laboratory. 92 p.

Kelz, J., Obernberger, I., Jalava, P. & Hirvonen, M. 2010. PM emissions from old and modern biomass combustion systems and their health effects. *18th European Biomass Conference and Exhibition*, pp. 1231–1243.

Tsybulya, S.V., Kryukova, G.N., Kriger, T.A. & Tsyrulnikov, P.G. 2003. Structural Aspect of a Thermal Activation Effect in the MnO_x/γ-Al_2O_3 System. *Kinetics and Catalysis* **44**(2), 287–296.

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Modelling of biomass cogeneration plant efficiency

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Abstract. The paper presents the analysis of operation conditions of biomass cogeneration plant (CHP). The data set for analysis comprises the data measured on an hourly basis at the cogeneration plant in Jelgava. The volume of the data set is 467 modes. By means of statistical processing of the change in the plant's specific fuel consumption, by applying the methods of regression analysis, the most important factors describing the operation of the equipment or independent parameters were identified. The relationship between the change in the plant's specific fuel consumption and the parameters impacting it, is established by the regression equation obtained in data processing. According to the performed analysis: the change in the plant's specific fuel consumption is determined by the following four statistically important parameters: boiler efficiency; power generation efficiency; heat production efficiency indicators and outdoor temperature. The specific fuel consumption rate, calculated using regression equation, is compared to the specific fuel consumption rate observed in the CHP during operation. The assessment of the percentage difference shows that the specific fuel consumption rates calculated using the equation are useful in describing the plant data and can also be used to estimate future fuel consumption. It was observed that the rate difference is within the margins of 3.6 to 6.7 per cent.

Key words: specific wood chips consumption, cogeneration plant, power and heat generation efficiency indicators regression analysis.

INTRODUCTION

Reasons for analysis of operation mode of wood chips fueled combined heat and power generation plan (CHP) are different. For example, Pantaleo et al. (2014) presented the case study in order to evaluate the energy service companies (ESCO) approach for biomass heating. Sources of wood chips are several: produced from agricultural pruning residues, clean industrial and commercial wood waste, urban tree waste and forestry residues. There are legislative constraints on usage of biomass residues, environmental impact and potential impacts of poor fuel quality on equipment operation and control must be taken into consideration as well. It was found that the most influencing factors are the heat load rate, the investment cost, the baseline fossil fuel costs and baseline conversion efficiencies (that influence the thermal energy selling price under the selected 'shared savings' ESCO approach). The results of Pantaleo et al. (2014) showed that the use of biomass and wood chips in this particular case is highly profitable high heat load rates and high fossil fuel costs.

Wood chip fueled CHP is one of the most common biomass fired CHP technologies. James Keirstead et al. (2012) model of ‘eco town’ heating is based on State-Task Network (STN) and resource-technology network (RTN) approach. Two types of fuel were considered in modeling scenarios – forestry residues and wood chips from wood processing companies.

Analysis of operation mode is important in case of co-firing different fuels. A life cycle analysis for biomass co-firing with coal in CHP has been performed by Zuwała (2012). It was concluded that forest residues was better fuel for co-firing than willow wood chops in terms of life cycle GHG emissions.

Other analysis of operation of CHP: technical, economic and exergo – economic assessment of a combined heat and power (CHP) plant implementation in an animal feed industry with two possible fuels charcoal and wood chips the results are presented by Marcos Luiz de Macedo Rodrigues et al. (2013). They show that without selling electric power to the grid wood chips were economically non-feasible.

Transition from local, small scale community heating projects to city wide district heating based on cogeneration plant are analyzed by Karen N. Finney et al. (2013). Authors of that paper looked at two cities Barnsley and Sheffield each at different stage of networking, decentralization, city-wide energy deployment. It was found during the case studies that wood chip boiler had lover CO and NO emissions than coal and wood pellet boilers, the highest PM_{10} concentration O_2 percentage in similar operation mode. Karen N. Finney et al. (2013) wood chip boiler had lower effect to climate change than wood pellet boiler.

The literature review traces a wide range of issues related to the use of biomass, including: the uses of different sorts of biomass; economic and thermo-economic aspects of biomass usage; properties of co-burning; emission levels of gases and solid particles; as well as operational factors that influence consumption. The efficiency of cogeneration plants can be described by a specific fuel consumption rate, which is determined by relating the amount of fuel with the amount of generated energy. All the reviewed studies distinguish the dependency of the obtained data on a specific mode of operation. The article focuses on determining the essential factors of CHP operation, obtaining quantitative equations in order to determine woodchip consumption depending on operational factors.

METHODOLOGY FOR PROCESSING OF EMPIRIC DATA

Empirical data were processed by applying statistical methods for data processing: correlation and regression analysis. By means of correlation analysis, the mutual link and its strength between two variables is determined. Regression analysis is used to identify the statistical importance of the multi-factor regression model and its coefficients. The article evaluates the steps of implementing the correct regression analysis as described by Blasnik (1995).

The computer software STATGRAPHICS Plus was used for the statistical processing of data and development of the multi-factor empirical model.

Short description of the cogeneration plant and the data set for analysis

A simplified principal diagram of the Jeglava cogeneration plant is seen in Fig. 1.

The Jelgava cogeneration plant was commissioned in September 2013. Using woodchips as fuel (in the diagramme present as FUEL B), the plant produces electrical power by generator G of turbine, which is then fed into a network, and heat energy that is used for the heating supply of Jelgava. The chips are burnt in a fluid-bed boiler with a double air supply, generating overheated steam under the pressure of P_{1st} = 115 bars and temperature T_{1st} = 520°C. Chungen Yin et al. (2008) underline that fluidized bed boilers with two stage air supply is one of main competing technology in biomass combustion for combined heat and power production. The steam is used in a counter-pressure turbine. An important role is played by users of the heating system, who consume low-potential heat. The steam from the turbine and the low-pressure outlet is then used for preparing water for the two-step network in water heaters DH1 and DH_2. The network water with forward temperature T_1 is then fed into the heating system, where it is supplied to users, cooling the water in process to return temperature T_2. One of the essential energy parameters in the CHP is the correlation of two amounts of energy types. Usually, biomass plants generate 5 times less electrical power than heat. This is not the case at the Jelgava cogeneration plant. Thanks to high initial steam parameters as well as low-pressure steam use in covering the heat load, the plant has a high ratio of electricity against heat, $\alpha \approx 0.43$. The steam from turbine outlets is used for heating the boiler's water supply in low-pressure (LP) and high-pressure (HP) water supply heaters. Deaerator D plays role of degassing equipment and accumulation tank of boiler feed water. In order to ensure that the gas is rid of solid particles, the plant is equipped with an electric filter.

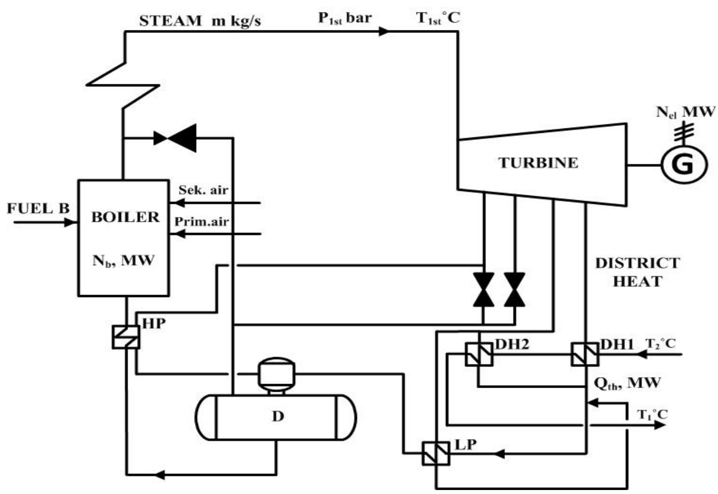

Figure 1. The principal technological diagram of the Jelgava cogeneration plant.

The data set for analysis comprises the data measured on an hourly basis at the cogeneration plant in Jelgava during the time period from 28 December 2013 to 23 January 2014. The volume of the data set is 467 modes, depending on the plant's heat and electric load.

The variables that were measured and used for analysis are as follows:

- Boiler capacity N_b, MW;
- Fuel consumption B, loose m^3 h^{-1};

- Heat load Q_{th}, MW;
- Flow of the network water G_{DH}, $m^3\ h^{-1}$;
- Forward temperature of the network water T_1, °C;
- Return temperature of the network water T_2, °C;
- Electrical capacity N_{el}, MW;
- Steam temperature at the inlet of the turbine T_{1st}, °C'
- Steam pressure before the turbine P_{1st}, bar;
- Steam flow in the turbine m_{st}, kg s^{-1};
- Outdoor temperature T_{out}, °C;

The relative variables describing the plant were identified on the basis of measured data:

- Specific fuel consumption of the plant - $b_{ch} = B/(Q_{th} + N_{el})$, loose $m^3\ MWh^{-1}$;
- Efficiency of heat production – Q_{th}/B, MWh/ loose m^3;
- Efficiency of power generation – N_{el}/B, MWh/ loose m^3;
- Efficiency of the boiler operation – N_b/B, MWh/ loose m^3;
- Ratio of the electrical and heat capacity of the plant $\alpha = N_{el}/Q_{th}$.

Correlation analysis of the data of the cogeneration plant

This chapter is aimed at establishing the linkage of parameters by means of performing the correlation analysis, in order to select the type of regression equation. In the article, the correlation analysis is considered to be a tool, which facilitates further regression analysis in order to render visible some useful connections between independent variables.

The strength of the mutual link of independent and dependent random variables (correlation) can be assessed by means of a correlation coefficient. In case of a single factor mathematic model, the Pearson's equation is used for its estimations:

$$r = \frac{\sum_{i=1}^{m}(x_i - x)(y_i - y)}{(m-1)S_x \cdot S_y}, \quad (1)$$

where: x_i, y_i – independent variables and pairs of corresponding dependent variables; x, y – mean arithmetic values of independent and dependent variables; S_x, S_y – selection dispersions of variables.

Correlation coefficients were used to evaluate the accuracy of mathematic models describing the strength of the correlation. It is assumed that a correlation is good if correlation coefficients equal 0.8; 0.9. It should be noted that in software for statistical data processing the squared correlation coefficient is usually calculated. When the value R^2 is multiplied by 100, the value (percentage) that characterises the changes of dependent variables described by the resulting empirical equation is obtained. For example, $R^2 = 0.9$ indicates that the relevant regression equation characterises 90% of the changes in dependent random variables.

In the present study, for the purpose of analysis of the operation of the plant, the correlation between the variable b_{ch} and independent variables is analysed.

The first correlation analysis is aimed at establishing whether there is a correlation between the dependent variable and the analysed independent variable describing the operation of the plant. The relationship between b_{ch} and the outdoor temperature T_{out} is presented as an example in Fig. 1.

However, the value of the correlation coefficient is low there is dispersion of data, leading to the conclusion that there is a considerable impact from other factors. The impact of other factors can be established by means of a multi-factor regression analysis.

Application of a multi-factor regression analysis is correct if there is no mutual correlation between independent variables. If there is such correlation the parameters will have to be excluded from the regression equation. The multi-factor regression analysis can be simplified by carrying out a single-factor correlation analysis of independent variables. Examples of this analysis are presented in Figs 2 and 3.

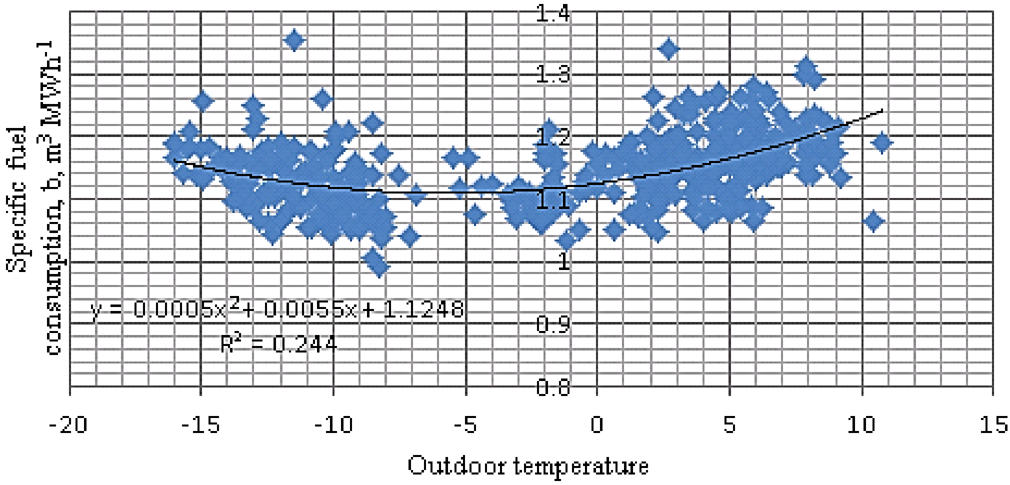

Figure 2. Change in specific fuel consumption depending on the outdoor temperature.

This figure shows a very good mutual correlation between both variables. The value of the squared correlation coefficient as determined by the analysis R^2 = 0.93. The relationship between the variables is non-linear and is defined by the following equation:

$$T_1 = 0.003 \cdot T_{out}^3 + 0.046 \cdot T_{out}^2 - 0.608 \cdot T_{out} + 48.87 \qquad (2)$$

The equation (2) explains 94%of the analysed changes in the data and can be used for calculations. 6% of changes in the return temperature should be explained by the impact of other parameters. This means that the impact of other parameters is negligible. From the point of view of the regression analysis, returne water temperature cannot be included in the analysis.

The correlation analysis of the data demonstrates that there is a close correlation between power generation and heat production in cogeneration. The changes of values are presented in Fig. 3.

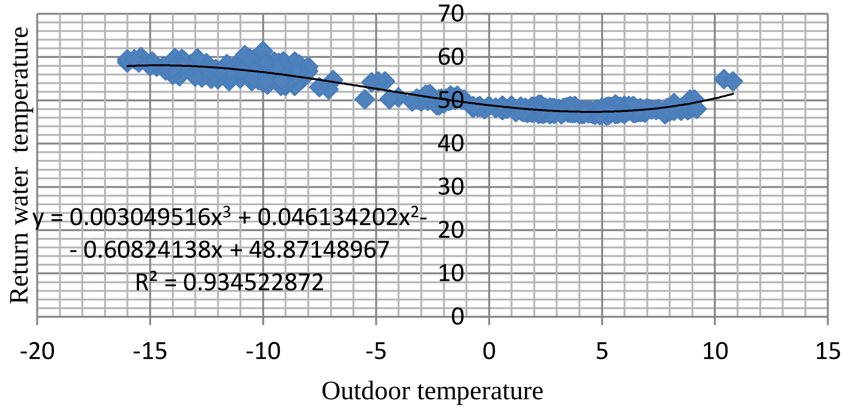

Figure 3. Change in return temperature of the heat network depending on the outdoor temperature.

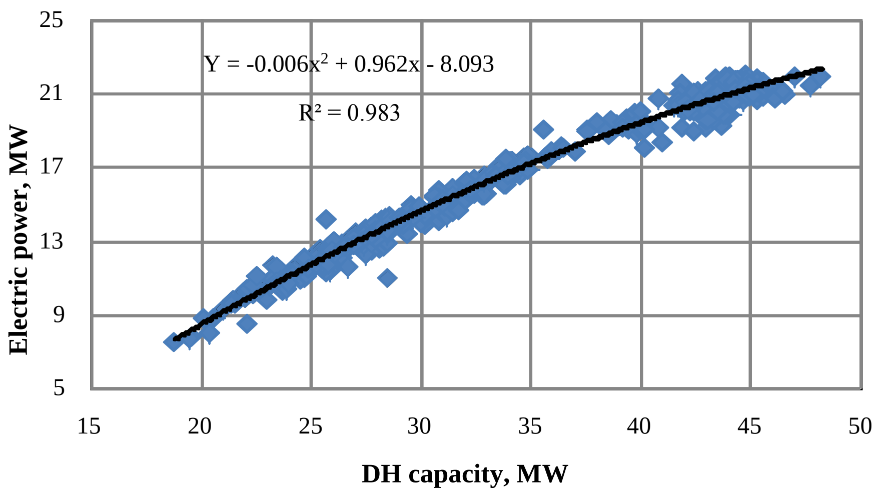

Figure 4. Change in the electrical capacity of the cogeneration plant depending on the heat load.

The mutual correlation of the analysed variables is described by the value of the squared correlation coefficient $R^2 = 0$. The relationship between the variables is non-linear and is defined by the following equation:

$$N_{el} = -0.006 \cdot Q_{th}^2 + 0.962 \cdot Q_{th} - 8.093 \qquad (3)$$

As the mutual correlation of the variables is very good, the equation (3) explains 98% of the changes in the studied data. The impact of other parameters is just 2% of the observed electrical capacity. The relationship between the electrical capacity vs the heat capacity is the relationship α describing the relevant technology. It means that two out of three variables – N_{el}, Q_{th} or α – can be used in the regression analysis. In the present study, new indices in the form of relationships between variables can be formed as Q_{th}/B, N_b/B or N_{el}/B.

In the result of the correlation analysis, it was concluded that within further multi-factor regression analysis the change of the dependent variable b_{ch} depending on the following four independent factors should be analysed – the boiler efficiency N_b/B, the power generation efficiency N_{el}/B, the heat production efficiency Q_{th}/B and the outdoor temperature

$$b_{ch} = f\left(\frac{N_b}{B};\frac{N_{el}}{B};\frac{Q_{th}}{B};T_{out}\right) \tag{4}$$

The data correlation analysis performed makes further regression analysis easier, as the set of factors that needs to be included in the multi-factor regression equation has been established.

Regression analysis of the data of the cogeneration plant

The regression analysis is aimed at obtaining an empirical equation that would provide a quantitative description of the change in the specific fuel consumption of the plant depending on statistically important operational indices of the plant and would serve as the basis for forecasting and evaluating the specific fuel consumption of the plant. Different use of regression model is discussed by Beloborodko et al. (2012). They developed empirical model for the evaluation of the quality for biomass pellets.

The regression analysis defines accurate quantitative parameters of the change in random variables, i.e. explains the importance of the stochastic link by functional relationships.

The sequence of the regression analysis was as follows:

- the law of the distribution of the dependent variable, i.e. the specific fuel consumption of the plant was verified;
- the regression equation was established by applying the smallest square method;
- the statistical analysis of the obtained results was performed.

According to Blasnik (1995), there are several main preconditions behind the application of the regression analysis. The use of the regression analysis of the data is correct if the normal distribution law is applicable to the dependent variable. This requirement is not applicable to independent variables. The above means that the analysis starts with the establishment of the distribution of dependent variables and the analysis may be continued if this distribution complies with the rule of the normal distribution.

The results of verification of the rule of distribution are presented in Fig. 4. The normal distribution within logarithmic coordinates is graphically presented with a line. As it can be seen in Fig. 4, the analysed data are placed close to the line in the graph. There are deviations at low and high values of the capacity. This means that the distribution is close to the rule of normal distribution and the application of the regression analysis is justified.

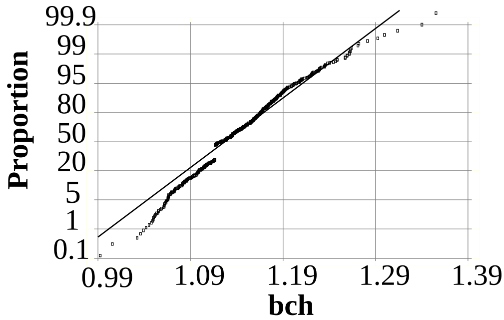

Figure 5. Distribution of the values of the specific fuel consumption of the plant.

When empirical models are developed in the form of the regression equation, several questions always need to be solved: whether the model comprises all the independent variables describing the analysed phenomenon and whether the model does not comprise unnecessary and non-essential variables, thus making the model too complicated. The answers to the above questions are provided by an evaluation of the statistical importance of the variables contained in the model and the dispersion analysis of the model.

The regression equation used by the authors does not contain the effects of the double and triple interaction of independent variables and it is as follows:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n + \varepsilon = b_0 + \sum_{i=1}^{n} b_i x_i + \varepsilon, \tag{5}$$

where: y – a dependent variable; b_0 – a free member of regression; $b_1 \ldots b_n$ – regression coefficients; $x_1 \ldots x_n$ – independent variables; ε – residual error.

The regression equation that corresponds to the expression (4) and was obtained as a result of statistical data processing contains statistically important independent variables

$$f_{ch} = b_0 + b_1 \cdot \frac{N_b}{B} + b_2 \cdot \frac{N_{el}}{B} + b_3 \cdot \frac{Q_{th}}{B} + b_4 \cdot T_{out}, \tag{6}$$

where: Nb/B – the boiler efficiency; Nel/B – the power generation efficiency; Qth/B – the heat production efficiency; Tout – the outdoor temperature.

The values of the coefficients of the regression equation and their statistical evaluation, as obtained by the dispersion analysis, is presented in Table 1.

In the data processing the level of importance P = 0.1 has been selected and corresponds to the probability of credibility 0.90. Using an importance level of P = 0.05, an outdoor air temperature with the importance level P = 0.1 becomes inessential and can be discarded from the regression equation. Outdoor air temperature T_{out} is important in terms of physical processes taking place in the plant, and for it to be retained in the equation it was decided to use a lower credibility interval.

Table 1. Coefficients of the regression equation and their evaluation

Coefficients b_i	Values	t statistics	P value
Constant b_0	2.2903	530.37	0.0000
Coefficient b_1	-0.0225	-3.2590	0.0012
Coefficient b_2	-1.3964	-88.061	0.0000
Coefficient b_3	-1.3064	-128.491	0.0000
Coefficient b_4	-0.0000393	-1.6221	0.1004

For the purpose of evaluation of the statistical importance of coefficients $b_0 ... b_n$ the t criterion with the Student's distribution with f freedom levels is applied.

$$f = m - (n + 1), \tag{7}$$

where: m – the volume of the data set subject to analysis; n – the number of independent variables in the regression equation.

The level of freedom is:

$$f = m - (n + 1) = 4{,}673 - (4 + 1) = 462$$

The value of the t criterion corresponding to these variables as taken from the tables of the Student's distribution is t_{tab} = 1.6. As it can be seen from Table 1, in all the cases the relation I t I > t_{tab} is valid. This means that all the parameters are important and should be maintained in the equation.

The study has resulted in obtaining a regression equation that determines the change in the specific fuel consumption depending on the operational data of the cogeneration plant Jelgava

$$b_{ch} = 2.2903 - 0.0225 \cdot \frac{N_b}{B} - 1.3964 \cdot \frac{N_{el}}{B} - 1.3064 \cdot \frac{Q_{th}}{B} - 0.0000393 \cdot T_{out} \tag{8}$$

The value of R^2 as determined in the result of the statistical processing of the data of the established empirical model equals 0.99. It means that the established model (8) explains 99% of the change in the analysed data. The other 1% refers to the independent variables that have not been included in the equation or defined in the study or the effect of their mutual interaction.

Evaluation of the adequacy of the regression equation

The evaluation of the adequacy of the equation (8) is performed by means of the dispersion analysis by applying Fisher's criterion F.

For this purpose, the dispersion relationship of the dependent variable to the balance dispersion is analysed:

$$F(f_1, f_2) = \frac{S_y^2(f_1)}{S_{atl}^2(f_2)}, \tag{9}$$

where: S2y(f1) – dispersion of the dependent variable y; S2atl(f2) – dispersion of the balance.

The balance is defined as the difference between the dependent variable and the value calculated by means of the regression equation y_i - $y_i^{apr.}$

The value as determined by means of the dispersion analysis performed by the software is F=26,392

The obtained value is compared to the table value of the criterion determined by applying the values of the freedom levels:

$$f_1 = m - 1 = 467 - 1 = 466 \quad \text{and} \quad f_2 = m - n = 467 - 4 = 463$$

The table value of Fisher's criterion is F_{tab} = 1.19. As it can be seen, the relationship $F > F_{tab}$ is valid and it means that equation (8) is adequate and can be used for describing the analysed data within the framework of their change: Nb/B – the boiler efficiency from 0.89 to 1.15 MWh $(m^3)^{-1}$; Nel/B – the power generation efficiency from 0.21 to 0.32 MWh $(m^3)^{-1}$; Qth/B – the heat production efficiency from 0.51 to 0.69 MWh $(m^3)^{-1}$; Tout – the outdoor temperature from +9°C to -15.2°C.

Verification of the rules of correct application of the correlation analysis

Following the establishment of the regression equation, it is possible to perform the rules verification of the correct application of the regression analysis based upon a range of other indices. These are autocorrelation, multicolinearity and heteroscedasticity.

Verification of autocorrelation. By applying the Durbin-Watson's test, in the course of statistical treatment of the data and the data analysis, the DW criterion has been established. Its value equals 1.6 and exceeds the marginal value of 1.4. This means that there is no considerable autocorrelation of the balance and the assessments of values by means of the smallest squared values method in the course of the analysis are not deformed.

Verification of multicolinearity. The verification has been performed by analysing the correlation matrix of the coefficients calculated by means of the regression equation, presented in Table 2.

Table 2. Correlation matrix of the coefficients of the regression equation

Coefficient	Constant, t.	N_b/B	N_{el}/B	Q_{th}/B	T_{out}
Constant	1.0000	-0.4639	0.0763	-0.2188	-0.1871
N_b/B	-0.4639	1.0000	-0.4397	-0.5008	-0.2341
N_{el}/B	0.0763	-0.4397	1.0000	-0.2692	0.1854
Q_{th}/B	-0.2188	-0.5008	-0.2692	1.0000	0.2828
T_{out}	-0.1871	-0.2341	0.1854	0.2828	1.0000

The analysis of the correlation matrix of the coefficients of the regression equation demonstrates that there is no considerable correlation between the coefficients and independent variables. This is attested by the low values of the correlation coefficient in Table 2. The values presented in the Table are below 0.5 or close to this level, and this means that the evaluation of the coefficients of the regression equation is correct.

The verification of the heteroscedasticity has been performed by means of a graph analysis of the distribution of balances depending on the outdoor temperature. If the increase of variations can be seen in graphs (the points form a triangle or a wedge), it means that there is heteroscedasticity.

The distribution of balances is presented in Fig. 4.

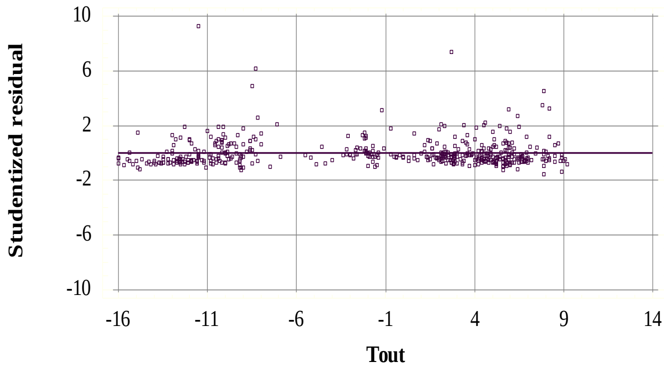

Figure 6. Distribution of balances depending on the outdoor temperature.

The figure shows that there are no considerable changes in the distribution of balances in the data set depending on the outdoor temperature. The balance values are similar along the whole range of changes in the outdoor temperature. The balance distribution has been analysed based upon other factors. In all cases, the conclusion is that there is no heteroscedasticity and the standard error has been identified correctly. The overall conclusion is that all terms of regression analysis have been correctly observed and the smallest square method values are undistorted; there are no observable errors in the evaluation of the regression equation coefficients – erroneous absolute values or incorrect marks; also, the standard error is observed correctly.

RESULTS AND DISCUSION

As a result of regression analysis, an empirical equation has been obtained, which can be used in determining the specific fuel consumption rate (b_{ch}) of woodchips for a unit of total generated heat and electrical power, m^3 MWh^{-1}. The equation includes such ratios:

- Boiler capacity against plant fuel consumption
- Plant electrical capacity against plant fuel consumption
- Plant thermal capacity against plant fuel consumption
- Outdoor temperature

The statistical relevance levels of all components are seen in Table 1. The ratios describe specific rates in relation to one cubic metre of fed fuel, and they correlate with the boiler’s electrical and generated heat efficiency. The ratios would directly describe the efficiency coefficient if they were related to the energy from the fed fuel. In case of solid fuel, there are difficulties in determining the amount of fuel and burning heat, especially for timber whose burning heat rate is influenced by a number of factors, including moisture content, ash content, origin (forest woodchips, processing residues, or mix), etc. Therefore, the article offers an equation whose components are determined by measures of the amount of fuel. Outdoor air temperature T_{out} influence on the specific fuel consumption rate is not essential. However, it does affect the capacity of the process. Reduced outdoor temperature increases consumed heat capacity and the amount of cogenerated electrical power, which increases the capacity of the boiler. Outdoor temperature determines the capacity the plant operates in.

Using data from the CHP with the ratios of the specific regression equation (6), a calculation of specific fuel consumption was made, comparing the results with the consumption rate observed at the plant. Calculation results are presented in Table 3.

Table 3. Specific fuel consumption ratios

Nr	N_b/B MWh $(m^3)^{-1}$	N_{el}/B MWh $(m^3)^{-1}$	Q_{th}/B MWh $(m^3)^{-1}$	T_{out} °C	CHP b_{ch} m^3 MWh^{-1}	Estimated b_{ch} m^3 MWh^{-1}	Difference %
1	0.99	0.27	0.41	-3.9	1.47	1.36	7.5
2	1.0	0.25	0.65	4.4	1.11	1.07	3.6
3	0.99	0.2	0.5	10.3	1.43	1.335	6.6
4	0.96	0.26	0.44	-15.4	1.425	1.33	6.7

The difference between specific fuel consumption rates, the one during the plant's operation and the calculated one, is compared against the specific consumption rate observed at the plant. The assessment of the percentage difference shows that the specific fuel consumption rates calculated with the equation are useful in describing the data from the plant and can be also used for estimating future fuel consumption. It can be noted that in case of small rates of specific consumption the difference is smaller. When comparing a cogeneration plant's energy-generation processes, it can be observed that the boiler has the highest rate of efficiency, followed by the heat generation process for consumer needs, while the lowest is in the process of generating electrical power. This can be explained by losses in the energy generation network, which are higher in the case of power generating than in heat generating for consumer needs. The reduction of the specific fuel consumption rate is determined by possibilities of loss reduction within the plant's energy generating processes.

One of the ways to verify the regression equation is related to the verification of the signs of its constituents and whether the fact if there is a logical explanation behind the identified changes in the equation from the point of view of the physical nature of the described processes. In the regression equation (6) for determining the change in the specific fuel consumption the signs of all the parameters are negative and an increase in their value lowers the specific fuel consumption. The visible trends comply with the nature of the processes and there is a logical explanation behind them. It seems logical that when increasing the efficiency of energy generation processes the consumption rate for one unit of energy in the plant decreases.

The question of completeness of the correlation between the results calculated by means of the regression equation and the analysed data is among the basic questions regarding the use of empirical equations. Only with a satisfactory correlation can it be stated that the model adequately describes the situation in practice and its use for simulating the situation is correct. For the purpose of verifying the adequacy of the empirical equation, the empirical and calculated data have been compared. The graphic presentation of the data comparison is in Fig. 7.

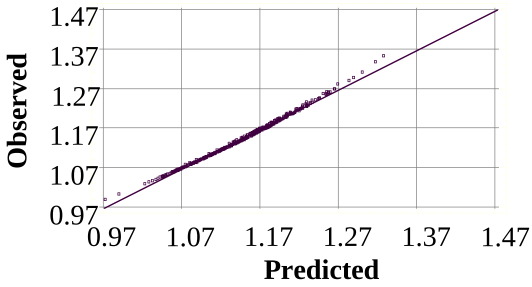

Figure 7. Comparison of analysed data on the change in the specific fuel consumption of the plant and the calculation data.

As seen from Fig. 5, there is a good correlation between both data sets. If the calculated value corresponded accurately to the surveyed data, the points would be located on the line in the figure. There is an increased dispersion of points at low and high values of the specific fuel consumption of the plant. This fact complies with the conclusion made apparent by the comparison of specific fuel consumption rates in Table 3.

CONCLUSIONS

1. By means of statistical processing of the change in the plant's specific fuel consumption, by applying the methods of regression analysis, the most important factors describing the operation of the equipment or independent parameters were identified. The relationship between the change in the plant's specific fuel consumption and the parameters impacting it, is established by the regression equation obtained in data processing:

$$b_{ch} = 2.2903 - 0.0225 \cdot \frac{N_b}{B} - 1.3964 \cdot \frac{N_{el}}{B} - 1.3064 \cdot \frac{Q_{th}}{B} - 0.0000393 \cdot T_{out} \quad (10)$$

2. According to the performed analysis the change in the plant's specific fuel consumption is determined by the following four statistically important parameters:

- Boiler capacity against plant fuel consumption
- Plant electrical capacity against plant fuel consumption
- Plant thermal capacity against plant fuel consumption
- Outdoor temperature.

3. Evaluation of the adequacy of the regression equation show that it is adequate and can be used for describing the analysed data within the framework of their change: Nb/B – the boiler efficiency from 0.89 to 1.15 MWh $(m^3)^{-1}$; Nel/B – the power generation efficiency from 0.21 to 0.32 MWh $(m^3)^{-1}$; Qth/B – the heat production efficiency from 0.51 to 0.69 MWh $(m^3)^{-1}$; Tout – the outdoor temperature from +9°C to -15.2°C.

4. Using the data from the CHP with the ratios of the specific regression equation, the calculation of specific fuel consumption was made, comparing the results with the consumption rate observed at the plant. The assessment of the percentage difference shows that the specific fuel consumption rates calculated with the equation are useful in describing the plant data and can also be used for estimating future fuel consumption. It can be seen that in the case of small rates of fuel consumption, the difference is 3.6 per cent, and it is smaller than with bigger consumption rates, where the difference is 6.7 per cent.

5. When comparing cogeneration plant's energy-generation processes, it can be observed that the highest rate of efficiency is in the boiler, followed by heat generation for consumer needs, while the lowest is in generating electrical power. It can be explained by losses in the energy generation network, which are higher in the case of power generating than in heat generating for consumer needs. The reduction of the specific fuel consumption rate is determined by possibilities of loss reduction within plant's energy generating processes.

6. Further research is associated with an in-depth study of energy-generation processes in the plant, including spring and summer modes of operation in order to improve the obtained empirical model.

REFERENCES

Beloborodko, A., Timma, L., Žandeckis, A. & Romagnoli, F. 2012. The regression model for the evaluation of the quality parameters for pellets. *Agronomy Research* **1**, Special Issue, 17–24.

Blasnik, M. 1995. *The need for statistical analysis and reporting requirements: some suggestions for regression models. Energy Program Evaluation Conference,* Chicago, 15–17 October, 1995, pp. 14.

Chungen Yin., Lasse A. Rosendahl, Soren & Kar, K. 2008. Grate – firing biomass for heat and power production. *Progress in Energy and combustion Science* **34**, 725–754.

James Keirstead, Nouri Samsatli, A. Marco Pantaleo &, Nilay Shah. 2012. Evaluating biomass energy strategies for a UK eco-town with an MILP optimization model// *Biomass and Bioenergy*, **39**(April), 306–316.

Karen, N. Finney, Jue Zhou, Qun Chen, Xiaohui Zhang, Chian Chan, Vida N. Sharifi, Jim Swithenbank, Andy Nolan, Simon White, Simon Ogden & Richard Bradford. 2013. Modelling and mapping sustainable heating for cities. *Applied Thermal Engineering* **53**(2), May 2013, 246–255.

Marcos Luiz de Macedo Rodrigue, Felipe Raúl Ponce Arrieta & José Ricardo Sodré. 2013. Small scale biomass CHP plant: An assessment for an animal feed industry. *Applied Thermal Engineering* **59**(1–2), 25 September 2013, 174–181.

Pantaleo, A., Chiara Candelise, Ausilio Bauen & Nilay Shah. 2014. ESCO business models for biomass heating and CHP: Profitability of ESCO operations in Italy and key factors assessment. *Renewable and Sustainable Energy Reviews* **30**(February), 237–253.

Zuwała, J. 2012. Life cycle approach for energy and environmental analysis of biomass and coal co-firing in CHP plant with backpressure turbine. *Journal of Cleaner Production* **35**(November), 164–175.

Agronomy Research **12**(2), 469–478, 2014

Productivity of poplar hybrid (*Populus balsamifera* x *P. laurifolia*) in Latvia

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Abstract. Fast growing poplar clones have been widely used for biomass production in Southern Europe; however, there is insufficient information about the growth of poplar in north-eastern Europe that might hamper its wider use. The aim of the study was to assess the productivity of poplar hybrid and its potential for biomass productions. Material for the study was collected in 14 stands (age 54–65 years) located in the central and western part of Latvia (56–57°N, 22–23°E), which were established on fertile drained mineral soil (*Mercurialiosa mel.*) and mineral soil with normal moisture regime (*Oxalidosa* and *Aegopodiosa*). Tree diameter and height were measured and biomass was estimated using equation developed based on 24 sample trees.

Mean tree diameter and height in stands on mineral soil varied greatly (from 29 ± 1.6 cm to 45 ± 3.9 cm and from 24 ± 0.9 m to 31 ± 0.8 m, respectively); however in stands on drained mineral soil mean diameter and height was 42 ± 2.1 cm and 27 ± 0.7 m, respectively. Mean diameter and height of poplar was 16.7–25.1% higher compared with Norway spruce and these differences were statistically significant (p-value < 0.05), differences with common aspen were not significant.

The number of fallen and standing dead trees, reaching up to 14–46% from the number of living trees, indicated aging and intense self-thinning. Mean annual volume increment of all stands was 11.8 m^3 ha^{-1} y^{-1} (in some of stands reaching 21.0 m^3 ha^{-1} y^{-1}), corresponding to 4.2–9.8 t of dry matter per year. Thus, the results suggest that poplar could be an efficient species for production of bioenergy.

Key words: *Salicaceae*, height, diameter, yield.

INTRODUCTION

Poplars are widely used across the Globe and increasingly cultivated in planted stands that in year 2012 reached an estimated total area of 8.6 million hectars (FAO, 2012). Most of the plantations in Europe are located in the southern, south-western part of the continent. So far there is insufficient information about the growth of poplar in the north-eastern Europe that might be one of the factors affecting its wider use.

Productivity of poplar stands is the main driver of its extensive use: at the age of 10–12 years stands accumulate 200 t of wood (Nervo et al., 2011) and reach mean annual volume increment of 29 m^3 ha^{-1} y^{-1} (Zsuffa et al., 1977; Labrecque & Teodorescu, 2005).

Main purpose for the establishment of poplar plantations is industrial roundwood production as well as fuelwood and biomass production. For these uses relative low initial costs, ensured by easy vegetative propagation with cuttings, are crucial. Poplar wood, in particular from plantations, is used for veneer and plywood as well as pulpwood production. Other minor uses are matches, poles, chips for OSB.

High productivity of plantations also ensures contribution to other goals – carbon sequestration, renewable energy production and areas for nature protection without compromising total wood availability. It has been found in Italy that at the age 10–12 years poplar plantation sequesters 50 t of carbon and energy content of its wood is equal to that of 35 t of crude oil (Nervo et al., 2011). Rate of carbon sequestration is higher than in agricultural lands (Rytter, 2006). Already in 1950th in Netherlands was found, that poplar plantation, occupying 2% from the total forest area, ensures 20% of wood yield (Houtzagers, 1952). These findings demonstrate, how wider use of poplar plantation can contribute to European Union goals to ensure 20% of its energy-consumption from renewable sources until 2020 (2009/31/EC) and with aim to continue increasing this share in future and limit net carbon emissions. Use of poplars for energy wood production is also more sustainable than serial agricultural crops, that can be a threat to many areas that have already been fragmented and degraded and are rich in biodiversity and provide habitat for many endangered and endemic species (Beringer et al., 2011).

To achieve the positive impact of poplar plantations an appropriate genetic material has to be used. Therefore active breeding, investigating high number of species and inter-specific hybrids, in southern Europe has been carried out already from the beginning of 20th century (Saliņš, 1971; Cagelli & Lefèvre, 1995; Stettler, 1996). Currently, only tested clones, that can be a result of hybridization for several generations, are used at commercial scale (1999/105/EC (2000)). Poplar breeding in the Nordic and Baltic countries has shorter history (since 1960th), has not been as extensive and has had long periods without any activity (Rytter et al., 2013) as the main tree breeding effort was dedicated to coniferous trees. Main *Populus* species tested in this region are *P.tremula*, *P.tremuloides*, *P.trichocarpa*, *P.maximowiezii*, *P.deltoides, P.nigra* and their hybrids (Rytter et al., 2013) and also *P. balsamifera*. The need to test more clones for selection of those more adapted to the northern climatic conditions has been noted (Christersson, 2006). There are notable areas of abandoned agricultural lands, like 300–500 thousand ha in Sweden (Anonymous, 2006; Larsson et al., 2009), similar areas in Latvia, that could potentially be used for the establishment of poplar plantations. Since the information on growth of poplars in Baltic countries is sparse, but there might be a notable potential of its use, the aim of the study was to assess the productivity of poplar hybrid and its potential for biomass production.

MATERIALS AND METHODS

Material was collected in 14 stands in 3 forest research stations (Fig. 1) located in the central and western part of Latvia (56–57°N, 22–23°E), which were established on a fertile drained mineral soil (forest type, based on classification used in Latvia *Mercurialiosa mel.*) and mineral soil with normal moisture regime (forest type *Oxalidosa* and *Aegopodiosa*).

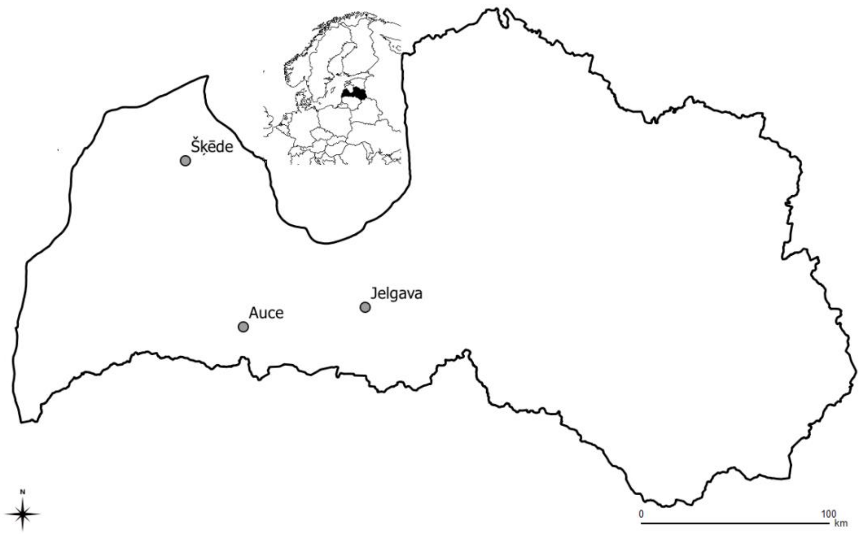

Figure 1. Locations of studied stands (forest research stations).

The initial spacing ranged from 5,000 to 7,000 trees per hectar, no commercial thinning has been done before sampling. Stand age at the sampling was 54–65 years. Diameter, height and damages were measured. Information from National Forest Inventory plots from common aspen and Norway spruce stands of the same age and forest type, from the same regions of Latvia were used for a comparison.

Twenty four trees from 3 stands, representing diameter distribution (ranging from 23 cm to 57 cm) were felled for the measurements of biomass components. Five sample disks (first at 1.3 m and one more after each fifth part from the rest of the tree height) from the stems of trees as well as four sample branches from each quarter of the living crown were taken for the assessment of the relative moisture of wood. The stem of the tree was cut into 0.5 m sections and weighted, living branches from each quarter of the living crown and dead branches were weighted separately. Afterwards dry biomass of the components was calculated as weighted average from the acquired relative humidity data using the measured weights of the respective parts of the tree as weights. Data from the dead branches were excluded from the analysis due to large variation both in relative moisture and measured biomass to minimize the error of the estimates. Tested poplar biomass models developed by other authors (Freedman et al., 1982; Zabek & Prescott, 2006) fit to the empirical data poorly, probably due to differences in diameter range. Therefore new model was developed to estimate dry biomass of stem and stem together with green branches (Jansons et al., submitted), demonstrating a good fit to empirical data (R^2 = 0.96), and used for calculations.

