Effects of Intentional Reduction in Moisture Content of Forest Wood Chips during Transport on Truckload Price

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Wood chip transportation is a widespread practice in Poland, with distances between forest sites and power or heating plants reaching 300 km and truck transport times of up to 6 h. Because the basic parameter affecting biomass quality for energy production is moisture content, the objective of the presented economic analysis was to determine its effect on the price of wood chips transported by semi-trailer trucks. This paper considered the possibility of drying biomass in the semi-trailer. No external energy consumption was envisioned; the heat needed for drying was obtained from the truck cooling or exhaust systems *via* heat exchangers. The moisture content of transported biomass had a dual effect on the final truckload price. While it increased biomass amount by adding to its weight, it decreased its price by lowering its calorific value. Mathematical analysis showed that a decrease in wood chip moisture content increased truckload price, justifying research on technological improvements of this process. Simulations indicated that by reducing moisture content during transportation, biomass suppliers increased their revenues approximately € 3.6 to € 30.0 per truckload, which translates into annual financial profit ranging from tens of thousands of euros (EUR) to more than € 23,810.

Keywords: Calorific value; Forest biomass; Moisture content; Transport; Wood chips

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INTRODUCTION

Biomass is the most important source of renewable energy (RES) (Gerasimov *et al*. 2013), accounting for 10.3% of the world's energy production according to the International Energy Agency (IEA 2017). In addition, biomass-based energy production promotes the energy independence of European Union (EU) countries. According to Sasaki *et al.* (2011), in Japan nuclear power plants could be replaced with biomass-based solutions. In turn, Grilli *et al.* (2015) claim that the bioenergy sector and its sustainability are critical to protected areas (*e.g.*, national and landscape parks), not only to attain EU renewable energy goals, but also satisfy maintenance requirements of the conserved areas.

Whether used for combustion in local or industrial plants or for processing into more advanced fuels, biomass must be appropriately prepared, usually by comminution or reduction of moisture content to less than 15% (Alakangas 2005; Alakangas *et al.* 2016).

In the case of obtaining wood chips from forest areas (Jodłowski 2003; Gendek and Nurek 2012; Picchio *et al.* 2012; Moskalik 2013; Belbo and Talbot 2014), forest residues are usually seasoned in the open air for several months (Thörnqvist 1985), during which time they naturally lose excessive moisture. The initial moisture content of wood chips produced in forest areas and transported to energy plants ranges from approximately 30% (Gendek *et al.* 2016) to approximately 55% to 62% (Talbot and Suadicani 2006; Gendek and Zychowicz 2015), which directly influences their calorific value. For fresh wood chips (50% to 60% moisture content), calorific value amounts to 6 GJ/Mg to 8 GJ/Mg, while for air-dry wood chips (10% to 20%) it increases to 14 GJ/Mg to 16 GJ/Mg, to reach approximately 19 GJ/Mg upon complete drying (Hałuzio and Musiał 2004; Gendek and Głowacki 2008; Gendek and Zychowicz 2014; Lieskovský *et al.* 2017). These figures are comparable to previous literature data for the calorific value of timber and biomass (Borowski 2007; Kent *et al.* 2009; Günther *et al.* 2012; Gejdoš *et al.* 2015).

High moisture content of wood chips has an adverse effect on their storage (Jirjis 1995) and is detrimental to suppliers who are paid for the calorific value of the fuel they provide. Fresh wood chips require additional costly drying treatments to obtain optimum moisture content (Gendek and Głowacki 2009; Głowacki and Gendek 2011).

An important element in the forest wood chip production and supply chain is the preparation of fuel for the needs of energy plants. In addition to moisture content and calorific value, other considerations include wood chip grade pursuant to the standard ISO 17225-4 (2014). In the literature, there is a substantial body of studies concerning particle size distribution for comminuted plant material (Lisowski *et al.* 2014, 2016, 2017; Hickman *et al.* 2016), including forest wood chips (Birta *et al.* 2008; Spinelli *et al.* 2011; Gendek and Nawrocka 2014). The size of wood chips may affect their arrangement and the filling of voids, and together with moisture content, it influences truckload weight. It should be remembered that forest roads with dirt or gravel surfaces have a limited load capacity and are not suitable for vehicles carrying heavy payloads (Trzciński *et al.* 2013).