RESULTS AND DISCUSSION

Mean tree diameter and height in poplar stands on mineral soil varied greatly: from 29 ± 1.6 cm to 45 ± 3.9 cm and from 24 ± 0.9 m to 31 ± 0.8 m, respectively (Fig. 2) and parameters of stands on drained mineral soil were within range of this variation: 42 ± 2.1 cm and 27 ± 0.7 m, respectively.

Poplars at the same age and forest type on mineral soils were statistically significantly higher than Norway spruce (on average by 16.7%), but non-significantly lower than common aspen (on average by 12.8%). Similarly, also mean diameter of poplars was significantly larger than for Norway spruce (on average by 25.1%), but differences with common aspen were not statistically significant (Fig. 2). Converting the detected differences in units of time: for Norway spruce stands on fertile mineral soils it would take on average additional 30 years to reach similar height and additional 15 years to reach similar diameter as poplar's, but for common aspen it would take on average 10 years less. It can be seen, that in such long rotation period tested poplar hybrid does not have an advantage in tree dimensions (influencing the outcome of sawn-timber) over native common aspen.

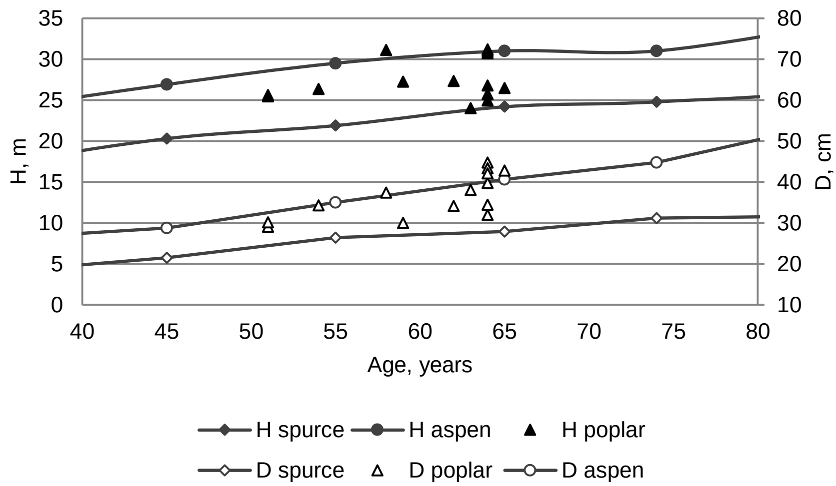

Figure 2. Mean height and diameter of poplars in comparison to Norway spruce and common aspen (NFI data).

Tree height and diameter was significantly influenced by stand age and also by density (height increasing and diameter decreasing with increasing stand density) that is in accordance with other studies in poplar plantations (Ze-Hui et al., 2007). Diameters of trees in our trails were notably smaller than found for poplars in USA at the age of 50 years (67.3 cm), and similar to that found at notably younger age: 20–25 years (von Althen, 1981). Diameter exceeding 20 cm was found in poplar plantations at the age of 20 (26.9 cm) years and 18 years (25.9 cm) in Sweden (Christersson, 2010, 2011) and at the age of 10 years (22.9 cm) in USA (Netzer et al., 2002). Tree height similar to that in our trials was found at the age of 10–15 years in USA (von Althen, 1981) and at the age of 37 years (29.6 m) in Ukraine (Saliņš, 1971). These results suggest that poplars can achieve notably faster growth that could be related both to genetic differences and soil.

For example in Sweden *Populus maximowiczii x P. trichocarpa* hybrid on former agricultural lands reached height of 28 ± 1.5 at the age of 20 years (Christersson, 2011).

Also poplar breeding programs report gains in stem volume while selecting the best-performing hybrids and clones. For example 15% increase in diameter growth as a result of selection has been found in three years old *Populus* × *wettsteinii* experiment in Finland (Yu & Pulkkinen, 2003). While selecting 8% of the best performing clones, 23–89% yield increase has been achieved at the age of six years in USA (Riemenschneider et al., 2001). Selection of the top 10% of a *Populus* × *wettsteinii* clonal distribution evaluated across multiple sites at age nine predicted a 45% increase in stem volume in Sweden (Stener & Karlsson, 2004). Site-specific selection for one third of fastest growing clones of *Populus* × *tomentosa* predicted a 34% improvement in 5th-year stem volume in Canada (Zhang et al., 2008). Best growth can be achieved on former agricultural lands, but also forest lands are suitable for poplars.

Forest type had a statistically significant influence on average height and diameter of trees also when only types on mineral soil with normal moisture regime (*Oxalidosa* and *Aegopodiosa*) were analysed.

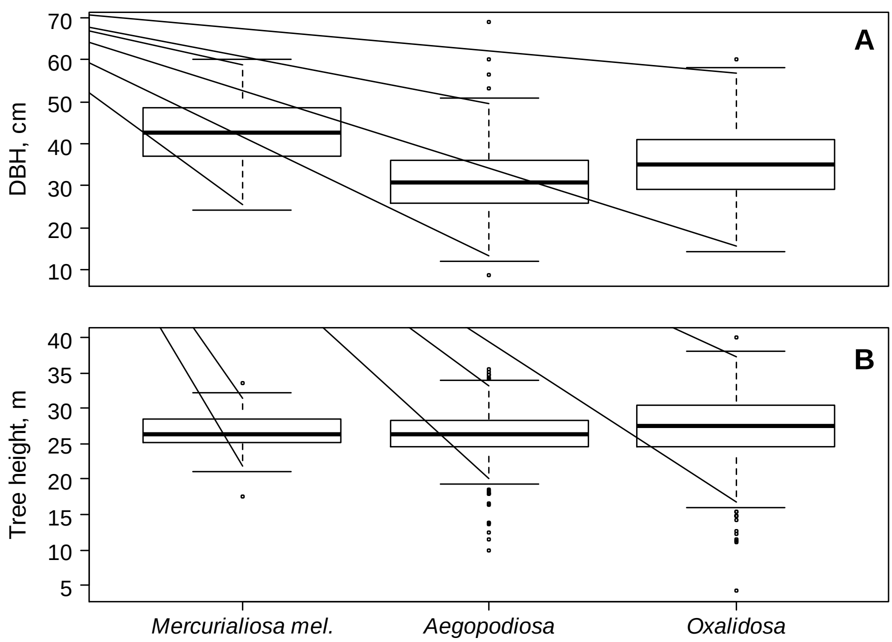

Figure 3. DBH (A) and height (B) of poplars in Mercurialiosa mel., *Aegopodiosa* and *Oxalidosa* forest types.

These findings could be related to differences in soil fertility, since poplars have been found to be very responsive to increase in soil nutrient (especially nitrogen) content (Brown & van den Driessche, 2002, 2005; Guillemette & DesRochers, 2008) as it has been studied in a number of fertilization experiments (Coleman et al., 2006; Guillemette & DesRochers, 2008; Lteif et al., 2008; Patterson et al., 2009; Pearson et al., 2010).

Significant differences in mean annual height and diameter increment between stands on mineral and drained mineral soil were found: 0.45 ± 0.004 m y^{-1} *vs.*

0.41 ± 0.010 m y^{-1} and 0.6 ± 0.01 cm y^{-1} *vs.* 0.7 ± 0.02 cm y^{-1}, respectively. However, due to differences in stand density and limited number of sample stands on drained mineral soils (peat layer up to 20 cm deep), no clear conclusions can be drawn on their suitability for the establishment of poplar plantations in comparison to sites on mineral soil with normal moisture regime. Also in literature different opinions can be found on suitability of soils with high peat content for poplar plantations: Klasa (2008) states that such sites shall be avoided, but Christersson (2010) finds a high productivity (23 m^3 ha y^{-1} at the age of 17 years) of polar stands on peat soils with pH > 6.

Table 1. Characteristics of poplar hybrid (*Populus balsamifera* x *P. laurifolia*) sample plots

Forest type	Stand age	Species	Number of trees	H, m	M, m^3 ha^{-1}	V, m^3	Stem biomass, t_{dry} ha^{-1}	Total biomass, t_{dry} ha^{-1}
Oxalidosa	59	Polar	158	27.3	442	1.01	209	232
		Total	328	22.7	613	0.67		
Aegopodiosa	51	Polar	136	25.5	385	0.94	191	212
		Total	266	20.0	449	0.57		
Aegopodiosa	51	Polar	22	25.6	566	1.00	279	312
		Total	38	21.7	641	0.66		
Oxalidosa	64	Polar	25	31.2	915	2.48	353	416
		Total	61	21.3	1011	1.12		
Oxalidosa	64	Polar	43	25.0	609	1.03	315	353
		Total	90	19.8	702	0.57		
Oxalidosa	64	Polar	25	31.0	1347	2.25	537	624
		Total	37	25.4	1417	1.60		
Oxalidosa	64	Polar	41	30.8	-	1.89		
Oxalidosa	63	Polar	141	24.0	-	1.41		
Oxalidosa	62	Polar	239	27.4	-	1.28		
Oxalidosa	64	Polar	211	25.7	-	1.22		
Oxalidosa	58	Polar	119	31.1	-	1.75		
Aegopodiosa	54	Polar	107	26.4	-	1.24		
Mercurialiosa mel.	65	Polar	40	26.5	-	1.87		
Mercurialiosa mel.	64	Polar	47	26.8	-	1.89		

Species: Poplar – poplar hybrid (*Populus balsamifera* x *P. laurifolia*); Total – including admixture of other species (Norway spruce, Silver birch) found in some of the sample plots;
H – height; D – diameter at breast height; M – yield; V – stem volume; Total biomass – total above-ground biomass.

Mean annual increment in studied poplar stands ranged between 7.5 m^3 ha^{-1} y^{-1} and 21 m^3 ha^{-1} y^{-1} and were on average 13.1 m^3 ha^{-1} y^{-1} in *Oxalidosa* and 9.31 m^3 ha^{-1} y^{-1} in *Aegopodiosa* forest type. It was in range of the estimates reported by other authors: 18–22 m^3 ha^{-1} y^{-1} at the age of 9–12 years (Karacic et al., 2003), 21–23 m^3 ha^{-1} y^{-1} at the age of 18–20 years (Christersson, 2010, 2011), however, also higher estimates can be found: 28 m^3 $ha^{-1}y^{-1}$ in *P.trichocarpa* stand in Sweden (Christersson, 2010) and even 39.6 m^3 ha^{-1} y^{-1} for hybrid poplar clone in riparian buffer strips (nutrient rich, well-drained soil) in southern Québec (Fortier et al., 2011). Comparisons might be influenced by stand density: in plantations outside the forests with aim to produce saw-log or veneer logs, density of the plantation usually is lower, thus increasing diameter increment of each tree, but not maximizing yield per hectar. Also stand age is of importance: in our trials number of fallen and standing dead trees, reaching up to 14–46% from the number of living trees, indicated intense self-thinning and stands had long-passed the peak of mean annual volume increment that is reported for poplars from age 6 to 15 years (von Althen, 1981; Netzer et al., 2002). Nevertheless, for most of the poplar trials annual volume increment is still higher than that at the peak for Norway spruce: 14 m^3 ha^{-1} y^{-1} (Eriksson, 1976), silver birch: 8–10 m^3 ha^{-1} y^{-1} (Elfving, 1986; Sonesson et al., 1994), grey alder and common aspen: ~9 m^3 ha^{-1} y^{-1} (Granhall & Verwijst, 1994; Johansson, 1999b). It exceeds also that found on average for Norway spruce, silver birch and common aspen stands at the age 51–60 years in Latvia (4.71, 4.52 and 7.12 m^3 ha^{-1} y^{-1} respectively), however, the numbers for those common tree species do not include volume of trees cut in commercial thinnings.

Absolute dry biomass in poplar trials ranged from 212 to 624 t per ha (Table 1), corresponding to 4.2–9.8 t ha^{-1} y^{-1}. Results are close to those achieved in plantations with sparse initial spacing (1,000 trees ha^{-1}) on former arable land at the age of 9 years: 9.2 t ha^{-1} y^{-1} and at the age of 11–12 years: 8.2-13.6 t ha^{-1} y^{-1} (Karacic et al., 2003; Zabek & Prescott, 2006). Slightly denser plantations on fertile former agricultural lands reached productivity of 18 t ha^{-1} y^{-1} (Zsuffa et al., 1977; Labrecque & Teodorescu, 2005). Plantations with dense spacing (10000 trees ha^{-1}) ensure notably faster accumulation of biomass: already at the age of four years mean annual biomass productions reaches 11.4 t ha^{-1} y^{-1} (Laureysens et al., 2004) and even figures as high as 35 t ha^{-1} y^{-1} have been reported (Scarascia-Mugnozza et al., 1997).

Stem biomass in our trials reaches on average 88% from total above-ground biomass that is slightly higher than observed in Sweden: 75.3% (Johansson & Karacic, 2011) most likely due to differences in stand age and density.

Above-ground biomass increment of poplar stands is notably higher than that of Norway spruce at the age of 40 years: 5.5 t ha^{-1} y^{-1} (Johansson, 1999a), but comparable with very dense (17–42 thousand trees ha^{-1}) young (7–15 years) stands of silver birch, common aspen, black and grey alder (7.2–8.6 t ha^{-1} y^{-1}) as well as coppice of hybrid aspen and salix at the age of 4 years: 9.0 t ha^{-1} y^{-1} and 4.9 t ha^{-1} y^{-1} respectively (Johansson, 1999b, 1999c, 2000; Rytter, 2006; Smaliukas et al., 2007).

CONCLUSIONS

1. Poplar hybrid (*Populus balsamifera* x *P. laurifolia*) planted with density 5,000–7,000 trees ha^{-1}, at the age of 54–65 years on mineral soils reached mean height 27.0 ± 0.23 m and breast height diameter 34.3 ± 0.47 cm, significantly exceeding that of Norway spruce at similar age. Both of these parameters were statistically significantly influenced by forest type.
2. Mean annual volume increment after its peak age in studied poplar stands (7.5–21 m^3 ha^{-1} y^{-1}) was in range of that reported by sparser plantations on former arable land, suggesting that growth conditions are suitable for this poplar hybrid in Latvia.

3. Total above-ground dry biomass increment (on average 88% of it – stem biomass) reached 4.2–9.8 t ha^{-1} y^{-1}, exceeding that of several other tree species and suggesting that poplars could be a viable alternative for biomass production in Latvia.

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REFERENCES

Anonymous. 2006. *Towards an oil independent Sweden.* Kommissionen mot oljeberoende, Stockholm, 45 pp. (in Swedish).

Beringer, T., Lucht, W. & Schaphoff, S. 2011. Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *Bioenergy* **3**(4), 299–312.

Brown, K.R.& van den Driessche, R. 2002. Growth and nutrition of hybrid poplars over 3 years after fertilization at planting. *Can. J. Forest Res.* **32**, 226–232.

Brown, K.R. & van den Driessche, R. 2005. Effects of nitrogen and phosphorus fertilization on the growth and nutrition of hybrid poplars on Vancouver Island. *New Forest* **29**, 89–104.

Cagelli, L. & Lefèvre, F. 1995. The conservation of *Populus nigra* L. and gene flow with cultivated poplars in Europe. *Forest Genetics* **2**(3), 135–144.

Christersson, L. 2006. Biomass production of intensively grown poplars in the southernmost part of Sweden: observation of characters, traits and growth potential. *Biomass Bioenerg.* **30**, 497–508.

Christersson, L. 2010. Wood production potential in poplar plantations in Sweden. *Biomass Bioenerg.* **34**, 1289–1299.

Christersson, L. 2011. The potential for production of biomass for biofuel by the cultivation of hybrid poplar and hybrid aspen in the South of Sweden. In Dos Santos Bernardes, M.A. (ed.): *Economic effects of biofuel production*. ISBN: 978-953-307-178-7. InTech.

Coleman, M., Tolsted, D., Nichols, T., Johnson, W.D., Wene, E.G. & Houghtaling, T. 2006. Post-establishment fertilization of Minnesota hybrid poplar plantations. *Biomass Bioenerg.* **30**, 740–749.

Elfving, B. 1986. Growing value of birch, aspen and alder on abandoned agricultural lands in southern Sweden. *Sveriges Skogsvårdsförbunds Tidskrift* **5**, 31–45 (in Swedish).

Eriksson, H. 1976. *Yield of Norway spruce in Sweden*. *Research notes 41*. Dep. of Forest Yield Research, Royal Collage of Forestry, Stockholm, 291 pp. (in Swedish, English summary).

FAO 2012. *Improving lives with poplars and willows. Syntesis of country progress reports – Activities related to poplar and willow cultivation and utilization – 2008 through 2011.* FAO, Rome, Italy, 93 pp.

Freedman, B., Duinker, P.N., Barclay, H., Morash, R. & Prager, U. 1982. *Forest biomass and nutrient studies in central Nova Scotia*. Can. For. Serv. Marit. For. Res. Centr. Inf. Rep., M-X-134, 126 pp.

Fortier, J., Truax, B., Gagnon, D. & Lambert, F. 2013. Root biomass and soil carbon distribution in hybrid poplar riparian buffers, herbaceous riparian buffers and natural riparian woodlots on farmland. *Sringerplus* **2**, 539.

Granhall, U. & Verwijst, T. 1994. Grey alder (*Alnus incana*) – a N_2-fixing tree suitable for energy forestry. In Hall, D.O., Grassi, G. & Scheer, H. (eds.): *Biomass for Energy and Industry*, Ponte Press, Bochum, Germany, pp. 409–413.

Guillemette, T. & DesRochers, A. 2008. Early growth and nutrition of hybrid poplars fertilized at planting in the boreal forest of western Quebec. *Forest Ecol. Manag.* **255**, 2981–2989.

Houtzagers, G. 1952. Forest genetics and poplar breeding in The Netherlands. *Euphytica* **1**(1), 10–14.

Johansson, T. 1999a. Biomass production of Norway spruce (*Picer abies* (L.) Krast.) growing on abandoned farmland. *Silva Fennica* **33**, 261–280.

Johansson, T. 1999b. Biomass equations for determining fractions of European aspen growing on abandoned farmland and some practical implications. *Biomass Bioenerg.* **17**, 471–480.

Johansson, T. 1999c. Biomass equations for determining fractions of pendula and pubescent birches growing on abandoned farmland and some practical implications. *Biomass Bioenerg.* **16**, 233–238.

Johansson, T. 2000. Biomass equations for determining fractions of common and grey alders growing on abandoned farmland and some practical implications. *Biomass Bioenerg.* **18**, 147–159.

Johansson, T. & Karacic, A. 2011. Increment and biomass in hybrid poplar and some practical implications. *Biomass Bioenerg.* **35**, 1925–1934.

Karacic, A., Verwijst, T. & Weih, M. 2003. Above-ground woody biomass production of short-rotation Populus plantations on agricultural land in Sweden. *Scand. J. Forest Res.* **18**, 427–437.

Klasa, A. 2008. Plantation site selection. In Heinsoo, K., Dimitriou, I., Foellner, S. & Buergow, G. (eds.): *Short rotation plantations: Guidelines for efficient biomass production with safe application of wastewater and sewage sludge*. BIOPROS, pp. 13–17.

Labrecque, M. & Teodorescu, T. 2005. Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). *Biomass Bioenerg.* **29**(1), 1–9.

Larsson, S., Lundmark, T. & Ståhl, G. 2009. *Opportunities for intensive cultivation of forests*. Slutrapport regeringsuppdrag Jo 2008/1885, SLU, 136 pp. (in Swedish, English summary).

Laureysens, I., Bogaert, J., Blust, R. & Ceulemans, R. 2004. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. *Forest Ecol. Manag.* **187**, 295–309.

Lteif, A., Whalen, J.K., Bradley, R.L. & Camire, C. 2008. Diagnostic tools to evaluate the foliar nutrition and growth of hybrid poplars. *Can. J. Forest Res.* **38**, 2138–2147.

Nervo, G., Coaloa, D., Vietto, L., Giorcelli, A. & Allegro, G. 2011. Current situation and prospects for European poplar culture: the role of research. In: *Third International Congress of Salicaceae in Argentina, March 16-19, 2011*. Patagonia Argentina - Neuquén City.

Netzer, D.A., Tolsted, D.N., Ostry, M.E., Isebrands, J.G., Riemenschneider, D.E. & Ward, K.T. 2002. *Growth, yield, and disease resistance of 7-to-12-year-old poplar clones in the north central United States. General Technical Report GTR-NC-229.* USDA Forest Service, North Central Research Station, 33 pp.

Patterson, S.J., Chanasyk, D.S., Naeth, M.A. & Mapfumo, E. 2009. Effluent effects on the nutrient concentrations and growth of reed canarygrass (Phalaris arundinacea L.) and hybrid poplar (Populus deltoides×P. Petrowskyana L.). *Can. J. Soil Sci.* **89**, 223–234.

Pearson, C.H., Halvorson, A.D., Moench, R.D. & Hammon, R.W. 2010. Production of hybrid poplar under short-term, intensive culture in Western Colorado. *Ind. Crop. Prod.* **31**, 492–498.

Riemenschneider, D.E., Berguson, W.E., Dickmann, D.I., Hall, R.B., Isebrands, J.G., Mohn, C.A., Stanosz, G.R. & Tuskan, G.A. 2001. Poplar breeding and testing strategies in the north-central US: Demonstration of potential yield and consideration of future research needs. *Forest. Chron.* **77**, 245–253.

Rytter, L. 2006. A management regime for hybrid aspen stands combining conventional forestry techniques with early biomass harvests to exploit their rapid early growth. *Forest Ecol. Manag.* **236**, 422–426.

Rytter, L., Johansson, K., Karlsson, B. & Stener, L.G. 2013. Tree species, genetics and regeneration for bioenergy feedstock in northen Europe. In Kellomäki, S., Kilpeläinen, A. & Alam, A. (eds): *Forest BioEnergy Production. Management, Carbon sequestration and Adaption*. New York, Springer, pp. 7–39.

Saliņš, S. 1971. Special types of forest plantations. In Bušs, M. & Mangalis, I. (eds.): *Forest plantations*. Zvaigzne, Rīga, pp. 379–409 (in Latvian).

Scarascia-Mugnozza, G.E., Ceulemans, R., Heilman, P.E., Isebrands, J.G., Stettler, R.F. & Hinckley, T.M. 1997. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. *Can. J. Forest Res.* **27**, 285–294.

Smaliukas, D., Noreika, R. & Karalius, D. 2007. Clonal selection of *Salix* L. taxa perspective for biofuel production, evaluation of their dendrometric characteristics and accumulation of biomass in short rotation plantations. *Biologija* **53**, 59–62.

Sonesson, J., Albrektson, A. & Karlsson, A. 1994. *Birch productivity on abandoned agricultural lands in southern and central Sweden. Report 88.* Dep. of Silvicult., Swed. Univ. of Agric. Sci., Umeå, 31 pp. (in Swedish).

Stener, L.G. & Karlsson, B. (2004). Improvement of *Populus tremula* × *P. tremuloides* by phenotypic selection and clonal testing. *Forest Genetics* **11**(1), 13–27.

Stettler, R.F. 1996. *Biology of Populus and its implication for management and conservation.* NRC Research Press, 539 pp.

von Althen, F.W. 1981. *Site preparation and postplanting weed control in hardwood afforestation: white ash, black walnut, basswood, silver maple, hybrid poplar. Information Report O-X-325.*Canadian Forest Service Publications, Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario, 17 pp.

Yu, Q. & Pulkkinen, P. 2003. Genotype-environment interaction and stability in growth of aspen hybrid clones. *Forest Ecol. Manag.* **173,** 25–35.

Zabek, L.M. & Prescott, C.E. 2006. Biomass equations and carbon content of aboveground leafless biomass of hybrid poplar in Coastal British Columbia. *Forest Ecol. Manag.* **223**, 291–302.

Ze-Hui, J., Xiao-Qing, W., Ben-Hua, F., Hai-Qing, R. & Xing-E, L. 2007. Effect of stand and tree attributes on growth and wood quality characteristics from a spacing trial with *Populus xiaohei*. *Ann. For. Sci.* **64**, 807–814.

Zhang, Z.,Wang, Z., Lin, S. & Zhang, Z. 2008. Comparison and early selection of new clones in *Populus tomentosa*. *For. Stud. China* **10**(3), 162–167.

Zsuffa, L., Anderson, H.W. & Jaciw, P. 1977. Trends and prospects in Ontario's poplar plantation management. *Forest. Chron.* **53**, 195–200.

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Combined management response and indicator based evaluation methodology of implementation of environmental management system at a wood pellet production industry

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Abstract. The sustainability factor stimulates industrial companies to be more active and precise in improving their performance in relation to energy efficiency and environmental indicators. One of the more widespread practises to introduce improvements in energy efficiency and environmental processes is through energy and environmental management systems. However until now, there is a lack of practical studies assessing the role of environmental management systems to the improvement of the wood fuel production sector. The paper describes an analysis of lessons learned based on combined management-response and indicator based analysis on the introduction of environmental management systems (in accordance with ISO 14001:2004) in an industrial enterprise. The chosen subject of this research is a wood pellet production facility located in Latvia. The research can be applied as a guideline for entrepreneurs in wood fuel production industry that are planning to implement energy and environmental management systems.

Key words: environmental performance, indicators, industry, Plan-Do-Check-Act.

INTRODUCTION

European Union member states have determined to reach both short-term and long-term goals in improving energy efficiency and increasing the use of renewable energy resources. The European Union energy and climate change package defines that energy consumption is to be reduced by 9% in 9 years from the results of energy efficiency *measures* (EU Climate and Energy package, 2010).

An efficient energy economy is possible by reviewing and defining the management of the system and the interaction among its engineering, economic and environmental issues with a common vision for sustainability of the energy sector – all which required a systematic approach. This means the creation, implementation and maintenance of a management system. The direct task of an energy management system is such, however environmental management systems can also provide contribution to better organization of the energy and environmental issues of any company.

The energy management model in principle does not differ much from the environmental management model whereby they both are based on continual improvement and the 'Plan-Do-Monitor-Act' cycle (also known as *Deming* circle)

(Gordić et al., 2010; Halila & Tell, 2013). The environmental management system according to ISO 14001 includes 5 basic elements: development of environmental policy at the enterprise with the commitment of senior management; environmental programmes developed with clear objectives and targets for environmental improvements; a clear, comprehensive system of implementation and operation; a system of checking and corrective action; a management review process to assure continuous improvement (Rondinelli & Vastag, 2000; ISO 14001 standart, 2005).

The environmental management scale includes 3 levels of operation:

- *Strategic (1st level).* Definition of environmental policy, setting environmental goals, division of roles and responsibilities, appropriate resource allocation.
- *Practical (2nd level).* Development and implementation of environmental management procedures, definition of action plans, how to define indicators, how to compare the current situation with the desired goals, etc.
- *Operational (3rd level).* Practical instructions on how to accomplish specific tasks, how to collect data, conduct calculations and evaluations, etc.

An additional level is the comparative level (level 0): evaluation of the accomplishments, utilizing a comparative analysis of indicators from other similar companies.

With pressures of competition, regardless of the size or activity of a company, certification of the energy efficiency of its activities is necessary to provide a testimony. The best such testimony is through internationally recognized systems like ISO 14001:2004 and EMAS in the sphere of environmental management. However there are alternative environmental management models such as the *Ekoscan* model which calls for the development a technically and financially viable Environmental Improvement Plan (EIP) (Heras & Arana, 2010).

In researching the interests of companies to implement environmental management systems, the following main reasons that motivate the companies have been mentioned in the scientific literature (Campos, 2012; Nguyen & Hens, 2013; Zhu, et al., 2013; Zobel, 2013; Testa et al., 2013; Liu & Rodríguez, 2014;To & Lee, 2014):

- Although studies are not conclusive, some argue that the introduction of such systems lead to real improvements in environmental performance;
- The fact that in some countries large companies do not choose to certify, might indicate that small – and medium-sized business might be more inclined in the hopes that this will increase their ability to have a competitive advantage;
- Some companies cite the interests in improving their reputation;
- Overall pressures from external stakeholders (other partner companies, the public, jurisdictions in which the enterprises hold their offices/production sites) is also mentioned;
- Socially conscious companies which are committed to environmental protection.

The most widely applied management system in Latvia is the quality management system ISO 9001. From around 700 registered companies in Latvia, over 130 of these have certified environmental management systems (ISO 14001 and EMAS). Due to the requirement of environmental management systems for continuous improvement, the impact of the companies activities on the environment needs to be continually improved through the respective programme. Such activities include, a reduction in emissions by improving the efficiency of energy use, improving air filtration systems, reducing waste from production processes and office facilities. The goal of the present research is to develop a methodological approach for the implementation of environmental management systems (EMS) in a pellet production company, to perform an analysis of lessons learned on the introduction of environmental management systems (in accordance with ISO 14001:2004), including identification of key environmental aspects which need to be reviewed in more detail in a wood pellets industrial enterprise. This study is presented as a case study and thus looked at only one company and the specific methods and experiences gained from this case.

The authors have not conducted a separate study on whether companies using environmental management systems are generally more successful than those that do not. However many companies in Latvia have chosen to certify environmental management systems due to growing requests for such certification from international partners. Thus, it is evident, that the scope of the companies' activities and the range of partners increases upon establishment of such system, thereby one can assume that these additional partners and tenders provide more revenue to the company than they would if such partnership would not be established due to the lack of such environmental management certification. Additionally, increase of number of companies included in the study will not provide a picture of the results of implementation environmental management, as such results can only be monitored and reported upon after more than one year of implementation. This study shows the potential impact that the process of developing an environmental management system may have on a company. An exit study after one or more years of implementation could be prepared to study the results of implementation (i.e. in 2015).

METHODS

Evaluation methodology

The evaluation methodology is based on three basic modules (see Fig. 1):

- Company level – analysis of the current management of environmental factors at the company (1st level), environmental audit (2nd level), recommendations for potential activities on improving environmental performance (3rd level).
- Sectoral level – comparative analysis of the company's performance indicators in relation to the same categories of indicators in other companies in the same sector (zero level).

Within the framework of this research only the environmental management systems module is analysed. The main driver of the system both at the company and sector level is continual improvement.

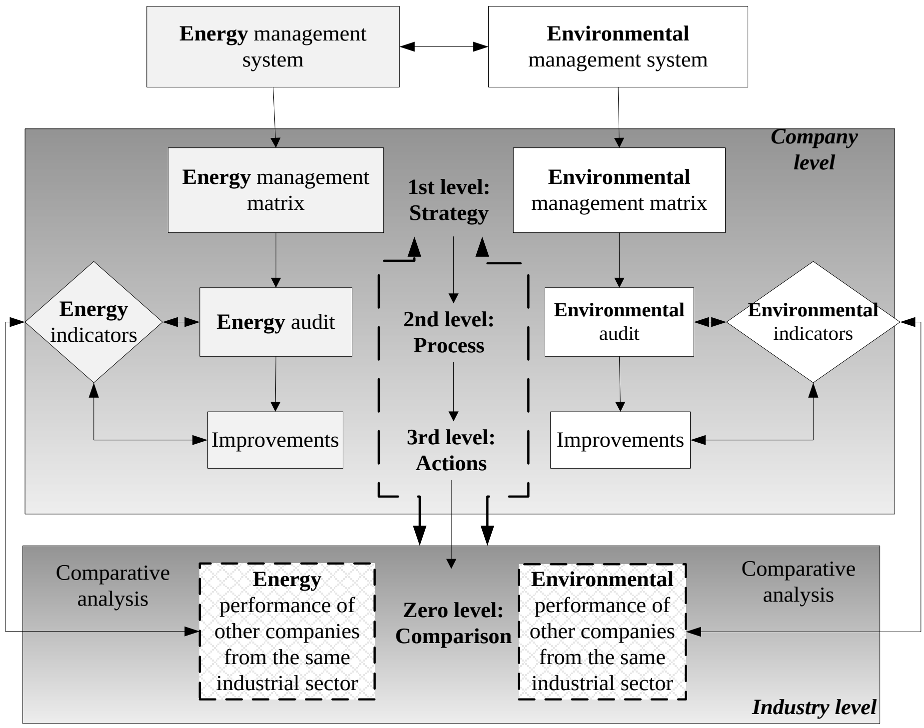

Figure 1. Evaluation algorithm of environmental management system at industry and sectorial level and its link with energy management system.

At the 1st level, the environmental matrixes are developed. The matrixes provide an effective way to gain insight into a current approach to environmental matters in a company. Each column of the matrix deals with one of six critical environmental management topics: environmental management policy, organising, staff motivation, tracking, monitoring and reporting systems, staff awareness/training and overall estimates of the level of investment needed for alternative options explored within the potential activities. The ascending rows, from 0 to 3, represent the increasingly sophisticated nature of the mentioned issues. The matrix shows the current status of a company's environmental management effort. It identifies those aspects where some further attention is required to ensure environmental management is developed in an effective way. Performance evaluation parameters are given in Table 1 (the defined matrix concept and the scale is partly based on (Gordić et al., 2010)).

Environmental audits are implemented at the 2nd level. The goal of the audit is to clarify the relationships between the performance of a company's results (production) and the environmental impact indicators, which are deemed the distinctive indicators. In case of environmental management, these indicators can reflect both the specific impact of production processes on the environmental (such as the level of emissions created to one unit of production), but also such indicators that are related to the energy efficiency of processes (such as the amount of electricity it takes to produce one unit). As energy use is one of the main realms of impact on the environment that any organization has a direct effect on, it is inevitable that the use of an efficient and environmentally sound energy system is at least partially examined within the development of an environmental management system.

Table 1. Environmental management matrix

Score	Environmental management policy	Staff awareness and training, awareness of the public	Monitoring and reporting
3	Environmental management policy integrated in company vision and action plan. Regular review of progress by top management. Environmental management integrated into management structure.	Formal and informal channels of communication regularly exploited by environmental manager and staff at all levels. Promotion of sound environmental management within the organization and beyond (in the municipality within which the organization operates through different programmes).	Comprehensive targets set within programme, monitors impacts, identifies irregularities, tracks public opinion and any impact beyond its system's boundaries, adjusts environmental programme in periods of profitability for continued improvement
2	Formal environmental management policy exists to some extent in company vision and action plan, but no active commitment from top management	Environmental manager main driver of the programme with key employees responsible for main impact/risk areas in the organization. General induction staff training and awareness. General information available to public.	Monitoring and targeting conducted annually, but programme shows no adaptation to changes in the organization (i.e. monitoring and review is formalized)
1	No formal integration of environmental management concerns, but environmental manager tracks impact	Environmental manager conducts ad hoc awareness raising of key organization employees in problem areas.	Only general monitoring and target reports prepared based on the minimum available data (water, electricity, materials) without analysis of impact
0	Informal ad hoc responses to environmental issues	General rules on emergency situations and fire hazards in place. Engagement with employees and public in emergency situations.	Formal reports compiled on specific data as part of the organization's reporting to the national environmental inspectorate.

At the 3rd level, based on the audit results, proposals for activities to optimize and improve the processes are defined. The activities are normally arranged in several ways to allow the organization to select the most appropriate needs in accordance with their priorities as an organization: (1) to achieve maximum energy- and/or environmental effectiveness (the largest emissions reductions, the largest energy economy); (2) to select the optimal activities in relation to expenses or pay-back period; and (3) time period needed to implementation (from quick-fixes to long-term implementation processes). In most cases, organizations will be looking at a combination of these approaches depending on urgency of environmental risks that may become apparent, available financial resources and impact that certain changes may have on production processes. It is highly essential that for each activity proposed for improvement, that there are specific indicators which are set to confirm that such improvement has been reached.

The zero level (optimal level) refers to the sector level and at this level a comparison of the specific company's indicators to the indicators of other companies within the same sector is anticipated (this part of the research has not been included in this article).

Description of case industry

The basic business of the researched company is the production and sale of industrial wood-chip pellets. The production of the wood pellets uses the chips, sawdust, branches and bark of both coniferous and deciduous trees. The pellets are made under high pressure thus making it possible to create the pellet without the use of any adhesive or other binding materials. The company has already created an integrated management system which attempts to address the requirements of two standards – ISO 9001:2008 quality management system, ISO 14001:2004 environmental management system.

The pellets produced are exported to European Union countries such as Denmark, Sweden, Belgium and the Netherlands, where they are used in power and cogeneration stations.

The technological scheme of production process at this company is illustrated in Fig. 2.

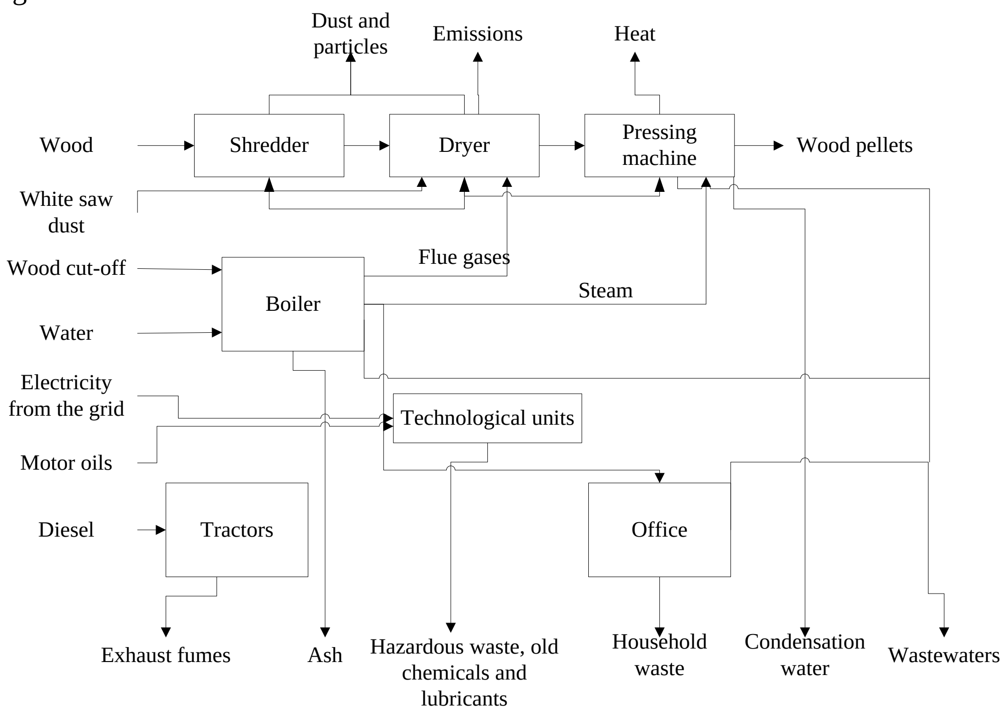

Figure 2. Technological scheme of the case industry plant.

A review of the environmental aspects which evolves from the company's activities is provided in the *Results and Discussion* section.

RESULTS AND DISCUSSION

Strategy level results: energy management and environmental management matrixes

Analysing the status of environmental management system in the wood pellet production company before implementation of the management systems, the overall situation in the field of environmental management can be defined as good, which is based on the following observations:

- The main environmental aspects are identified and addressed within the management system of the company.
- Clear procedures are developed and followed to monitor work processes from which the main environmental aspect may arise.
- Environmental manager is not included in the management group, although the quality system manager is. The integrated system in some areas may present problems in implementation as the approaches to issues which are both environmental- and quality-related are not connected in a comprehensive management response. Due to the organizational hierarchy, in the event of conflict between an action which affects both environment and quality, one can guess that quality argument may gain favorable position in any management decision.
- Internal communication on environmental aspects is structured through induction training and regular monitoring. External communication with the public indicates a clear mechanism developed for reporting incidents and concerns.

The indicative summary of the environmental matrixes is given in Fig. 3.

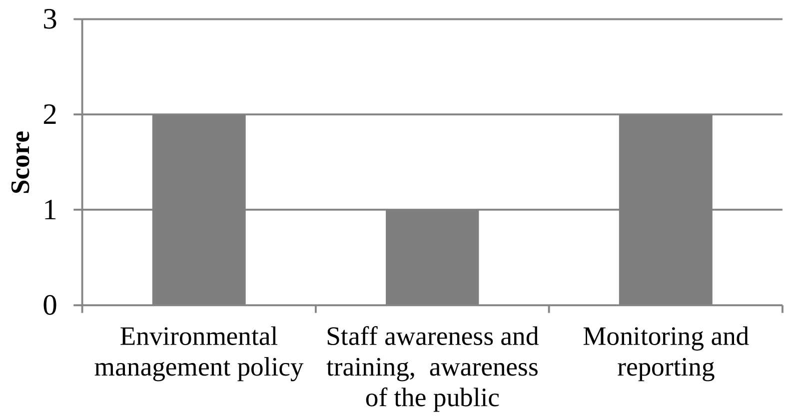

Figure 3. Resulting scores of the wood processing company environmental issues at the strategic level.

Environmental aspects are an essential element of the environmental management system, on the basis of which the environmental policy, its goals, tasks and subsequent monitoring and measurements are built. In order to identify environmental aspects, it is necessary to understand and evaluate the impact or hazards that the company's activities can potentially have. It is also important to understand how these various aspects interrelate. Environmental aspects are divided into direct and indirect aspects and they arise from input (materials) and output (production, waste) flows (see also Fig. 2). The direct aspects of the company are listed in Table 2. These aspects are defined in three categories: (1) scale of aspect – global, regional or local; (2) degree of impact – volume or size of pollution, waste amount, etc.; (3) effect of aspect – reversible or irreversible harm on environment. Each aspect receives a rating from 1 to 3 where one denotes small impact, 2 – medium impact, 3 – significant impact. The selected scale from 1 to 3 is based on the guidelines of EMS according to ISO14001 standard. The positive side of this simple scale is that it is easily understood by all parties involving in planning, implementing and monitoring the programme – those introducing the system (consultants), the company employees at all levels, auditors and the public at large. The total valuation of the aspect is defined by multiplying the values from each category.

Table 2. Direct environmental aspects at the wood pellet production plant

Environmental aspect	Scale	Degree	Effect	Total score
Energy consumption (electricity)	2	2	1	4
Energy consumption (heat)	3	2	2	12
Water consumption	1	1	1	1
Diesel consumption	1	1	2	2
Motor oils/lubricants	1	1	3	3
Paper consumption	1	1	1	1
Municipal waste	1	1	1	1
Hazardous waste	1	1	3	3
Wastewater	1	1	2	2
Emissions to air	1	3	2	6
Noise	3	1	2	6
Odours	1	1	1	1
Risk of explosion and accidents	3	3	2	18

The maximum points are – 27, the minimum – 1. The critical aspects are those which have received the maximum points (27), or in this concrete case – 18 which was the highest number of points received. Important aspects are those ranging from 8 and 18 points, however, depending on the situation, this can change. The remaining aspects (under a 6 point total) still remain as aspects to be monitored, but are not deemed important for immediate action.

Process level results: environmental management indicators

The role of indicators in the optimization of environmental processes is highly recognised in research (Botta, & Comoglio, 2012; Comoglio & Botta, 2012; Dörr, Wahren, & Bauernhansl, 2013; Petrosillo, De Marco, Zvingule et al., 2013). Similar to the evaluation of other environmental processes (as project effectiveness, energy efficiency) the indicators used in environmental management also need to be (1) reliable; (2) comparable; and (3) indicative.

As far as the case of wood pellet production, the following criteria meets the above requirements:

Electricity consumption to one manufactured unit of product (hereinafter manufactured unit of product is 1 tonne of wood pellets);

- Heating (wood) consumption to one manufactured unit of product;
- Evaluation of the internal logistics fuel consumption and the motor oil and chemical consumption to one manufactured unit of product;
- Number of fire incidents per year;
- Number of accidents per year;
- Volume of emissions (NOx, CO, particles) to one manufactured unit of product;
- Amount of dust produced to one manufactured unit of product;
- Amount of ash to one manufactured unit of product;
- Amount of wastewater (from office and production processes) to one manufactured unit of product;
- Water consumption (from office and production processes) to one manufactured unit of product;
- Amount of hazardous and municipal waste (from office and production processes) to one manufactured unit of product;
- Noise level to one manufactured unit of product;
- Odour level to one manufactured unit of product.

In order to evaluate the efficiency of the environmental management system, the analysis of the indicators needs to take place before, and after introducing the environmental management system (Comoglio & Botta, 2012). In regard to the organization reviewed, the data after environmental management systems implementation is not yet available and thus this aspect is not included in this article.