In Poland, the transport of biomass in the form of wood chips is a widespread practice (Moskalik *et al.* 2016). According to previous findings (Zychowicz and Gendek 2015; Gendek and Nurek 2016), transport distances may reach 300 km, possibly undermining the profitability of wood chip combustion for energy purposes. For comparison, according to Talbot and Suadicani (2006) in Denmark, the average transport distance is 40 km to 50 km. It should be noted that the transport of chips to such distances is often done using trains. An exemplary analysis of the profitability of rail transport of chips was performed by Wolfsmayr *et al.* (2015). Under the circumstances, it is important to analyze the factors influencing the price of biomass supplied to energy plants and to identify ways to improve the economic effectiveness of its delivery. How much energy plants pay for biomass depends on the amount of energy that can be recovered. The weight and volume of biomass are of lesser importance; they are taken into consideration only in preliminary calculations before the actual moisture content and calorific value can be determined. In the final calculation, the amount of biomass is converted into the amount of energy it contains, which is multiplied by price per unit of energy (€/GJ).

The choice of calorific value as a determinant of price is justified not only from the point of view of energy plants, but also for objective reasons. As mentioned, the amount of energy that can be recovered from biomass takes precedence over its weight or volume; otherwise suppliers might attempt to manipulate the payloads to artificially inflate the amount of wood chips provided.

In this situation, suppliers are interested in delivering the greatest amount of energy (GJ) contained in the wood chips, which depends on two parameters: weight of biomass truckload (Mg) and calorific value of biomass, which depends on its moisture content (GJ/Mg).

A preliminary analysis of the two parameters specified above shows that their effects on the financial results are contradictory. In contrast, higher moisture content may be deemed beneficial because, within the constraints of the constant volume of a semi-trailer, it leads to higher weight, and hence, a higher price for the payload. Alternatively, increased moisture content decreases the calorific value of the wood chips. Therefore, the question arises as to how wood chip suppliers could optimize profitability.

According to literature reports on the thermal balance of diesel engines (Ajav *et al*. 2000; Jadhao and Thombare 2013; Singh *et al.* 2015), only approx. 30% of the fuel energy is converted into useful energy, with approx. 20% lost through the exhaust system, and 30 to 40% through cooling and direct release of heat to the environment. In their papers on internal combustion engines, Dolz *et al.* (2012) and Wang *et al.* (2011) studied the possibilities of recovering heat expelled in exhaust gases and otherwise lost to the environment. However, a major problem observed by Dolz *et al.* (2012) was the low temperature of the available energy sources. Heat recovery systems were also described in US patents (Isoda *et al.* 1998; Hara 2003). Another solution was developed by Di Battista *et al.* (2015), who investigated the recovery of thermal energy in light duty vehicles. In that case, efforts to recover energy from exhaust gases led to slightly increased fuel consumption (by 2 to 5%).

The present paper considers the possibility of drying biomass in the semi-trailer. Taking into consideration the fact that the average biomass transport distance is 300 km (Zychowicz and Gendek 2015; Gendek and Nurek 2016), and assuming a mean truck speed of 60 km/h to 70 km/h, travel time during which biomass moisture content may be reduced, amounts to approximately 5 h. No external energy consumption is envisioned; the heat needed for drying could be obtained from the truck cooling or exhaust systems *via* heat exchangers (similar solutions are known from construction vehicles).

METHODOLOGY

The price of biomass delivered to energy plants can be calculated from Eq. 1,

$$C_{\mathrm{TL}} = m_{\mathrm{R}} \cdot \mathrm{CV_u} \cdot P_{\mathrm{u}} \tag{1}$$

where C_{TL} is the truckload price, or the payment received by the supplier for the biomass (€), m_{R} is the weight of biomass delivered to the buyer's facility (truckload "at the gate") (Mg), CV_{u} is the biomass calorific value (GJ/Mg), and P_{u} is the unit price of energy (€/GJ).

The authors' research aims to determine the technical possibilities and economic efficiency of biomass drying during transport (without supplying external energy). Thus, one should evaluate the change in wood chip moisture content that occurs between the point of wood chip production and the point of delivery, as well as assess the effects of that change on the other parameters.

Effects of changes in moisture content on truckload weight

The relationship between truckload weight and moisture content may be obtained from a transformation of Eq. 2, describing moisture content in a truckload of wood chips,

$$M_{\mathrm{LR}} = \left(\frac{m_{\mathrm{R}} - m_{\mathrm{D}}}{m_{\mathrm{R}}}\right) \cdot 100 \tag{2}$$

where M_{LR} is the moisture content of biomass delivered to the buyer's facility (%), m_{R} is the truckload weight at the buyer's facility ("at the gate") (Mg), and m_{D} is the dry biomass weight (Mg). At the same time,

$$M_{\mathrm{LF}} = \left(\frac{m_{\mathrm{F}} - m_{\mathrm{D}}}{m_{\mathrm{F}}}\right) \cdot 100 \quad (3)$$

where M_{LF} is the biomass moisture content "in the forest" (%) and m_{F} is the truckload weight "in the forest" (Mg).

A juxtaposition of the relationships obtained from both formulas leads to Eq. 4,

$$m_{\mathrm{F}} \cdot \left(1 - \frac{M_{\mathrm{LF}}}{100}\right) = m_{R} \cdot \left(1 - \frac{M_{\mathrm{LR}}}{100}\right) \quad (4)$$

As a result, the weight of biomass delivered to the buyer's facility may be determined from Eq. 5,

$$m_{R} = \frac{m_{\mathrm{F}} \cdot \left(1 - \frac{M_{\mathrm{LF}}}{100}\right)}{\left(1 - \frac{M_{\mathrm{LR}}}{100}\right)} \quad (5)$$

or, defining the biomass drying ratio α as,

$$\propto = \frac{(1 - M_{\mathrm{LF}}/100)}{(1 - M_{\mathrm{LR}}/100)} \quad (6)$$

and the weight of biomass truckload may be obtained from Eq. 7:

$$m_{\mathrm{R}} = m_{\mathrm{F}} \cdot \propto \quad (7)$$

As shown in Eq. 1, truckload price is also dependent on the calorific value of wood chips, which is in turn directly related to their moisture content. Gendek and Nurek (2016) described payment schemes offered by energy plants to biomass suppliers taking into account those parameters.

Real data on biomass deliveries to energy plants was used to determine a function describing the relationship between the calorific value and moisture content of wood chips (Gendek and Nurek 2016), which is presented in Eq. 8:

$$CV_{\mathrm{u}} = -0.2098 \cdot M_{\mathrm{LR}} + 18.5328 \quad (8)$$

Given Eqs. 7 and 8, the final price of the biomass delivered to the buyer CV_{u} is expressed by the following Eq. 9:

$$CV_{\mathrm{u}} = m_{\mathrm{F}} \cdot \propto \cdot \left(-0.2098 \cdot M_{\mathrm{LR}} + 18.5328\right) \cdot P_{\mathrm{u}} \quad (9)$$

Because the objective of the current analysis involves determination of changes in the price of wood chips during transport (as a result of reduced moisture content), it is necessary to take into account the initial biomass weight at the point of truck loading at the supplier's end. In this approach, it is possible to perform calculations in which the dry weight of biomass is the same in both locations: at the supplier's end (with initial moisture content) and at the buyer's end (with final moisture content). Previous research has shown that the mean weight of one truckload of wood chips is 22 Mg (Gendek and Nurek 2016). Taking into account loss of moisture, it was assumed in this study that the initial truckload weight (m_{F}) was 24 Mg. This assumption enables comparison of the price of forest wood chips with different initial moisture content.