Actions level results: improvement activities in the field of environmental management

Based on the prioritization of direct environmental aspects (see Table 2), some recommendations were made within the research on how to reduce negative impact of environmental aspects:

- *Risk of explosion and accidents*: The largest risk identified was that of fire hazard which is associated with different phases of the production processes and the flammable characteristics of the materials use. Recommendations were made to ensure regular monitoring and self-assessment of hazardous situation in the system.
- *Energy consumption (heat):* Since the boiler is not located within a building, it would be necessary to find ways on how to reduce heat loss from its surface.

Another way to minimize heat consumption would be to utilise the heat generated from pellets during the compression process. The pellet's temperature after compression is up to 70 ^{o}C, and thus, by installing a recuperation apparatus, this heat can partially be recovered and used to heating the premises.

- *Emissions to air:* There is a fair amount of particles which come from the production process in the work atmosphere. An air filtration system could minimize the effects of these particles on the health of the workers, as well as make it possible to collect such particles for use in the technological process.
- *Noise:* Noise is generated mainly from the production units. It is possible to reduce this aspect by installing a sound insulation wall around the company's territory.

CONCLUSIONS

The paper describes an analysis of lessons learned based on combined management-response and indicator based analysis on the introduction of environmental management systems (in accordance with ISO 14001:2004) in a wood pellets production enterprise. The combined management-response un indicator-based Environmental Management System (EMS) evaluation methodology makes it possible to offer real improvements in industrial companies: a comparative analysis of indicators before and after the introduction of the EMS allows the company to set effectiveness for introducing the EMS, to evaluate both the reduction of environmental impacts and also the economic benefits of the expenses related to these reductions. At the same time the results of the research confirm that in case of the wood pellet production plant, energy planning system elements are more highly developed than those related to environmental management. This can be explained due to the fact that the company recognizes the direct economic benefits which stem from energy efficiency activities – they give a direct return in financial terms. The improvement of environmental factors, however, rarely produce large economic savings due to the current low environmental tax levels in Latvia (natural resource tax and GHG quota prices).

Lessons-learned from wood pellet production are the following:

- External pressures from large consumers place environmental issues and their certification in internationally-recognized standards at a high priority
- Energy issues are the main concern of companies in respect to the environment due to overall scale of the costs associated with this in the total production costs
- Upper management commitment to environmental issues is important, however engaged and knowledgeable middle-managers (in a medium-sized company) can also be enough to carry a good system, if such managers are trusted and given appropriate level of authority in the company.

In further studies work needs to be done on the inclusion of zero level evaluation in the research, specially taking into account the rapid development of the wood pellet industry in Latvia and the fact that the produce is primarily exported, which puts additional responsibilities on producers to follow international standards and maintain the certification of these quality and environmental management systems. The expansion of the analysed system with an energy management system would make it possible to estimate the impact of the energy management on the environmental management of the company and vise versa. It would also be beneficial to include the investment part in the evaluation matrix and to calculate cost-efficiency of environmental activities.

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REFERENCES

Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage. Brussels, Euroepan Commission. 2010.

Campos, L.M.S. 2012. Environmental management systems (EMS) for small companies: a study in Southern Brazil. *Journal of Cleaner Production* **32**, 141–148.

Comoglio, C. & Botta, S. 2012. The use of indicators and the role of environmental management systems for environmental performances improvement: a survey on ISO 14001 certified companies in the automotive sector. *Journal of Cleaner Production* **20**(1), 92–102.

Dörr, M., Wahren, S. & Bauernhansl, T. 2013. Methodology for Energy Efficiency on Process Level. *Procedia CIRP*, *7*, 652–657. doi:10.1016/j.procir.2013.06.048

Gordić, D., Babić, M., Jovičić, N., Šušteršič, V., Končalović, D. & Jelić, D. 2010. Development of energy management system – Case study of Serbian car manufacturer. *Energy Conversion and Management* **51**(12), 2783–2790.

Halila, F. & Tell, J. 2013. Creating synergies between SMEs and universities for ISO 14001 certification. *Journal of Cleaner Production* **48**, 85–92.

Heras, I. & Arana, G. 2010. Alternative models for environmental management in SMEs: the case of Ekoscan vs. ISO 14001. *Journal of Cleaner Production* **18**(8), 726–735.

International Organization for Standardization. Environmental management systems – with specification with guidance for use. Geneva, Switzerland: International Organization for Standardization; 2005.

Liu, H. & Rodríguez, R.M. 2014. A fuzzy envelope for hesitant fuzzy linguistic term set and its application to multicriteria decision making. *Information Sciences* **258**, 220–238.

Nguyen, Q.A. & Hens, L. 2013. Environmental performance of the cement industry in Vietnam: the influence of ISO 14001 certification. *Journal of Cleaner Production* XXX, 1–17.

Petrosillo, I., De Marco, A., Botta, S. & Comoglio, C. 2012. EMAS in local authorities: Suitable indicators in adopting environmental management systems. *Ecological Indicators* **13**(1), 263–274.

Rondinelli, D. & Vastag, G. 2000. Panacea , Common Sense , or Just a Label ? The Value of ISO 14001 Environmental Management Systems, **18**(5), 499–510.

Testa, F., Rizzi, F., Daddi, T., Gusmerotti, N.M., Frey, M. & Iraldo, F. 2013. EMAS and ISO 14001: the differences in effectively improving environmental performance. *Journal of Cleaner Production*. *In press.*

To, W.M. & Lee, P.K.C. 2014. Diffusion of ISO 14001 environmental management system: global, regional and country-level analyses. *Journal of Cleaner Production* **66**, 489–498.

Zhu, Q., Cordeiro, J. & Sarkis, J. (2013). Institutional pressures, dynamic capabilities and environmental management systems: investigating the ISO 9000--environmental management system implementation linkage. *Journal of Environmental Management* **114**, 232–42.

Zobel, T. 2013. ISO 14001 certification in manufacturing firms: a tool for those in need or an indication of greenness? *Journal of Cleaner Production* **43**, 37–44.

Zvingule, L., Kalnins, S. N., Blumberga, D., Gusca, J., Bogdanova, M. & Muizniece, I. 2013. Improved Project Management via Advancement in Evaluation Methodology of Regional Cooperation Environmental Projects. *Scientific Journal of Riga Technical University. Environmental and Climate Technologies* **11**, 57–67.

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Mechanical ventilation with a heat recovery system in renovated apartment buildings

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Abstract. Renovation of existing buildings offers a great opportunity to reduce energy consumption, but often it also reduces indoor air quality, as buildings which were originally designed for natural ventilation are made highly air tight. A solution to the problem would be a mechanical ventilation system, but several problems are experienced when implementing it – no place for installing air ducts, cold air inflow or additional energy needed for incoming air preheating. Ventilation using heat recovery units is the one method out of many other energy saving measures. The advantage of using heat recovery units is energy saving, and as a result, savings on costs of the operation of the ventilation system. This paper describes the renovation carried out in 4-storey apartment buildings. In the course of the study, two buildings were analysed, both belonging to the series buildings of the Soviet Era (103 series), built in 1970 using the same materials, the same construction solutions. The renovation was carried out by one company, using the same materials and the same renovation principles for both buildings. The only difference after the renovation is that a new centralized mechanical ventilation system with a heat recovery unit is installed in one of the buildings, while in the second building the natural ventilation system is preserved. The arrangement of the mechanical ventilation system is rather innovative as the ventilation ducts in the building for fresh air supply are integrated into the facade’s insulation layer and enter the living room through the wall directly behind heating radiators. The main questions studied in the course of the research are the efficiency of the mechanical ventilation system heat recovery, the building’s air tightness, and the overall system efficiency.

Key words: mechanical ventilation, heat recovery, building renovation, energy efficiency.

INTRODUCTION

The building sector is the largest user of energy and the largest CO_2 emitter in the European Union (EU) and is responsible for about 40% of the EU’s total final energy consumption and CO_2 emissions. The EU has established an ambitious target that all new buildings must be nearly zero energy buildings by 31 December, 2020 (Directive 2010/31/EU). However, even if all buildings in the future will be built according to the nearly zero energy building standard, this would still only mean that the increase in energy demand will be reduced, but it would not reduce the exiting demand. Only measures taken in existing buildings will have a significant effect on the total energy demands of building stock.

Since the residential building stock in Baltic countries is very old, mainly built prior to the 1970s or even the 1960s, the current average specific heat consumption in buildings is between 220 and 250 kWh $(m^2)^{-1}$ per year (Cabinet Decree No. 571). Retrofitting of existing buildings offers a great opportunity for reducing energy consumption and greenhouse gas emissions.

The first retrofit alternatives to be considered for existing residential buildings are improvement of the thermal insulation and air tightness. The usual standard renovation of multi-storey apartment buildings includes facade insulation, end wall insulation, thermal insulation of the attic and basement ceiling and replacement of old windows, and heat substation renovation; with this standard renovation, it is possible to reach approximately 50% energy savings (Blumberga, 2008). In absolute terms based on the current Latvian building code, this translates into energy consumption between 75–85 kWh m^{-2} per year. To reduce energy consumption even more and improve the indoor climate, the heat distribution systems and ventilation systems have to be addressed.

In fact, heat losses by ventilation become the main source of heat losses after proper thermal insulation of the building envelope, which can be as high as 30–40% of energy consumption (Klavina, 2012). A study (Orme, 2001) about the energy impact of ventilation and air infiltration in residential buildings in 13 countries shows that the energy losses due to ventilation and air infiltration represent about 48% of the energy delivered for space heating. Tommerup and Svedsen (Tommerup & Svendsen, 2006) reported the ventilation heat losses in typical Danish residential buildings to be 35–40 kWh $(m^2\ a)^{-1}$ per year. As until the 1990s building were designed with natural ventilation, they become airtight buildings after renovation and the air infiltration rate is often not sufficient to maintain acceptable indoor air quality. Shortcuts between different ventilation ducts often become a problem after renovation, resulting in both high discomfort and energy losses.

Indoor air quality is greatly influenced by the amount of fresh air that enters the building. This fresh air replaces the exhausted air, which contains biological pollutants, excess moisture, and volatile organic compounds released from building materials, carpets, furniture, and other household items as a result of aging, decomposition, or curing.

A good solution in such buildings is mechanical ventilation with heat recovery to recover the heat from exhaust air and in such way also reduce the ventilation heat losses. A good strategy for maintaining good indoor climate and reduce energy consumption in a building would be airtight a building with a mechanical ventilation system and heat recovery. This solution may satisfy energy conservation goals in a cost-effective manner without reducing the indoor air quality. Heat recovery systems typically recover about 60–95% of the heat in exhaust air and have significantly improved the energy efficiency of buildings (Mardiana-Idayu & Riffat, 2012).

MATERIALS AND METHODS

There are a number of issues that should be considered during the design phase and before installation of a new ventilation system in existing buildings. Narrow and unsatisfactory functional links between premises, as well as low ceilings, which in most cases do not exceed 2.45 m. These are the usual characteristics of apartments in the multi-storey buildings constructed in series in Latvia. Because of the low ceiling height, it is not convenient to build a centralized system with air ducts going through apartments, besides, the owners of the apartments are against fitting of ventilation channels on the ceiling of rooms. One of the solutions is installation of a decentralized system as has, for example, been implemented in a number of projects in Estonia. However, this solution has shown rather high investment costs and fewer adjustment possibilities as well as problematic maintenance – the need to access all flats or left to the house owner's responsibility (Koiv, 2008; Koiv et al., 2012).

During the design phase, a new solution was found, a centralized ventilation system with air ducts placed outside of the building – in the facade insulation. There are already two examples of public buildings in Latvia (Ventspils City Council and Ergli Vocational School) (Kamenders, 2013) where this solution is used, as well as in Europe (Kalz & Dinkel, 2013). But so far, such solution has not been applied to multi-apartment residential buildings.

Experimental facility

There are two similar renovated residential buildings located at 11 and 17 Zirnu Street, Cesis. Both are 4-storey buildings with a basement and technical floor and belong to the 103 series, built around 1970. Energy audits were carried out in March 2012 before renovation. Renovation works were finished in January 2014.

The situation before renovation was similar. In most of apartments (≈ 53–54%), windows had been replaced by the owners. The attic floor was partially insulated with loose wool (thickness100–200 mm). In the basement, water pipe insulation works had been carried out in a poor quality, certain places were not completely covered. Masonry damages were observed on the external walls. The buildings were equipped with a one-pipe heating system. The radiators were not equipped with special thermostats, even the ones which the owners had replaced; therefore, individual control of room temperature was impossible. Building heating substations were equipped with an automatic control system that provided heat generation according to the outdoor temperature.

According to the information provided by the residents of the buildings, the indoor air temperature in apartments was around 18–21°C. The apartments near the end walls had lower indoor air temperature characteristics. In a part of the apartments, poor circulation in the heating risers was detected.

Originally, the buildings were designed with a natural ventilation system providing air supply through cracks, windows, slots and air extraction through kitchen, toilet and bathroom ventilation shafts. During the visits, mould was detected in most of the apartments.

The renovation carried out in Zirnu street, Cesis, included the following steps:

- Facade and end wall insulation from the outside with 100 mm insulation, window boxes insulation with 30 mm insulation;
- The basement slab insulation (including the walls bordering the apartments) with 100 mm insulation and building plinth insulation with 50 mm extruded polystyrene;
- Staircase roof insulation with 100 mm insulation and attic floor insulation, ensuring a 300 mm layer of insulation all over the floor area;
- Replacement of apartment windows and staircase windows;
- Replacements of attic and entrance doors;

– Renovation of the heating system;
– Renovation of the hot water distribution system.

Table 1 shows the thermal properties of the building components before renovation and the planned ones.

Table 1. Thermal properties (U value (W (m^2 K)$^{-1}$) of the building components before renovation and planned properties

	Basement slab	Facade walls	End walls	Windows	Doors	Attic	Staircase roof
Before	0.56	0.89	0.93	1.8–2.8	3.00	0.28–0.77	1.02
After	0.21	0.28	0.29	1.4	1.6	0.12	0.29

In one of the two buildings (17 Zirnu Street) a new mechanical ventilation system with a heat recovery unit was installed. The main concept of the renovation is to minimize heat losses and maximize heat gains and to ensure high quality indoor climate.

A mechanical ventilation system with three air handling units which are located in the building stairwells at the attic level was installed. Each staircase has its own air-handling unit (Zehnder ComfoAir 550 R Luxe Enthalpie with moisture recovery) designed with a counter flow plate heat exchanger with a highly efficient heat recovery rate and moisture recovery (enthalpy). Preheating of the fresh air is ensured with an electrical coil. The ventilation system corresponds to the 'Passive House' (Passivhaus Institute Dr. Wofgang Feist) requirements. The Latvian Construction Standard LBN 231-03, 'Heating and ventilation of residential and public buildings', requires at least 15 m^3 h^{-1} of fresh air per person if the only indoor air pollution source is the residents. The Construction Standard LBN 211-98, 'Multi-storey residential buildings', states that the air exchange rate per hour in living rooms and bedrooms should be at least 3 m^3 m^{-2} and the indoor air temperature during the heating season should be at least 18°C. The designed air exchange rate is 20–30 m^3 h^{-1} in each room, which corresponds to 1–2 persons per room. During the ventilation design process, the following design parameters were used: minimum outdoor temperature -23.8°C in winter and maximum outdoor temperature +22.3°C in summer; indoor temperature +21°C during the heating season.

The ventilation system is designed so that exhaust air is extracted through the existing ventilation shafts (kitchen and bathroom). Flow regulation is ensured with balancing valves and exhaust grilles with a flow control option. The outputs of all ventilation shafts are collected in a single system with galvanized steel ducts in the building's attic. The ducts are covered with a heat insulation layer (at least 100 mm). Additionally, it is embedded in the attic floor insulation layer.

The air supply system is arranged by flexible plastic air ducts (diameter 75 mm) separately to each living room and bedroom. The air ducts are mounted on the building's facade and enter into living rooms through the wall directly behind the heating radiators (see Fig. 1). The vertical duct parts are built into special wells, which are filled with loose thermal insulation (at least 100 mm). They go down the facade form the attic to the first floor apartments. Fig. 2 shows the air ducts coming from the facade to the attic.

Figure 1. Air ducts are mounted into the facade's insulation layer, enter the living room through the wall directly behind the heating radiators.

Figure 2. Air ducts coming from the facade into the attic (without insulation and already insulated).

The horizontal duct parts are made of flexible plastic duct *Flat 51* 51 × 138 mm. These ducts integrated into the facade insulation so that there is at least 50 mm of thermal insulation between the duct and outdoor air. The supply air stream rate is lower than 1.5 m s^{-1}. The plastic input unit is industrially manufactured with the diameter of 125 mm. The air ducts meet the increased requirements for air density class according to the standard EN 60529, the mechanical perimeter strength of more than 8 kN m^{-2}, and high hygiene requirements. The special constant flow valves installed in the distribution lines placed in the attic control the supply of airflow in each room. Each air duct (Ø75 mm) has its own flow valve.

RESULTS AND DISCUSSIONS

The aim of this study is to compare the energy consumption in the buildings before and after renovation and to compare the indoor climates of 11 Zirnu Street equipped with a natural ventilation system and 17 Zirnu Street, where a new mechanical ventilation system is installed. Monitoring data for this heating season is not yet available.

A study with the energy simulation software TRNSYS for dynamic calculations is performed. The model will be validated with actual measurement data from 17 Zirnu and 11 Zirnu.

To determine the thermal efficiency of the heat recovery unit, heat transfer rate and pressure drop, and indoor climate, the following measurements have been started:

1. Temperature of the fresh and exhaust stream at the inlet and outlet sections of the heat recovery unit.
2. Air flow rates in both circuits.
3. Temperature of the fresh air supply at the attic level and at the first floor level.
4. Pressure between inlet-inlet, outlet-outlet and inlet-outlet sections.

For the temperature and airflow rates in both circuits, the combined airflow and temperature transmitter IVL 10/N is used (see Fig. 3).

To compare indoor air quality, humidity, indoor temperature and CO_2 concentration are measured in two apartments of each building – one with a mechanical ventilation system and one without. For the measurements, the CO_2 sensors *Telaire 7001* equipped with the data loggers *Hobo* (see Fig. 4), which record data about temperature, CO_2 concentration and humidity level with a 5 min interval, are used.

Figure 3. Placement of the combined airflow and temperature transmitter.

Figure 4. CO_2 sensor *Telaire 7001* and data logger *Hobo* placed in a second floor apartment, 11 Zirnu Street.

The standard efficiency of the extracted ventilation air heat recovery will be established. Electricity consumption for whole system and for preheating will be determined.

It is calculated that after renovation, the building's energy consumption for space heating should reduce from 161 kWh (m^{2}a)$^{-1}$ to 64 kWh (m^{2}a)$^{-1}$ in 17 Zirnu Street and from 143 kWh (m^{2}a)$^{-1}$to 74 kWh (m^{2}a)$^{-1}$ in 11 Zirnu Street. Fig. 5 shows the energy consumption before renovation and the expected consumption after renovation in 17 Zirnu Street (kWh (m^{2}a)$^{-1}$ (i.e. energy consumption per unit of useful area per year). The biggest savings are given by the buildings' envelopes' insulation (saves 28 kWh (m^{2}a)$^{-1}$), and old window replacement (saves 22–23 kWh (m^{2}a)$^{-1}$).

Installation of the ventilation system with a heat recovery unit in 17 Zirnu Street gives additional savings of 16 kWh (m^{2}a)$^{-1}$). These results were obtained assuming that the heat recovery unit works with 85% efficiency; the infiltration rate is 0.2 1 h^{-1}; the air exchange rate of mechanical ventilation is 0.5 1 h^{-1} with the total building volume of 4,421 m^3.

If the building at 11 Zirnu Street would have the same ventilation system with a heat recovery unit, the energy consumption after renovation would be 57.7 kWh (m^{2}a)$^{-1}$), because additional energy savings for heating (16.3 kWh $(m^2a)^{-1}$) due to heat recovery would be obtained.

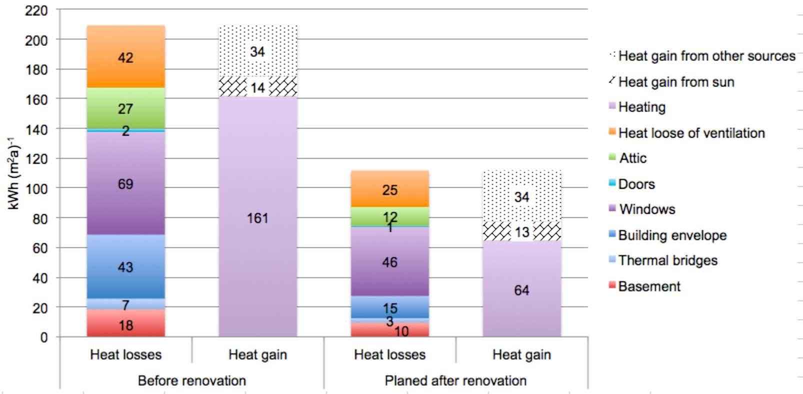

Figure 5. Calculated heat losses and heat gains at 17 Zirnu Street, Cesis, before and after renovation.

Fig. 6 shows the difference in energy consumption for heating in case of a standard renovation that fulfils the normative requirements and in the current case with a new ventilation system installed. The savings compered to the *before* situation range from 44% to 60%, respectively.

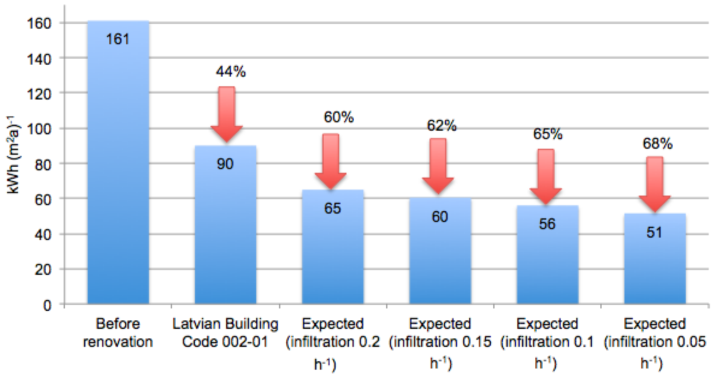

Figure 6. Energy consumption for heating in 17 Zirnu Street, Cesis.

Also Fig. 6 shows how infiltration rate can influence total heat demand. With the infiltration rate 0.05 1 h^{-1} (the same efficiency of the heat recovery unit: 85%) the energy consumption for heating goes to 51 kWh $(m^2a)^{-1}$. It shows that in order to get more from renovation, passive house standards should be strived towards and infiltration rate should be reduced.

The leakage factor of the renovated building was not measured before the beginning of the experiment.

CONCLUSIONS

Calculations of the energy consumption of buildings with and without a mechanical ventilation system were made. The results obtained show how big thermal energy savings are achieved with mechanical ventilation with a heat recovery unit – up to 16 kWh $(m^2a)^{-1}$. In addition, the impact of infiltration on the buildings' energy consumption was evaluated. It shows that in order to achieve bigger thermal energy savings, passive house standards should be used to reduce the infiltration rate as much as possible.

For now, there are two main aspects to think about – the infiltration rate and the efficiency of the heat recovery unit. The infiltration rate has a significant effect on the total energy consumption. It is essential to build highly airtight buildings and strive towards passive house standards. The efficiency of the heat recovery unit is responsible for the recovered amount of heat.

In the end of the heating season, monitoring data will be available and it will be possible to compare the calculated and expected results with the actual situation.

REFERENCES

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

Cabinet Decree No 571 'Energy Development Guidelines for the 2007–2016. The informative part', 1–112 (in Latvian).

Kļaviņa, K. & Rochas, C. 2012. Future Energy Efficiency Benchmark for Renovated Multi-Apartment Buildings. *Riga Technical University 53rd International Scientific Conference: Dedicated to the 150th Anniversary and the 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni: Digest, Latvia, Rīga, 11.-12,*159–159.

Koiv, T.A. 2008. Indoor climate and ventilation performance on top floors of typical old-type apartment buildings. *Estonian Journal of Engineering* **14**(1), 17–28.

Koiv, T.A., Mikola, A. & Kuusk, K. 2012 Energy Efficiency and Indoor Climate of Apartment Buildings in Estonia. *International Journal of Energy Science* **2**(3), 94–99.

Blumberga, A., Kamenders, A. & Žogla, G. 2008 Energy Performance of Renovated Soviet Time Apartment Building. *RTU zinātniskie raksti. Vides un klimata tehnoloģijas* **13**(1), 127–133 (in Latvian).

Orme, M. 2001. Estimates Of The Energy Impact Of Ventilation And Associated Financial Expenditures. *Energy and Buildings* **33**(3), 199–205.

Tommerup, H. & Svendsen, S. 2006. Energy Savings In Danish Residential Building Stock. *Energy and Buildings* **38**(6), 618–626.

Mardiana-Idayu, A. & Riffat, S.B. 2012. Review on heat recovery technologies for building applications. *Renewable and Sustainable Energy Reviews* **16,** 1241–1255.

Kamenders, A., Vanaga, R. & Krauklis, E. 2013. Post-Occupancy Evaluation of Dormitory Building with Aim of EnerPHit Renovation. No: *17th International Passive House Conference 2013*, Germany, Francfurt, 19–20. april, 2013. Frankfurt: Passive House institute, ISBN 9783000413469, 533–538.

Kalz, D. & Dinkel, A. 2013. IEA SHC Task 47: Renovation of Non-Residental Buildings towards Sustainable Standards, Brochure.

Agronomy Research **12**(2), 499–510, 2014

Experimental study on optimisation of the burning process in a small scale pellet boiler due to air supply improvement

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Abstract. The specific weight of biomass and pellets in thermal energy production has recently started to increase rapidly. The continually growing price of fossil fuels and European Union requirements to increase the share of renewable energy in thermal energy production are the main reasons of the biomass specific weight increase. Unfortunately, Latvia uses only a small part of the country's existing biomass potential for the time being. A growth of the amount of biomass utilisation for energy production can be foreseen in the future, because such type of energy production has a number of advantages, one of which is the lesser amount of emissions that arise during the combustion process. However, the amount of emissions that arise during the combustion of wood pellets can get lower due to optimisation of the combustion process. Air supply is one of the main factors which have effect on the heat loss, boiler efficiency, and emissions levels.

The main goal of this study is to optimise the pellet combustion process in a small scale pellet boiler due to the air supply improvement. Experimental research of the combustion process of a pellet boiler with nominal capacity 25 kW was carried out during the work. First at all, the effect of changes in the amount of air supplied to the boiler combustion process was determined. Then, approbation of two methods for combustion process improvement was made.

The first method was based on flame dissipation, but the second method included the opposite method – flame concentrating. However, the main task of both methods applied was to improve the process of mixing air and fuel. It was important to reduce the rate of air supplied, too. Four different gratings were used for dissipation of the flame. Cylinders without and with a spiral for flow swirl were used for flame concentration. The results of the study show that both methods, in general, have a positive impact on the combustion process.

Key words: pellet boiler, air supply, flame dissipation, flame concentrating.

Nomenclature

C	Carbon content of test fuel (as fired basis), % of mass
CO	Carbon monoxide content in dry flue gases, % of volume
H	Hydrogen content of test fuel (as fired basis), % of mass
NO_x	Nitric oxides content in dry flue gases, % of volume
O_2	Oxygen content of dry flue gases, % of volume
PM	Dust content of dry flue gases, % of volume
T_{fg}	Temperature of flue gas, °C

INTRODUCTION

Combustion process is a complicated process where exothermic chemical reaction between the fuel and the oxidant happens and some amount of the heat gets free. The emission from the combustion process can be divided into two groups – unburned pollutants and pollutants that are produced by combustion. CO, hydrocarbons, polycyclic aromatic hydrocarbons, and tar form the unburned pollutants. Ash, particulate matter, different nitrogen, and sulphur emissions make the second group. The amount of the emission from the first group can be decreased if optimal combustion parameters are organised (Khan et al., 2009). It is important to minimize the amount of CO in flue gas to have high combustion efficiency. A specific condition must be organised in the pellet boiler furnace to reduce the amount of CO (Hansen et al., 2009).

Nowadays, utilisation of the renewable energy from agro biomass for heat production is becoming more and more popular in the world and, especially, in the Northeast European countries (Mikkola & Ahokas, 2011; Beloborodko et al., 2013). Biomass has high potential, because it is an environmentally friendly heat production method with low amount of harmful emission (Jasinskas et al., 2011). Pellet is one of the most popular kinds of agro biomass. There is a wide range of heating devices available for pellet combustion.

Pellet combustion efficiency varies highly for different pellet boilers. Combustion process efficiency in a pellet boiler can vary highly and depends on many factors. Pellet boiler construction is one of the main parameters which have a dominant effect on the combustion process. There are three main burner types available for pellet boilers – underfed, horizontally fed, and top fed burners. Each of the burner types has some specific characteristic and differences in the air supply and ash removal (Haapa-Aho et al., 2011). In the study done by Verma et al. (2011a), a pellet boiler with different burner types was tested. The results show that top fed boilers have higher CO concentrations and lower efficiencies. The properties of the pellets that are used have an important role on the combustion process (Verma et al., 2012). The fuel with high ash content has a negative effect on the air supply and combustion process in general (Stahl & Wikström, 2009). The ash content has an impact on the dust content in flue gas (State of the art …). There are pellets with different properties available in Latvia, thus it is important to check pellet quality (Kirsanovs et al., 2012).

Air supply has one of the dominant roles on the combustion process in a pellet boiler. Air supply must be organized in such a way so as to reach a qualitative air and fuel mixing process. Air must be left in the burner and furnace for a sufficient time to achieve complete combustion. The amount of CO largely depends on the air supply organisation (Johanssona et al., 2004). The amount of air supply affects the temperature in the furnace, but temperature in the furnace influences all chemical reactions and emission formatting. A study done by Verma et al. (2011b) shows that CO has an effect on the amount of dust in flue gas. The higher the concentration of CO, the higher the amount of the particulate matter in flue gas. The losses due to unburned combustibles in flue gas depend on the dust content. The work done by Fernandes & Casta (2011) presents a similar connection between CO and the dust content in flue gas. The results also show that the amount of emissions depends on the boiler capacity. The closer the boiler capacity is to nominal, the lower amount of emissions.

There are different methods to improve the combustion process in a pellet boiler and some of them are based on air supply optimisation. Firstly, the optimal amount of oxygen in flue gas must be determined. This optimal value can vary depending on the boiler's technological properties. If air supply is too high, the amount of CO increases. Heat losses with outlet gases grow up too, and this is the main problem. Flue gas flow rises as well. The heat transfer to water goes down, because the time during which the hot gas is placed in the heat exchanger decreases (Loo et al., 2008). Nowadays, lambda sondes have become more and more popular for oxygen concentration regulation in flue gas. A study done by L. Carvalho (2008) shows the advantages of lambda sondes. The experimental research was done using different boilers with and without lambda sondes. There are other methods for combustion process control (Biomass combustion …, 2008; Haapa-aho et al., 2011).

Air staging is one of the commonly used methods to improve the combustion process. Primary air was used for lighting and fuel drying, but secondary air was used to burn out the combustible volatiles. Sometimes tertiary air was used as well. The required amount of air in different parts of a boiler furnace can be organised if air staging is used (Eskilsson et al., 2004). It is important to calculate the optimal ratio between primary and secondary air supply to reduce the amount of emissions and increase combustion efficiency (Žandeckis et al., 2013a). The location of secondary air and distance from primary air injection and the burner have important roles as well (Chaney et al., 2012). There are many other studies where the advantages, main details, and specific features of the air staging utilisation are described (Nussbaumer et al., 2003; Klason & Bai, 2007; Liu et al., 2013).

Different pellet boiler burner design modifications can be used for combustion process improvement and emission reduction. The main part of the goal of design optimisation is to make air and fuel mix better. One of such methods is continual or periodical fuel mixing. Different technological solutions exist. A study done by L. Terrazzano et al. describes one of such burner design improvements (Terrazzano et al.).

METHODS AND MATERIALS

Description of the experimental stand

To achieve the goal of the research, a set of experiments were conducted using an experimental stand which is intended for biomass boiler testing according to the standard LVS EN 303-5 'Heating boilers - Part 5: Heating boilers for solid fuels, manually and automatically stocked, nominal heat output of up to 300 kW – Terminology, requirements, testing and marking' (2012). The experimental stand is shown in Fig. 1. The laboratory stand consisted of a 25 kW pellet boiler, monitoring equipment, a heat accumulation tank, and a heat exchanger for boiler cooling.

For determination of flue gas chemical composition (NO_x, CO, O_2), the flue gas analyser Testo 350XL was used. All concentrations were calculated under equal conditions – at 10% of O_2. Flue gas temperature, chemical composition, amount of dust content in flue gas flow rate, chimney draught, fuel consumption, and thermal performance of the boiler were monitored during the test. The K-type thermocouples were used for the flue gas measuring.

The water flow rate was measured using a magnetic flow meter. PT 100 temperature sensors were used for water temperature measuring. The pressure into the flue gas stack was regulated manually and was determined using the differential manometer DPT ± 100-R2-Az-D-Span. For determination of fuel consumption, the pellet boiler was put onto the industrial weighing platform Svenska Vag HCPS-4 and changes in the weight were recorded automatically.

All data was gathered scientifically using Campbell data and was transferred to a PC for data processing.

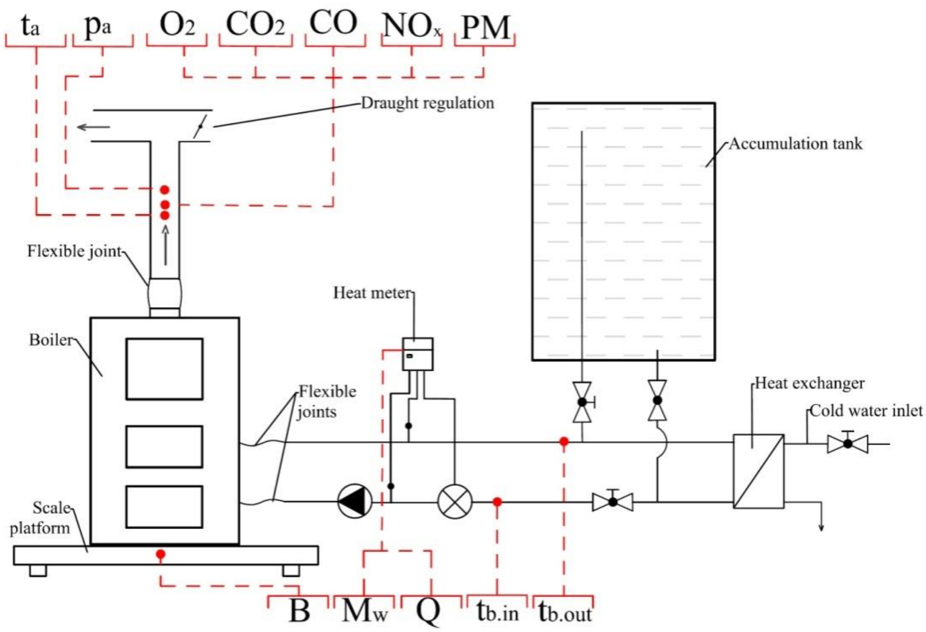

Figure 1. The principal scheme of the boiler stand (Žandeckis et al., 2013b).

The nomenclature used in Fig. 1: B – mass of the test fuel (kg h^{-1}), M_w – water flow rate (kg h^{-1}), Q – heat output (kW), B – heat input (kW), Q_b – chemical heat losses in the flue gases, referred to the unit of mass of the test fuel, (kJ kg^{-1}) t_a – flue gas temperature (°C), p_a – draught in the chimney (Pa), $t_{b.in}$ – boiler input temperature (°C), $t_{b.out}$ – boiler output temperature (°C).

The boiler efficiency was calculated according to the standard EN 303-5:2001 using the direct method. The amount of the fuel used, produced heat, and the net calorific value were taken into account for the boiler efficiency calculations. The heat losses with outlet gases and heat losses by incomplete burning from chemical causes were calculated according to the standard LVS EN 13240:2002 'Roomheaters fired by solid fuel – Requirements and test methods' (2002). For the flue gas flow rate determination, direct and indirect methods were used. It was done to increase the veracity of the acquired data. The Vortex VA40 ZG7 flow meter was used for direct the method. The indirect method is the calculation of the flow rate using the data about the fuel chemical composition, moisture content, and calorific value.

Description of the pellet boiler

The experiments were done using a 25 kW pellet boiler (see Fig. 2). The burning process happens in the automatic regime, the amount of pellets supplied and the control of on/off sequences is the function of the water temperature in the boiler. Pellets from a container next to the boiler are fed through a horizontal screw type conveyor into a vertical, bottom fed burner. The amount of the fuel supply was constant for each test. The required amount of combustion air was supplied with a fan which was controlled by manually changing the ON/OFF intervals of the air blower. The amount of air supplied was different to get different values of oxygen concentration in the flue gas in the range from 5% to 13%.

Figure 2. The pellet boiler Grandeg GD_BIO 25.

Description of the fuel used for tests

Three different types of pellets were used for combustion tests. It was done to make three series of combustion test with changed oxygen concentrations in the flue gas in the range from 5% to 13%, and to increase the veracity of the acquired results. The physical and chemical parameters of the pellets used for the tests are described in the Table XX. The laboratory analysis was based on the methodology given in the CEN/TS standards, see Table 1.

Table 1. The chemical and physical parameters of the pellets

Parameter	Pellet A	Pellet B	Pellet C	Method
Ash content, %	1.23	1.39	0.56	CEN/TS 14775 (EN, 2009)
Moisture content, %	6.71	11.84	8.56	CEN/TS 14774-3 (EN, 2009)
Net calorific value, MJ kg^{-1}	17.7	16.4	17.4	CEN/TS 14918 (EN, 2009)
Gross calorific value, MJ kg^{-1}	20.5	20.2	20.5	CEN/TS 14918 (EN, 2009)
C, %	45.7	43.2	44.8	
H, %	5.79	5.47	5.67	

Description of the methods for flame dissipation and concentration

A grate made of steel pipes with outside diameter 2.4 cm and wall thickness 2.2. mm was used for flame dissipation (see Fig. 3). In general, the construction was made of the more than 90 tubes. The length of the tubes was 12 cm. The diameter of the grate was about 22–23 cm. The height of the construction could be regulated with legs. The grate was installed over the boiler burner and the flame that reached the bottom part of the grate dissipated and went through pipes. The resistance of flue gas grew and the process of air and volatiles blending was improved.

Figure 3. The grate for flame dissipation.

The second method to improve the combustion process was based on the opposite method. A steel cylinder with a spiral for flow swirl was used for flame concentration (see Fig. 4). The diameter of the cylinder was 18 cm and the height 30 cm. The cylinder was installed over the burner and the flame went through it. An increase of the reaction time between oxygen and volatiles was reached. It promoted a more complete combustion process.

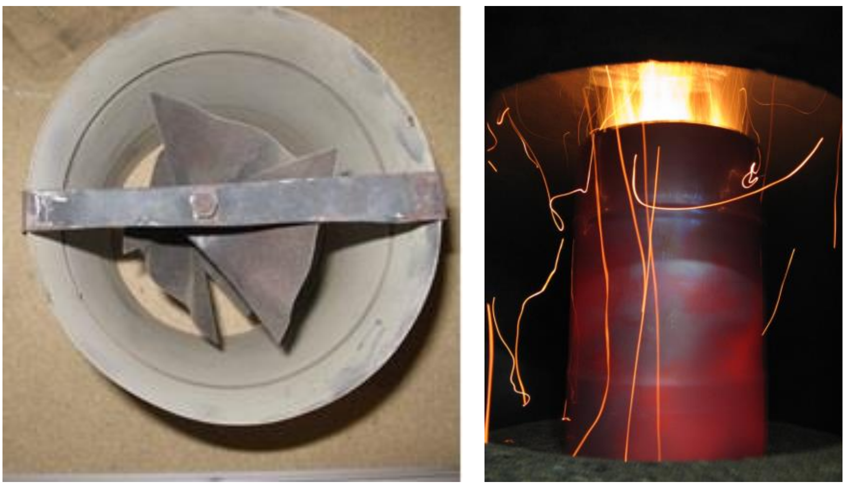

Figure 4. The cylinder for flame concentrating with a spiral for flow swirl.

RESULTS

Oxygen concentration changes the influence on the combustion process

The results of the tests carried out during the research show that changing the oxygen concentration in flue gases from 5 to 13%, changes the flue gas temperature from 125°C to 170 °C (see Fig. 5). The flue gas temperature grows with oxygen concentration increase. NO_x concentration also grows, but not so sharply. The minimum amount of CO is 30–50 ppm calculated under normal conditions with the oxygen concentrations of the flue gas of 6–7%. The amount of CO was up to 25 times higher in the flue gas with oxygen concentration 13%. The heat losses with outlet gases average from 5% to 14% depending on the oxygen concentration in flue gases. The heat losses by incomplete burning from chemical causes were significantly lower – only 0.1% with the oxygen concentration of exhaust gas of 6–7% and 1.5% with high concentrations of oxygen when the CO concentration in flue gas is high. The heat losses with outlet gases and by incomplete burning from chemical causes have a dominant effect on the combustion efficiency. Boiler efficiency varies in the range of 76 to 90%. The maximum efficiency was established at the oxygen concentration of the flue gas of 6.5%.

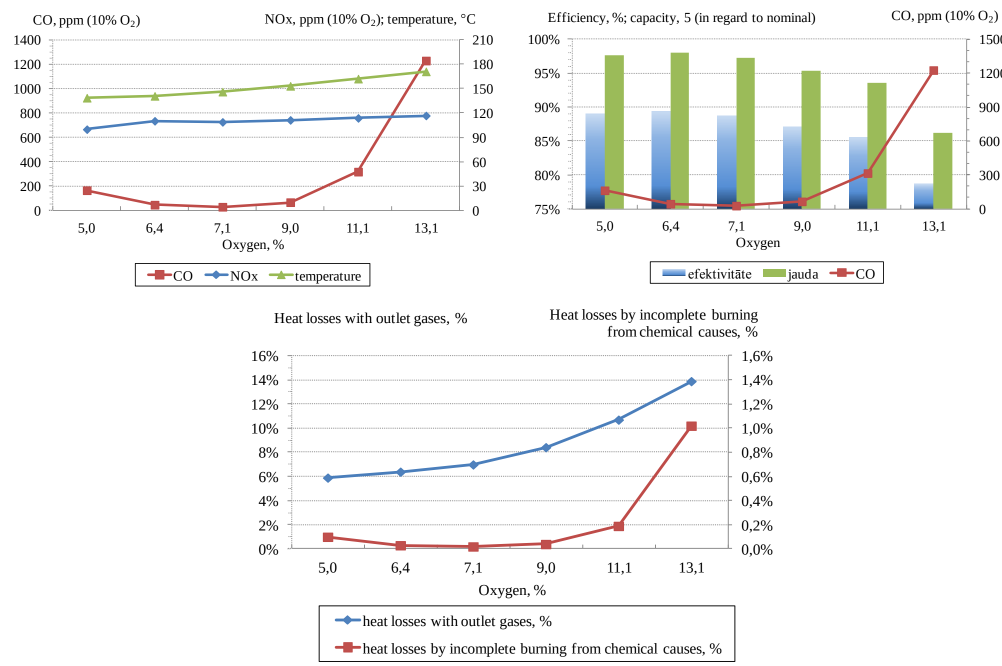

Figure 5. The influence of changes in oxygen concentration on the combustion process.

Fig. 6 presents the changes of the flue gas velocity depending on the oxygen content in the flue gas. The flue gas velocity was determined directly using a flow meter and an indirect method was used too. The flue gas velocity was measured in a chimney with a diameter of 16 cm. The results show that the calculated data was similar to the measured data. The flue gas velocity increases sharply from 0.7 m s^{-1} at the oxygen concentration of exhaust gas of 5% to 1.4 m s^{-1} at the oxygen concentration of exhaust gas of 13%. An increase in flue gas velocity has a negative impact on combustion efficiency, because the time during which the hot gas is in the heat exchanger decreases.