Given the considerable amount of waste heat produced by internal combustion engines and the benefits derived from decreasing the moisture content of biomass for energy purposes, the objective of the present study was to assess the possibility of using that waste heat for the drying of transported biomass as well as to evaluate the profitability of such a system, taking into account the cost of constructing a heat recovery system and equipping the semi-trailer with a drying air distribution system (*e.g.*, a perforated double floor). Preliminary analysis of literature data shows that it would be more beneficial to utilize the hot dry air from the engine compartment of the vehicle, which can be immediately directed to the semi-trailer carrying biomass. Solutions involving exhaust heat recovery require the application of heat exchangers to eliminate the risk of fire and to prevent biomass contamination with the noxious substances contained in the fumes.

RESULTS AND DISCUSSION

This study was conducted in the north-eastern part of Poland. Based on data obtained from a supplier who delivered forest wood chips to a cogeneration power plant 485 days during the years 2013 to 2017, the mean daily amount of wood chips delivered was determined at 350 Mg/day (approximately 15 truckloads), ranging from 22 Mg (one truckload) to 1056 Mg (approximately 55 truckloads). The wood chips were transported by semi-trailer trucks with 91 m^3 trailer capacity. The mean moisture content of forest wood chips delivered to the power plant is presented in Fig. 1.

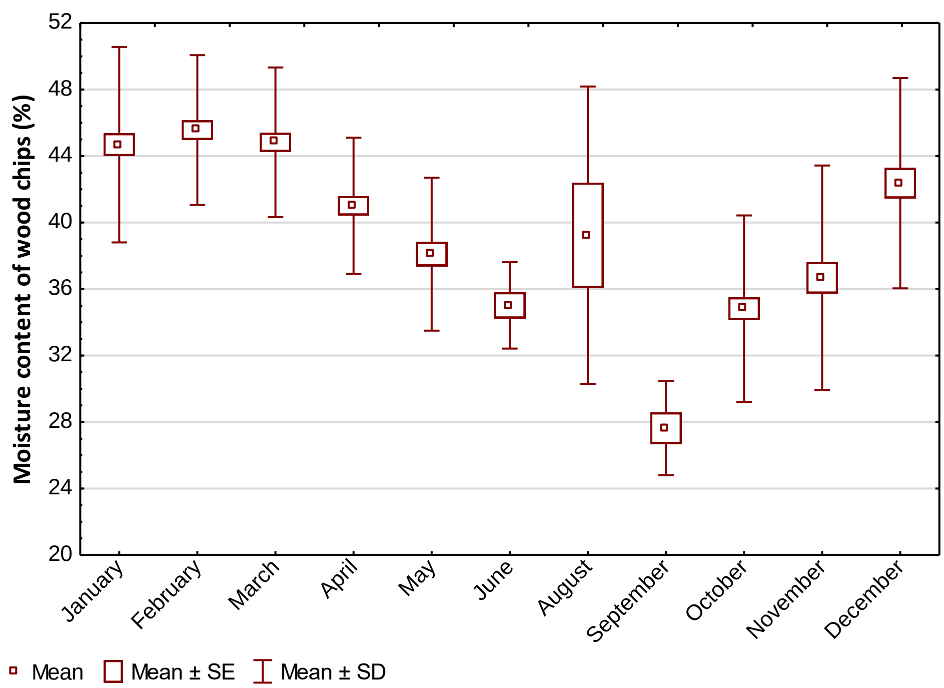

Fig. 1. Mean moisture content by month of forest wood chips delivered to the power plant

The moisture content of wood chips varied noticeably with the month of delivery, with the highest moisture found in the wintertime (42% to 46%) and the lowest was in September (approximately 28%). Due to the planned maintenance work at the cogeneration power plant, no wood chips were delivered in July, when the supplier cleaned the forest areas and comminuted the residues, with the wood chips being transported to storage areas. Because stacked wood chips have a propensity for self-heating and moisture absorption, the truckloads of previously stacked biomass delivered in August were characterized by high moisture content (approximately 39%). The mean annual moisture content of wood chips delivered to the power plant was 40.8% (± 6.9%).