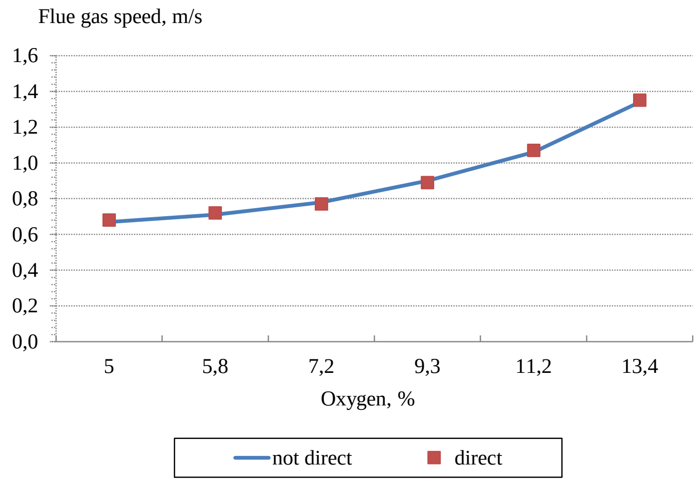

Figure 6. The flue gas velocity depending on oxygen content.

Data verification using a different fuel

Two additional series of tests were made using pellet B and pellet C to ensure that the acquired results were not accidental and to increase the veracity of the data. The received data about flue gas temperature, CO concentration, heat losses, dust content, and total efficiency show similar results in general (see Fig. 7). The flue gas temperature using pellet A was a little bit higher, but the reason for this was that pellet A has higher calorific value. The amount of CO using pellet B was slightly higher and therefore the heat losses by incomplete burning from chemical causes were higher too. The main reason for this can be explained considering that pellet B has higher ash content. The heat losses with outlet gases were higher with pellet A, because the flue gas temperature was higher using this pellet. The efficiency in all three test series was similar. The dust content in flue gas was determined using pellets A and B. The results of the utilisation of different pellets were similar as well. The dust content was minimal at the oxygen concentration of the flue gas of 6.5%, but higher at the oxygen concentration of 13%. These results prove that CO concentration has an important role on particulate matter.

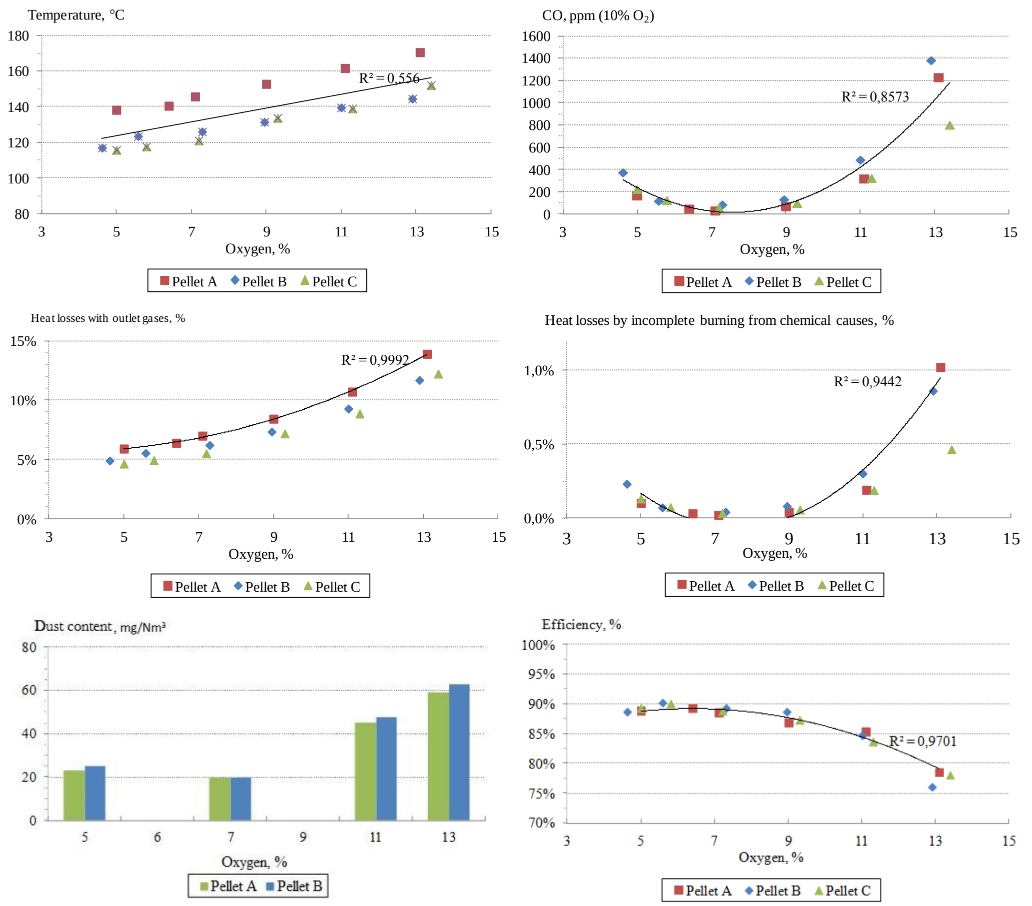

Figure 7. The influence of oxygen concentration changes on the combustion process used with different types of the fuel.

Air supply optimisation. Flame dissipation and concentration

The tests with flame dissipation and concentration were carried out using pellet A; therefore the results from the first testing series were used as reference data to determine the effect of both methods. The results show that both approbation methods have a positive effect (see Fig. 8). The biggest CO emission value decrease was achieved using the flame concentration method. An especially high decrease was achieved at a high oxygen concentration. The temperature drops by 10°C at a low oxygen concentration and by 20 °C at a high concentration were achieved using the concentration method as well. The temperature decrease promotes the heat losses with outlet gases to go down too, but the CO concentration drop affects the decrease of heat losses by incomplete burning from chemical causes. An efficiency rise was obtained using both methods, but comparing the two methods, the biggest effect belongs to the flame concentration method, especially at a high temperature.

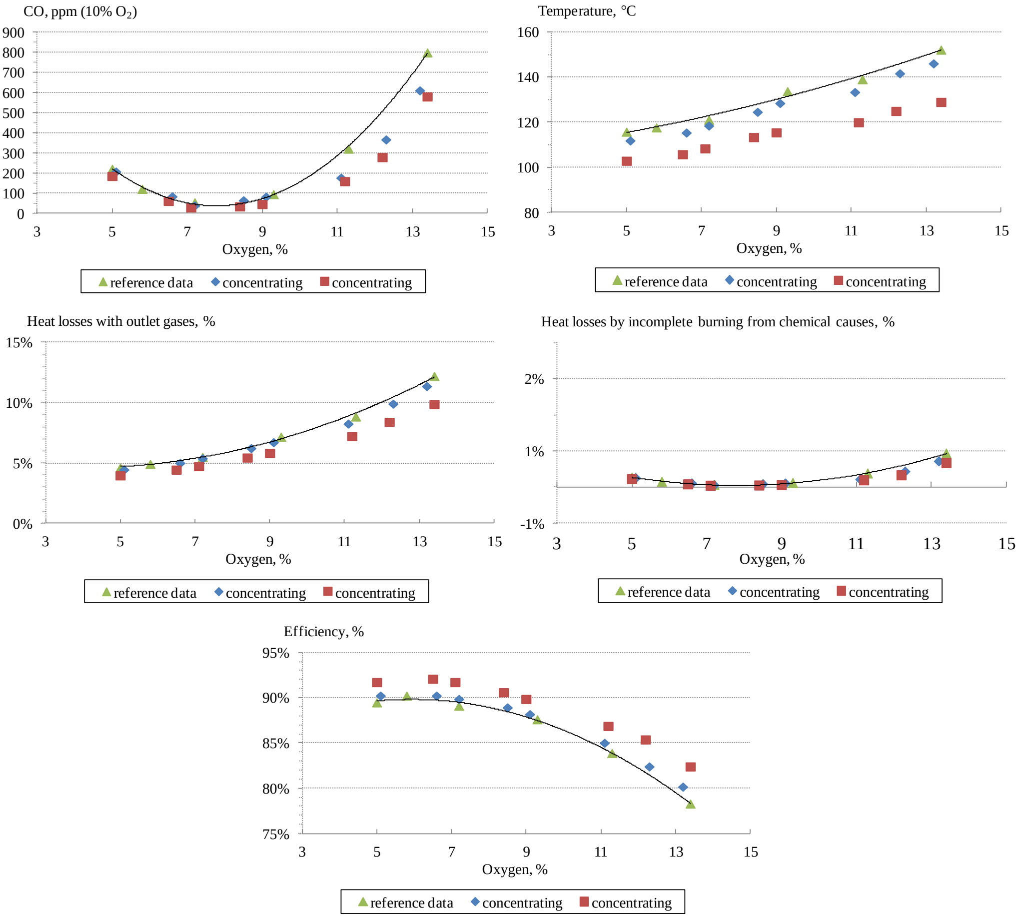

Figure 8. The effect of flame dissipation and concentration on the combustion process.

CONCLUSIONS

Experimental studies showed that air supply and oxygen concentration changes in flue gas have an important role in the combustion process. The minimum amount of CO and the highest efficiency of the boiler were achieved at the concentration of oxygen in the flue gas of 6–7%. Increasing or decreasing the concentration of oxygen in the flue gases promotes growth of the CO concentration and a decrease in the efficiency of the pellet boiler or vice versa.

The largest heat loss formed with outlet gases – an average from 5% to 14% depending on the oxygen concentration in the flue gases. The rise of the temperature during the increase in the oxygen concentration is the main reason of high heat losses with outlet gases. Heat loss due to mechanically incomplete combustion is generally higher at a high concentration of oxygen in the flue gas. The main reason for this is the flue gas velocity increase.

It was determined that the flue gas flow rate increases from 0.68 m s^{-1} at low concentrations of oxygen in the flue gas to 1.35 m s^{-1} at the oxygen content in the flue gas of 13%. The air and fuel mixing process deteriorates with an increase in the flue gas flow. This is evidenced by a growth of the amount of CO at high oxygen content.

An increase in the flue gas velocity promotes a decrease in the time spent by the flue gas in the heat exchanger. Therefore, the smaller the amount of heat transfers from the flue gas to water, which circulates through the boiler. This is evidenced by reduction of the efficiency of the boiler and the flue gas temperature rise with increasing the amount of oxygen in the flue gas.

Two methods for the boiler combustion process improvement and better air and fuel mixing were validated: flame dissipation and concentration. If we compare the two methods, concentration of the flame shows better results. A CO reduction of about 20 to 40 ppm was achieved at low concentrations of oxygen and 170 to 240 ppm at high concentrations of oxygen in the flue gas utilisation. The largest boiler efficiency improvement was achieved by using a cylinder with a spiral for flow swirl. The boiler efficiency increased by around 2% at low concentration of oxygen in exhaust gases and around 4% at high oxygen content. The efficiency improvement was achieved thanks to better air and fuel mixing and flue gas flow rate reduction, due to fuel combustion time increase, improved boiler heat exchange process, and decrease of the flue gas temperature.

REFERENCES

Beloborodko, A., Klavina, K., Romagnoli, F., Kenga, K., Rosa, M. & Blumberga, D. 2013. Study on availability of herbaceous resources for production of solid biomass fuels in Latvia. *Agronomy research* **11**, 283–294.

Biomass combustion in Europe: Overwiev on technologies and regulations. Final report. 2008. *New York State Energy Research and Development Authority (NYSERDA)*, –97.

Carvalho, L., Lundgren, J., Wopienka, E. & Ohman, M. 2008. Challenges in small-scale combustion of agricultural biomass fuels. *International Journal on Energy for a Clean Environment* **9**, 127–142.

Chaney, J., Liu, H. & Li, J. 2012. An overview of CFD modelling of small-scale fixed-bed biomass pellet boilers with preliminary results from a simplified approach. *Energy Conversion and Management* **63**, 149–156.

EN 14775:2009 'Solid biofuels – Determination of ash content'. European Committee for Standardization.

EN 14774-3:2009 'Solid biofuels – Determination of moisture content – Oven dry method – Part 3: Moisture in general analysis sample'. European Committee for Standardization.

EN 14918:2009 'Solid biofuels – Determination of calorific value'. European Committee for Standardization.

Eskilsson, D., Ronnback, M., Samuelsson, J. & Tullin, C. 2004. Optimisation of efficiency and emissions in pellet burners. *Biomass and Bioenergy* **27**, 541–546.

Fernandes, U. & Costa, M. 2011. Particle emissions from a domestic pellets-fired boiler. *Fuel Processing Technology* **103**, 51–56.

Haapa-Aho, J., Korpela, T., Björkqvist, T., Hrdlička, J., Plaček, V., Vrána, S. & Šulc, B. 2011. Continuous control issues concerning operation improvement of small-scale biomass boilers. *18th IFAC world conference* in Milan.

Haapa-Aho, J. 2011. Combustions improvement of small-scale pellet boiler by continuous control. *Master of Science Thesis*, Tampere University of technology, –87.

Hansen, T.M., Rosentoft Jein, A. & Hayes, S. 2009. English Handbook for Wood. Pellet Combustion. – Great Britain: National Energy Foundation.
Jasinskas, A., Ulozevičiūte, I., Šakalauskas, A. & Puskunigis, M. 2011 Determination of energy plant chopping quality and emissions while burning chaff. *Agronomy research* **9**, 49–61.
Johanssona, L., Leckner, B., Gustavsson, L., Cooper, D. & Tullin, C., Potter, A. 2004. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmospheric Environment* **38**, 4183–4195.
Khan, A.A. de Jong, W. & Jansens, P.J. 2009. Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Processing Technology* **90**, 21–50.
Kirsanovs, V., Timma, L., Žandeckis, A. & Romagnoli, F. 2012. The quality of pellets available on the market in Latvia: classification according EN 14961 requirements. *Environmental and climate technologies* **8**, 36–41.
Klason, T. & Bai, X.S. 2007. Computational study of the combustion process and NO formation in a small-scale wood pellet furnace. *Fuel* **86**, 1465–1474.
Liu, H., Chaney, J., Li, J. & Sun, C. 2013. Control of NOx emissions of a domestic/small-scale biomass pellet boiler by air staging. *Fuel* **103** 792–798.
Loo, S. & Koppejan, J. 2008. The Handbook of Biomass Combustion and Co-firing. Great Britain: Erthscan, – 442.LVS EN 13240:2002 'Roomheaters fired by solid fuel – Requirements and test methods'.
LVS EN 303-5:2012 'Heating boilers – Part 5: Heating boilers for solid fuels, manually and automatically stocked, nominal heat output of up to 500 kW – Terminology, requirements, testing and marking'.
Mikkola, H. & Ahokas, J. 2011. Renewable energy from agro biomass. *Agronomy research* **9**, 159–164.
Nussbaumer, T. 2003. Combustion and co-combustion of biomasas: fundamentals, technologies, and primary measures for emission reduction. *Energy & Fuels* **17**, 1510–1521.
Stahl, M. & Wikström, F. 2009. Swedish perspective on wood fuel pellets for household heating: A modified standard for pellets could reduce end-user problems. *Biomass and Bioenergy* **33**, 803–809.
State of the art of small-scale biomass combustion in boilers. Prof. Ingwald Obernberger. Presentation. Austria.
Terrazzano, L., Allouis, C., Beretta, F., Pagliara, R. & Martino, G. Optimization of Combustion Performances of Pellet Burners. Napoli.
Verma, V.K., Bram, S., Delattin, F., Laha, P., Vandendael, I., Hubin, A. & De Ruyck, J. 2012. Agro-pellets for domestic heating boilers: Standard laboratory and real life performance. *Applied Energy* **90**, 17–23.
Verma, V.K., Bram, S., Gauthier, G. & De Ruyck, J. 2011b. Evaluation of the performance of a multi-fuel domestic boiler with respect to the existing European standard and quality labels: Part-1. *Biomass and Bioenergy* **35**, 80–89.
Verma, V.K. Bram, S., Vandendael, I., Laha, P., Hubin, A. & De Ruyck, J. 2011b. Residential pellet boilers in Belgium: Standard laboratory and real life performance with respect to European standard and quality labels. *Applied Energy* **88**, 2628–2634.
Žandeckis, A., Kirsanovs, V., Dzikēvičs, M., Blumberga, D. 2013a. Experimental study on the optimisation of staged air supply in the retort pellet boiler. *Agronomy research* **11**, 381–389.
Žandeckis, A., Timma, L., Rochas, C., Rošā, M. & Blumberga, D. 2013b. Solar and pellet combisystem for an apartment buildings. Heat losses and efficiency improvements of the pellet boiler. *Applied Energy* **101**, 244–252.

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A study of pressure drop in an experimental low temperature wood chip dryer

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Abstract. The use of wood materials, and logging residues in the energy sector is growing rapidly, and will follow the same trend in the following years in the entire EU. This development is related to the target of 20% renewable energy share in the primary energy consumption. Thus it is very important to increase the value of fresh wood materials by application of drying technologies. Drying allows increasing the efficiency and flexibility of combustion, transportation, and storage processes.

The goal of this research is to study wood chip drying process in low temperature conditions as a promising solution for the use of low exergy energy sources, such as solar energy, geothermal, and waste heat. Low temperature drying processes typically require high parasitic consumption of electrical energy that is required to provide the air change in the wood chip body, but allows reduction of heat loss. This study was developed to collect experimental information required for designing, optimization and operation of low temperature dryers.

Experimental setup was used to study wood chip drying process in controlled laboratory conditions. Air pressure loss is settled as the dependent variable. Thickness of wood chip layer and airflow rate were changed between the experiments. A comprehensive analysis of the obtained monitoring data is carried out.

Key words: Biomass dryer, low potential thermal energy, renewable energy.

INTRODUCTION

In 2011 the natural gas price fell by 45% in the USA; however this did not stop the number of woody biomass facilities to grow in 2011 and 2012 (UNITED NATIONS 2012), thus indicating that the growth of wood chip demand will also continue to increase despite the fluctuations in oil prices. Wood chips are used as a source of primary energy for power plants, cogeneration plants, and production processes because of its low prices and renewable energy status.

The carbon released from the biomass fuels when burned is recirculated in the life cycle of biofuels when a new growth absorbs it in the growing process, thus the biomass fuels are largely presumed as carbon neutral. However when taking in to account the full biofuel life cycle, it has to be noted that some additional actions need to be implied in order to bring the raw material to its final user. These actions for harvesting residues (wood chips) are such as forwarding, comminution, transportation and storage (Jäppinen et al., 2014). Each of these actions consume energy and create GHG emissions as well as additional costs. So despite the fact that biomass fuels are renewable, and can serve as a replacement for fossil fuels, it is crucial to use these recourses efficiently.

In the literature it is mentioned that dry wood chips can substitute a good quality fossil fuel while not contributing to the climate change (Le Lostec et al., 2008). Biomass drying is significant for increasing the combustion process efficiency – it allows recovering the heat otherwise used for the evaporation of water during the combustion, the net calorific value is increased, so dimensions of the boiler can be reduced; the unburned solid particulate matter emissions decrease (Li et al., 2012). Storage of fresh wood chips can result in high loss of dry matter (Nurmi & Hillebrand 2007; Pettersson & Nordfjell, 2007) that leads to energy losses and greenhouse gas emissions (GHG) (Jäppinen et al., 2014), so wood chip drying can also be used as a tool for increasing wood chip storage time and quality.

Conventionally it is common that the logging residues are dried in stacks at the roadsides of the logging sites. The drying usually takes 6 to 12 months before chipping. In this way, if the piles are covered with a special paper, the wood chips can reach around 35% moisture content (Lazdāns et al., 2009). In a study by Nord-Larsen et al. (2010) the asymptotic moisture content of firewood left in the open is noted to be 18.7% and for firewood covered with a roof 15.3%. These methods are not optimal because of the necessary long time period leading to the loss of dry matter while the end moisture content still is quite high, and there has to be an extensive area available for the whole drying period.

There are many industrial dryer systems but most of them have some drawbacks. The indirect dryers – contact or conductive dryers – are suitable for fine or granulated solids that cannot be directly exposed to the heat carrier (Devahastin & Mujumdar 2006) and won't be fit for wood chip drying. The direct-heat rotary dryers usually use 400–450 K for steam and 800–1,100 K for oil and gas fired burners (Krokida et al., 2006), these temperatures don't leave an opportunity for the use of low potential heat sources. The fluidized bed dryers have a high drying rate but this method is characterized with high electrical power consumption, and might have some problems with the particulate fluidization (Law & Mujumdar, 2006). A dryer with a perforated floor, and a forced air supply from the bottom is chosen for the investigation in this research. Low temperature settings are chosen to allow the experimental results to be used for the development of a low temperature dryer.

Different mathematical modelling approaches have been applied for the analysis of drying process. In the study by Gebreegziabher et al. (2013) the Fick's second law of diffusion is used for modelling the biomass drying process to determie the optimum operating costs, capital investments and product value. Mahmoudi in his study (Mahmoudi et al., 2014) is applying the Extended Discrete Element Method (XDEM) for a numerical simulation of packed bed biomass drying. In this approach the dried mass is considered to consist of a finite number of particles, for each particle mass and energy equations are solved, and a continuous model applied for the surrounding gas. The whole process is characterised by the summation of all the individual particle processes (Mahmoudi et al., 2014). Another mathematical approach that is used for the characterization of drying process is the Computational fluid dynamics (CFD). CFD has been used in the study by Ström (2013), here both the devolatilization and drying process is described. Apart from the above mentioned some commercially available analysis tools specifically for drying process designing are available, like Simprosys, dryPAK, and DrySel (Gong & Mujumdar, 2008). Nevertheless most often the biomass dryer designs are 'experience based', and there are few scientific studies dealing with the kinetics of the biofuel drying process (Wimmerstedt, 2006). Few experimental studies concerning the pressure drop for the dryer ventilation due to the biofuel layer have been done. Yazdanpanah has studied the pressure drop for wood pellets. In this study the pressure drop was measured for three pellet size categories with airflow rates from 0.0142 to 0.7148 $m^3\ sm^{-2}$. The pressure drop increases with the increase of the airflow rate, and the increase becomes more and more significant with greater airflows. The smallest pellets have the highest pressure drop, while larger pellets or a mix of different pellet sizes has lower resistance (Yazdanpanah et al., 2011). In the papers by Kristensen & Kofman (2000) and Kristensen et al. (2003) the pressure drop depending on different wood chip, and chunk-wood types is studied. The wood chipping methods are taken into account for the wood chip particle size distribution. Airflows from 0.1 $m\ s^{-1}$ for ten (Kristensen & Kofman, 2000) and twenty two (Kristensen et al., 2003) wood chip sample types from common tree species are studied. Here the results indicate that depending on the chipping method the pressure drop can be either the same or higher than that for the wood pellets. The conclusion that the pressure drop decreases with an increasing particle size coincide with the work of Yazdanpanah et al. (2011). Wider studies are made for grain and other agricultural product drying, like the study by Pupinis (2008), Kocsis et al. (2011), Aboltins & Palabinskis (2013) and Jokiniemi et al. (2011). The greatest difference between biomass and grain drying is the different dimensions of the dried particles, different initial moisture content, and also different value of the dried product expressed in terms of mass.

The objectives of this research were to develop and collect experimental data on the pressure drop of ventilated wood chips, and to carry out a comprehensive analysis.

MATERIALS AND METHODS

Design of experiment

The selected variable factors in this study are the airflow velocity and thickness of wood chip layer in the dryer. The Table 1 shows an overview of the defined factors.

Table 1. Defined factors

Factor name	Units	Type	Role	Lower limit	Upper limit
Airflow velocity	$m\ s^{-1}$	Continuous	Controllable	0.04	0.22
Thickness	m	Continuous	Controllable	0.5	1.5

The Lower limit of the airflow velocity is chosen so that it would provide the approximate necessary air amount that is standard practice for solid drying (Francescato et al., 2008). The upper limit of the airflow velocity is chosen based on the screening of literature sources of similar experiments (Kristensen & Kofman, 2000; Kristensen et al., 2003) common practice (Francescato et al., 2008), and also the selected air fan capacity. When designing a dryer that could service large amounts of wood chips the thickness of the wood chip layer in the dryer is strictly related to the area that the dryer is about to take. Thus the lower limit is chosen to match the layer thickness used in some dryers

(Ivanova et al., 2012), and the upper limit is chosen to evaluate the possibilities for increasing the dryer layer thickness. The defined response is the pressure drop.

For the pressure drop experiment Changing a single factor at a time (COST) approach is selected. The airflow velocity is varied from 0.04 to 0.22 m s^{-1} with a 0.01 m s^{-1} step for each wood chip layer thickness (0.5; 1.0 and 1.5 m). One replicate experiment is carried out, and in total 108 measurements are recorded.

Based on fluid-dynamic principles that describe the pressure drop as a non-linear function of the flow rate, see the Ergun-type model equation (1) (Kashaninejad et al., 2010)

$$\Delta P = A \cdot Q + B \cdot Q^2 , \quad (1)$$

where ΔP is pressure drop (Pa m^{-1}), A, B is the Product dependent coefficients, and Q is the airflow rate (m^3 Sm^{-2}), a quadratic model is selected to describe the factor interactions. The general form of the quadratic model is the following (Eriksson et al., 2008):

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2 . \quad (2)$$

The STATGRAPHICS Centurion 16.1.15 statistical data analysis tool is used to create the design of the model.

Wood chip sample preparation

Wood chips are sampled manually from an uncovered pile. The used wood chips are visible in Fig.1.

Laboratory analysis are carried out determining the ash content, initial moisture content (as received), calorific value, bulk density of the sample, and fraction distribution. The summary of the analysis results is visible in Table 2.

Figure 1. The sample of wood chips used in the experiment.

Table 2. Parameters of the wood chips used

Parameter	Value	Unit	Testing method
Moisture content, as received	50.8	%	LVS EN 14774-2
Ash content, dry basis	1.8	%	LVS EN 14775
Gross calorific value	19.65	MJ kg^{-1}	LVS EN 14918
Net calorific value, as received	7.76	MJ kg^{-1}	LVS EN 14918
Bulk density, as received	330	kg m^{-3}	LVS EN 15103
Bulk density, dry mass	170	kg m^{-3}	LVS EN 15103

The moisture content of the wood chips varies between the experimental runs, with the average value of 53.3% but the maximum deviation from the average is 2.0%. The fractional distribution of the wood chip particles is determined according to LVS

CEN/TS 15149-1 standard method. Fig. 2 represents the cumulative particle share in the wood chip mass.

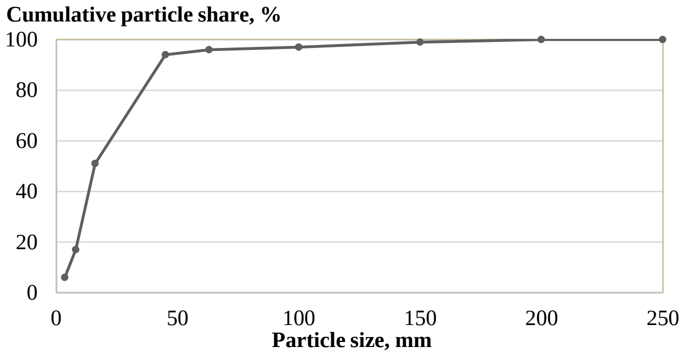

Figure 2. Wood chip cumulative particle share.

The tested wood chip sample has a high share of fine particles. According to the previous literature review this causes higher pressure drop than for coarse wood chips.

Experimental Setup and Procedure

The experiment takes place in a vertically ventilated drying bin with a perforated floor. The bin has a square base with 0.6 x 0.6 m dimensions and 2 m sides. The floor of the bin consists of a honeycomb layer with 0.01 m holes. The schematic representation of the experimental set-up is displayed in Fig. 3.

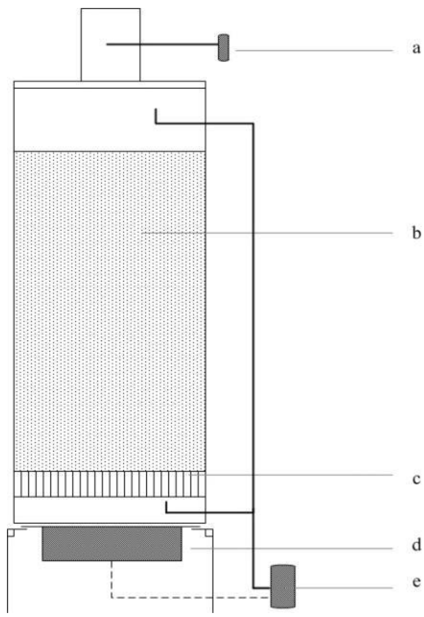

Figure 3. Experimental set-up (a – hot-wire anemometer; b – wood chips; c – honeycomb layer for flow stabilization; d – fan; e – pressure and flow speed gauges).

The wood chips are loaded manually in to the experimental dryer bin from the top, the material falls naturally, and no additional compaction is applied.

RESULTS AND DISCUSSION

Statistical model has been applied to the response variable. The model P-value below 0.05 indicates that the selected model is statistically significant at the 5.0% significance level. The R-squared of the model equals 99.155%. The adjusted R-squared equals 99.105%, this indicator is used for the comparison with other models that have a different number of independent variables. The Durbin-Watson statistic test shows no indication of autocorrelation in the residuals at the 5.0% significance level.

The Pareto chart in Fig. 4 presents the effects of the factors on the pressure drop.

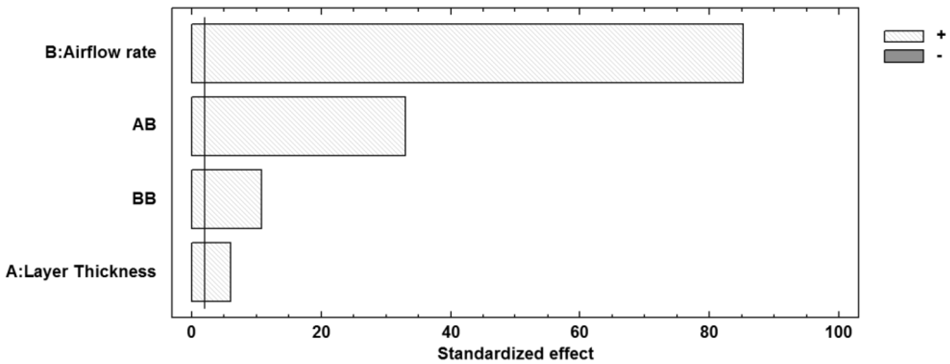

Figure 4. Pareto chart for pressure drop.

The bar fill shows weather the effect is positive or negative, it can be seen that both analysed factors have a positive effect – increasing the wood chip layer thickness, and airflow rate increases the pressure drop.

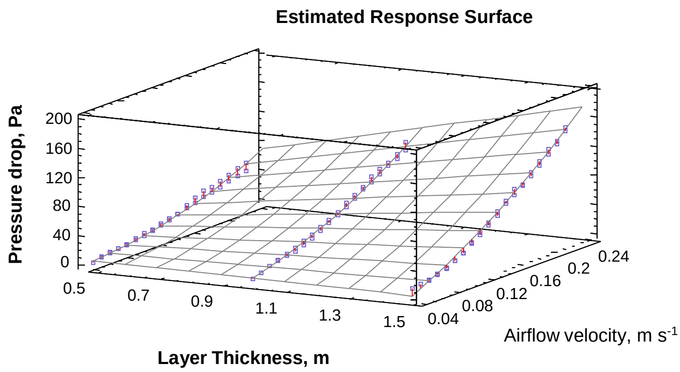

Figure 5. Estimated response surface for pressure drop.

The quadratic regression equation (2) is fitted to the experimental data, and the equation for the analysed model is retrieved as follows:

$$\Delta P = 17.4532 - 24.1817 \cdot H - 341.178 \cdot v + 530.515 \cdot H \cdot v + 1478.27 \cdot v^2 \quad (3)$$

where ΔP is the pressure drop (Pa); H – the wood chip layer thickness (m) and v – the airflow velocity (m s^{-1}). The Fig. 5 displays the experimental equation (3) in a surface plot.

The statistical mesh in Fig. 5. has three rows of dots representing the three series of experimental point values at different layer thicknesses. It is visible that the equation has a good representation of the real data. At low airflow velocities the influence of increasing wood chip layer thickness is very weak, while with increasing airflow velocities the influence of layer thickness becomes more and more significant. This is consistent with the Ergun equation (1).

CONCLUSIONS

The air exchange in the layer of dried biofuels, and the removal of evaporated moisture is one of the key mechanisms affecting the efficiency of drying process. However, higher air velocities will cause higher pressure drop and higher parasitic energy consumption as a result. Increase of the layer thickness should not be considered as a stand-alone solution for reduction of construction expenses, because it also has a significant negative effect on the pressure drop. These aspects cannot be ignored during the designing process of wood chip dryers. The optimum thickness of drying bed, and airflow speed, together with the drying time, has to be obtained in every case to balance capital, and operational costs.

The set of experiments were planned, and carried out to evaluate the aerodynamic pressure drop in function of the air velocity, and thickness of the wood chip layer. A non-linear empirical model was developed, and validated using the experimental results. Data analysis shows a statistically very high significance between the independent variables, and the pressure drop. This model can be used for planning, designing, and optimisation of the wood chip drying process.

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REFERENCES

Aboltins, A. & Palabinskis, J. 2013. New types of air heating solar collectors and their use in drying agricultural products. *Agronomy Research* **11**(2), 267–274.

Devahastin, S. & Mujumdar, A.S. 2006. Indirect Dryers. In *HANDB OOK OF INDUSTRIAL DRYING*. pp. 137–148.

Eriksson, L. Johansson, E., Kettaneh-Wold, N., Wikstrom, C. & Wold, S. 2008. *Design of Experiments. Principles and Applications* 3rd Edition. MKS Umetrics AB, Umea, pp.459.

Francescato, V., Antonini, E. & Bergomi, L.Z. 2008. *WOOD FUELs HANDBOOK*. AIEL – Italian Agriforestry Energy Association, Agripolis, pp.83.

Gebreegziabher, T., Oyedun, A.O. & Hui, C.W. 2013. Optimum biomass drying for combustion – A modeling approach. *Energy* **53**, 67–73.

Gong, Z.-X. & Mujumdar, A.S. 2008. Software for Design and Analysis of Drying Systems. *Drying Technology* **26**(7), 884–894.

Ivanova, T., Havrland, B., Hutla, P. & Muntean, A. 2012. Drying of cherry tree chips in the experimental biomass dryer with solar collector. *Research in Agricultural Engeneering* **58**(1), pp.16–23.
Jäppinen, E. Korpinen, O.-J., Laitila, J. & Ranta, T. 2014. Greenhouse gas emissions of forest bioenergy supply and utilization in Finland. *Renewable and Sustainable Energy Reviews*, **29**, pp.369–382.
Jokiniemi, T., Kautto, K., Kokin, E. & Ahokas, J. 2011. Energy efficiency measurements in grain drying. *Agronomy Research* **9**(1)**,** 69–75.
Kashaninejad, M. Maghsoudlou, Y., Khomeiri, M. & Tabil, L.G. 2010. Resistance to airflow through bulk pistachio nuts (Kalleghochi variety) as affected by moisture content, airflow rate, bed depth and fill method. *Powder Technology* **203**(2), pp.359–364.
Kocsis, L., Herdovics, M., Deakvari, J. & Fenyvesi, L. 2011. Corn drying experiments by pilot dryer. *Agronomy Research* **9**(1)**,** 91–97.
Kristensen, E.F. & Kofman, P.D. 2000. Pressure resistance to air ow during ventilation of di □ erent types of wood fuel chip. *Biomass and Bioenergy* **18**, 175–180.
Kristensen, E.F., Kofman, P.D. & Jensen, P.D. 2003. Counter pressure on ventilation of different types of wood chip and chunkwood. *Biomass and Bioenergy* **25**(4), pp.399–408.
Krokida, M., Marinos-Kouris, D. & Mujumdar, A.S. 2006. Rotary Drying. In A. S. Mujumdar, ed. *HANDBOOK OF INDUSTRIAL DRYING*. pp. 151–172.
Law, C.L. & Mujumdar, A.S. 2006. Fluidized Bed Dryers. In A. S. Mujumdar, ed. *HANDBOOK OF INDUSTRIAL DRYING*. pp. 174–201.
Lazdāns, V., Lazdiņš, A. & Zimelis, A. 2009. Technology of biofuel production from slash in clear-cuts of spruce stands. *Forest Science* **19**(52), 109–121.
Li, H. Chen, Q., Zhang, X., Finney, K.N., Sharifi, V.N. & Swithenbank, J. 2012. Evaluation of a biomass drying process using waste heat from process industries: A case study. *Applied Thermal Engineering* **35**, pp.71–80
Le Lostec, B., Galanis, N., Baribeault, J. & Millette, J. 2008. Wood chip drying with an absorption heat pump. *Energy* **33**(3), pp.500–512.
Mahmoudi, A.H., Hoffmann, F. & Peters, B. 2014. Application of XDEM as a novel approach to predict drying of a packed bed. *International Journal of Thermal Sciences* **75**, 65–75.
Nord-larsen, T., Bergstedt, A., Farver, O. & Heding, N. 2010. Drying of firewood – the effect of harvesting time , tree species and roofing of stacked wood. *Submitted to Biomass & Bioenergy*, pp.22.
Nurmi, J. & Hillebrand, K. 2007. The characteristics of whole-tree fuel stocks from silvicultural cleanings and thinnings. *Biomass and Bioenergy* **31**(6), pp.381–392.
Pettersson, M. & Nordfjell, T. 2007. Fuel quality changes during seasonal storage of compacted logging residues and young trees. *Biomass and Bioenergy* **31**(11–12), 782–792.
Pupinis, G. 2008. Grain drying by use of changeable air flow method. *Agronomy Research* **6**(1), 55–65.
Ström, H. & Thunman, H. 2013. CFD simulations of biofuel bed conversion: A submodel for the drying and devolatilization of thermally thick wood particles. *Combustion and Flame* **160**(2), 417–431.
UNITED NATIONS, 2012. *Forest Products Annual Market Review 2011–2012*. United Nations Publications, New York, Geneva. pp.178.
Wimmerstedt, R. 2006. Drying of Peat and Biofuels. In A. S. Mujumdar, ed. *HANDBOOK OF INDUSTRIAL DRYING*. Taylor & Francis, Boca Raton, pp.743–755.
Yazdanpanah, F., Sokhansanj, S., Lau, A.K., Lim, C.K., Bi, X. & Melin, S. 2011. Airflow versus pressure drop for bulk wood pellets. *Biomass and Bioenergy* **35**(5), 1960–1966.

Evaluation of sustainability aspect – energy balance of briquettes made of hemp biomass cultivated in Moldova

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Abstract. Biomass is currently a significant source of energy mainly for its availability and high potential. Energy crops suitable for energy purposes must have a positive energy balance within the whole production cycle. Industrial hemp (*Cannabis sativa L.*) has a high yield in a short period of time and reaches a gross calorific value similar to that of wood. Two hemp cultivars were experimentally sown in the Republic of Moldova in order to determine the yield and energy balance for utilization of solid fuels in the form of briquettes. Briquettes were considered to be used in small – scale boilers for heating purposes with a thermal efficiency of 80%. Hemp harvested as a green plant in autumn was left under a roof for losing moisture, to keep yield as high as possible and left the field for another crop in rotation system. The energy balance included all forms of inputs – energy of human labor, energy in fuels, in seeds and in the machines during the technological process according to common practises in Moldova. Energy Return on Energy Invested (EROEI), due to the large share of manual labor and agricultural practices without using of fertilizers, exceeded the value of 12.6. This means that it is classified as very suitable for energy purposes. Hemp appears to be a promising energy crop in temperate climate and it is able to contribute solving the energy situation in Moldova.

Key words: energy yield**,** energy balance, Energy Return on Energy Invested (EROEI), energy inputs, energy outputs.

INTRODUCTION

Moldova is currently a priority country of the Czech Republic in the framework of Development Cooperation. One of the areas of assistance is also focused on energy. The Republic of Moldova has very insignificant reserves of solid fossil fuels, petroleum and gas. This has led to a high dependence on energy imports from Russia reaching 96% of total energy consumption in 2010 (Karakosta & Dimopoulou, 2011). To ensure sufficient amount of energy supplies for future generations and less dependency on foreign imports, we must find a proper alternative to fossil fuels. The solution can be found through growing energy crops.

The efforts of most industrialized countries around the world to use fossil fuels more efficiently as well as to replace them with renewable sources of energy have attracted scientific research towards testing energy crops whose potential can be ranked higher than other renewable sources of energy (Prade et al., 2011). Most of the research published in the available literature focuses primarily on the evaluation of the potential of the energy crop according to the following criteria: energy balance, tonnage value and productivity as well as environmental impact (Prade et al., 2012; Kreuger et al., 2011; Gill et al., 2011).

Hemp (Cannabis sativa) is a plant that has been prohibited for years in relation to the psychoactive effect of some of its secondary metabolites – terpenoids (Sladký, 2004). However, it has been experiencing a worldwide revival in the last 10 years (Prade et al., 2011). This crop and most of the industrial situations involving it is currently grown mainly for the production of its very tough fibers that are unique in composition as well (Li et al., 2012). Such a situation is, from an energy point of view, not endowed to many crops. Hemp can also be used as a feedstock for the production of solid biofuels – briquettes and pellets (Prade et al., 2011) as well as a source of biomass for biogas generators (Kreuger et al., 2011). Prade et al. (2012) evaluated the physical and chemical properties of solid biofuels. They mentioned that these attributes influence suitability and competitiveness among solid biofuels. However, the above mentioned physical properties (particle size, bulk density, angle of repose and bridging tendency) can be changed by specific treatment processes (grinding, milling or compaction), but its chemical properties (content of major alkali and earth alkali metals) are hard to change once the crop has been harvested (Prade et al., 2011). Furthermore, because of the high concentration of cellulosic fibers thus glucose, hemp could be a suitable second generation crop for the production of cellulosic ethanol (Tutt & Olt, 2011).

Finally, adding to the potential of hemp on the energy market, seeds can also be used for energy production since the oil they contain could be converted into biodiesel (Gill et al., 2011). Available literature resources mainly discuss the optimization, oil characteristics and fuel property analysis made of these oils and their blends (Gill et al., 2011).

Industrial hemp is well known for its high productivity as well as gross calorific value, which can be compared to wood (Prade et al., 2011). The uniqueness of this plant lies in its ability to yield more than 24 tons of green biomass per hectare (corresponding to 10.9 t ha^{-1} of dry biomass) within 140 days (Kolarikova et al., 2013).

Prade (2012) and his team calculated the energy balance and output-to –input ratio for hemp production for CHP (combined heat-electricity), from spring-harvested baled hemp; heat from spring-harvested briquetted hemp and vehicle fuel from autumn-harvested hemp processed into biogas in an anaerobic digestion process. They took into consideration Swedish conditions. Net energy yield of CHP and heat production from the hemp biomass were above average. Both other conversion possibilities suffered from high energy inputs and lower conversion efficiency. According to Prade hemp competes with perennial crops (willow) in the production of solid biofuels (Prade et al., 2012).

The high energy potential of hemp and lack of information about its cultivation, harvest and environmental suitability has led to further research to obtain new information.

The main objective of this work is to do a system analysis of energy effectiveness (EROEI) of hemp biomass from the autumn harvest for the production of solid biofuel-briquettes and its use in small- scale boilers to obtain heat in the conditions of the Republic of Moldova.

MATERIAL AND METHODS

Definition of system boundaries

To calculate the energy balance, a model situation was chosen. Taken into account were aspects of the current Moldovan agriculture i.e. large share of manual labour and non mineral fertilizers. The model included the situation of the farmer, who farms on 4 ha of land useing classic crop rotation, which includeshemp. The Produced bio-fuel - briquettes will produce energy in the form of heat for the personal use of the farmer.

The system boundaries include soil preparation, to processing into the form of briquettes, transporting to the farmer's house and combusting in the small scale boiler for heating purposes. Technological processes include - stubble treatment, ploughing, seedbed preparation, sowing, harvesting (mowing, sheaves), transport and briquetting (when moisture content reaches 15%).

Hemp harvested as a green plant in autumn was left under a roof for losing moisture, to keep yield as high as possible and left the field for another crop in the rotation system.

Determination of energy output and losses

Biomass yield (BY)

A variety of hemp of Polish origin Bialobrzeskie and French Ferimon was cultivated in Chisinau (Republic of Moldova) in 2013 in order to obtain biomass for the energy yield evaluation from its autumn harvest. Hemp was grown on a trial plot of 100 m^2(50 m^2 each) with a seed rate of 60 kg ha^{-1} and the biomass yields of the small-scale samples (determined by collecting and weighing all plants) were extrapolated to a biomass yield per hectare (BY).