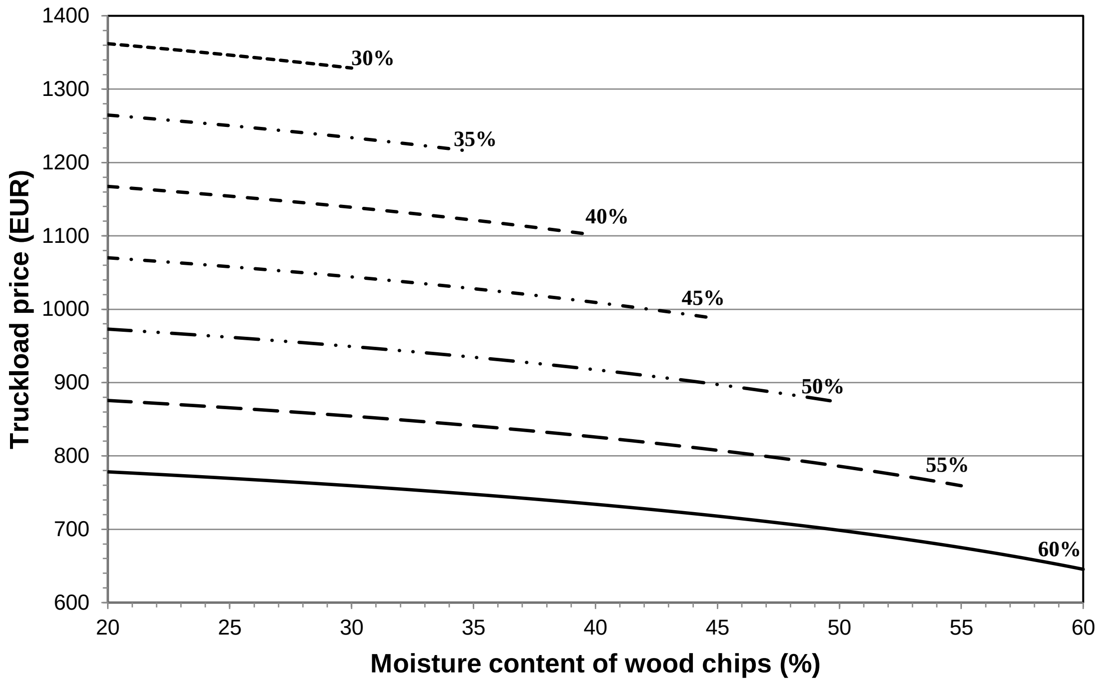

Fig. 2. Effect of moisture content (M_{LR}) of wood chips on truckload price (C_{TL}) at the energy plant (for different initial moisture contents)

Changes in wood chip price depending on moisture content are given in Fig. 2, according to Eq. 9. Assuming that truckloads have a constant initial weight of m_F = 24 Mg (Gendek *et al.* 2016), and the unit price of energy was P_u = 4.58 €/GJ (based on delivery documents from December 31, 2015), the curve showed an increase in truckload price with decreasing moisture content (30% to 60%) for different initial moisture content levels.

Table 1 presents the supplier's revenue per truckload depending on the initial moisture content (in the forest area) and the final moisture content upon delivery to the energy plant. Due to the fact that in practice moisture content may decline approximately 7%, the area of increased revenue was highlighted. For a slight decline in moisture content (approximately 1%), the supplier's financial gain per truckload amounted to € 3.6 to € 4.8, while for a reduction of 7%, the gain would be € 23.8 to € 30.0.