Samples experiments

The plants used for sampling were subjected to the following experiments during which determined: moisture content (MC), gross calorific value (GCV) and dry matter yield (DM) according to EU norms.

Harvestable biomass

To account for losses during harvest, hemp DM yield was reduced by 10% for autumn harvest.

Biomass energy yield (BEY)

The biomass gross energy yield (BEY) per hectare describes the total mass of energy stored in biomass (potential energy yield). It was calculated by multiplying the dry matter (DM) yield by corresponding gross calorific value (GCV), i.e.:

$$BEY = GCV \cdot DM [\mathrm{GJha^{-1}}] \qquad (1)$$

Useful heat calculation (Energy output –E_O)

According to lower calorific value (formula 2) of briquettes made of hemp and taking into consideration losses during combustion process (20%) it was possible to calculate useful heat for household use in small scale boilers (efficiency 80%)

$$LCV = GCV - 24.42 \cdot (w + 8.94 \cdot H_a) \quad (2)$$

where: w – moisture content in briquettes [%]; H_a – content of hydrogen in sample [%].

Energy inputs calculation

The amount of energy inputs (Ei) was determined as the conversion of spent labour and materials (hours of human labour, kWh, kg, etc.) in the energy equivalent (Table 1 and 2).

Direct energy inputs include that of human labour (E_1) and energy in fuels (E_2). Indirect energy inputs consist of energy embedded in machines (E_3), in seeds (E_4), and in fertilizers (E_5) see formula

$$E_I = E_1 + E_2 + E_3 + E_4 \text{ [GJ ha}^{-1}] \quad (3)$$

$$E_1 = S_{hl} \cdot e_{hl} \text{ [GJha}^{-1}] \quad (4)$$

where: S_{hl} – spent human labour per hectare [hha^{-1}]; e_{hl}– energy equivalent of human labour [MJ h^{-1}].

$$E_2 = S_f * e_{ff} + S_e \cdot e_e \text{ [GJ ha}^{-1}] \quad (5)$$

where: S_f – fuel consumption [l ha^{-1}]; e_{ff} – energy equivalent of fuels [MJ l^{-1}]; S_e –spent electricity per hectare [kWh ha^{-1}]; e_e – energy equivalent of electricity [MJ kWh^{-1}].

$$E_3 = W \cdot K_e \cdot T_s \cdot K_{rm} / T_{wh} \text{ [GJ ha}^{-1}] \quad (6)$$

where: W – weight of machine[kg]; K_e – conversion equivalent [MJ kg^{-1}]; T_s – time spent on operation [h]; K_{rm} – repairing and maintenance coefficient; T_{wh} – total number of working hours per machine's service life [h].

$$E_4 = S_s \cdot e_s \text{[GJ ha}^{-1}] \quad (7)$$

where: S_s – seeding rate[kg ha^{-1}]; e_s – energy equivalent [MJ kg^{-1}].

Table 1. Energy conversion equivalents

Item	Unit	Energy equivalent	Source
Human labour	1 h	2.3 MJ h^{-1}	Preininger (2009)
Diesel	1 l	35.8 MJ l^{-1}	Špička, Jelínek (2008)
Electricity	1kWh	3.6 MJ (kWh)$^{-1}$	Preininger (1987)
Steel	1 kg	25 MJ kg^{-1}	Hill et al. (2006)
Seeds	1 kg	22.9 MJ kg^{-1}	Abrham et al.(2009)

Machines and equipment used in Technological process are as follows with technical specification in table 2.

- Stubble treatment (carrier–Privatroto 430 +Tractor 81 kW BELARUS)
- Ploughing (4 furrow plough – Overum + Tractor)
- Seedbed preparation (combined cultivator Pracant + Tractor)
- Sowing (Amazone AD +Tractor)
- Harvesting (hand tools + manual work 250hours per hectar)
- Transport (tractor +trailer)
- Grinding (hammer mill 9FQ-40C, power 7.5 kW)
- Briquetting (BRIK-STAR 50–12, power 4.5 kW)

Table 2. Machines and equipment specification

Machine/ equipment	Weight [kg]	Conversionequivalent[a]	Mantenance coefficient[b]	Lifetime [years] [c]	Annualuse [h] [d]	Indirect energy [MJ h^{-1}] [e]	Spent time in operation [h][f]	Spent fuel in operation [l] [g]
TractorBelarus	4,295	95.7	2	12	1,800	38.06	n.a.	n.a.
Privatroto 430	1,750	99.2	1.7	10	750	39.34	0.35	9.1
Overum	1,110	99.2	1.7	10	500	37.43	1.43	19.1
Pracant	2,480	99.2	1.7	10	250	167.29	0.58	7.9
Amazone AD	1,850	95.4	2.1	10	350	105.89	0.83	11.2
Trailer NS 9	3,400	95.4	1.3	10	600	70.28	1.4	13.4
Hamermill	180	37.5*	2	10	720	1.88	28.46	213**
BrikStar50–12	790	37.5*	1.7	10	720	6.99	284.6	1,537**

[a]Source: Špička&Jelínek (2008)
[*]own calculation according to Hill et al. (2006) on the basis of energy needed for steel production (25 MJ kg^{-1}) increased by 50%
[b]Source Kavka et al. (2008)
[c], [d], [f], [g]Source: Abrham et al. (2009), Kavka et al. (2008)
[e]indirect energy in machine /equipment in MJ per hour – own calculation
**kWh

Energy profit, EROEI determination

The energy profit was calculated as the difference between the energy outputs (Eo) and energy inputs (Ei).The energy output represents the energy derived as useful heat from the conversion process, and energy inputs as a total sum of direct and indirect energy for biomass production.

The parameter EROEI or energy efficiency is a ratio of energy yield and energy inputs:

$$EROEI = (E_o) / (E_I) \quad (8)$$

RESULTS AND DISCUSSION

Energy outputs as results of field and laboratory measurements as shown in Table 3. Energy inputs results are in Table 4.

Table 3. Moisture content, biomass yield, dry matter, lower calorific value, Energy in Harvested Biomass, harvest losses, energy in harvestable biomass, combustion heat losses, useful heat

	Bialobrzeskie	Ferimon
BY [tha^{-1}]	28.9	31.1
MC [%]	58.3	61.2
DM [tha^{-1}]	12.05	12.07
LCV [GJt^{-1}]	17.7	17.1
Energy in harvested biomass [$GJha^{-1}$]	213.3	206.4
Harvest losses [%]	10	10
Energy in Harvestable biomass	191.9	185.7
Combustion losses [%]	20	20
Useful heat [GJ t^{-1}]	**153.5**	**148.6**

Table 4. Energy inputs for commodity balance of hemp [MJ]

	Direct energy		Indirect energy		
	Human labour	Fuel consumption	Energy in machines	Energy in seeds	Sum
Stubble treatment	0.81	325.78	27.09		353.68
Ploughing	3.30	683.78	107.95		795.03
Seedbed preparation	1.33	282.82	119.09		403.24
Sowing	1.91	400.96	119.48	1,374	1,896.35
Harvesting	575.00				575.00
Transport	3.22	479.72	151.67		634.61
Grinding	65.46	833.22	1.88		900.56
Briquetting	654.58	5,532.62	6.99		6,194.19
Total	1,305.61	8,538.9	534.15	1,374	**11,752.66**

Energy profit and EROEI are shown in Table 5.

Table 5. Energy profit, EROEI

Cultivar	Energy profit	EROEI
Bialobrzeskie	141.7 GJ	13.1
Ferimon	136.9 GJ	12.6

The share of energy inputs is as follows: energy in fuels (72.7%), energy in seeds (11.7%), energy of human labour (11.1%), and energy in machines (4.5%).

The highly demanded operation is biomass briquetting, which spent more than 5.5 GJ of energy in the form of electricity, which is 65% of total energy in fuels.

A similar experiment on energy balance of hemp cultivars was done in the Czech Republic. The EROEI was determined to be 7.1 for Bialobrzeskie and 7.2 for Ferimon (Kolarikova et al., 2013). The big difference is caused by the elimination of mineral fertilizers, and a high share of manual labor at harvest, which are both common practices of Moldovan agriculture.

Prade et al. also evaluated hemp briquettes for heating in household boilers, however he considered as the best practise harvest in the spring, when yield is lower, but moisture content also decreases. His result 5.1 is quite low due to differences in the technological processes used (Prade et al., 2012).

High hemp DM yield (12t ha^{-1}), GCV similar to wood and ability to suppress weeds determine this crop among the most suitable in moderate climate. Drawbacks are seen in quite problematic mechanization of harvest due to high tenacity of fibre and some restrictions for cannabis cultivation -varieties used shall have a THC content not exceeding 0.2%, only certified seeds of certain varieties can be used, and areas growing hemp require administrative approval.

CONCLUSION

The energy balance is a fundamental element to indicate how much energy is produced by the crop per unit of energy input; it can reveal existing reserves and optimize energy inputs in the manufacturing process. The inventory analysis serves as well as the environmental impact evaluation (LCA) and possibility of CO_2 (greenhouse gases) reduction.Industrial hemp has good energy output-to-input ratios.

Targeted scientific research in yield improvement may determine this crop among the best energy crops for the whole temperate climate; it can be a good solution in improving the energy situation in Moldova.

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REFERENCES

Abraham, Z., Kovářová, M., Mužík, O., Richter, J., Herout, M. & Scheufler, V. 2009. *Technology and economics of crops – Industrial Hemp.* Research Institute of Agricultural Engineering Prague. Available on line at: http://svt.pi.gin.cz (in Czech).

Gill, P., Soni, S.K, &Kundu, K. 2011. Comparative study of Hemp and Jatropha oil blends used as an alternative fuel in diesel engine. *CIGR Journal* **13**(3), 71–77.

Hill, J., Nelson, E., Tilmand, D. & Polansky, S. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the United States of America* **103**(30), 11206–11210.

Karakosta, Ch., Dimopoulou, S., Doukas, H. & Psarras, J. 2011. The potential role of renewable energy in Moldova. Renewable Energy 36(12), 3550–3557.

Kavka, M., et al. 2008. Norms for agriculture and food production. Institute of Agricultural and food information, Praha, ISBN 80-7271-163-6 (in Czech).

Kolaříková, M., Ivanova, T. & Havrland, B. 2013. Energy balance of briquettes made of hemp (Cannabis sativa L.) cultivars (Ferimon, Bialobrzeskie) from autumn harvest to produce heat for household use. In *Engineering for Rural Development.* Latvia University of Agriculture, Jelgava, Latvia, pp. 504–508.

Kreuger, E., Prade, T., Escobar, F., Svenson, J., Englund, E. & Bjorsson, L. 2011. Anaerobic digestion of industrial hemp – Effect of harvest time on methane energy yield per hectare. *Biomass & Bioenergy* **35**(2), 893–900.

Kreuger, E., Sipos, B., Zacchi, G., Svensson, S.E, & Bjorsson, L. 2011. Bioconversion of industrial hemp to ethanol and methane: the benefits of steam pretreatment and co-production. *Bioresource Technology* **102**(3), 3457–3465.

Li X., Wang S., Du G., Wu Z., Meng Y. & Wang L. 2012. Variation in physical and mechanical properties of hemp stalk fibers along height of stem. *Industrial Crops and Products* **42**(1), 344 348.

Prade, T., Svensson, S.E. & Mattsson, J.E. 2012. Energy balances for biogas and solid biofuel production from industrial hemp. *Biomass & Bioenergy* **40**(7), 36–52.

Prade, T., Svensson, S.E., Andersson, A. & Mattsson, J.E. 2011.Biomass and energy yield of industrial hemp for biogas and solid fuel. *Biomass & Bioenergy* **35**(7), 3040–3049.

Preininger, M. 1987. *Energy evaluation of manufacturing processes in crop production.Methodology No. 7/1987*. Institute for Scientific and Technical Information in Agriculture, Praha, 25 pp. (in Czech).

Sladký, V. 2004. *Hemp, opportunity for agriculture and industry*. Institute for Agricultural and Food Information, Praha. (in Czech).

Špička, J. & Jelínek, L. 2008. Energy analysis of agricultural enterprises – methological approach. *Economy and Management* **2**(3), 1–10 (in Czech).

Tutt, M. & Olt, J. 2011. Suitability of various plant species for bioethanol production. *Agronomy Research* **9**, pp. 261–267.

Agronomy Research **12**(2), 527–542, 2014

Determinants of household electricity consumption savings: A Latvian case study

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Abstract. In order to assess the potential for energy efficiency in households it is important to understand the implications for household electricity consumption by analyzing the factors that impact consumption. Moreover some recent studies suggested that changes in household electricity consumption are more likely to be explained by user behavioural aspects than technical solutions. This paper examines the influence of household's personal, demographic, socio–economic, the stock and use of electrical appliances, structural characteristics, external factors (such as weather, location etc.) by analysing data obtained from a smart metering pilot project currently being implemented in 500 Latvian households. The preliminary results show a decrease of the electricity consumption in 2013 (April–December) by 23% for the target group and 5% for the control group. The aim of the study is to introduce a novel model for assessing electricity consumption and savings achieved in households. The main tasks of this study is to examine the main characteristics determining electricity consumption savings, in particular, to evaluate the extent of smart metering influence on electricity consumption savings by using linear regression model.

Key words: Smart metering, electricity consumption, linear regression, energy efficiency.

INTRODUCTION

Notwithstanding the benefits of increased demand response activities in the past years, residential electricity consumption is still rising. In the EU Member States residential electricity consumption increased by 3.6% between 2009 and 2010 thus accounting for 29.71% of total final electricity consumption in the year 2010 (Energy Bertoldi, 2012). In 2012 residential buildings consumed 26% of the total final electricity consumption in Latvia (Central Statistical Bureau of Latvia). Therefore residential sector is the third most consuming sector after the commercial and public sector with 41% and industry and construction with 29%. Electricity consumption for appliances unit consumption per dwelling in Latvia has increased by 35.4% from year 2000 to 2010 (ODYSSEE, 2012). As a main reason of increased electricity consumption was mentioned growing number of appliances utilized in households (e.g. freezers, washing machines, dishwashers, PCs and other small appliances).

Several studies have assessed that electricity demand by households is expected to increase over the next 20 years – during period up to 2020 electricity demand in residential sector is expected to increase 1.5% annually, then decreasing to 0.7% annual growth after 2020 contributed by energy efficiency improvements in appliance design and other energy efficiency measures (European Energy and Transport 2030 report). Therefore, detailed planning and execution of demand–side energy efficiency programs is needed to reduce residential electricity consumption in order to meet obligations concerning improvements in energy efficiency for end users. Smart metering systems have been identified as a promising pathway by promoting energy efficiency in households (JRC, 2012, Ernst & Young, 2012).

Many European countries are only just now getting started with smart meter roll–outs. 10% of the EU households have smart meters, but they are being deployed rapidly to meet a mandate that 80% of the EU households should be provided with smart meters by 2020 (DIRECTIVE 2009/72/EC; JRC, 2012). Starting from April 1st, 2013 Latvia is carrying the first medium scale smart metering pilot project 'Promotion of energy efficiency in households using smart technology' launched by JSC 'Latvenergo' within which 500 smart meters are installed in households by replacing old analogue electricity meters. In total there are around 1 million households in Latvia, which means that only 1% of total electricity customers have been approached (Ernst & Young, 2012). Other objectives within this project have been discussed already previously (Laicane et al., 2013a; Laicane et al., 2013b; Laicane et al., 2013c). When looking at Latvian situation in long term, still there is no strategy either for smart metering diffusion in the market, nor legislation, as well as any vision for much greater roll–out.

Up to now, preliminary results of the pilot project are quite surprising. Total electricity consumption of the target group in 2013 (April–December) was 4,649 MWh. In the meantime the total electricity consumption of 500 control group households (i.e., the reference group without smart meters which was established with the aim to compare result before and after the project) was 3,664 MWh. The results show a significant decrease of electricity consumption by 23% for the target group and 5% for the control group in 2013 (April–December). The results in monthly scale are presented in Fig. 1.

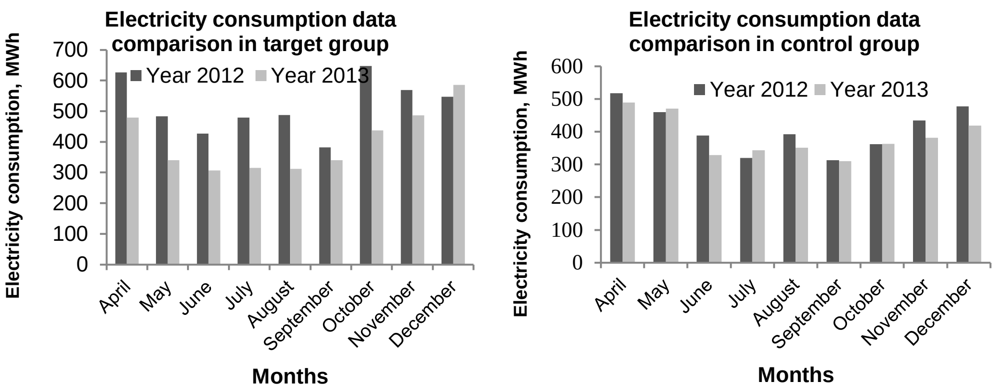

Figure 1. Comparison of electricity consumption in target group and control group households in 2012 (April–December) and in 2013 (April–December).

When looking at these results (see Fig. 1) it is evident that in–depth analysis needs to be carried out in order to explain these results. Understanding of the determinants that drive households' electricity consumption such as personal characteristics (age, gender, education level of residents, and other), floor area, average outside temperature, numbers of occupants, user behavioural factors etc. are needed. As a case study a large data set from project households' is used.

In the following sections a review of methodologies for analysing residential electricity consumption is performed. Factors influencing household electricity consumption are analysed. Based on the analysis of influencing factors a novel model for household electricity consumption has been presented. Finally, the results of regression analysis are presented and potential causes for the results are described.

MATERIALS AND METHODS

Review of modelling approaches and factors influencing residential electricity consumption

Countless studies have proposed models to explain determinants of residential electricity consumption, each of them have their individual strengths and weaknesses. Three approaches, namely top–down, bottom–up engineering and bottom–up statistical regression models are the most commonly used. In the early studies bottom–up models was used for adopting an econometrics perspective attempting to explain aggregate consumption data based on a selected stock of appliances. Therefore, the effect of behaviour and other variables such as climate are merged with the effect of appliances thus minimizing the amount of data requirements for end use consumption estimation (Aydinalp et al., 2003; Swan & Ugursal, 2009). Other studies explained the decision making process of the households, explaining how the consumers respond to changes in price and analyzing only a partial set of residential electricity consumption determinants, e.g., appliance stock, weather conditions or behavioural factors (Cayla et al., 2011; Sütterlin et.al., 2011).

Different linear regression models were used in several studies by assessing the statistically significant variances associated with electricity consumption. Changes in electricity consumption are affected both on the specific variables and conditions behind it, as well as the interaction to each other. The analysis of literature shows that there are many factors that affect residential electricity consumption. A review of studies analysing influencing factors and their impact on electricity consumption is summarized, as shown in the following Table 1.

As indicated above major categories determining household electricity consumption are users' personal, socio–economic factors, physical characteristics of the building, weather and location, appliance stock, occupancy and occupants' behaviour towards energy consumption. Through the review modelling approaches it can be found that the most frequently used factors in describing changes in electricity consumption are: housing type, household income, electrical appliance holdings and number of occupants. Strong correlations among these factors with each other, thus another task is to evaluate correlations among independent variables.

Table 1. A summary of influencing factors and their impact on electricity consumption

Factors	The impact on electricity consumption (analysis of literature)
1. Residents' personal characteristics: • *Age* • *Gender (female/male)* • *Education level* • *Marriage status* • *Family size and composition (the number of people living in household (i.e., occupancy)*	Residential electricity use rises with age (Sardianou, 2007; McLoughlinet al., 2012; Chen et al., 2013; Kavousian et al., 2013; Zhou & Teng, 2013). For households with household heads older than 50 years, electricity consumption is higher by approximately 3% (Zhou & Teng, 2013). If age of people increase, energy saving actions decreases (Carlsson–Kanyama et al., 2005; Linden et al., 2006; Sardianou, 2007) and opposite results found Chen et al., 2013. Some studies found different behaviour between men and women (Bar et al., 2005; Hunter et al., 2005), but another studies found that respondents' gender, educational level and marital status are not significant variables affecting electricity consumption and saving activities (Sardianou, 2007). Families with higher education have higher electricity consumption than middle or lower classes (Santamouris et al., 2007; McLoughlinet al., 2012; Zhou & Teng, 2013). Household electricity consumption increases by approximately 8% points for every additional family member (Zhou & Teng, 2013). Adults living with children consume considerably more electricity than those living alone or with other adults (Bartusch et al., 2012; McLoughlinet al., 2012).
2. Residents' socio–economic factors: • *Household monthly income* • *The share of household's expenditures for electricity consumption* • *Electricity price* • *Rebound effect*	Higher income households consume more electricity (Carlsson–Kanyama et al., 2005; Linden et al., 2006; Santamouris et al., 2007; Vringer et al., 2007; Filippini, 2011; Theodoridou et al., 2011; Zhou & Teng, 2013). Others studies found no significant correlation between electricity consumption and income level (Kavousian et al., 2013). Consumer's private monthly income and electricity expenditures are statically significant variables affecting conservation altered behaviour (Poortinga et al., 2003; Sardianou, 2007). More affluent households have more energy–efficient appliances on average (Kavousian et al., 2013) and live in new constructions (Theodoridou et al., 2011). An increase in electricity price by 10% reduction in demand by 4.5 % can be observed (Kilian, 2007). Some studies estimated that in some cases rebound effect leads to an overall increase in energy consumption by 5–15% (Druckman et al., 2011).
3. Stock and holdings of electrical appliances: • *Stock of electrical appliances* • *Frequency of use* • *The share of energy efficient appliances*	More electric appliances lead to a high growth of electricity consumption (Ouyang & Hokao, 2009, Zhou & Teng, 2013). Older households have fewer household appliances than younger households (Carlsson–Kanyama & Linden, 2007). In some cases home appliances account for over three quarters of total household electricity consumption (Murata et al., 2008). More frequent use of appliances leads to higher electricity consumption (Kavousian et al., 2013). The existence of energy efficient appliances is associated with lower power consumption (Sardianou, 2007; Al–Ghandoor et al., 2009; Ouyang & Hokao, 2009; Theodoridou et al., 2011; McLoughlinet al., 2012; Bartusch et al., 2012; Sanquist et al., 2012; Chen et al., 2013; Kavousian et al., 2013; Zhou & Teng, 2013).
4. Household structural characteristics: • *Type of housing*	In general, electricity consumption by dwellings is higher than in apartments (McLoughlinet al., 2012; Kavousian et al., 2013). Households residing in detached houses are more willing to engage in energy conservation activities than those living in apartment (Sardianou, 2007). Larger dwelling size results in higher household electricity consumption

• *Household size in m2* • *Household age* • *Electrical heating type* • *Indoor temperature maintained during winter time and summer time*	(Yohanis et al., 2008; Bartusch et al., 2012; McLoughlinet al., 2012; Zhou & Teng, 2013). A significant variance in electricity consumption has been established in households with electrical heating system (Theodoridou et al., 2011; Bartusch et al., 2012). Older houses are less energy efficient (O'Doherty et al., 2008), in contrary other studies found that older houses has no significant impact on electricity consumption if compared to younger ones (Kavousian et al., 2013). Newer buildings are better insulated and have energy–efficient lighting installed compared to older buildings resulting to electricity consumption reduction (Abrahamse et al., 2005; Linden et al., 2006; Kavousian et al., 2013). In some studies it was found that mean indoor temperature in wintertime does not significantlly affect electricity consumption (Wiesmann et al., 2011).
5. Residents' behavioural factors: • *The effect of information* • *Knowledge / awareness / attitude level on electricity consumption*	Recent studies reported savings in the ranges of 5–15% when evaluating the effects of feedback information on electricity consumption (Darby, 2006; Burgess & Nye, 2008; Fischer, 2008; Gyberg & Palm, 2009; Ouyang & Hokao, 2009; Darby, 2010; Hargreaves et al., 2010; Vassileva et al., 2012). Some studies show higher effect, i.e., 22% (Jensen, 2003) or lower effects, i.e., – 4.5% in Austria (Schleich et al., 2013), 3% in Denmark, (Gleerup et al., 2010), 2.7% in US (Allcott & Mullainathan, 2010). Consumers' income, family size positively affect energy conserving actions, but expenditures and age of the respondent are negatively associated with energy conserving actions that a consumer is willing to adopt (Sardianou, 2007).
6. Other factors: • *Location, geographic area* • *weather characteristics*	Location of household may contribute by up to 46% to the variability in consumption (Kavousian et al., 2013). Significant relationship between external temperature and electricity consumption that tended to be stronger during periods of cooler weather can be observed (Parker, 2003; Hart & de Dear, 2004). Ouyang & Hokao, 2009 found that change in temperature by 0.8°C can significantly increase electricity consumption.

Household electricity consumption model

Model setup

A novel model for assessing factors that determine electricity consumption savings and electricity use in households has been proposed as shown in Fig. 2. Conceptual foundation of the model is developed based on modelling the relationships between people's individual choice, household's energy profile and external factors for determining savings. The idea of the model is to contextualize household electricity use to find out how do households inhabitants, activities and appliances together determine behaviour.

The model is build on the basis of: a) classification of independent variables (households personal, demographic, socio–economic, the stock and use of electrical appliances, structural characteristics, external factors (such as weather, location etc.), b) implementation of smart metering as an energy efficient measure; c) understanding and selection of interaction among independent variables to each other and with electricity consumption.

Investigation of households' individual choice characteristics are based on people's individual choice theories found in previous studies (Gadenne et al., 2011; Lingyun et al., 2011; Wang et al., 2011; Wenshun et al., 2011; Poortinga et al., 2012; Bamberg, 2013; Klockner, 2013; Webb et al., 2013).

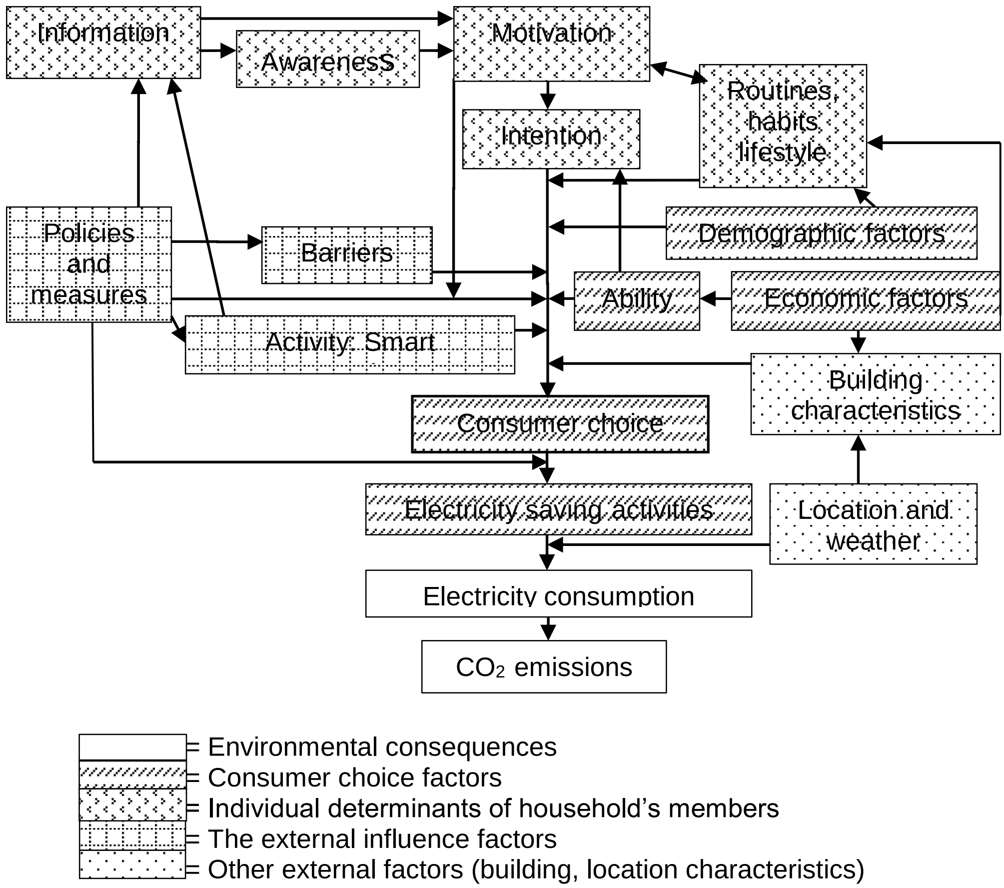

Figure 2. Model of assessing household electricity consumption.

In this model individual determinants of household's members include predisposing factors, information, awareness, motivation, routines, habits, lifestyle and intention. Predisposing factors are behaviour, psychological factors, biological and social–cultural factors. Information is related to respondent's personal factors, as well as source and channels of information provided. Awareness is resident's knowledge, cues to action and possibilities for risk perception and other factors. Motivation is defined like residents attitude towards energy savings, including consideration of Pros & Cons, rational & emotional thinking, as well as motivation depends on social influence, including social norms and public pressure. Resident's are also determined by daily routines, habits and lifestyle factors. As a result, intention is formed based on precontemplation, contemplation and preparation to act. Consumer choice determinants used in the model are defined as economic factors (income level, expenditure pattern etc.), demographic factors (residents' age, gender, education level, number of persons in household etc.), and users' abilities (action plans and skills) that finally determines household choice. The external environment are defined as smart metering implementation in household (related to design and feedback activities for consumer involvement in energy efficient measures), policies and measures (regulations regarding final energy consumption reduction targets and smart metering and subsidies for consumers), barriers for smart metering adoption, as well as building characteristics (type of housing, number of rooms, area in m^2, heating system etc.) and location and weather characteristics (geographic area, heating degree days or cooling degree days).

We consider that environmental consequences occur due to the impact and interaction of individual determinants of household's members, consumer choice decisions, as well as external environment. Household's energy profile have been constructed based on integrated approaches for household energy analysis and energy use reflecting buying, maintenance and usage decisions of electrical appliances (Xu et al., 2008; Gadenne et al., 2011; Kowsari & Zerriffi, 2011; Oltra et al., 2013; Yue et al., 2013). At the end environmental consequences are stock and use of electrical appliances and electricity saving activities resulting in household electricity consumption and CO_2 emissions.

In the model, in particular, we focused on links between the interventions: smart metering, feedback/information and other variables. With the data available, the purpose of the study is to examine a part of the model, in particular:

a) to investigate the main characteristics determining electricity consumption savings by testing all variables that can be observed and measured;
b) to evaluate the impact of smart metering on electricity consumption savings;
c) to assess the interaction of independent variables with each other.

Regression analysis

As mentioned before project households' consumption in 2013 were lower than in 2012 both in target group and control group. The variation in household electricity consumption depends on the various households' aspects. In order to explain the factors that influenced changes in consumption, as well as to assess the impact of smart metering a separate linear regression model for smart metering and other independent variables were developed. We assume, that those determinants whose contribution to electricity savings has a linear relationship with electricity savings. The regression model is given by the following equation:

$$y_j = \beta_{0j} + \sum_{i=1}^{M} \beta_{ij} X_{ij} + \epsilon, \quad (1)$$

where y_j is the electricity consumption savings in kWh of household j (difference in electricity consumption in 2012 and 2013); β_{0j} is is a constant; X_{ij} is the value of the determinant for household j; β_{ij} is the regression coefficient for that determinant; M is the total number of variables (household features); ϵ is the error term.

Data summary, explanatory variables and pre-processing

For our analysis we used electricity consumption data in 2012 and 2013 normalized by annual consumption. Before the implementation of smart meters, the majority of target group and control households paid for electricity using self declaration method (monthly self–reading and payment). When looking at consumption data in 2012, it was found that most of households made irregular payments during the year 2012. A large part of them paid for electricity just once or twice per year or made the payments for almost the same amount of electricity for several months both in winter and in summer. Another lack of data was that a large part of households made payments according to adjusted payment plan (payment of equal monthly consumption rate through the year). Thus the following historical payment data does not reflect the actual monthly consumption. Self-declaration method and payments according to adjusted payment plan method are not really appropriate and suitable for the analysis of consumption data directly. Therefore we use an additional electricity consumption data set of meter readings in 2012 conducted by electricity supply company (JSC 'Latvenergo'). Electricity consumption data in 2012 were normalized based on consumption data from the meter reading during 2012 multiplied by 365 days and divided by the number of days between the last and the first meter reading during 2012.

As mentioned above, control group households are not equipped with smart meters. Also most of control group households pay for electricity using self declaration method and payment plan method. Likewise, we use an additional electricity consumption data set of control group households' meter readings in 2013 which was obtained from electricity supply company making a similar data normalization as in 2012. Much better situation is regarding to target group data. Here consumption data were obtained from smart meters during 9 months (April – December, 2013), i.e. – 275 days. Therefore, electricity consumption of target group in 2013 were normalized by multiplying smart metering data for 9 months period with 365 days and divided by 275 days.

Empirical data analysis (i.e., regression analysis) is supported by an extensive household survey and electricity consumption data in the period from year 2012 to 2013. A large data set both for the target group and the control group were taken from the survey responses carried out at the beginning of the project in April – May, 2013. Responses of 729 households were available from this survey of which 429 belonged to the target group and 500 to the control group. The household survey includes questionnaire about the occupant's personal, socio–economical, dwelling characteristics, electrical appliance stock, occupancy and occupants' behaviour towards energy consumption and other information (see Table 1 in Laicane et al., 2013a). Sequentially, the set of 267 variables is established on the basis of data obtained from survey. First, we aim to assess the effect of smart metering based on electricity consumption savings achieved in 2013 both in the target group and the control group. Selection of cases was based on consumption data available for both years – 2012 and 2013. For 13 target group households' and for 379 control group households consumption data in 2012 and 2012 and/or 2013 were not available, respectively. These cases were removed from the subsequent analysis of smart metering effect on electricity consumption savings. Finally, 537 cases were selected for the analysis. Second, we used aggregate consumption data of 2013 in order to assess the main characteristics determining electricity consumption savings in 2013 both for the target group and the control group. Due to lack of consumption data in 2013, 359 control group households were removed from the subsequent analysis. None of cases in target group were excluded from analysis. As a result, 570 cases were selected for linear regression analysis.

RESULTS AND DISCUSSION

Preliminary regression analysis results. The effect of smart metering

Statistical analysis for all the computations has been carried out using SPSS 21 data mining and statistical analysis software. The impact of smart metering on electricity consumption savings was evaluated by linear regression model. The significant effects between target group and control group were evaluated by using the independent variable 'group of participance' and dependent variable 'electricity consumption savings in 2013'. It was assumed that all data are normally distributed represented by a dummy variable which takes on the value of 1 if the survey respondent is assigned to target group and 0 if otherwise. Dummy titled 'smart' is supposed to capture the effect of feedback from the smart metering.

The preliminary results indicate that smart metering has a statistically important influence on electricity consumption savings. 21.3% of variance in electricity consumption savings can be explained by the belonging to the group of participance. Higher savings has been achieved in the target group if compared to the control group. This indicates that smart metering is a promising pathway in contributing to electricity consumption savings. This hypothesis is in agreement with previous studies (Haakana et al., 1997, Jensen, 2003).

Preliminary regression analysis results. The effect of various variables

For the purpose to identify the most important determinants of residential electricity consumption and describe the variability among observed, correlated variables, linear regression model was used. Regression analysis was carried out based on the data set of 267 variables – i.e., responses of survey questionnaire. These 267 variables were used as the independents variables, but electricity consumption savings as the dependent variable. The next Table 2 shows the linear regression results and overall fit statistics.

Table 2. The results of linear regression

Model Summary									
R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin–FWatson
				R Square Change	F Change	df1	df2	Sig. Change	
.816	.666	.338	5813.108	.666	2.033	264	269	.545	1.846

From Table 2 it can be concluded that the adjusted R^2 of our model is 0.338 and the R^2 is 0.666. Such high difference can be explained by the large number of variables include in the model (267 variables). It means that the variables included in the linear regression explain only 33.8% variance in electricity savings. Therefore, the most part of variance in electricity savings can be explained by other important variables while not included in this model.

Preliminary results indicate that the variables 'electric gates', electric sauna or electric bath house', 'heat pump' 'solar collectors' and 'group of participance' is among the most statistically significant determinants that positively affect electricity consumption savings (higher positive value of factors indicate the larger savings). We hypothesize that the positive effect on electricity consumption savings by ‘electric gates’, electric sauna or electric bath house’, ‘heat pump’ can be explained by the fact that in general only a small number of households have such electrical devices. Results also indicate that higher energy savings has been achieved in households where solar collectors are installed. The variable ‘type of housing’ (detached house, apartment, other type of residence) has been found as the most statistically significant variable that impact electricity savings achieved by households with a negative sign (higher negative value of factors indicate the decline in savings). That means that greater electricity savings can be achieved in larger detached houses rather than in apartments. Also variables ‘central heating’ and ‘the possession, number and use of LED TV sets’ affect electricity consumption savings with a negative sign. That means – more households have central heating and LED TV sets, less electricity savings achieved. However, together these variables explain only 17% variance in electricity consumption savings. The greater part of variance in electricity consumption savings therefore can be explained by other variables.

One of the tasks within this study also was to assess the interaction of independent variables with electricity consumption savings and their correlation to each other. It allows determining if the main effects are independent of each other. For this purpose correlation matrix obtained from the preliminary regression analysis were investigated. First, it is important to look at the t values for single independent variables in order to assess the extent of significance of individual variables. In most cases t values for a single independent variables are low that indicate that there are high correlation among variables. Correlations among variables are described below. It the model the Durbin–Watson test for auto–correlation was included in order to test that the residuals from a linear regression or multiple regression are independent. The Durbin–Watson is 1.846, which is between the two critical values of $1.5 < d < 2.5$ and therefore we can assume that there is no first order linear auto–correlation in the linear regression data. Significant effects between the different variables are evaluated by Kaiser–Meyer–Olkin and Bartlett’s test of sphericity. The Kaiser–Meyer–Olkin selection is appropriate, because a) it is a measure of sampling adequacy tests whether the partial correlations among variables are small and b) it is an index for comparing the magnitudes of the observed correlation coefficients to the magnitudes of the partial correlation coefficients. Bartlett's test of sphericity is used to test the null hypothesis that the variables in the population correlation matrix are uncorrelated. The observed significance level is 0.545.

By analysing the regression coefficients it can be concluded that most of variables have no statistically significant influence on electricity consumption savings. It is also important to notice that 267 variables included in the analysis have a different statistical data type, a part of these variables have a nominal values, ordinal values, or binary values. The number of variables we used is too large for regression analysis and more sophisticated approach is needed to evaluate the most important determinants explaining electricity consumption savings. However, the first predicting correlation results indicate that greater or smaller correlations among different independent variables can be observed. Main high positive and negative correlations among variables are listed in Table 3.

Table 3. Observed correlations among various variables

Variable	High positive correlation	High negative correlation
Group of participance	Iron, cooker hoods, electric kettles and water filtering system	Income, language and gender of respondent
Gender	Electric sauna or electric bath house	Lightning, refrigerator, home cinema system, tablet PC, the average indoor temperature in winter
Age	Analogue TV set, freezers, storage water heaters (boiler)	The number of household members living in the same residence, laptop, dishwasher, electric stove
Number of occupants	Income, average time of staying home, refrigerator, electric kettles, washing machine, electric stove, electric ovens, dishwasher, cooker hoods, analogue TV set, iron, laptop, energy–saving light bulbs	Type of housing, the average degree of education in family, residents age, central heating from energy supply company
The average degree of education in family	Age of respondent, electric sauna or electric bath house, use of washing machines together with a dryer, vacuum cleaners	Occupancy, average time of staying at home
Type of housing	Insulated exterior walls and roof	Income, occupancy, average time of staying at home, refrigerator, freezer, electric stove, electric sauna or electric bath house, storage water heater (boiler), heat pump
Household area	Year of construction, solar panels, acoustic sound systems or music centres, air humidifiers	No significant negative correlations
Year of construction	Household area, central heating from energy supply company, insulated exterior walls, roof	Dishwasher, electric gates, the average indoor temperature in winter
Electrical heating	The use of electric heaters, electric under floor heating system, electric stove together with electric oven, storage water heater (boiler)	Natural gas heating
Income	The number of occupants, household type, electric stove, cooker hoods, dishwasher, laptop, natural gas heating	Central heating from energy supply company

Whereas, relatively high correlations are observed among the independent variables indicating that these variables are not really independent from each other and some common factors can be found behind them. Some have high logical interdependencies or high statistical correlation. That's why a regression with all variables leads to only few statistic significances.

More data are needed to validate some of the findings of this paper. Specifically, household data from a more heterogeneous sample over a larger period of time are needed for validating the generality of smart metering effect on electricity consumption savings. Re–surveying would be advisable in order to gain information about major changes in households during the first year of the project, for example, whether household income, composition has been changed or new electrical appliances purchased etc. during this time. Re–surveying At the beginning of the project re–surveying was planned in April–May, 2014, however up to now, is not clear, whether it will take place in planned timeframe.

Some of the further tasks will be also to test, whether electricity demand will be significantly influenced by socioeconomic factors or it is more dependent on changes in the building characteristics, user behavioural factors or electricity price.

Currently, electricity price for households is regulated by Public Utilities Commission and is 11.64 euro cents per kWh up to 1,200 kWh (start tariff) and 15.15 euro cents per kWh when 1,200 kWh level is exceeded (basic tariff). According to electricity market opening conditions all electricity users, including households, need to buy electricity on the open market. Households consume about 25% of all electricity use In Latvia. In April1st, 2014 it was planned to open the electricity market for households, however, the Latvian government decided to postpone the opening of electricity market for households until 1st January, 2015. It is expected that with the opened electricity market, electricity price could rise by up to 40%. Therefore further steps of analysis will be also to assess whether increase in electricity price result in lower electricity consumption.

CONCLUSIONS

The rationale of this study is a part of smart metering case study in Latvia. The preliminary results show a decrease of electricity consumption by 23% for the target group and 5% for the control group in 2013 (April–December). In order to gain a first impression of what factors directly affected the reduction in electricity consumption, a novel model for assessing household electricity consumption has been proposed. The aim of this model was to understand how households' inhabitants, activities and appliances together determine electricity consumption and savings. This model will be further improved by including all possible influences and interlinkages in order to analyze the results of the project, by differentiating between consumption and savings model. The potential follow up of this research will be to develop a subset of hypothesis to be tested in order to find out the most significant factors affecting electricity consumption and electricity saving actions.

As indicated in recent literature appropriate energy efficiency measures for reducing energy consumption can be designed and implemented based on the influencing factors that determine household electricity savings. Understanding of interactions among different factors (e.g., the relationship between weather, appliance load, lighting load, and heating load) offer considerable potential for improving energy efficiency (Abrahamse et al., 2005).

Based on data available up to now a part of the model has been tested by using a set of an extensive survey of household data and electricity consumption data of 2012 and 2013. The main tasks were to evaluate the extent of smart metering influence and influence of other main factors that determine electricity consumption and savings. Linear regression model was used for this purpose. The preliminary linear regression results indicate that belonging to the target group seems to have a strong, statistically significant influence on consumption and savings by explaining 21.3% of variance in electricity savings. Smart metering matters need to be further developed. The inclusion of other variables in the linear regression model (267 variables in total) showed that only 33.8% variance in electricity savings can be explained with these variables. Therefore, the most part of variance in electricity savings can be explained by other important variables while not included in this model. Thus adequate regression analysis (taking into account that there are metric, ordinal and binary variables as independent variables) with a smaller number of more significant variables need to be carried out by evaluating to which extent the assumptions of the respective regression model applied are valid. In addition, with the data available it might be better to explain household consumption rather than savings.

When assessing the interaction of independent variables with electricity consumption savings and their correlation to each other, relatively high correlations among variables were found. It indicates that these variables are not really independent, but there are some common factors behind it. The number of variables included in analysis is too large and more sophisticated approach is needed to evaluate the most important determinants explaining electricity consumption savings. A potential follow–up to this study is to find the most appropriate methodology for reducing the number of variables by extracting the correlated variables to more independent ones. Identifying of independent variables and factors behind them can be developed by using factor analysis, principal component analysis and logical derivation from the model.

REFERENCES

Abrahamse, W., Steg, L., Vlek, C. & Rothengatter, T. 2005. A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology* **25** (3), 273–91.

Al–Ghandoor, A., Jaber, J.O. & Al–Hinti, I., 2009. Mansour I.M. Residential past and future energy consumption: Potential savings and environmental impact. *Renewable and Sustainable Energy Reviews* **13**, 1262–1274.

Allcott, H. & Mullainathan, S. 2010. Behavior and energy policy. *Science* **327**, 1204–1205.

Aydinalp, M., Ugursal, V. & Fung, S. 2003. Modelling of residential energy consumption at the national level. *International Journal of Energy Research* **27**(4), 441–453.

Bamberg, S. 2013. Changing environmentally harmful behaviors: A stage model of self–regulated behavioral change. *Journal of Environmental Psychology* **34**, 151–159.

Bar, S., W, Gilg A. & Ford, N. 2005. The household energy gap: examining the divide between habitual– and purchase–related conservation behaviours. *Energy Policy* **33**, 1425–1444.

Bartusch, C., Odlare, M., Wallin, F. & Wester, L. 2012. Exploring variance in residential electricity consumption: Household features and building properties. *Applied Energy* **92**, 637–643.

Bertoldi, P. Hirl, B. & Labanca, N. Energy Efficiency Status Report 2012,

Cayla, J.–M., N. Maizi & C. Marchand. 2011. The role of income in energy consumption behaviour: Evidence from French households data. *Energy Policy* **39**(12), 7874– 7883.

Carlsson–Kanyama, A., Linden, A–L., Eriksson, B. 2005. Residential energy behaviour: does generation matter? *International Journal of Consumer Studies* **29**(3), 239–252.

Carlsson–Kanyama, A. & Linden, A.–L. 2007. Energy efficiency in residences––challenges for women and men in the North. *Energy Policy* **35**(4), 2163–2172.

Chen, J., Wang, X. & Steemers, K. 2013. A statistical analysis of a residential energy consumption survey study in Hangzhou, China. *Energy and Buildings* **66**, 193–202.

Darby, S. 2006. The effectiveness of feedback on energy consumption. A review for DEFRA of the literature on metering, billing, and direct displays, Environmental Change Institute, Oxford University.

Darby, S. 2010. Smart metering: what potential for householder engagement? *Building research & Information* **38**(5), 442–457.

DG for Energy and Transport. 2007. European Energy and Transport 2030.

DIRECTIVE 2009/72/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC // Official Journal of the European Union, 55/112L, 14.8.2009.

Druckman, A., Chitnis, M., Sorrell, S. & Jackson, T. 2011. Missing Carbon Reductions? Exploring Rebound and Backfire Effects in UK Households. *Energy Policy* **39**(2), 3575–3581.

Ernst & Young. 2012. Advanced Metering Infrastructure in CSE countries – current implementation status, plans, and perspectives.

Filippini, M. (2011). Short– and long–run time–of–use price elasticities in Swiss residential electricity demand. *Energy Policy* **39**(10), 5811–5817.

Fischer, C. 2008. Feedback on household electricity consumption: a tool for saving energy? *Energy Efficiency* **1**, 79–104.

Gadenne, D., Sharma, B., Kerr, D. & Smith, T. 2011. The influence of consumers' environmental beliefs and attitudes on energy saving behaviours. *Energy Policy* **39**, 7684–7694.

Gleerup, M., Larsen, A. Leth–Petersen, S. & Togeby, M. 2010. The Effect of Feedback by Text Message (SMS) and Email on Household Electricity Consumption: Experimental Evidence. *The Energy Journal* **31** (3), 111–130.

Gyberg, P. & Palm, J. 2009. Influencing households' energy behavior – how is this done and on what premises? *Energy Policy* **37**, 2807–2813.

Haakana, M., Sillanpää, L. & Talsi, M. 1997. The Effect of Feedback and Focused Advice on Household Energy Consumption. In: *Printed Proceedings of the 1997 ECEEE Summer Study*, 1997.

Hargreaves, T., Nye, M. & Burgess, J. 2010. Making energy visible: a qualitative field study of how householders interact with feedback from smart energy monitors. *Energy Policy* **38**, 6111–6119.

Hart, F.M. & de Dear, R. 2004. Weather sensitivity in household appliance energy end use. *Energy and Buildings* **36**(2), 161–174.

Hunter, Lori M., & Toney, Michael B. 2005. Religion and Attitudes toward the Environment: A Comparison of Mormons and the General U.S. Population. *Social Science Journal* **42**(2), 25–38.

Institute of Physical Energetics. 2012. Energy Efficiency Policies and Measures in Latvia. ODYSSEE– MURE 2010. Monitoring of EU and national energy efficiency targets.

Jensen, O.M. 2003. Visualisation turns down energy demand. In: Proceedings of the 2003 summer study of the European Council for an energy efficient economy, Stockholm: ECEEE, 451–454.

Joint Research Center. 2012. Energy: Commission paves the way for massive roll–out of smart metering systems.

Kavousian, A., Rajagopal, R. & Fischer, M. 2013. Determinants of residential electricity consumption: Using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior. *Energy* **55**, 184–194.

Kilian, L. 2007. The economic effects of energy price shocks. Discussion paper 6559, CEPR, Londen, www.cepr.org, November 2007.

Klockner, C. 2013. A comprehensive model of the psychology of environmental behaviour—A meta–analysis. *Global Environmental Change* **23**, 1028–1038.

Kowsari, R. & Zerriffi, H. 2011. Three dimensional energy profile: A conceptual framework for assessing household energy use. *Energy Policy* **39**, 7505–7517.
Laicane, I., Blumberga, A., Rošā, M. & Blumberga, D. 2013a. Assessment of Changes in Households' Electricity Consumption. *Agronomy Research*, **11**(2), 335–346.
Laicane, I., Blumberga, A., Rošā, M., Blumberga, D. & Bariss, U. 2013b. The Effect of the Flows of Information on Residential Electricity Consumption: Feasibility Study of Smart Metering Pilot in Latvia. *In: 2013 European Conference on Smart Objects, Systems and Technologies (SmartSysTech)*, Germany, Erlangen/Nuremberg June 11-12, 2013, 1–9.
Laicane, I., Blumberga, A., Rošā, M., Blumberga, D. & Bariss, U. 2013c. Forecasting electricity consumption based on smart metering case study in Latvia. *In: The 8th WSEAS International Conference on Energy & Environment (EE'13)*, Greece, Rhodes Island, July 15-17, 2013, 148–156.
Linden, A–L., Carlsson–Kanyama, A. & Eriksson, B., 2006. Efficient and inefficient aspects of residential energy behaviour: what are the policy instruments for change? *Energy Policy* **34**(14), 1918–1927.
Lingyun, M., Rui, N., Hualong, L. & Xiaohua, L. 2011. Empirical Research of Social Norms Affecting Urban Residents Low Carbon Energy Consumption Behavior. *Energy Procedia* **5**, 229–234.
McLoughlin, F., Duffy, A. & Conlon, M. 2012. Characterising domestic electricity consumption patterns by dwelling and occupant socio–economic variables: An Irish case study. *Energy and Buildings* **48**, 240–248.
Murata, A. Kondou, Y., Hailin, M. & Weisheng, Z. 2008. Electricity demand in the Chinese urban household–sector. *Applied Energy* **85**, 1113–1125.
O'Doherty, J., Lyons, S. & Tol, R. 2008. Energy–using appliances and energy–saving features: determinants of ownership in Ireland, *Applied Energy* **85**(7), 650–662.
Oltra, C., Boso, A., Espluga, J. & Prades, A. 2013. A qualitative study of users' engagement with real–time feedback from in–house energy consumption displays. *Energy Policy* **61**, 788–792.
Ouyang, J. & Hokao, K. 2009. Energy–saving potential by improving occupants' behavior in urban residential sector in Hangzhou City, China. *Energy and Buildings* **41**, 711–720.
Parker, D.S. 2003. Research highlights from a large scale residential monitoring study in a hot climate. *Energy and Buildings* **35**(9), 863–876.
Poortinga, W., Steg, L., Vleg, C. & Wiesma, G., 2003. Household preferences for energy–saving measures: a conjoint analysis. *Journal of Economic Psychology* **24** (1), 49–64.
Poortinga, W., Spence, A., Demski, C. & Pidgeon, N.F. 2012. Individual motivational factors in the acceptability of demand–side and supply–side measures to reduce carbon emissions. *Energy Policy* **48**, 812–819.
Sanquist, F.T, Orr, H., Shui, B. & C.Bittner, A. 2012. Lifestyle factors in U.S. residential electricity consumption. *Energy Policy* **42**, 354–364.
Santamouris, M., Kapsis, K., Korres, D., Livada, I. & Parlou, C., Assimakopoulos M.N. 2007. On the relation between the energy and social characteristics of the residential sector. *Energy and Buildings* **39**, 893–905.
Sardianou, E. 2007. Estimating energy conservation patterns of Greek households. *Energy Policy* **35**, 3778–3791.
Schleich J., Klobasa M, Gölz S. & Brunner M. 2013. Effects of feedback on residential electricity demand—Findings from a field trial in Austria. *Energy Policy* **61**, 1097–1106.
Sütterlin, B., Brunner, T.A. & Siegrist, M. 2011. Who puts the most energy into energy conservation? A segmentation of energy consumers based on energy– related behavioral characteristics. *Energy Policy* **39**(12), 8137–8152.

Swan, L.G. & Ugursal, V.I. 2009. Modeling of end–use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews* **13**(8), 1819–1835.

Theodoridou, I., Papadopoulos, A.M. & Hegger, M. 2011. Statistical analysis of the Greek residential building stock. *Energy and Buildings* **43**, 2422–2428.

Vassileva, I., Odlare, M., Wallin, F. & Dahlquist, E. 2012. The impact of consumers' feedback preferences on domestic electricity consumption. *Applied Energy* **93**, 575–582.

Vringer, K., Aalbers, T. & Blok, K. 2007. Household energy requirement and value patterns. *Energy Policy* **35**(1), 553–566.

Wang, Z., Zhang, B., Yin, J. & Zhang, Y. 2011. Determinants and policy implications for household electricity–saving behaviour: Evidence from Beijing, China. *Energy Policy* **39** (6), 3550–3557.

Webb, D.A., Soutar, G.N., Saldaris, P. & Mazzarol, T. 2013. Self–determination theory and consumer behavioural change: Evidence from a household energy–saving behaviour study. *Journal of Environmental Psychology* **35**, 59–66.

Wenshun, W., Xiaohua, L. & Hualong, L. 2011. Empirical Research of the Environmental Responsibility Affected on the Urban Residential Housing Energy Saving Investment Behavior. Energy Procedia **5**, 991–997.

Wiesmann, D., Azevedo, I.L., Ferrão, P., Fernández, J. 2011. Residential electricity consumption in Portugal: Findings from top–down and bottom–up models. *Energy Policy* **39**, 2772–2779.

Xu, M., Hu, Z., Wu, J. & Zhou, Y. 2008. A hybrid society model for simulating. *International Journal of Electrical Power & Energy Systems* **30**(10), 569–574.

Yohanis, Y.G., Mondol, J.D, Wright, A. & Norton, B. 2008. Real–life energy use in the UK: how occupancy and dwelling characteristics affect domestic electricity use, *Energy and Buildings* **40**(6), 1053–1059.

Yue, T., Long, R. & Chen, H. 2013. Factors influencing energy–saving behavior of urban households in Jiangsu Province. *Energy Policy* **62**, 665–675.

Zhou, S. & Teng, F. 2013. Estimation of urban residential electricity demand in China using household survey data. *Energy Policy* **61**, 394–402.

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The first three-year development of ALASIA poplar clones AF2, AF6, AF7, AF8 in biomass short rotation coppice experimental cultures in Latvia

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Abstract. Hybrid aspen and willows are the fastest growing tree species used for biomass production in short rotation coppice (SRC) cultures in Latvia. Poplars are suitable for cultivation in Latvia, however, their potential for this purpose as SRC in Latvia and North Eastern Europe has not yet been investigated. There is an increasing interest in using poplar clones to establish short rotation plantations. The aim of this study is to analyse the productivity of the Italian poplar clones AF2, AF6, AF7, AF8 and their potential use for biomass production, as well as the effect of fertilization on the development and survival of trees.

The experimental plot consisted of drained mineral soil with the initial spacing of trees ranging from 9,000 to 10,000 trees ha^{-1} (1.5 m x 0.7–0.5 m). Weed management has been carried out on the plantation once per season every year. Four management methods were tested – control (no fertilization), fertilization with waste water sludge 10 t DM ha^{-1}, wood ash 6 t ha^{-1}, mineral fertilizer NPK (12:5:14) 100 kg ha^{-1}.

In the second year, the height of the trees ranged from 0.2 to 2.64 m, on average 1.12 ± 0.005 m. The annual increments during the third year ranged from 0.01–2.14 m, on average 0.787 ± 0.004 m. At the end of the third season, the tree diameters at breast height of all clones varied greatly from 0.36 cm to 4.4 cm. The trees reached average diameters of 1.48 ± 0.007 cm; the tree heights ranged from 0.36 m to 4.24 m and were 1.99 ± 0.01 m, on average at the end of the third season. Depending on the clone and treatment, the amount of fresh biomass was 1.57–10.67 t ha^{-1}(planting density 10,000 trees), and one fifth of the biomass, on average, was located in branches.

Sewage sludge fertilizer contributed to the development of the micropatogen *Venturia sp.*, resulting in lower initial retention and delayed development. Mineral fertilizers were the most effective. No animal and frost damages were observed. Overall, the results indicate a significant potential for us for using poplar for bioenergy production, with the optimal rotation age for bioenergy production being more than 3 years.

Key words: *Populus*, fertilization, growth, increment.

INTRODUCTION

During the period from 2009 to 2013, the cultivation of *Populus sp.* and *Salix sp.* in short rotation coppices (SRC) gradually developed into an energy wood production business in Latvia. This resulted in the need for a supply of appropriate planting material, the availability of specialised contractors for planting and harvesting measures, as well as the practical 'know how' to establish and maintain *Salicaceae,* including *Populus sp.*, plantations. The knowledge of how to develop *Populus* plantations in their calculated stand time and with the predictability of the expected growth and biomass yields related to a certain site type is still lacking. In addition, there is a demand for productive poplar and willow clones in Latvia.

Bioenergy plantations are expected to become the most important source of biomass for energy purposes on a global scale (Mizey & Racz, 2010), while in Latvia, it is just expected to be an additional source of woody biomass (Būmanis, 2007; Būmanis, 2012). In Latvia, no more than 100 ha of poplars are planted. Investors from Scandinavia and 'Old Europe' are mostly interested in establishing SRC.

Several projects were supported with experimental plantations by the Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources) and other institutions with a view to answer questions about the practical cultivation, profitability and selection of suitable species and varieties in Germany. The total area of short-rotation coppices in Germany has increased to 4,000–5,000 ha since 2012 and continues to increase significantly (Wühlisch, 2012).

Italy's interest to increase the contribution of agro-energy towards national energy demand is increasing and new incentive-providing instruments have been approved. For example, the so-called Renewable Energy Certificates (Gasol et al., 2010), specifically focussed on electricity and thermal energy generation (González-García et al., 2012), like in Latvia (LME, 2013). Recent changes in the Common Agricultural Policy of Europe incentivize farmers to grow energy crops and rapid development of the bioenergy sector. During last year's short rotation, coppices were established on about 6,500 ha, mainly in the Po Valley area (Spinelli et al., 2008; Fiala et al., 2010). In Italy, the woody species suitable for SRC are poplars, willows, black locust and eucalyptus; however, most plantations consist of specific poplar clones (Fiala et al., 2010).

In Sweden, substantial areas of willow coppice were established between1980 and 1990 when the Swedish government subsidized land conversion, with the aim of decreasing the farmland area by 0.5 million hectares. As a result, 15,000 ha of commercial SRF willow plantations, along with 500 ha of poplar plantations, existed by the end of 1990 (Johansson & Karacic, 2011). Over the long-term, the mean annual yield of hybrid poplars of the Swedish experiment was 6.7 ton ha^{-1} $year^{-1}$, in a 24 year rotation period. After 6–12 years of growth (1,100–5,000 trees ha^{-1}), high yields were recorded in Southern and Central Sweden (Telenius, 1999; Karasisc et al., 2013).

The Department of Forest Tree Genetics and Breeding Institute of Forestry of the Lithuanian Research Centre for Agriculture and Forestry has collected approximately 74 poplar clones; however, in practice, willows and hybrid poplars are mainly planted on agriculture land (personal communication with Dr. Habil. Alfas Pliura Senior Research Scientist).

Poplar research activities in Estonia were active in the 1960s (Tamm, 1967). Like in Latvia (Saliņš & Smilga, 1960), it was planned at the time to use poplars for greening and as 'fast wood' for pulp and timber production. Nowadays, research activities are mainly related to hybrid aspen investigations (Tullus et al., 2012).

The interest among Latvian scientists and practitioners to increase the contribution of the agro-energy system based on short rotation crops to the national energy demand has increased in recent years and, nowadays, direct payments are granted directly to farmers under a support scheme – the Single Area Payment Scheme (SAPS) for cultivating fast growing ligneous plants, such as *Populus sp., Salix sp. and Alnus incana* (Rural Support Service, 2014), specifically focussed on electricity and thermal energy generation.

Poplar, like hybrid aspen, is desirable for longer period cultivation, because it has high quality timber, which can be used as sawn timber, panels, pulpwood production, and veneer (Spinelli et al., 2008; Johansson & Karacic 2011; González-García et al., 2012).

MATERIALS AND METHODS

An experimental plot was established on agricultural land in the central part of Latvia (56°41 N and 25°08 E) in the spring of 2011. The experimental plot (16 ha) is divided into compartments of different species establishing agroforestry systems to investigate the growth of herbaceous energy plants together with trees as a multifunctional plantation of short rotation energy crops and deciduous trees. Poplars were planted on 2 ha in total.

The ALASIA poplar hybrid clones AF2 (*P. deltoides 145-86 x P. nigra 40*), AF6 (*P. x generosa 103-86 x P. nigra 12*), AF7 (no information), AF8 (*P.xgenerosa 103-86 x P.trichocarpa PEE*) (www.http://www.alasiafranco.it) were planted using 20 cm long cuttings with the density of 15 cm x 70–50 cm. Cutting producers and suppliers were performed by an Italian company, ALASIA NEW CLONES. Weed management was performed once per season.

The soil type is *Phaeozems/ Stagnosols* with the dominant loam (at 0–20 cm depth) and sandy loam (at 20–80 cm depth) soil texture. The soil chemical content and nutrients added in the course of initial fertilization have been described in earlier articles (Rancane et al., 2012; Bārdule et al., 2013), first class (according to the Regulation of the Cabinet of Ministers of the Republic of Latvia No. 362) waste water sludge (wws) (dose 10 t DM ha^{-1}) from Ltd. 'Aizkraukles ūdens' (Aizkraukle Water) and stabilised wood ash from a boiler house in Sigulda (dose 6 t DM ha^{-1}) were spread mechanically before the planting (Table 1).

Table 1. Chemical composition (content of elements, g kg^{-1}) of wastewater sludge and wood ash

Fertiliser	N	P	K	Ca	Mg	Mn	Fe	Na
Wood ash	0.40	10.9	31.6	224.8	30.9	3.1	4.6	1.6
Wastewater sludge	25.9	16.3	2.2	10.9	11.3	0.3	23.4	0.2
Minerals NPK	12	5	14		*			

The growth parameters of poplar clones - diameter of stem, length and annual increment, fresh biomass of shoots were statistically analysed by applying the OpenOfficeCalc, Gnumeric T-test and analysis of variance (ANOVA).

RESULTS AND DISCUSSION

Short rotation coppice can be subdivided into SRF – plantation with short cutting frequency (1 or 2 years) and MRF – plantation with medium cutting frequency (> 5 years). Pant densities vary highly: 10,000–14,000 plants ha^{-1} (annual plantation with twin rows), 5,000–6,000 plants ha^{-1} (biennial plantation with single rows) and 1,000–1,800 plants ha^{-1} (in MRF) are used in Italy (Fiala et al., 2010). Nowadays, the larger part of Italian short rotation crops are based on 2-year cuts (VSRC), the best quality of biomass comes from 5-year plantations (SRC), and it is possible that in the near future SRC plantations will be more widespread due to the lower ash content in the bark (Guidi et al., 2008) and the longer the rotation, the better the result in both biomass yields and cellulose content under the same conditions (Guidi et al., 2009). According to the Latvian law, the maximum rotation for SRC in agriculture is 5 years. The current plantation will be cultivated till this age and then harvested; now, data of the third year potential yield are presented.

Single-factor ANOVA comparison shows that height differences between all clones are only significant at end of the second season (Table 2). The heights and diameters of all poplars grown on the sample plots with initial treatments with waste water sludge (wws), wood ash and control are not different at a significant level. After using mineral fertilizers, the differences became significant for all parameters of current year increment, height and diameter.

Table 2. Anova one-factor comparison (P-values) between the means of parameters

Factors compared	Second season	Third season		
	height	increment	height	diameter at breast height (1.3 m)
Clones	0.001	0.660	0.154	0.218
Initial fertilization treatment	0.573	0.297	0.348	0.129
All treatments including minerals		0.000	0.011	0.007

After the second season, under all initial fertilization treatments, the stems of clone AF6 were higher, in spite of the negative effect on growth by giving of initial fertilizers, because of the sensitivity to ground vegetation concurrence. In Italian conditions, AF6 has a 15 days shorter vegetation period compared to others (http://www.alasiafranco.it), but in Latvia, in the first three seasons, AF6 was faster-growing and had significantly better height results compared to the other three clones (Table 3, Fig. 1). In the ENERWOODS project, poplar fertilization with the mineral fertilizer NPK 12:5:14 100 kg ha^{-1} was performed in the third season.

Table 3. P-values of the differences between poplar clone height at end of the second vegetation season

Cone	AF 2	AF7	AF8
AF6	0.003	0.002	0.007
AF2		0.186	0.563
AF7			0.556

All clones show different reaction to initial fertilization. The amounts of fertilizer applied on the field where poplar experiment is conducted are 2 ha of 16 ha, in some cases, it was not the main factor impacting on the height growth of the trees (Rancane et al., 2012), for example, in the first two seasons on both unfertilized parts of the field, one later used for testing of the effect of mineral fertilization, the height of the shoots varied (Fig. 1). During the first two seasons, a statistically non-significant but positive effect on the growth of poplars was observed under treatment with wood ash. Additional N, taken into the soil by WWS, caused decreasing of resistance to *Venturia sp.*, which affected the plants in the first season, and was the reason of the more vigorous vascular plants development – ground vegetation competed for nutrients in the second season.

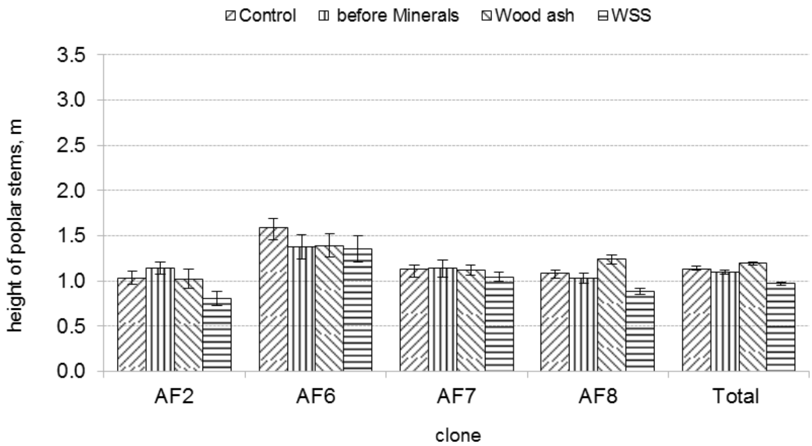

Figure 1. Height of poplar clone stems in the end of the second vegetation season after different initial fertilization treatments.

The third season increments, after fertilizing with fertilizers, using an experiment design similar to the ENERWOODS project, poplar fertilization in Denmark and Sweden (mineral fertilizer NPK 12:5:14 100 kg ha^{-1}) were impressive and significantly better than another treatments (Fig. 2, Fig. 3). Clone AF2 started to grow faster.

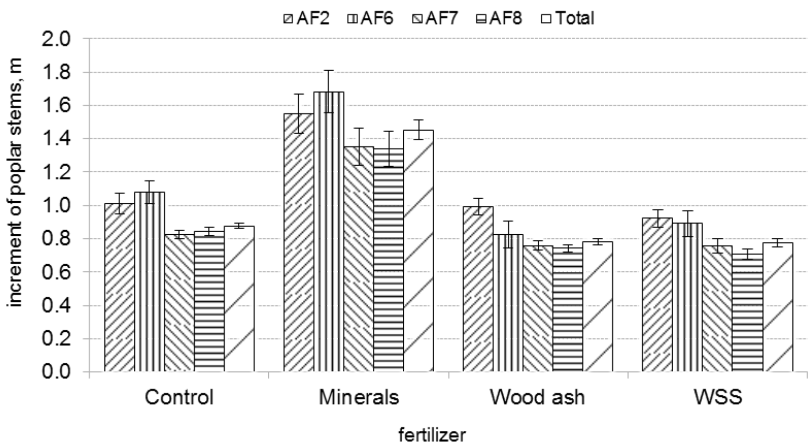

Figure 2. Third season annual increments of poplar clone stems after different initial fertilization treatments.

As in the second season, the clone AF6 had larger increments and higher stems in the third season as well (Fig. 3).

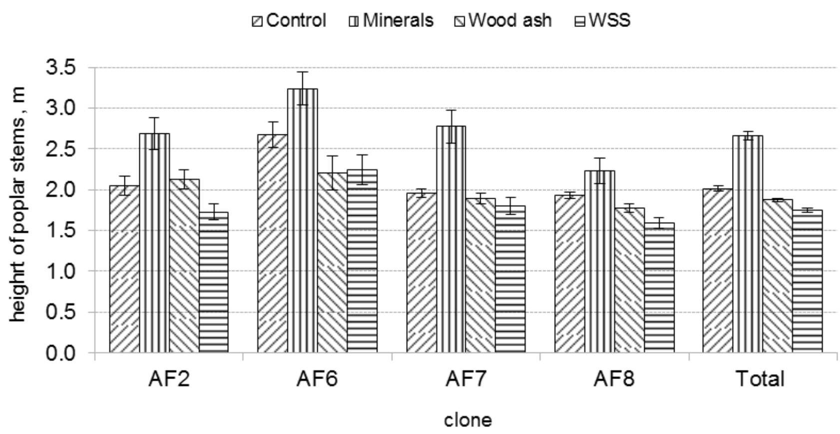

Figure 3. Height of poplar clone stems in the end of the third vegetation season after different initial fertilization treatments.

The trees of clones AF2 and AF8 had relatively higher increments in the third growing season compared to others (Fig. 4), which means that their growth strategy is different and it is necessary to follow the growth rate for a longer period before making conclusions regarding which clones to choose and recommend for cultivation in Latvia.

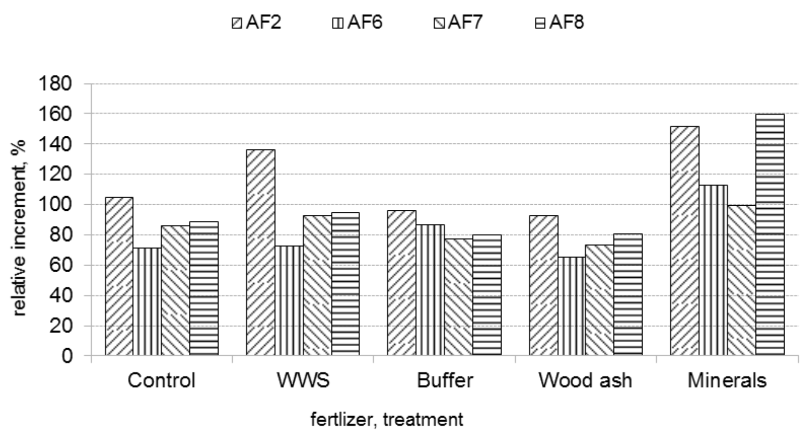

Figure 4. Relative third season increment (%) to initial height in the spring.

The clones with better growth rates also developed thinner shoots. Fertilizers mainly influenced shoot growth in height (Fig. 5).

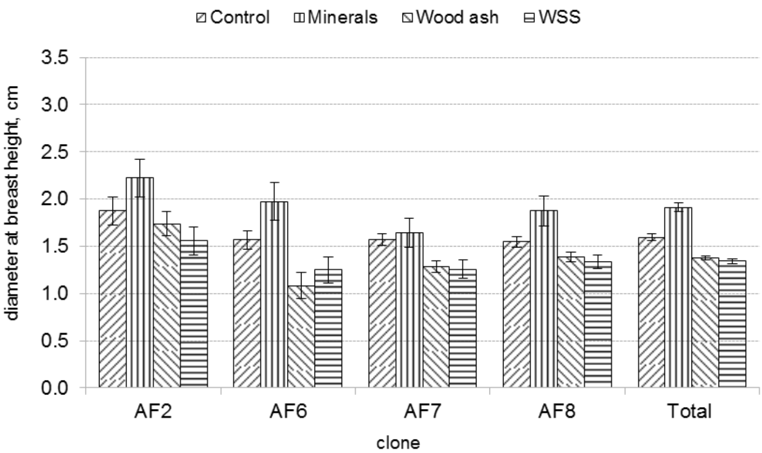

Figure 5. Breast height diameter value differences of poplar clone stems in the end of the third vegetation season after different initial fertilization treatments.

The maximum measured values are promising and show that poplars are quite promising forest plantation tree in the case of better growth conditions and appropriate management systems (Table 4), because of the easy vegetative propagation and establishment by cuttings or rods. The highest values of each parameter under each treatment are highlighted in bold in Table 4, for example, in 2012, the clone AF2 showed the best results under all treatments, but in 2013, the height of the clone AF2 in control was higher and AF 7 had very positive response to the use of minerals. Initially, it has been considered on the basis of the data on a poplar plantation growth in the Po Valley area in Italy that mainly10 years cutting time 5 years (biomass yield 40 $t_{wet\ biomass}$ ha^{-1}·year (at 55% of moisture content wet biomass)) is optimal. In these conditions, a ratio between the output and input energy of 30 and between GHG absorption and GHG emission of 56 with the production cost of € 60 t DM were pointed out. In addition to the positive energy and environmental balances, even the economical sustainability of medium rotation forests (MRF) with the gain of € 820 ha^{-1} per year appears interesting (Fiala et al., 2010). It seems that in Latvian conditions, poplars could be cultivated as MRF plantations as a forest plantation culture or as the maximum duration agricultural SRC, because poplars are slower 'starters' that willows, where the optimal harvesting is 2–3 year rotation (Lazdina, 2010).

Table 4. Maximum measured values of poplar clones in the autumn of the third vegetation season

Data	Height 2012, cm				Increment				Height 2013, cm				DBH 2013,cm			
Clone	AF2	AF6	AF7	AF8	AF2	AF6	AF7	AF8	AF2	AF6	AF7	AF8	AF2	AF6	AF7	AF8
Control	2.22	**2.51**	2.12	1.95	**1.95**	1.81	1.51	1.94	**3.93**	3.91	3.02	3	**4.4**	2.5	3	3.2
WWS	1.52	**2.43**	2.16	1.76	1.37	1.31	**1.59**	1.43	2.58	**3.74**	3.02	3.04	**3.1**	2.1	2.9	2.9
Wood ash	2.11	**2.3**	2	2.08	1.5	1.5	1.26	**1.92**	3.33	**3.56**	3.2	3.01	**3**	1.8	2.4	**3**
Minerals *					2.1	**2.14**	2.02	**2.14**	4.09	4.14	**4.24**	3.62	**3.9**	3.3	3.1	3.6

*treatment in 2013 NPK

The biomass of fresh shoots was determined by cutting down of shoots and weighting stems and branches separately. The cut shoots were measured and an equation for the average biomass grown on experimental fields was created using shoot height as an argument (Fig. 6). The biomass of the branches of clone AF2 was 29% of total the above-ground biomass, the biomass of clone AF6 – 22% and the biomasses of clones AF7 and AF8 21 % of the total above-ground biomass.

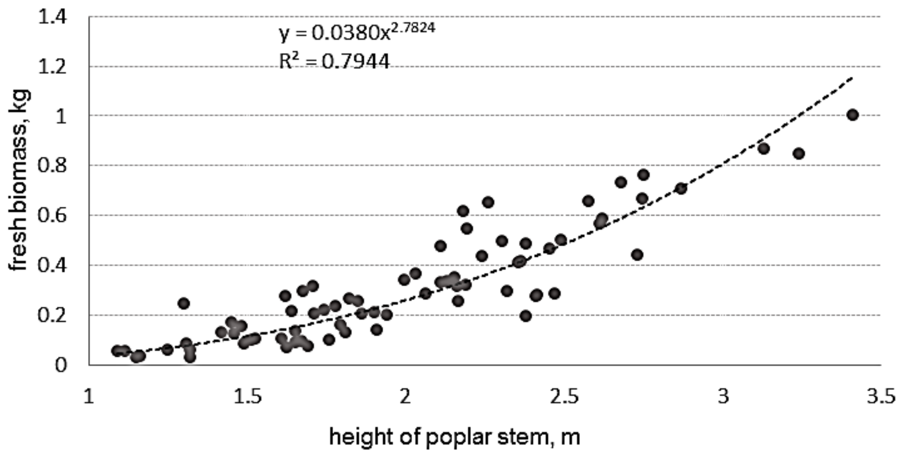

Figure 6. Stem total biomass and height of poplars in the end of the third vegetation season.

From the equation obtained through stem measurements and weighted biomass, the potential yields of the ALASIA clones under various fertilizers in Latvian conditions were calculated for the density of 10,000 plants per ha at a 3-year rotation period (Table 5), the maximum values are in bold.

Table 5. Potential biomass from cultivation of poplars as SRC under a 3-year rotation period

Treatment, year/clone	Control	Sludge, 2011	Wood ash, 2011	Minerals 2013	Buffer zone of minerals	Total average
AF2	3.34	1.90	3.52	6.72	2.90	3.52
AF6	6.62	4.18	3.88	**10.64**	5.54	**6.19**
AF7	2.73	2.31	2.54	**7.37**	2.96	2.96
AF8	2.66	**1.57**	2.19	4.18	3.95	2.82
Total average	3.08	2.11	2.54	**6.76**	3.63	3.19

AF6 had the highest biomass under all treatments. In contrast to willows (Lazdina, 2010), fertilization with waste water sludge does no give positive results and wood as the fertilizer only had a positive impact on the biomass of the clone AF2. On the current field, the three-year rotation cycle is too short for calculations of the economical reasonability of hybrid poplar cultivation.

CONCLUSIONS

The height of poplars in the spring of the third vegetation season ranged from 0.2 to 2.64 m, on average 1.12 ± 0.005 m, the annual increment during the third year ranged from 0.01–2.14 m, on average 0.787 ± 0.004 m, in autumn, tree height ranged from 0.36 m to 4.24 m and was 1.99 ± 0.01 m on average.

The tree diameter at breast height of all clones varied greatly and ranged from 0.36 cm to 4.4 cm; the trees reached the average diameter of 1.48 ± 0.007 cm at the end of the third vegetation season.

Clone AF6 had significantly better growth results and could be recommended for plantation in Latvia, clone AF2 had moderate results. All clones should be tested till reaching at least five years to evaluate the suitability for usage in SRC systems or plantation forests.

Clones AF8 and AF7 are taller and had less biomass of branches than the other two more productive clones AF 2 and AF 6 (AF2 – 29%, AF6 – 22%, AF7, AF8 – 21%).

Depending on the clone and treatment, fresh biomass ranged from 1.57–10.67 tha^{-1} (density 10,000 trees ha^{-1}).

Three-year rotation period is too short in Latvia conditions for obtaining high yield from hybrid poplar short rotation crop fields.

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REFERENCES

Bārdule, A., Rancāne, S., Gūtmane, I., Bērziņš, P., Stesele, V., Lazdiņa, D. & Bārdulis, A. 2013. The effect of fertiliser type on hybrid aspen increment and seed yield of perennial grass cultivated in the agroforestry system. *Agronomy Research* **11**, 13–25.

Fiala, M., Bacenetti, J., Scaravonati, A. & Bergonzi, A. 2010. *Short rotation coppice in Northern Italy: comprehensive sustainability. In, 18th European Biomass Conference and Exhibition*. Lyon, France, 7.

Gasol, C.M., Brun, F., Mosso, A., Rieradevall, J. & Gabarrell, X. 2010. Economic assessment and comparison of acacia energy crop with annual traditional cropsin southern Europe. *Energy Policy* **38**, 592–597.

González-García, S., Bacenetti, J., Murphy, R.J. & Fiala, M. 2012. Present and future environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management systems. *Journal of Cleaner Production* **26**, 56–66.

Guidi, W., Piccion, E., Ginanni, M. & Boran, E. 2008. Bark content estimation in poplar (Populus deltoides L.) short-rotation coppice in Central Italy. *Biomass and Bioenergy* **32**, 518–524.

Guid, W., Tozzini, C. & Bonari, E. 2009. Estimation of chemical traits in poplar short-rotation coppice at stand level. *Biomass Bioenergy* **33**, 1703–1709.

Johansson, T. & Karacic, A. 2011. Increment and biomass in hybrid poplar and some practical implications. *Biomass and Bioenergy* **35**, 1925–1934.

Karasisc, C.A, Verwijst, T. & Weih, M. 2003. Above-ground woody biomass production of short-rotation Populus plantations onagricultural land in Sweden. *Scandinavian Journal of Forest Research* **18**, 427–37.

Lazdina, D. 2010. Willows for production of bioenergy. *In: Solutions on harmonizing sustainability and nature protection with socio-economic stability (ed.Līviņa, A.) Vidzeme University of Applied Sciences*, 95–101.

Ministry of Economics of the Republic of Latvia, 2013. Latvijas enerģētika skaitļos / Latvian energy in figures, Vispārējā informācija General data, 43.

Mizey, P. & Racz, L. 2010. Cleaner production alternatives: biomass utilization options. *Journal of Cleaner Production* **18**, 767–770.

Rancane, S., Karklins, A. & Lazdina, D. 2012. *Perennial grasses for bioenergy production: characterization of the experimental site. Research for Rural Development 2012 Annual 18th International Scientific Conference Proceedings Jelgava*, LLU, Volume 1, 31–38.

Saliņš, S. & Smilga, J. 1960. Apses, Latvijas Valsts izdevniecība, Rīga, 91 (Poplars in Latvian).

SIA 'Meža un koksnes produktu pētniecības un attīstības institūts'. 2007. Enerģētiskās koksnes plūsmas teorētiskā un eksperimentālā modeļaizstrāde un produktu kvalitātes prasību izvērtējums", Meža attīstības fonds, Lauku atbalsta dienesta līguma numurs: Nr. 250707/ S295. 37 (in Latvian).

SIA 'Meža un koksnes produktu pētniecības un attīstībasinstitūts' 2012. Koksnes biomasasizmantošanasenerģijas ieguvē monitorings, Meža attīstības fonds, Lauka atbalsta dienesta līguma Nr.060912/S107.,78 (in Latvian).

Spinelli, R., Nati, C. & Magagnott, N. 2008. Harvesting Short-Rotation Poplar plantations for biomass production. *Croatian Journal of Forest Engineering* **29**, 129–139.

Tamm, U. 1967. Poplar-growing in Estonia, Metsanduse Tead. Uurim. Lab. Metsandusl. Uurim Tallinn. 5, 47–89.

Telenius, B.F. 1999. Stand growth of deciduous pioneer tree specieson fertile agricultural land in southern Sweden. *Biomass & Bioenergy* **16**, 13–23.

Tullus, A., Lukason, O., Vares, A., Padari, A. Lutter, R., Tullus, T., Karoles, K. & Tullus, H. 2012. Economics of hybrid aspen (*Populus tremula L.* × *P. tremuloides* Michx.) and silver birch (*Betula pendula* Roth.) plantations on abandoned agricultural lands in Estonia, *Baltic Forestry* **18**(2), 288–298.

Wühlisch, G. (editor) 2012. Poplars and Willows in Germany: Report of the National Poplar Commission, Johann-Heinrich von Thünen-Institut (vTI) Bundesforschungsinstitut für Ländliche Räume, Wald und Fischerei, Time period: 2008–2011, 26.

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AC-link based new microgrid system for research of local power flow management

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Abstract. This paper gives an overview of a distributed energy technology laboratory, where diverse approaches are studied to effectively integrate distributed generation into power systems. The laboratory is equipped with small-scale power generation devices including wind turbine (3.5 kW), PV array (2.5 kW), synthetic energy generator (3.6 kW) and also batteries, ultra capacitor, programmable load (6.2 kW), weather station, power flow and power quality control and monitoring system. The laboratory is used for researching and applying energy-management technics to control energy storage and increasing power reliability and power quality in small-scale generation units. On-site measured data of power consumption and production can be linked to the laboratory and simulated online with synthetic energy generator and programmable load. It is also possible to scale the measured data and model systems with variable sizes. As a result the stability of variable systems can be tested with different storage capacities and load management techniques.

Key words: renewable resources, energy management, power quality, research laboratory, hybrid energy system.

INTRODUCTION

The energy industry is transitioning from a traditional centralized energy generation network to a network with many additional dispersed generation units, also called distributed energy generation (DG). DG systems may include different technologies like photovoltaic, wind turbines, electrical generators and many more. Increasing proportions of DG devices connected to the grid can potentially affect the power quality of supplied energy. Some critical issues must be resolved in order to provide stable and cost competitive energy to consumers.

High penetration of renewables means that centralized power plants and distribution networks have increased requirements to adapt to the high stochastic nature of renewable power sources. One option to overcome this problem is to control the energy generation process, which in terms of renewables requires energy storage and power flow management. Another way is to use load management (LM) in accordance with energy production by shifting the use of appliances towards peak period of DG output.

Investigations on grid integration of DG can be done in a theoretical way by analysis or simulation. Practical measurements at real systems can be done with field tests or at downscaled systems in laboratories. The following provides an overview of Digital Electronics Laboratory located in Estonian University of Life Sciences Institute of Technology. Location of the laboratory: 58°23'19'' North, 26°41'37'' East, Elevation 76.5 m a.s.l., Tartu, Estonia.

Renewable energy sources like wind and solar have a stochastic nature and neither one is usable without special measures for reliable energy supply. Different approaches are used to mitigate the stochastic nature of these energy sources: grid connection, combining different energy sources, adding storage elements to micro grid, shifting loads (Annuk et al., 2013) etc. The main problem is the determination of the optimal mix of energy sources and control techniques with the focus on the economical optimization to maximize the proportion of the produced energy that is consumed on site (Atwa et al., 2010; Caralis et al., 2011). Fig. 1 presents a one day wind turbine and PV system power output measured in the laboratory on 14-th March 2014 to describe the variable nature of these energy sources.

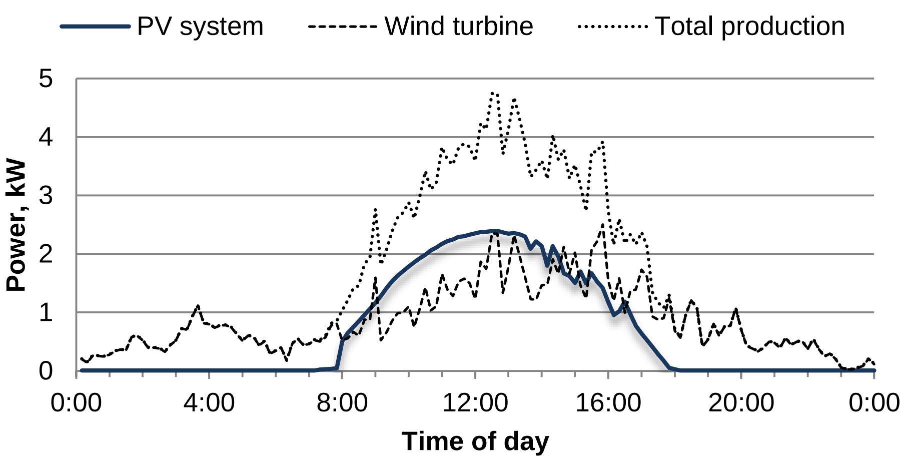

Figure 1. Laboratory PV system and wind turbine power output (14.03.2014).

Taking into account network restricted capacity and decreasing support for renewables in future, it is reasonable to use the produced electricity on site: not to sell energy to the grid but cover a part of the consumption with energy produced on site. The actuality of the problem is, how to control energy flows in grid supported renewable based micro grids to use maximum energy on site by minimum storage capacity amounts and by maximum economic benefit. The topic is highlighted under subject B.2.6 in the Horizon 2020 Work Programme 2014–1015 of the European Union (Horizon, 2013): The realization of reliable, economically efficient and stable energy supply systems, including in the recent years the question of optimal integration of an increasing share of variable renewable energy.

BACKGROUND

Design Objectives

One of the main research fields at Estonian University of Life Sciences Department of Electrical Engineering is Integrated Energy Systems. It focuses on how power systems based on one or more renewable sources can be designed, controlled and integrated to existing grids, delivering a regulated reliable power supply. Three types of renewable energy sources are in the focus of the research: wind, solar and biogas. The fore mentioned research topics are also listed in the Horizon 2020 programme, along with other relevant topics for the laboratory, like electricity grids and energy storage (European Commission 2014). The research topics can be divided into five major groups:

- Energy conversion – evaluate the potential of renewable resources in local energy production.
- Energy storage – storing excess energy generated by renewable resources in peak time and using it when energy consumption exceeds energy production. Defining storage equipment and capacities for various conditions and different systems.
- Load management – balancing the supply of electricity on the network with consumption behaviour. Finding methods to engage consumers' attention in the power balancing process.
- Power quality – analysing the impact of DG in power quality.
- Production curve´s fitting – mitigation of sources power output fluctuations to increase the share of renewable´s on site and decrease battery capacity amounts.

The pilot scale biogas research and development laboratory was opened in 2009, but so far there weren't laboratories where wind and solar energy conversion processes could be researched. Department of Electrical Engineering is currently in the phase of introducing and testing of the `Digital Electronics Laboratory` (DEL), a state of art laboratory with small scale solar and wind energy hybrid system connected to the electricity grid and have possibilities to work autonomously. In the planning process following requirements for the laboratory were set:

1. The laboratory is aimed for teaching and research purposes in the field of renewable energy.
2. The laboratory should facilitate experiments on combining micro-sources (PV panels, wind turbine) and energy storage devices.
3. The design needs to be such that every energy source and conversion process can be tested separately.
4. The laboratory needed to have one synthetic energy generator (SEG) which can be controlled online based on power production measured on-site.
5. The laboratory must be connected to the public university AC network.
6. It must be possible to connect the energy sources to variable load banks and operate dependent on the experiment requirements in island regime (micro grid) or in on-grid regime.
7. Online controlling of variable load banks according to on-site measured consumption data.

8. Completely digitized and centralized monitoring system for all system variables including a weather station and database where the information is stored for research purposes.
9. Transmission of the laboratory parameters over the internet so that they can be used in lectures.

The laboratory will be used by researchers, professors, PhD students, and also by Master's level students conducting their thesis projects supervised by the afore-mentioned.

MATERIALS AND METHODS

System overview

The laboratory equipment was chosen among typical components available on the market, according to the design requirements. One objective was to provide maximum analysis capabilities of present day technologies of solar and wind energy conversion systems. The power ratings were kept in the scale of residential applications. Grid integration of commercial or industrial scale energy resources can be measured and analysed with downscaled parameters in the laboratory. This method is cost- and time saving compared to field tests. Table 1 provides the specifications of selected components.

Table 1. Laboratory main components

Device	Specification
Battery-based grid inverter	SMA Sunny Island 6.0H
Horisontal axis wind turbine	3.5 kW PMSG passive yaw control
Polycrystalline PV Array	10 x (250 W, 30 V) PV module
Synthetic energy generator	Inverter SMA Windy Boy 3600TL
Ultra-capacitor	Maxwell BMOD0165 48.6 V DC, 165 F, 96 A
Batteries	8 x Deep Cycle AGM 220 Ah, 12 V
Resistive loads	Variable 0–2.2 kW and fixed 2 x 2 kW
Weather station	Vantage Pro2

The laboratory energy sources and consumers are connected to the output bus of a battery-based inverter system (SMA Sunny Island 6.0H), forming a one phase AC-coupled system. In stand-alone mode the inverter generates an AC voltage and frequency supply independent of grid AC source. Eight deep cycle AGM (Absorbent Glass Mat) VRLA (Valve Regulated Lead Acid) batteries and one ultra-capacitor (Maxwell BMOD0165) are used for energy supply and storage in case of unbalances in energy consumption and production. In the on-grid mode excess power generation in laboratory can be exported to the utility.

Three different energy production units are used. Solar energy is integrated to the system with 2.5 kW PV array (DelSolar 250 W D6P250B3A), positioned to South at adjustable tilt to the horizon. A current-source 2.75 kW inverter (SOLIVIA 2.5 EU G3) is used for converting DC to AC. Wind energy is present with a 3-blade horizontal wind turbine (Windspot 3.5), with a 3.5 kW permanent magnet synchronous generator. For controlled generation of energy a synthetic energy generator (SEG) is added to the system with a maximum power output of 3.6 kW.

The SEG consists of a frequency drive, rectifier and a grid-direct inverter. SEG draws power from the utility network and transfers it to the laboratory AC system. The power output can be a fixed variable, controlled by a predefined time based power curve or linked to an online variable measured on-site, that can be scaled if needed. The SEG can be used as balancing power source for smoothing solar and wind energy conversion power outputs.

A programmable load bank (PLB) is connected to the system to simulate consumer loads. The PLB is composed of one controllable and two discrete switching resistive loads with a total power variation of 0–6.2 kW. The PLB can be controlled in a same way as the SEG. An overview of the system architecture is presented in Fig. 2.

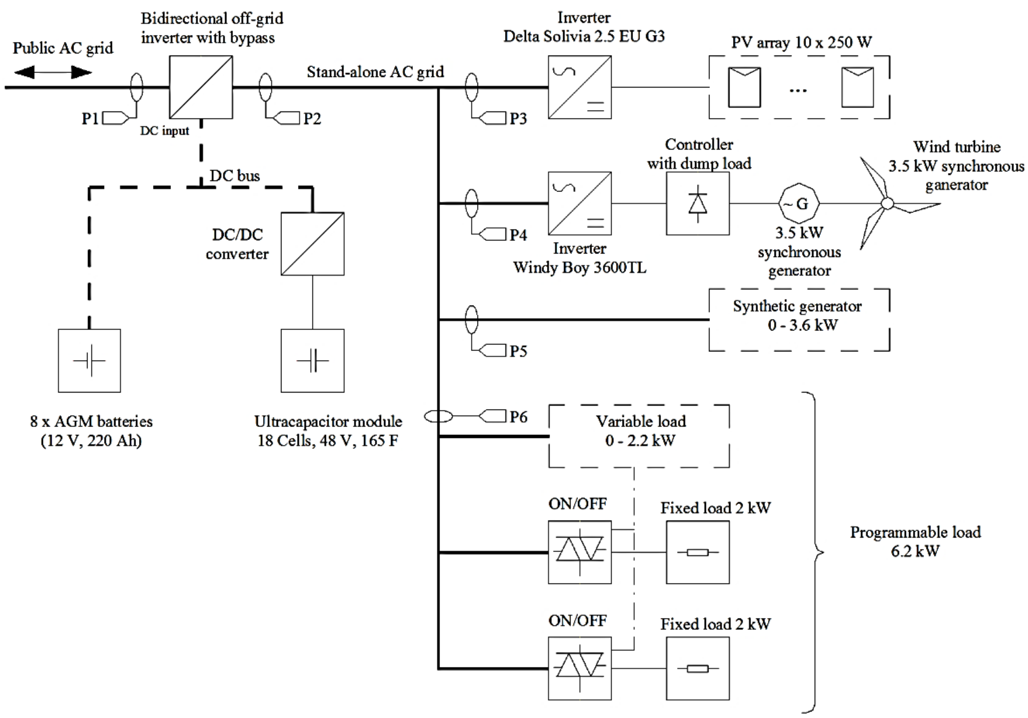

Figure 2. Main architecture of the system (*P1- P6* power flow and quality measuring points).

Control, measuring and storage devices are arranged in one enclosure (Fig. 3), which is placed in the control room. Inverters and loads are installed to the same room (Fig. 4). Energy emitted by loads is used for room heating.

Figure 3. Laboratory main switchboard.

Figure 4. Laboratory control room.

Outdoor components (wind turbine, weather station and solar panels) are installed on the rooftop of Institute of Technology. The placement is shown on Fig 5.

Figure 5. Equipment on rooftop.

Data acquisition and control system

All measurement results collected from sensors and devices are stored in the laboratory server, which is also connected to the university network and to the internet. Overview of data flow architecture is presented on Fig. 6.

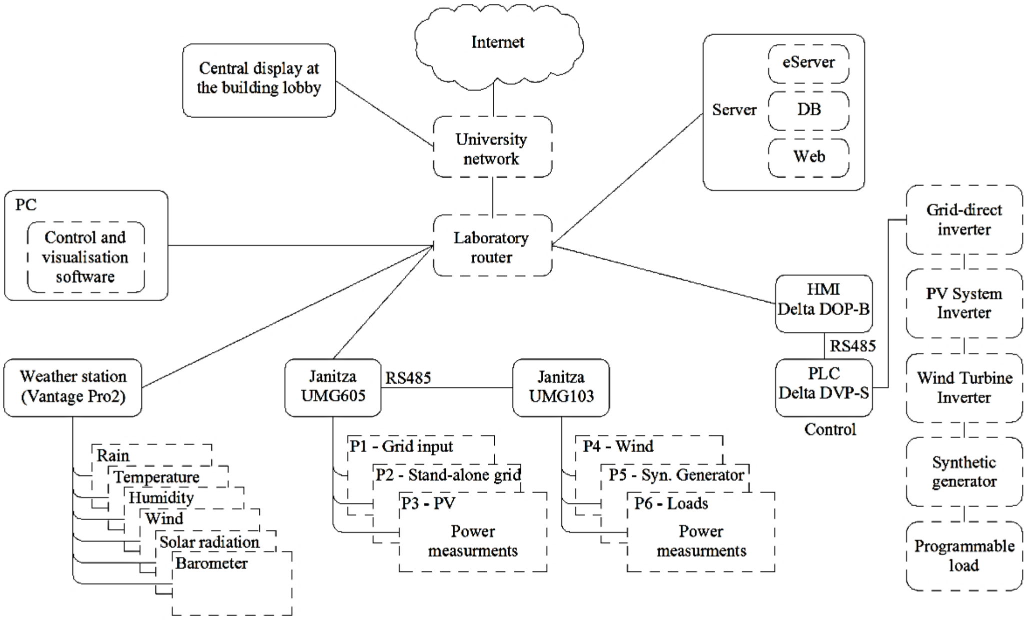

Figure 6. Data connection of measuring and control devices.

A Vantage Pro2 weather station is used for real-time data collecting from rain collector, barometer, temperature, humidity and solar radiation sensors and anemometer. Power flow and quality parameters are measured with power quality analysers (Janitza UMG605 and UMG103). Programmable logic controller (PLC) is used to interact with inverters, synthetic generator and programmable load. Also the safety rules of switching devices are defined in the PLC program logic. All the information is stored in the server computer database.

Reports, data tables and charts are composed based on that database and displayed in three different locations:

1. Laboratory PC enables full online overview of system parameters, control of system devices and export of historical data.
2. Central display at building lobby displays system parameters in real-time on one summarised page.
3. On the laboratory web page an online overview of full system and individually of components are present.

In order to control the synthetic energy generator and the programmable load online accordingly to site-based measure result the laboratory control system has to be linked to an on-site metering device with network connectivity. In a site-based control mode the power output of the SEG and the load of the PLB are determined by a programmable logic controller (PLC). A LabVIEW based software platform needs to be customized to define the interface that automatically updates the PLC with the current tag value given by the metering device. The variable tag can be processed in the software to make scaling or modifications in the system.

Similar existing laboratories

The nearest similar laboratories with hybrid wind- and PV microgeneration can be found at the Tallinn University of Technology (Rosin, 2012) and the Faculty of Engineerging of the Latvia University of Agriculture in Jelgava (Osadcuks et al., 2013).

The laboratories mentioned above and the laboratory that is in the focus of the present article have similar installed capacities of energy generation devices, which makes their data comparable and is a good prerequisite for future cooperation (Table 2).

Table 2. Similar laboratories in the proximity

Laboratory location	Installed capacity of PV, kW	Installed Wind turbine or turbines, kW	Storage devices	Coordinates
Estonian University of Life Sciences	2.5	3.5 kW, HAWT	8 x Deep Cycle AGM 220 Ah, 12 V	N58°23/E26°41
Tallinn University of Technology	1.8	3 kW, WAWT	4 x 220 Ah, 12V	N59°23/E24°40
Latvia University of Agriculture	2.5	0.3 kW, HAWT	2x VRLA, 100 Ah, 12 V,	N56°39/E23°43

Laboratories with similar purpose but slightly southern latitudes can also be found in Ballymena in Northern-Ireland (N54º52/W6º17) (Mondol et al., 2006) and in Pennsylvania in the U.S.A. (N40º47/W77º51) (Pennsylvania State University 2014). It has to be noted that the laboratory in Ballymena is concentrated on solar energy research and has no wind turbines.

When compared with the laboratories mentioned above, then the main difference of the laboratory in Estonian University of Life Sciences is the existence of controllable synthetic load and synthetic generator, which can import remote data. In turn, some of the other laboratories (in Jelgava and in Pennsilvania) have electric vehicle charging stations that lacks in the laboratory which is in the focus of this paper, but could be considered as future development.

DISCUSSION AND FUTURE WORK

Conventional energy networks designed for one way power flow from grid to consumers have to adapt to the growing share of distributed energy production from renewable resources. They are influencing the whole energy system complicating significantly the work of large centralized power plants. Today, conventional power plants are already supporting the management of the grid by providing reserve and balancing power to cope with the stochastic nature of renewable sources. As the share of fluctuating renewable generation is growing, a critical question is: what is the maximum capacity that can be accommodated in the existing electricity network.

Different approaches in the field of DG are researched. One way to flatten the power output of renewable energy is the use of energy storage technologies. It can be used for storing electricity at peak times and discharging it at off-peak times. One of the main research fields of energy storage technologies is developing advanced energy storage materials to increase storage capacity and power densities. The presented laboratory gives good possibilities for testing different electrical energy storage technologies and algorithms for storage control according to real-time site-based measure results.

Another option is to involve end-users in the process of balancing energy production and consumption. It can be done using real-time tariff systems. This means that the consumer price changes in real time according to the network load i.e. availability of wind or solar energy, system load, power quality in network etc. In particular, this means that the networks have to be equipped with information technology such as smart meters and communication interfaces.

Different approaches exist when modelling the use of micro renewable energy generation devices. The laboratory gives opportunities to test previously simulated computer-models. There is also a variety of applied research opportunities for this kind of equipment, especially since the public sector has interest in the field of solar and wind energy applications in urban areas (Muiste & Veskimeister 2013). The main scientific topics that are planned to be implemented in the laboratory:

- Evaluations of optimal PV, wind and storage devices mixture depending on consumers load characteristics and location;
- Research in the field of load management and production control based on real online measured consumption and production data linked to the laboratory programmable load and synthetic generator;
- Evaluation of PV and wind charts peak period cutting technologies to fit consumer consumption curves;
- Assessment of power quality impacts of distributed generation.

Solutions of this laboratory expected to common use in few years. This will be used in dwelling energy supply but in advance for energy societies. The sizes of the devices in the laboratory enable to scale the experiments and transfer the results to any energy system sizes. Most important are the relative sizes of wind and solar device´s capacities and relation to consumer's average capacity. These sizes are developed by correspondingly to characters of wind, solar and consumer's production and load graphs. The laboratory can be further expanded to cover more topics like electric vehicle charging, smart metering fuel cell stacks etc.

CONCLUSIONS

In this article, a Digital Electronics Laboratory located in Estonian University of Life Sciences Institute of Technology was described. The laboratory electrical energy producers and consumers are connected to a stand-alone AC system, which can be disconnected from the utility network. To compensate the imbalance between supply and demand, electrical energy storage equipment is used. The maximum output of power supply units are 9.6 kW (PV array 2.5 kW, wind turbine 3.5 kW and synthetic generator

3.6 kW). This laboratory is designed from typical elements that are used in traditional 230/400 V AC microgrid systems. This system may be as prototype for developed real microgrid solutions.

When compared with similar laboratories, then the main difference of the laboratory of at the Estonian University of Life Sciences is the controllable synthetic load and synthetic generator, which can import remote data. The novelty of this laboratory idea is the possibility not only register energy flow data but also control energy flows under considered algorithm.

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REFERENCES

Annuk, A., Allik, A., Pikk, P., Uiga, J., Tammoja, H., Toom, K. & Olt, J. 2013. Increasing renewable fraction by smoothing consumer power charts in grid-connected wind-solar hybrid systems. *Oil Shale* **30**(2S), 257–267.

Atwa, Y.M., El-Saadany, E.F., Salama, M.A. & Seethapathy, R. 2010. Optimal renewable resources mix for distribution system energy loss minimization, *IEEE Transactions on Power Systems* **25**, 360–370.

Caralis, G., Delikaraoglu, S. & Zervos, A. 2011. Towards the optimum mix between wind and PV capability in the Greek power system. *European Wind Energy Conference & Exhibition Scientific Proceedings*, 75–79.

European Commission, Horizon 2020 The EU Framework Programme for Research and Innovation, Energy. Available at: http://ec.europa.eu/programmes/horizon2020/en/area/energy

Horizon 2020. Work Programme 2014–2015. 10. *Secure, clean and efficient energy*. 2013.(European Commission Decision C (2013)8631 of December 2013). 135 p.

Mondol, J.D., Yohanis, Y., Smyth, M. & Norton, B. 2006. Long term performance analysis of a grid connected photovoltaic system in Northern Ireland. *Energy Conversion and Management* **47**, 2925–2947.

Muiste, M. & Veskimeister, J. 2013. Tuule ja päikeseenergia kasutamine Tartu linnas. Taastuvate energiaallikate kasutamine 21. sajandi linnas, http://www.tartu.ee/index.php/?page_id=58&lang_id=1&menu_id=6&lotus_url=/uurimused.nsf/Web/teemad/DFE85EF5E585A0AFC2257C2F00290BD7 (in Estonian).

Osadcuks, V., Pecka, A. & Selegovskis, R. 2013. Energetic balance of autonomous hybrid renewable energy based EV charging station in winter conditions. *Agronomy Research* **11**, 357–366.

Pennsylvania State University, Hybrid and Renewable Energy Systems (HyRES) Lab Available at: http://sustainability.psu.edu/learn/students/programs/hybrid-and-renewable-energy-systems-hyres-lab

Rosin, A. 2012. MicroGRID ehk väike-tarkvõrk Tallinna Tehnikaülikoolis. *Elektriala* **6**, 22–24 (in Estonian).

Agronomy Research **12**(2), 563–574, 2014

Case study of increasing photovoltaic energy solar fraction in a conventional office building in northern latitudes

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Abstract. Current trends in planning office buildings are moving towards reducing primary energy consumption for heating, hot water heating and cooling. Availability of the solar energy resource and the low temperatures in northern latitudes from early spring until autumn provide the possibility to use photovoltaic (PV) energy for heating, cooling and other energy needs. This article calculates the heating, cooling, hot water and electricity demand of an office building with a glass facade of 65% of the total wall area. The calculated annual total energy consumption is 120 kWh m^{-2}. To reduce the heat and electricity consumption from district heating and the power network, PV modules are integrated into the roof and facade and the solar fractions of the PV energy of the four energy loads (heating, cooling, hot water, and electricity) are found. Optimization of the PV module tilt angles on the facade and roof results in the maximum solar fraction for cooling, heating, preparing hot water, and electricity consumption, 98.4%, 32.1%, 71.7%, and 51.6% respectively. For total load, the calculated maximum solar fraction is 49.8%.

Key words: solar fraction, photovoltaic, building, cooling, heating.

INTRODUCTION

Integration of photovoltaic (PV) modules in the facades of buildings has been investigated since the first PV modules were created. Since integration of solar technology modules in wall and roof surfaces is easy and cheaper compared to wind turbines, the attractiveness of building integrated PV (BIPV) technologies is still there (Shyam, 2013). The potential yields of a PV installation can be derived from the sunlight falling on the building facade. Depending on the geographical coordinates and facade azimuth, the yearly solar yields vary from 500 kWh m^{-2} to 900 kWh m^{-2} (Hussein et al., 2004, Hwanga et al., 2012). The periodically adjustable tilt angle of the PV module in cold and hot seasons has also been investigated and it has been found that changing the tilt angle could improve the quantity and homogeneity of the produced power (Mehleri et. al., 2010), but small deviations in tilt angle do not change the output power more than 20% (Santos & Rüther, 2014). Solar fraction has been investigated in Southern European conditions and it has been found that depending on building compactness, horizontally inclined modules can deliver 95% of the electrical energy and the modules integrated in the eastern facade 41% (Hussein et al., 2004). At the same time, in the case of buildings with small rooftop, but large wall area, a PV installation can cover up to 5.1% of the power consumption (Hwanga et al., 2012). For solar cooling application, it has been found that the yearly solar fraction in Hong-Kong with a PV on roof is 0.68 and with a BI PV 0.477 (Fong & Lee, 2012) – a 21% difference in solar fraction between building integrated and roof top installations. Integration into facades of buildings has shown that the efficiency of a module depends on the ventilation of the PV modules and can drop 2–3% depending on the power-temperature coefficient %/K (Clarke et al., 1996). The results of different solar fraction simulations or direct measurements are not adaptable to the Northern European weather and building demand conditions. In addition to estimating the solar irradiation falling on a BIPV of a typical office building, the solar fractions to hot water, cooling, heating and electricity have to be found separately and in total. Optimization of the PV angle on a facade considering the maximum solar fraction must be analysed in all facades and the roof together.

MATERIALS AND METHODS

Simulation of the cooling, heating, hot water, and electrical energy demand of an office building

The building surface area to volume ratio (A/V) has an important role to the cooling and heating demand of a building (Hwanga et al., 2012). A/V ratio 0.317 has been chosen that represents the typical compactness of existing office buildings in urban conditions (Eicker et al., 2013). The chosen one thermal zone building is 79 m long and 24 m wide and the total height is 9.6 m. Fig. 1.

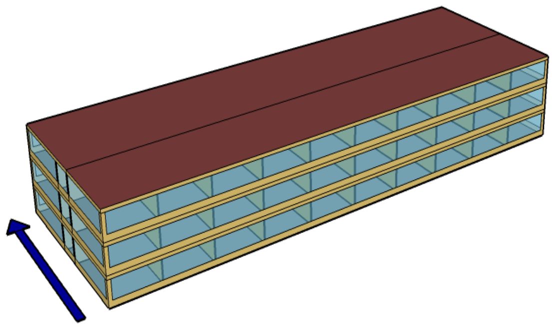

Figure 1. 3D view of the simulated office building (view from the southern facade).

The building has three floors with a treated floor area (TFA) of 5,040 m^2. The storey height is 3.2 m and the net storey height is 2.8 m. From the total volume of 18,202 m^3, the net air volume is 12,500 m^3. The total and PV installation areas (A_{tot}, A_{inst}) and glazing fractions are given in Table 1. For the thermal mass, wood based furniture is used with the volume of 300 m^3 and the specific heat capacity of 196 MJ K^{-1}.

The U-value of the external walls in all azimuths is 0.319 W m^{-2} K and the U-value of the window is 1.1 W m^{-2} K with the total solar energy transmission value (g-value) of 60% and the fraction of incident solar energy transferred through the glazing (b-value) of 40%. The solar transmittance of the internal shading devices was defined as 40%. The internal loads for lightning, equipment and people were defined as 10 W m^{-2}, 15 W m^{-2} and 5 W m^{-2}, respectively (15 m^2/per person) (Estonian Ministry of Economic Affairs and Communications, 2012). The detailed schedules of internal load profiles are different in weekdays (from 8 a.m. to 5 p.m.), Saturdays and Sundays. The schedule types selected are the default EnergyPlus schedules for light, occupancy and electrical equipment.

For the building simulation, the EnergyPlus software was used. The cooling and heating demands were simulated in Tõravere, in Estonia, at the geographical coordinates of E26°27’ longitude, N58°15’ latitude, and elevation of 70 m. The hourly resolution weather data generated for Estonia was used (Kalamees & Kurnitski, 2006). The yearly mean ambient dry bulb temperature is 5.74°C. The global horizontal irradiance is given in Table 1.

Table 1. Building surface, PV area and global irradiation values on the surface

		Azimuth of the vertical surface area				Roof area	Total area
		south	east	north	west	m^2	m^2
		0°	-90°	180°	90°	-	-
Total surface area	m^2	758.40	230.40	758.40	230.40	1,896.00	3,873.60
Glazing fraction	-	65%	60%	65%	60%	0%	
Installation area	m^2	265.44	92.16	265.44	92.16	1,896.00	2,611.20
Yearly global irradiation of surface	kWh m^{-2}	853.43	636.69	342.89	634.56	948.33	3,415.91

The indoor temperature is scheduled at 21°C for heating and 25°C for cooling. For cooling, a building compression chiller system with an Energy Efficiency Ratio (EER) of 2.8 is used. The EER ratio also takes into account all auxiliary devices needed to cool the building. For heating, the building ground-sourced heat pump system with a collector heating indoors is considered. The yearly Coefficient of Performance (COP) with auxiliary devices of 3.0 is used. Humidification is not used.

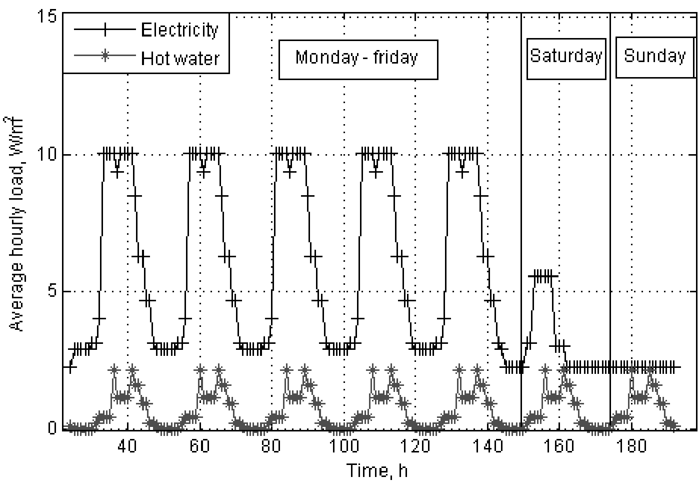

Figure 2. Hot water and electricity consumption load profiles for a typical weekday and weekend.

The hot water and electrical energy demand is dependent on the function of the building. For office buildings, different loads are given for weekdays and weekends. The yearly average hot water load is 100 litres m^{-2} and the electrical consumption

45 kWh m^{-2}. The resulting yearly total hot water load is 30.2 MWh and the electrical consumption 230.5 MWh. Hot water is heated with the same heat pump that is used for heating the building and the yearly average COP with auxiliary devices is 2.7. The maximum hot water and electricity load depends on the treated floor area of the office building. See Fig. 2. The weekly loads of hot water and electrical energy consumption are considered identical over the year.

Solar fraction calculation

For the calculation of solar yields from the building ambient air facing surfaces, the TRNSYS® simulation software and the hourly weather data in Tõravere were used. The installation surface area A_{inst} of the surfaces was taken into account for calculating the solar yields. Calculation of the solar irradiation falling on the PV modules installed on vertical surfaces was performed so that 100% of the A_{red} was used for the PV modules. As the PV modules are inclined, shading behind the PV modules occurs. Shading will be avoided if the glazing area is 60% or more and the PV modules are installed in one row placed vertically over the windows. The additional shading caused by the PV modules to the glazing was not taken into account.

On the horizontal surface (the roof of the building), the surface area of the PV modules is dependent on the tilt angle (α) of the modules. As the tilt angle increases, the pitch of the side-by-side positioned solar rows increases. Taking into account that shading of the PV modules should not occur in the period from 1 March and 31 October starting from 7A.M., the pitch in meters and the surface area of the PV modules can be calculated. When altering the tilt angle, the shaded area behind the PV modules changes. No PV modules can be installed in the shaded area. After calculating the pitch distance, the surface area of the PV module rows and the shaded area was found. In every simulation, the ratio of $A_{PV,hor}$ to the total area of the horizontal A_{hor} was calculated according to the derived equation 1.

$$R_{PV,hor} = \frac{\tan\beta}{c \times (\sin\alpha \times \cos\gamma + \cos\alpha \times \tan\beta)}, \qquad (1)$$

where: $R_{PV,\,hor}$ is the ratio of $A_{PV,\,hor}$ to A_{hor}; c is the width of the PV module, α is the tilt angle of the PV module; β is the hour angle of the sun, and γ is the azimuth angle of the sun at 7A.M. in Tõravere. Multiplying the $R_{PV,\,hor}$ by the A_{hor}, the $A_{PV,\,hor}$ is found and can be later used in calculating the electrical energy produced by the PV modules. Solar fraction (P) is the percentage of the energy produced by PV modules in the building energy demand. If the energy from PV modules is higher than the demand, the residual electrical energy is forwarded to the grid. Solar fraction ratio can be calculated separately for each building azimuth surface or in total. The following equation calculates the difference between the electrical energy from PV and the load.

$$\begin{cases} \frac{Q_{load,i}}{\eta_{load}} - Q_{sol,i} \times A_{inst,N} \times \eta_{PV} \geq 0 \Rightarrow D_i = Q_{sol,i} \times A_{inst,N} \times \eta_{PV} \\ \frac{Q_{load,i}}{\eta_{load}} - Q_{sol,i} \times A_{inst,N} \times \eta_{PV} < 0 \Rightarrow D_i = \frac{Q_{load,i}}{\eta_{load}} \end{cases} \quad (2)$$

where: $Q_{load,\, i}$ is the energy load of the building in kWh; $Q_{sol,\, i}$ – the solar yield on one surface of the building in kWh m^{-2}; η_{load} – the COP or EER value of heating, cooling or hot water heating (electricity η_{load}=1); η_{PV} – system efficiency of the PV installation; $A_{inst,\, N}$ – installation area of the PV installation in m^2; D_i – the difference between the building load and PV energy production in kWh.

The following equation 2 sums up all the calculated hourly differences and results in the solar fraction over a one year period.

$$P = \frac{\sum_{i=1}^{8760}(D_i)}{\sum_{i=1}^{8760}(Q_{load,i})} \quad (3)$$

where P is the solar fraction of electrical energy produced by PV to demand.

RESULTS AND DISCUSSION

Building energy load

An office building is modeled dynamically in three different placements to investigate the influence of heating and cooling to the longer side of the building. The dynamical EnergyPlus building simulation provides both heating and cooling in Tõravere conditions in the period of more than 5,000 hours between September and May and between April and the second part of September, respectively. The heating and cooling do not take place at the same time. The rather long cooling period for N58 latitude is caused by the high percentage of glazing, low tilt angle of the solar rays to the glass surfaces and high internal yields. The maximum cooling demand of 277 kW is lower, then heating demand is 305 kW. The yearly cooling load is 36.6 kWh m^{-2} and the heating load is 33.17 kWh m^{-2}. The reason for the high cooling load is that outer shading devices are not used and low elevation solar radiation can heat the rooms in spring and autumn. Another reason is the high internal yields. In Fig. 3, the building cooling and heating loads and the solar yields for the longer side of the building with the azimuth of 0° (south) are given.

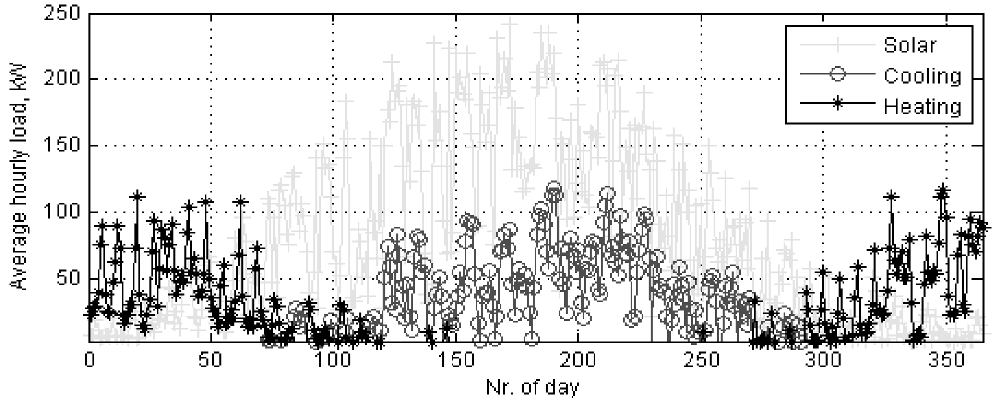

Figure 3. Heating, cooling, hot water and electrical loads and solar irradiation of the longer side of a south oriented office building.

If the building's longer side is placed to south-west or west, the cooling load is higher in the afternoon. To increase the solar fraction, shifting the cooling load towards the afternoon is more suitable as the elevation angle of the sun is high enough then for the PV array to work in the nominal power region on the modules and deliver most power for the cooling equipment. See Fig. 4.

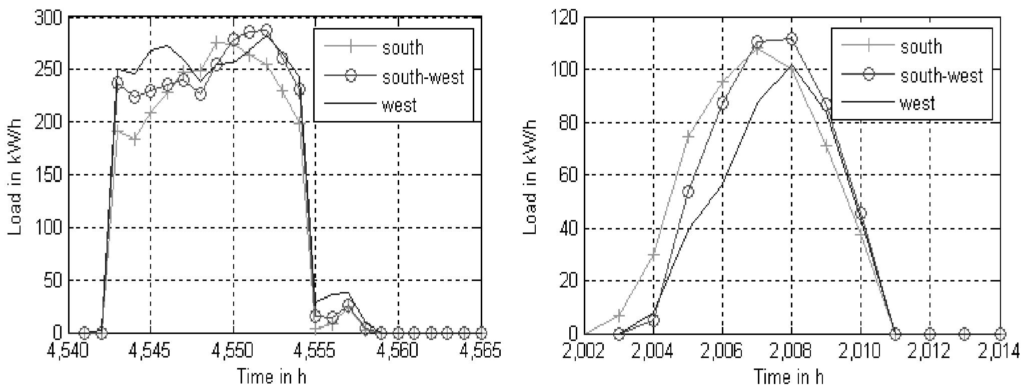

Figure 4. Hourly values of the cooling load in an average summer and spring day.

After iterating the cooling load of the building over one year period, we can conclude that for the lowest cooling load, the longer side of the building must be placed to south (azimuth 0°), if possible. See Table 2.

Table 2. Cooling and heating load maximum, mean and total values over the period of one year

	Cooling			
	South	South-West	West	
Maximum	276.97	287.12	283.74	kW
Mean	20.74	21.85	22.43	kW
Total	181.72	191.45	196.51	MWh/year
Total, per m^2	36.06	37.99	38.99	kWh m^{-2} year
	Heating			
Maximum	304.89	306.31	307.97	kW
Mean	19.08	19.55	19.86	kW
Total	167.17	171.30	173.94	MWh $year^{-1}$
Total	33.17	33.99	34.51	kWh m^{-2} year

The heating load of the building is the lowest in the case of south-oriented building placement. One reason is the low U-values of the building and the good area to volume of 0.317. Secondly, the more the house is south-faced, the lower the heating load in winter months, as solar rays rarely fall on the west and east side of the building. On Fig. 5, the influence of afternoon solar energy if a building is oriented to south can be observed.

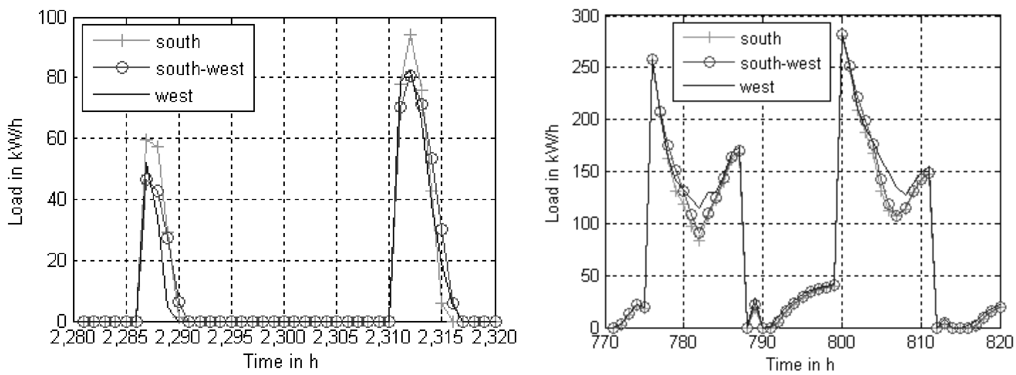

Figure 5. Hourly values of the heating load over a typical spring and winter day.

In further simulations, only south-oriented building placement is used, as this is the best case for low cooling and heating load.

Solar fraction of the facade and roof PV module installation

The solar fraction of one side of the building depending on the tilt angle of the PV modules was found. Next, the load profiles were summarized and the solar fraction angle was calculated separately for every building side. See Fig. 6. The tilts of the PV modules in the north, east, west, south side and on the roof were altered between 0° and 90°. PV module installation on zero degrees in any azimuth except on the roof of a building is difficult to implement. Shading of lower modules is unavoidable. Still, simulation for all possible angles was performed. The solar fraction increases significantly as the module tilt decreases to zero degrees. The reason is that a horizontal solar module will be attacked with the same amount of solar rays as solar panels on the roof, as shading from the wall is not taken into account. The highest altitude angle in Tõravere is N55°23’. Therefore, in further calculations, the PV tilt angles on the north, west and east facade from zero to 55° are not used, as shading by the wall should occur (Duffie & Beckman, 2006). The PV module tilt angle on the southern facade to reach the maximum solar fraction is 30° for cooling and 80° for heating. The reason is that in the case of heating, the seasonal solar altitude is low and therefore it is useful to have the PV modules on a high tilt angle. If the purpose is to get as high solar yield as possible to reduce electrical energy consumption, the PV module tilt angle must be around 40°. The reason is that electrical energy consumption has identical profile in every week of the year and in the summer months there is maximum solar energy production. The solar fraction for the roof PV module installation is dependent on the tilt angle and for all load cases the tilt angle delivering the highest solar fraction is 0°. The main reason for this is that the PV installation area can be increased as the tilt angle decreases and more power can be produced on the roof surface. For a fixed PV installation area, the optimal angle for reaching high solar fraction must be overlooked.

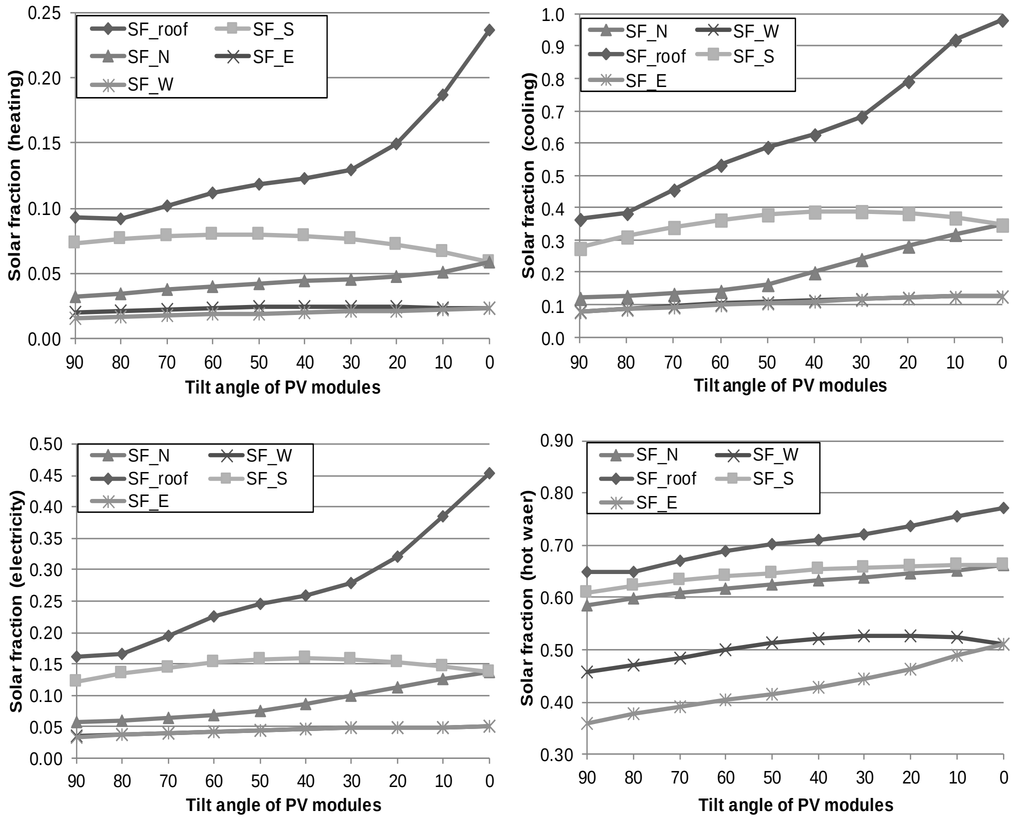

Figure 6. Solar fractions (SH) of five solar module configurations under different load profiles – heating, cooling, electricity, and hot water. Every line depicts results for north (N), east (E), south (S), west (W) facades or the roof.

Electricity produced by PV modules is used for all load types. Therefore, is important to find the PV module tilt angle when the total energy demand of the building is considered. To find the total energy demand in every time step, the loads of cooling, heating, hot water and electricity are summed up. The equations 2 and 3 were used to find the solar fraction for roof and facade installations. When PV modules are installed only on one facade of the building, the solar fraction can be as high as 10.6%, and if on the roof, the total solar fraction is 43% (Fig. 7). The solar fraction for the total energy demand is strongly dependent on how the solar yields are used – for heating or electricity, as these load types have the lowest solar fraction. In the current case, the loads are summed up and the difference between the total load and the solar yields is calculated. To increase the solar fraction of heating demand, the PV modules have to produce more energy in spring and autumn. For this reason, the PV module tilt angle for the south facade has a higher tilt, see Fig. 7. At the same time, the tilt angle cannot increase too much, as near the spring and autumn equinox the PV electricity production in northern latitudes is still low.

As the PV electricity production is related to the installation area (see Table 1) of the building, the solar fraction of the east and west facade could be higher in the case of another A/V ratio.

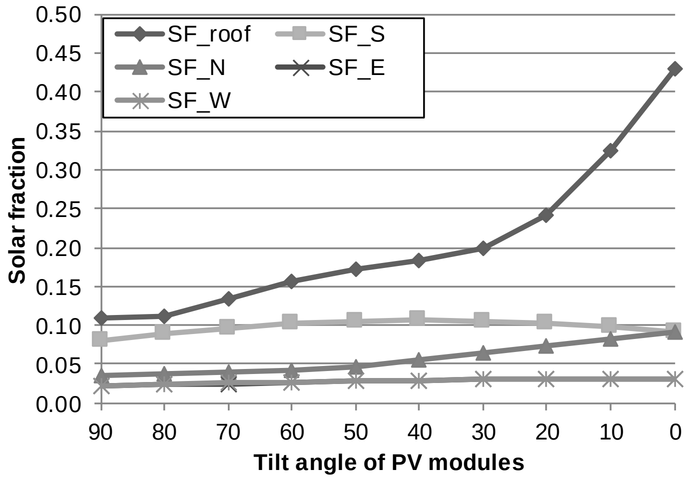

Figure 7. Solar fraction of four facades and the roof to the total energy consumption.

Maximizing solar fraction on two or more facades

In order to find the maximum solar fraction on the whole building, a parametric optimization problem must be solved because of large number of combinations. The same TRNSYS® simulation is used for this, but optimization is solved in the Hybrid Generalized Pattern Search Algorithm with the Particle Swarm Optimization Algorithm. The algorithm uses the Von Neumann neighbourhood topology with the neighbourhood size 5 and the number of particles and the number of generations equal to 10. The cognitive and social acceleration parameters are 2.8 and 1.3, respectively; the yield maximum continuous velocity and constriction yield parameter 0.6; the remaining four parameters needed for the model are the default values defined in the GenOpt® user manual (Wetter 2011, 44). Four scenarios of optimization problems were prepared. Five solar tilt angles were either fixed or limited with minimum and maximum values. See Table 3.

Table 3. Tilt angle of PV modules for four different optimization tasks

	Minimal tilt angle (maximum-90), °				
Scenario nr.	North	East	South	West	Roof
1	55	55	45	55	0
2	90	90	0	90	0
3	90	90	45	90	0
4	90	90	45	90	15

As a result of the optimization, maximum solar fraction was found and corresponding tilt angles were calculated. See Fig. 8. The optimized tilt angle did not differ from the minimum values described in table above for cooling in first and second scenario. The optimum tilt angle found in first scenario for the west azimuth was almost the specified minimum value of 58°56', and in the second scenario for south, 12°68'. The change in the minimum angle for south is explainable by the optimum tilt angle depicted in Fig. 8. The highest cooling solar fraction of 98.29% is achieved with the first scenario and the lowest with the fourth scenario 93.60%. The change in the solar fraction between the first and fourth scenario is 4.69% and this indicates that if installation of PV as described in the fourth scenario is cheaper and more suitable, then high tilt angles should be selected for the facade and low for the roof.

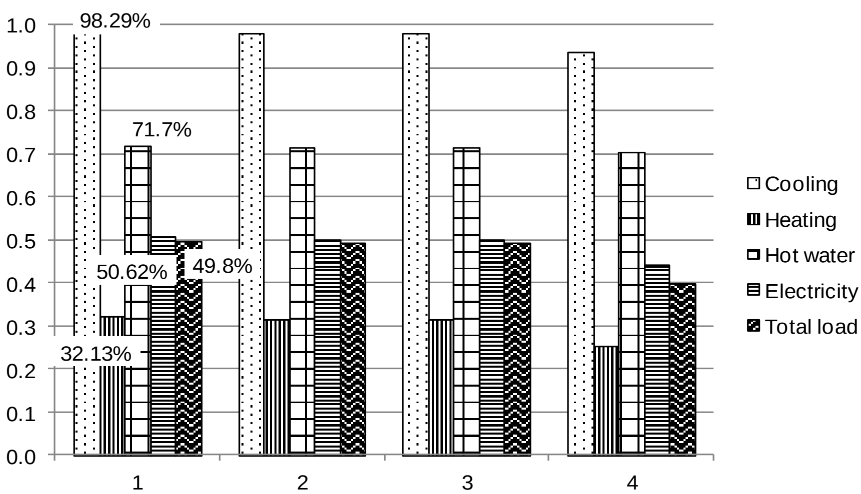

Figure 8. Solar fractions of four scenarios and load profiles.

For heating, the optimal tilt angles are similar to the values given in Table 3, but the south angle must be as high as 54°25'. A higher south angle enables to use the spring and autumn solar yields more efficiently. If the 15° tilt angle is used for the roof installation, then the optimal southern angle is 47°49'. At the same time, the solar fraction of heating drops 6.64%. The hot water solar fraction is less affected by the change in the PV installation tilt. If the PV modules on the roof are inclined from zero to 15°, the solar fraction does not drop more than 1.65%. To establish the highest solar fraction from electricity consumption, the tilt angles defined in the first scenario must be used, but using the third configuration while losing only 0.07% in solar fraction is also a good alternative. If the PV installation on the roof is inclined to 15°, then the solar fraction drops 6.42% compared to the first scenario. The solar fraction for total energy demand is similar in first three scenarios, but if the PV installation on the roof is inclined to 15°, then the solar fraction drops 9.77%, which is a significant difference in energy – 35.4 MWh per year^{-1}.

CONCLUSION

The article is a case study about the load profiles of an office building and the possibilities for reducing the energy consumption of the building with a BIPV installation in northern latitudes. The cooling, heating, hot water, and electrical equipment energy demands of a building were simulated with the dynamical simulation software EnergyPlus. The resulting yearly cooling load is 36.6 kWh m^{-2} and the heating load 33.17 kWh m^{-2}. The treated floor area was 5040 m^2 and the surface area to volume ratio 0.317. The weekly hot water and electricity loads were simulated and the resulting yearly energy consumption is 30.2 MWh and 230.5 MWh, respectively. Next, the solar irradiation, the PV installation electricity production with the system efficiency of 0.13, and the energy demand of a ground-sourced heat pump for cooling, heating and hot water heating were calculated. With an hourly step, the solar fractions of the PV installation to four different loads were found separately and finally total solar fraction of the loads was calculated. The roof installation has the biggest influence on the solar fractions as the roof has largest surface area, 1,896 m^2. The differences in the solar fractions for facade and roof installations are dependent on the type of loads. After optimization of the tilt angles of the PV modules on each facade and the roof, the maximum solar fractions for cooling, heating, hot water heating, covering electrical consumption and all the loads in total are 98.35%, 32.1%, 71.7%, 51.6% respectively, and 49.8% in total. Characteristically to a case study, the results are dependent on the building geometry. To understand how building A/V ratio and geometry affect solar fraction, further analysis is needed.

REFERENCES

Clarke, J.A, Hand, J.W., Johnstone, C.M., Kelly, N. & Strachan, P.A. 1996. Photovoltaic-integrated building facades. *World Renewable Energy Congress Renewable Energy, Energy Efficiency and the Environment.* Renewable Energy,UK , pp. 475–479.

Duffie, J.A. & Beckman, W.A. 2006. *Solar Engineering of Thermal Processes. 3rd ed. Wiley,* New York, pp. 936.

Eicker, U., Pietruschka, D., Haag, M. & Schmitt, A. 2013. Energy and economic performance of solar thermal cooling systems for office buildings in different climates. *Hochschule Stuttgart,* Stuttgart.

Estonian Ministry of Economics and Communication. 2012. *Methodology for calculating energy losses of the building. MKM,* Tallinn.

Fong, K.F. & Lee, C.K. 2012. Comparative study of solar cooling systems with building-integrated solar collectors for use in sub-tropical regions like Hong Kong. *Applied Energy* **90**, 189–195.

Hussein, H.M.S., Ahmad, G.E. & El-Ghetany, H.H. 2004. Performance evaluation of photovoltaic modules at different tilt angles and orientations. *Energy Conversion and Management* **45**, 2441–2452.

Hwanga, T., Kangb, S. & Kima, J.T. 2012. Optimization of the building integrated photovoltaic system in office buildings—Focus on the orientation, inclined angle and installed area. *Energy and Buildings*, 92–104.

Kalamees, T. & Kurnitski, J. 2006. Estonian test reference year for energy calculations. *Proceedings of the Estonian Academy of Sciences* **12**(1), 40–58.

Mehleri, E.D., Zervas, P.L., Sarimveis, H., Palyvos, J.A. & Markatos, N.C. 2010. Determination of the optimal tilt angle and orientation for solar photovoltaic arrays. *Renewable Energy* **35**(11), 2468–2475.

Santos, Í.P. & Rüther, R. 2014. Limitations in solar module azimuth and tilt angles in building integrated photovoltaics at low latitude tropical sites in Brazil. *Renewable Energy* **63**, 116–124.

Shyam, M. 2013. *PV Technology and Cost Outlook, 2013–2017*. Boston: GTM Research.

Wetter, M. 2011. *Generic Optimization Program*. Lawrence Berkeley National Laboratory, Berkley, pp. 9.

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Cleaner production in biowaste management

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Abstract. The article provides a study concerning possible future developments in biowaste management in Latvia. In the article, planning, impact assessment, implementation and improvement phases, as well as the required improvements in these phases of biowaste management, are analysed. Furthermore, the problems faced by the energy sector with resource scarcity and energy dependency from one side, and waste management and EU targets for the minimization of the deposited amount of biodegradable waste, from the other side, are presented. The possibility to reach targets concerning the share of renewable energy sources through the use of biowaste resources and possible impacts are presented. During the research, principles of cleaner production in waste management were created and analyzed. The paper presents new assessment methods based on a combination of different methods for the impact assessment of the waste sector, and the implementation of cleaner production in biowaste management.

Key words: cleaner production, impact assessment, biowaste treatment, anaerobic digestion, evaluation methodology.

INTRODUCTION

Currently, global attention, including in Latvia, is being paid to two aspects of the energy crisis – energy dependency and climate change. The global experience has proven that with an increase in the consumption of energy, a deficiency of energy resources occurs. In this situation, public officials have increased the import of energy resources, rather than encourage a reduction of consumption. Consequently, the state becomes more dependent on imported energy resources. At the same time, scientists are researching alternative energy resources, and the development of new technology. Latvia is a country with limited resources. The development of the national economy is unthinkable without an increase in the manufacturing sector. In turn, the development of the manufacturing sector is connected with the intensification of manufacturing capacity, and the resulting consequences to the environment.

Resource scarcity is thus the 1st dimension of the problem. The 2nd dimension of the problem faced in the power industry is energy dependency. The power industry in Latvia has acquired a stable position in the national economy. It is necessary to elaborate on the common approach of EIA power projects. During the process of impact assessment, principles of 'from-cradle-to-grave' should be implemented. This would enhance the quality and efficiency of the impact assessment. The use of these principles in the process of the impact assessment will allow for the assessment of the designed activities and environmental impact of proposed alternatives to have greater objectivity.

The move from a fossil fuel economy to an economy of renewable energy sources (RES) is a complicated process which requires a long-term development strategy and a concerted effort to ensure its implementation. The use of biowaste as a resource allows Latvia to move closer to the EU's common objectives by reducing the amount of waste disposed in landfills. There are possibilities to utilize biowaste for energy production in Latvia. If biowaste is used to produce biogas, then biogas upgrading to biomethane quality and the distribution of biomethane through the natural gas network is an opportunity to efficiently use renewable energy in more populated (urban) areas, as well as increase the energy independence of the country. Thus, the 3rd dimension of the problem that Latvia is facing is the undeveloped biowaste management system. The 4th dimension of the problem is the lack of a harmonized methodology for impact assessment and cleaner production in waste management.

The primary motivation for this research came from the above mentioned four dimensions of the problem.

The Latvian energy supply is characterized by a strong dependence on energy imports, and the highest share of renewable energy in the whole European Union. Latvia has the highest share of renewable energy in gross electrical consumption among the most recent EU member states (Patlitzianas and Karagounis, 2011) and the highest share of renewable energy in the final consumption of energy (Roos et.al., 2012). The latter consists of approximately one third of the total energy consumed. Imported energy sources account for roughly two thirds of Latvia's total energy consumption. Except for peat, which can be found in approximately 10% of its soil, Latvia has no fossil resources for energy production worth mentioning. Natural gas, oil products, and coal are mainly imported from Russia. However, renewable energy sources are substantial. Forests cover approximately 55% of Latvia's territory, making biomass the largest domestic resource currently used in heat generation. Wind power gained importance in recent years and has good potential as wind is abundant. This is particularly the case along the coast where, in addition, the transmission network is particularly well-developed.

The target for renewable energy as a share of final consumption is 40% by 2020 according to the EU-Directive 2009/28/EC on the promotion of the use of energy from renewable sources. At the same time, in many European countries the main practice for waste management is landfilling. Only in the most developed countries as Germany, England, Sweden, Denmark, Austria, France (Monson et.al., 2007; Niklass et.al., 2012) do biogas plants use organic waste for biogas production (Zhang et.al., 2012; Tampio et.al., 2014). Anaerobic digestion (Kastner et.al., 2012), incineration with energy recovery, mechanical biological treatment (MBT) with anaerobic digestion (Siddiqui et.al.; 2013), and gasification are possibilities both to manage biowaste and a waste-to-energy option (Walker et.al., 2009; Križan, 2011). European countries have to comply with the Landfill Directive 1999/31/EC, and with the Waste Framework Directive 2008/98/EC to considerably reduce the landfilling of the biodegradable part of municipal solid waste (MSW). Unfortunately, the implementation of the European targets is still lagging behind. The use of biowaste as a resource will help to reach the above mentioned targets regarding the use of renewable energy and the reduction of landfilling as a part of the biodegradable part of the MSW.

To summarize, the objectives for this research work were:

1. The problems faced by the energy sector with resource scarcity and energy dependency;
2. EU targets for the minimization of the deposited amount of biodegradable waste and RES must be achieved;
3. Principles for cleaner production in waste management should be implemented;
4. A new assessment method based on the combination of different methods for impact assessment of the waste sector and the implementation of cleaner production in biowaste management should be developed.

METHODOLOGY

To achieve the goal of this study, a combination of multi-criteria analysis (MCA) and System Dynamics (SD) modelling, as well as a correlation-regression analysis (CRA) was developed. The developed methodologies for the assessment of biowaste management scenarios, and the implementation of cleaner production principles in biowaste management, were investigated by simulating different biowaste treatment scenarios (see Fig. 1).

It is crucial to offer an evaluation tool that reflects the criteria of applicability, consistency, reliability and affectivity from a practical point of view.

Within the framework of this work, a quantitative and qualitative analysis of existing waste management, environmental impact assessment, and energy projects practice was performed. The work identifies qualitative and quantitative indicators of the materiality of effect. The inventory phase includes a selection of criteria for the assessment of principles of cleaner production in biowaste management. The second phase of the methodology is based on the use of MCA for the evaluation of biowaste management scenarios. To find and evaluate the optimal treatment scenario, TOPSIS (the Technique for Order of Preference by Similarity to Ideal Solution) was applied.

The empirical model was processed by using two statistical data processing methods: correlation and regression analysis. The statistical analysis of data, and the multi-factor empirical model, were developed using the computer program STATGRAPHICS.

The last step of the proposed methodological framework was based on the use of System Dynamics modelling. Integrating MCA and SD methods can help to structure complex problems, respond to the interests of multiple stakeholders, avoid the weaknesses of each individual modelling approach, and perform an overall assessment of complex problems.

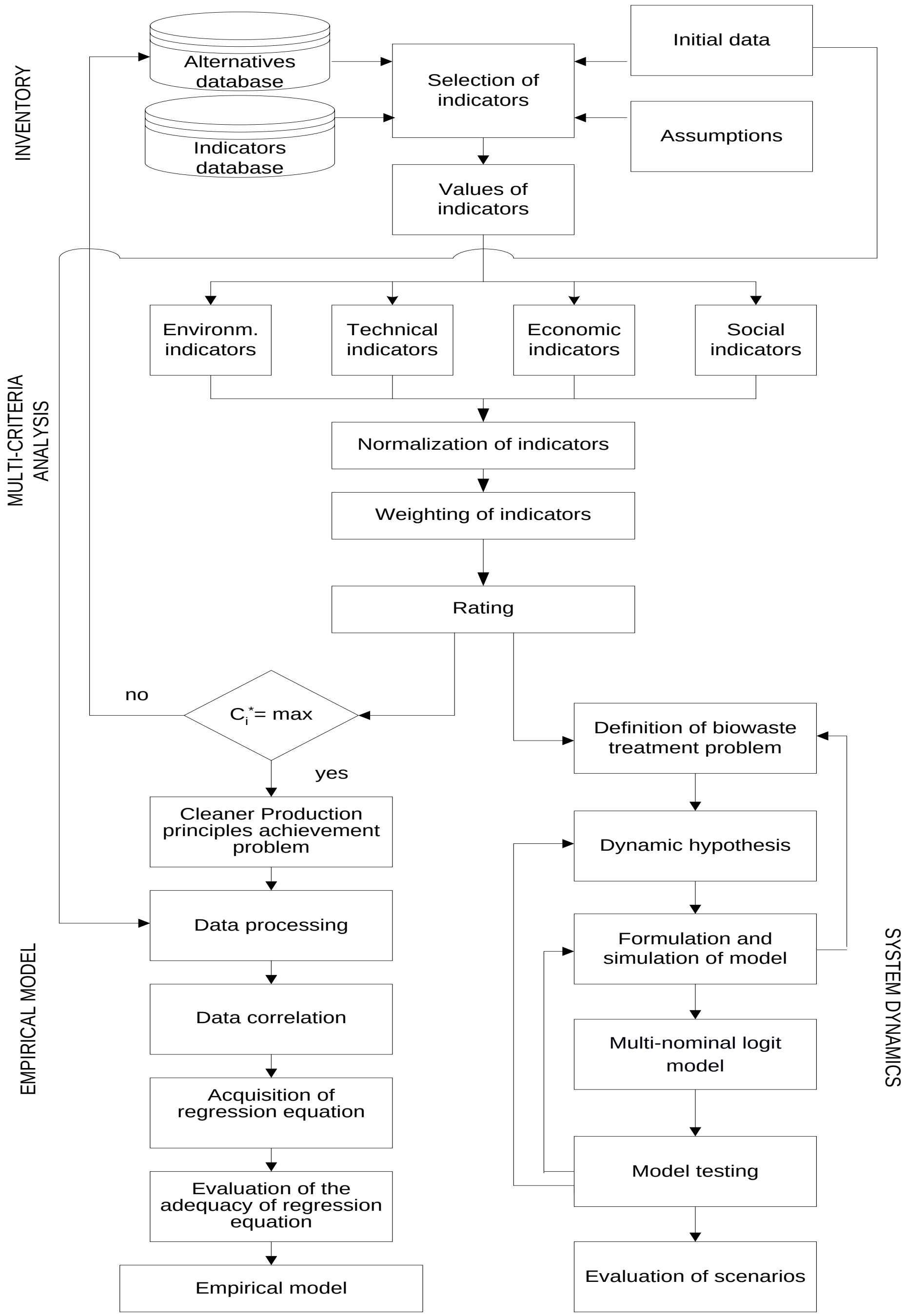

Figure 1. Methodological algorithm.

In the study, planning, impact assessment, implementation, and improvement phases in biowaste management were described (see Fig. 2).

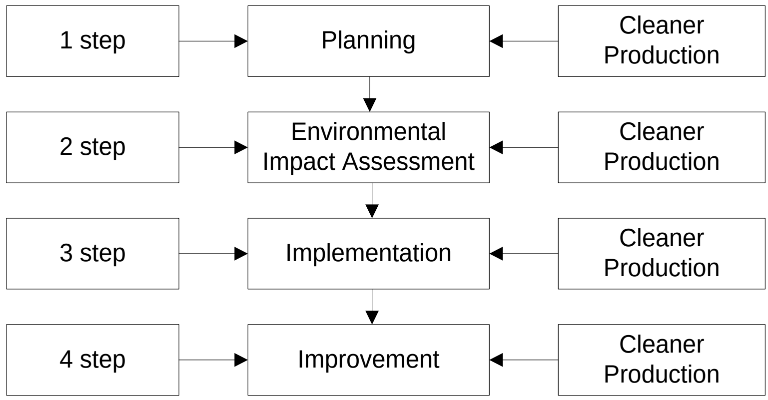

Figure 2. Biowaste management scheme.

Planning and Environmental Impact Assessment

The previous research (Pubule et al., 2012) regarding environmental impact assessment, analyzing the planning stage of energy projects in Latvia, showed that for the achievement of renewable energy sources energy efficiency of used energy resources must be ensured, and energy sources must be constructed where fossil fuels are replaced by renewable ones. As the only legislative tool in the planning phase of energy and waste projects, Environmental Impact Assessments should include a common approach which allows for the enhancement of the quality and efficiency of the EIA. Therefore, cleaner production principles should be analyzed and implemented in the first step of the project implementation – EIA, or the preliminary screening procedure.

The aim of the screening phase is to determine if the project is subject to an EIA. During the screening, it is decided whether the EIA process for the project or activity is necessary or not. Without this verification, some actions can be evaluated very precisely while others can be forgotten or even ignored. While carrying out an effective assessment, a list with the activities planned, accompanied by the values and criteria for determining whether an action should be evaluated, must be formulated (Toro et al., 2010). The criteria of the significance of the impact include the description of the threshold value for identification. The threshold values in Latvia are environmental quality standards, emission limit values, and other limits and restrictions set in various pieces of legislation. Since the various restrictions and environmental quality standards vary in different areas, and for various types of activities, then in most cases the significance of impacts are assessed individually in each case. Often the significance of the impact is not only dependent on the type, amount, and hazard of the planned action, but also the characteristics of the selected place have an important role. In some cases, the impacts of small objects which do not exceed the allowable thresholds are potentially dangerous if they are planned in a sensitive or congested area. Therefore, these projects apply to the EIA procedure. But at the same time, the relatively large objects with possible impact parameters similar to EIA application volumes may not require the application of the EIA procedure, because of the optimal choice of location, and the projected technology to be used which allows for the impacts to be reduced to an insignificant amount.

So we can say that the screening stage is one of the most important and responsible steps in the process of the EIA. A faulty decision could lead to substantial financial losses for the future performance of the project, if an unreasonable decision is made to apply the full environmental impact assessment procedure, which requires substantial financial investment and time, to the project.

Of no less importance, and perhaps even greater losses are possible, if technical regulations are not fully prepared because the possible impact is not fully assessed for the proposed action. Furthermore, if the implementation of the project has already started, while not realizing the potential problem situations and risk factors resulting in damage to the environment, it is known that in most cases, the consequences of the negative effects requires more resources and time than measures that could have prevented or reduced the possibility of the caused damage.

Implementation and Improvement

Nowadays, different methods for municipal solid waste treatment are used:

1. Mechanical Biological Waste Treatment (MBT);
2. Mechanical Biological Stabilisation (MBS);
3. Mechanical Physical Stabilisation.

Furthermore, energetic utilization of wastes has started to become more popular in Europe. Numerous waste incinerators (WIP), facilities for waste and refuse derived fuels (RDF), were built and often controversially discussed. Since the price of primary energy carriers has increased in the last years, waste as an energy resource has become more and more attractive. Therefore, the energetic utilization of high calorific fraction from municipal solid waste (MSW) and commercial waste is processed in power stations for refuse derived fuels.

On top of this, high calorific solid recovery fuels (SBS) are used with high energy efficiency as quality assured co-firing material in power plants and in cement kilns.

The situation in Europe is very different with waste treatment technology, for example, the biowaste sector is not developed in Latvia, but in Germany the plant operators are ready to import waste for treatment from other European Countries due to overcapacities.

Previous research (Pubule et al, 2013) has shown that the existing biowaste management system in the Baltic States is ineffective; therefore, other solutions regarding organic waste should be sought. In Latvia and Lithuania, the percentage of biowaste treatment is very low since the vast majority of biowaste is landfilled.

The concept of cleaner production is well known in industrial environmental management. The key principles of cleaner production are:

1. The Precautionary Principle;
2. The Preventive Principle;
3. The Public Participation Principle;
4. The Holistic Principle (Nilsson et al., 2007; Dubrovin and Melnychuk, 2010).

In biowaste management, these principles are related with the use of more sustainable technologies for biowaste treatment.

Clean production is an integrated approach to production, constantly asking what happens throughout the life cycle of the product or process (Dovi et al., 2009). It is necessary to think in terms of integrated systems, which is how the living world functions (see Fig. 3).

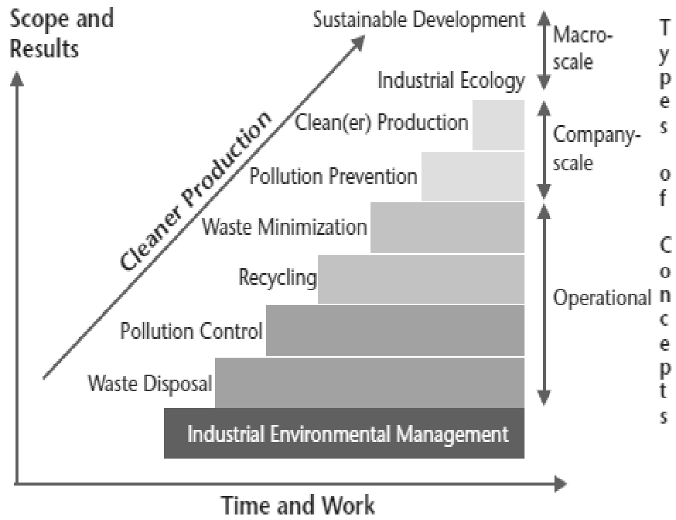

Figure 3. Cleaner production scheme (Nilsson et al., 2007).

Identification and analysis of cleaner production indicators

During the study, different possible options for biowaste management were analysed. Based on the economic situation, climatic conditions, infrastructure, amount, and composition of biowaste, seven more suitable scenarios were found to be more appropriate:

1. Anaerobic digestion of separately collected biowaste (A1).
2. Composting of separately collected biowaste (A2);
3. MBT with anaerobic digestion (A3);
4. MBT with composting (A4);
5. Waste incineration with energy recovery (A5);
6. Waste incineration without energy recovery (A6);
7. Landfilling of biowaste (existing practise) (A7).

Anaerobic digestion of separately collected biowaste is an option with a lot of advantages thanks to the high energetic output (Murphy & Power, 2007); closed energetic cycle (Rutz et al., 2012), lower emissions (Bozano Gandolfi et al., 2012), as well as the positive impact on the social environment and employment.

In the case of this scenario, a separate biowaste collection system must be introduced. For the treatment of biowaste, some existing biogas stations can be used, and there is a necessity for new plants close to urban areas to be constructed. Anaerobic digestion plants should be constructed close to the main organic waste producers to optimize feedstock transportation. As well, plants can be located in the territory of existing MSW treatment facilities. The location of the biogas plants close to urban areas might be economically feasible in the case of source separated organic waste being collected and delivered to the biogas plant near the city. This would allow for savings on transportation costs compared to the scenario if the biogas plant is located in landfills.

During these years, equipment for mechanical waste preparation and separation (Department for Environment Food & Rural Affairs, 2005; Department for Environment Food & Rural Affairs, 2013) will be installed in Latvian landfills. Waste preparation and separation equipment will be installed for the production of RDF and the minimization of the amount of the landfilled biodegradable part of MSW. Questions concerning the biological treatment of the prepared and separated MSW are still unresolved. There are 3 options which are the most suitable for biological treatment in Europe (Muller, 2009; Di Maria et al., 2013):

1. Aerobic – Bio-drying/ Biostabilisation: partial composting of the whole waste;
2. Aerobic – In-Vessel Composting: may be used to either biostabilise the waste or process a segregated organic rich fraction;
3. Anaerobic Digestion: used to process a segregated organic rich fraction (see Fig. 4).

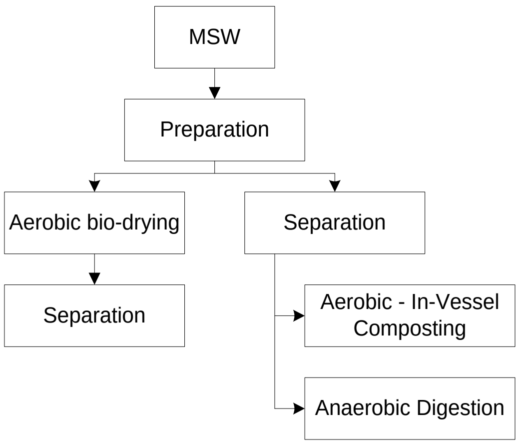

Figure 4. Biological treatment of MSW.

The first MSW plants with MBT in Latvia use aerobic treatment, since the amount of waste is small and composting can be done in existing composting facilities in landfills. In landfills with bigger amounts of biodegradable waste, anaerobic digestion should be introduced for the treatment of waste after the mechanical treatment. In the case of MBT, only dry fermentation technologies can be used, since waste contains impurities. In the case of MBT, the energetic output will be lower.

MBT scenarios can be applied for collected MSW. At the same time, the separate collection of biowaste should be supported and promoted.

In accordance to an EC report on the assessment of the options to improve the management of biowaste in the European Union (European Commission, 2010), the best method for biowaste treatment is composting. Composting is the only method mentioned in Latvian legislation for minimizing the amount of biowaste and biowaste treatment. During the development process of the waste management system, several solid waste disposal landfills in Latvia established composting facilities. The aim of the composting facilities was to minimize the amount of biowaste to be deposited in the country; however, practical experience shows that these composting areas are not being used to their full potential (Pubule et al., 2013a).

Waste incineration, with or without energy recovery, is a well-known technique in Europe. There are no incineration plants in Latvia, and a small amount of RDF is co-combusted in cement kilns. The construction of incineration plants was accompanied with substantial investments and public protests. Therefore, the realistic option is waste export to incineration plants in neighbouring countries coupled with existing incineration plants.

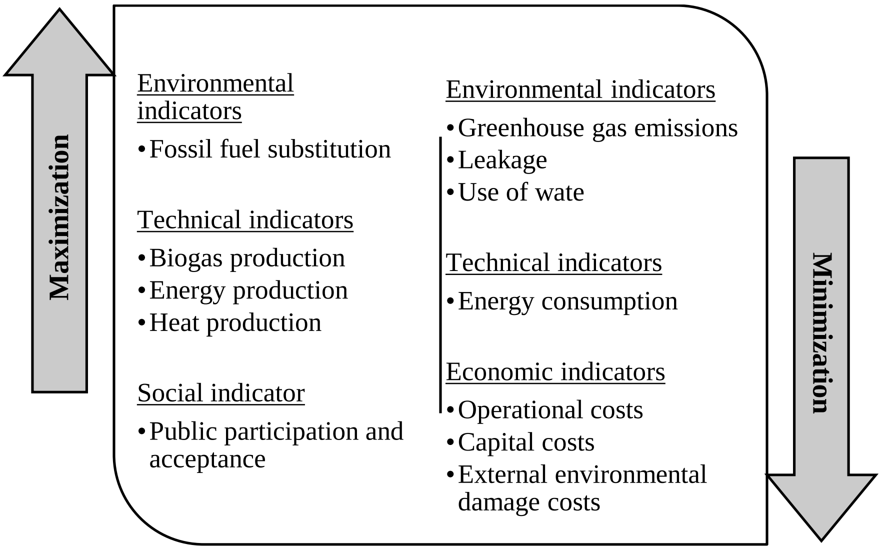

Figure 5. Cleaner production indicators in biowaste management.

Landfilling is the current practice in Latvia. Landfilling is the cheapest option and no investments are needed for this scenario. Waste landfill operators are still making loan payments. Since the income of landfills depends on the amount of landfilled waste, and the amount of landfill gas produced, landfill operators are uncertain about the introduction of biowaste treatment scenarios. At the same time, landfilling has the biggest impact on the environment (Cherubini et al., 2009, Boldrin et al., 2011), the energetic output is low (Assamoi& Lawryshyn, 2012), and the EU targets regarding landfilling cannot be achieved.

During the study, the 12 biowaste management indicators with the highest significance were selected. These indicators must be analysed during all project development stages, starting with Planning and Environmental Impact Assessment until the Implementation and Improvement of the project. An analysis of the set indicators should be done continuously. The proposed indicators can be used in the Environmental

Impact Assessment process of biowaste management projects, especially during the screening phase of the procedure. These indicators help to identify basic conditions for the introduction of principles of cleaner production in biowaste management (see Fig. 5).

Methodology for integration of cleaner production into biowaste management

MCA

Based on the results described above, a multi-criteria analysis for the definition of cleaner production principles was completed. The input data for a TOPSIS biowaste treatment alternative analysis are shown in Table 1.

Table 1. Input data for a TOPSIS biowaste treatment alternative analysis

Criterion / Altern.	Environmental dimension				Technical dimension			
	GHG emissions	Leakage	Fossil fuel substitution	Water usage	Biogas production	Energy consumption	Energy production	Heat production
A_1	0.49	0	0.63	0.14	110	20	250	250
A_2	0.49	0	0	0	0	52.5	0	0
A_3	0.7	0	0.355	0.05	75	40	145	140
A_4	0.7	0	0	0	0	20	0	0
A_5	0.36	0	1.44	0	0	142	450	1,000
A_6	0.36	0	0	0	0	142	0	0
A_7	1.47	0.145	0.22	0.052	20	2.8	23	20

Criterion / Altern.	Economical dimension			Social dimension
	Operational costs	Capital costs	External environ. damage costs	Social participation and acceptance
A_1	28.00	376	22.24	5
A_2	8.00	124.5	8.66	6
A_3	28.00	372	22.24	2
A_4	14.00	176	8.66	3
A_5	20.00	651	12.63	4
A_6	22.00	631	19.95	7
A_7	5.00	119	62.09	1

An evaluation of the biowaste management scenarios using TOPSIS was performed. The results showed that pertaining to the Latvian conditions, there are three options: separate collection and anaerobic digestion, incineration with energy recovery, and separate collection with composting (see Fig. 6).

These all share the highest rating. Therefore, selection between these options can be made based on different local factors, such as, the decision-makers preference or the amount of skills necessary for the introduction of a specific biowaste treatment practice. Landfilling is the least feasible option.

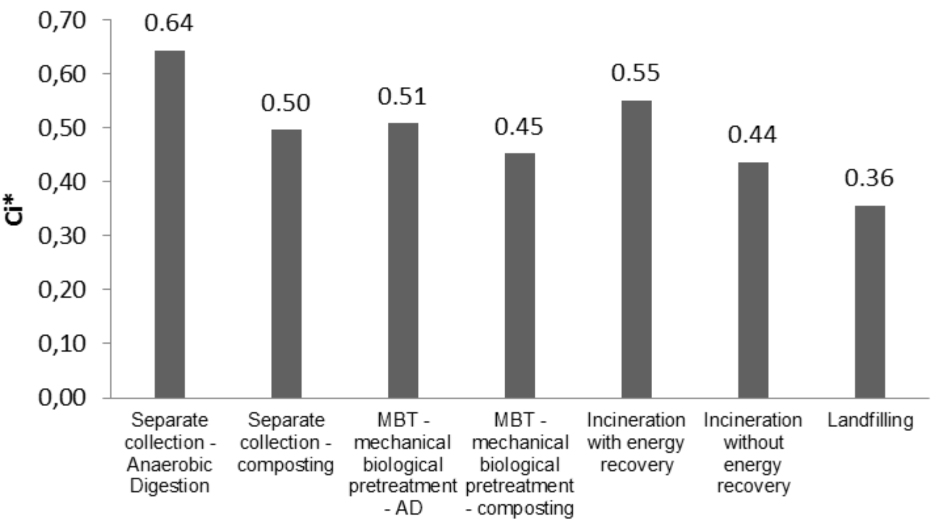

Figure 6. MCA results.

Empiric Model

During the research, the cleaner production principles achievement problem was analysed, and a multifactor empirical model was created. The main aim of the created multi-factorial empirical model was a determination of the regression equation which could then determine the reduction of GHG emissions.

A database based on the existing biowaste treatment plants was created and analysed. During the research, the above mentioned cleaner production indicators and parameters of the existing plants was processed.

During the research, data correlation, acquisition of the regression equation, and an evaluation of the adequacy of the regression equation was completed.

The completed analysis shows that the reduction of GHG emissions is determined by three statistically significant parameters:

- energy consumption;
- energy production;
- heat production.

System Dynamics

During the research SD model was created: biowaste treatment problem, hypothesis were defined, formulation and simulation of model using Powersim program was done. Model was tested on Latvian conditions.

DISCUSSIONS AND CONCLUSIONS

The problems faced by the energy sector concerning resource scarcity and energy dependency can be partly solved if biowaste is used as a resource for energy production.

EU targets for the minimization of the deposited amount of biodegradable waste and RES can be achieved if anaerobic digestion of separately collected biowaste or mechanical biological treatment of unsorted biowaste with future anaerobic digestion is introduced into waste management in Latvia. Another possibility is to export waste and the incineration of biowaste with energy recovery to Lithuania, Estonia, or Germany. The principle of cleaner production in waste management must be implemented starting from the planning and impact assessment of each biowaste management project.

Today, one of the central EU waste management issues is biowaste management. Carbon dioxide emissions causing global warming are a seemingly inevitable by-product of biowaste disposal. Threats to groundwater, as well as general environmental damage, are a result of pollution from landfilled biowaste. In this light, policy- and decision-makers are constantly facing the complex nature of this multidimensional management on which economic, technical, environmental, and social perspectives always have prominent and interconnecting roles. As a response to these challenges, different technological and legal strategies are discussed by the parties involved.

This study proposes an integrated methodological approach by having a combination of MCA, SD and CRA modelling. This approach has been applied within a case study, specifically for Latvia, proposing an effective analytical framework that allows policy- and decision-makers to compare various alternatives in order to strengthen the most promising waste management technology.

The proposed method basically acts in three main phases: the first is addressed to the identification of the optimal solution for a biowaste management strategy with the identification of selected indicators to be used within the MCA approach by using the TOPSIS method, the second based on creation of multi-factorial empirical model, the third implements a complex system analysis through SD modelling. As reported from other literature findings (Forester, 1980; Blumberga et.al., 2010) the goal of a general system dynamics study is the identification of the fundamental reason, that is the key issue, generating a specific problematic behaviour. This is a crucial point in order to find the most sensitive aspect within the system that is effectively the problematic behaviour in itself. In other words, through the second step, it would be possible to not only find the optimization of the system, which is fixed in a specific time frame, but to give the opportunity to create an optimization based on a time scale reference. The identification of leverage points is thus essential for the further definition of action (in terms of 'policies') that can improve the situation, or reveal the proper way to reach a fixed target. In the proposed case study, this is represented by the EU directive 1991/31/EC sorting target.

The proposed methodological approach applied for the case study provides a real insight into the behaviour of the biodegradable waste market in Latvia.

The proposed methodology was used to evaluate seven competing solutions for the biowaste management systems of Latvia.

The proposed approach, integrating the three methodologies, can be applied to the waste sector.

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EIROPAS SOCIĀLAIS FONDS

EIROPAS SAVIENĪBA

IEGULDĪJUMS TAVĀ NĀKOTNĒ

REFERENCES

Assamoi, B. & Lawryshyn, Y. 2012. The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. *Waste Manage* **32,** 1019–1030.

Blumberga, A., Blumberga, D., Bazbauers, G., Davidsen P., Moxnes E., Dzene, I., Barisa, A., Zogla, G., Dace, E. & Berzina, A., 2010. *Systemdinamic for Environmental Engeneering Students*. Madonas Poligrafists, Madona.

Boldrin, A., Lund Neidel, T., Damgaard, A., Bhander, G.S., Mųller, J. & Christensen, T.H. 2011. Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. *Waste Manage.* **31,** 619–630.

Bozano Gandolfi, P., Nosiglia, V. & Vitali, G. 2012. Anaerobic Digestion Of Municipal Solid Waste, Biowaste & Commercial Wastes – Examples Of: 1) Successful Revamping Of Existing Plants 2) Co-Digestion Of Biowaste And Commercial Waste With Agricultural Residues. In ETA-Florence Renewable Energies (eds): *Proceedings of the 20 EU BC&E*. ETA-Florence Renewable Energies. Milan, Italy. 1468 – 1472.

Cherubini, F., Bargigli, S. & Ulgiati, S. 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. *Energy* **34**, 2116–2123.

Department for Environment Food & Rural Affairs. 2005. *Mechanical Biological Treatment & Mechanical Heat Treatment of Municipal Solid Waste*. Crown, London, 18.

Department for Environment Food & Rural Affairs. 2013. *Mechanical Biological Treatment of Municipal Solid Waste* Crown, London, 57.

Di Maria, F., Sordi, A. & Micale, C. 2013. Experimental and life cycle assessment analysis of gas emission from mechanically–biologically pretreated waste in a landfill with energy recovery. *Waste Manage* **33,** 2557–2567.

Dovı, V.G., Friedler, F., Huisingh, D. & Klemes, J.J. 2009. Cleaner energy for sustainable future. *J Clean Prod*. **17**, 889–895.

Dubrovin, V. & Melnychuk, M. 2010. Cleaner Production of Biomass and Biofuels. *Agronomy Research*. 8(1), 33–38.

European Commission. 2010. *Assessment of the options to improve the management of bio-waste in the European Union*. European Commission. Brussels, 237.

Forrester, J.W. & Senge, P.M., 1980. Tests for building confidence in system dynamics models, in Legasto, A.A., Forrester, J.W., Lyneis, J.M. (Eds.), *System Dynamics*. North Holland, Amsterdam.

Kastner, V., Somitsch, W. & Schnitzhofer, W., 2012. The anaerobic fermentation of food waste: a comparison of two bioreactor systems. J Clean Prod. 34, 82–90.

Križan, P. Matúš, M., Šooš., Kers, J., Peetsalu, P., Kask, Ü. & Menind, A. 2011. Briquetting of municipal solid waste by different technologies in order to evaluate its quality and properties. *Agronomy Research* **9**(1), 115–123.

Monson, K.D., Esteves, S.R., Guwy, A.J. & Dinsdale, R.M. 2007. *Anaerobic Digestion of Biodegradable Municipal Wastes. A review.* University of Glamorgan, Pontypridd 366.

Müller, W. 2009: Mechanical Biological Treatment and its role in Europe. *Waste-to-Resources. III International Symposium MBT & MRF*. Hanover, Germany. pp.1–7.

Murphy, J. & Power, N.M. 2007. A Technical, Economic and Environmental Comparison of Composting and Anaerobic Digestion of Biodegradable Municipal Waste. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering* **41**(5), 865–879.

Niklass, M., Pubule, J., Henning, H., Rutz, D., Güntert, D., Surowiec, M., Ribic, B. & Schinnerl, D., 2012. *Good practice examples for the management and logistics of organic urban waste*. ZAAO, Valmiera, 26.

Nilsson, L., Persson, P.O., Rydén, L., Darozhka, S. & Zaliauskiene, A. 2007. *Cleaner Production. Technologies and Tools for Resource Efficient Production*. Baltic University press. Uppsala, 319.

Patlitzianas, K. & Karagounis, K., 2011. The progress of RES environment in the most recent member states of the EU. *Renew Energ*. **36**, 429–436.

Pubule, J., Blumberga, D., Rosa, M., Romagnoli, F. 2012. Analysis of the Environmental Impact Assessment of Power Energy Projects in Latvia. *Manage Environ Qual: Int J*. **23** (2), 190–203.

Pubule, J., Blumberga, D. & Romagnoli, F. 2013a. An Assessment of the Potential and Finding the Optimal Method of Biowaste Treatment in Latvia. In ETA-Florence Renewable Energies (eds): *Proceedings of the 21th European Biomass Conference and Exhibition*. ETA-Florence Renewable Energies. Copenhagen, Denmark. 1860–1864.

Pubule, J., Romagnoli, F. & Blumberga, D. 2013. Finding an Optimal Solution for Biowaste Management System in the Baltic States. *Conference Proceedings of the 8th Conference on Sustainable Development of Energy, Water and Environment Systems*. International Centre for Sustainable Development of Energy, Water and Environment Systems. Croatia, Dubrovnik..0213-1-0213-13.

Roos, I., Soosaar, S., Volkova, A. & Streimikene, D., 2012. Greenhouse gas emission reduction perspectives in the Baltic States in frames of EU energy and climate policy. *Renew Sust Energ Rev*. **16**, 2133–2146.

Rutz, D., Janssen, R., Ramanauskaite, R., Hoffstede, U., Hahn, H., Kulisic, B., Bosnjak, R., Kruhek, M., Ribic, B., Surowiec, T., Surowiec, M., Nogueira, M.A., Martins, A.S., Duarte, F., do Céu Albuquerque, M., Martins, M., Dzene, I., Niklass, M., Pubule, J., Schinnerl, D., Kalandyk, K. & Zapora, D. 2012. The Use of Bio-Waste for Biomethane Production in European Cities. In ETA-Florence Renewable Energies (eds): *Proceedings of the 20th European Biomass Conference and Exhibition*. ETA-Florence Renewable Energies. Milan, Italy. 1481–1490.

Siddiqui, A.A., Richards, D.J. & Powrie, W., 2013. Biodegradation and flushing of MBT wastes. *Waste Manage* **33**, 2257–2266.

Tampio, E., Ervasti, S., Paavola, T., Heaven, S., Banks, C. & Rintala, J., 2014. Anaerobic digestion of autoclaved and untreated food waste. *Waste Manage* **34**, 370–377.

Toro, J., Requena, I. & Zamorano, M. 2010. Environmental impact assessment in Colombia: Critical analysis and proposals for improvement. *Environ Impact Asses*, **30** (4), 247–261.

Walker, M., Banks, C.J. & Heaven, S., 2009. Two-stage anaerobic digestion of biodegradable municipal solid waste using a rotating drum mesh filter bioreactor and anaerobic filter. Bioresource Technol. 100, 4121–4126.

Zhang, Y., Banks, C.J. & Heaven, S., 2012. Anaerobic digestion of two biodegradable municipal waste streams. J Environ Manage. 104, 166–174.