Taking into account the mean moisture content of wood chips in each month, and assuming that a reduction in that parameter would be greater for higher initial moisture, Fig. 3 illustrates the supplier's mean financial profit per truckload in the various months. Simulations showed that the mean gain per truckload could amount to approximately € 9.5 (September) to approximately € 28.6 (January and February).

More importantly, better effects could be obtained when drying transported wood chips with higher moisture content, because according to the dynamics of drying, the process takes place at a higher rate in the initial phase, due to removal of free water. This has been confirmed in a study of forest wood chip drying conducted by Gendek and Głowacki (2009), who reported that a 40 °C airflow decreased wood chip moisture content from approximately 40% to approximately 23% after 100 min. In this study, under natural conditions, it was difficult to obtain such a result for technical reasons, and so it was assumed that the moisture content of wood chips during transport may be reduced 4% to 7%. Therefore, analysis was limited to the range from an initial moisture content of M_{LF} = 45% to a final moisture content of M_{LR} = 20%.

Table 1. Supplier's Financial Profit (EUR) Per Wood Chip Truckload (24 Mg) Delivered to the Power Plant Depending on Initial and Final Moisture Content

	Initial moisture content – In the forest (%)																
Final moisture content – At buyer´s facility (%)	**45**	**44**	**43**	**42**	**41**	**40**	**39**	**38**	**37**	**36**	**35**	**34**	**33**	**32**	**31**	**30**	**29**
20	83.0	79.7	76.4	73.1	69.7	66.4	63.1	59.8	56.5	53.1	49.8	46.5	43.2	39.9	36.5	33.2	29.9
21	80.7	77.4	74.0	70.6	67.3	63.9	60.5	57.2	53.8	50.4	47.1	43.7	40.4	37.0	33.6	30.3	26.9
22	78.3	74.9	71.5	68.1	64.7	61.3	57.9	54.5	51.1	47.7	44.3	40.9	37.5	34.1	30.7	27.3	23.8
23	75.9	72.5	69.0	65.6	62.1	58.7	55.2	51.8	48.3	44.9	41.4	38.0	34.5	31.1	27.6	24.2	20.7
24	73.4	69.9	66.4	62.9	59.4	55.9	52.4	48.9	45.4	42.0	38.5	35.0	31.5	28.0	24.5	21.0	17.5
25	70.9	67.3	63.8	60.2	56.7	53.1	49.6	46.1	42.5	39.0	35.4	31.9	28.3	24.8	21.3	17.7	14.2
26	68.2	64.6	61.0	57.4	53.9	50.3	46.7	43.1	39.5	35.9	32.3	28.7	25.1	21.5	18.0	14.4	10.8
27	65.5	61.9	58.2	54.6	51.0	47.3	43.7	40.0	36.4	32.8	29.1	25.5	21.8	18.2	14.6	10.9	7.3
28	62.7	59.0	55.4	51.7	48.0	44.3	40.6	36.9	33.2	29.5	25.8	22.1	18.5	14.8	11.1	7.4	3.7
29	59.9	56.1	52.4	48.6	44.9	41.2	37.4	33.7	29.9	26.2	22.5	18.7	15.0	11.2	7.5	3.7	
30	56.9	53.1	49.3	45.5	41.8	38.0	34.2	30.4	26.6	22.8	19.0	15.2	11.4	7.6	3.8		
31	53.9	50.1	46.2	42.4	38.5	34.7	30.8	27.0	23.1	19.3	15.4	11.6	7.7	3.9			
32	50.8	46.9	43.0	39.1	35.2	31.3	27.4	23.4	19.5	15.6	11.7	7.8	3.9				
33	47.6	43.6	39.7	35.7	31.7	27.8	23.8	19.8	15.9	11.9	7.9	4.0					
34	44.3	40.3	36.2	32.2	28.2	24.2	20.1	16.1	12.1	8.1	4.0						
35	40.9	36.8	32.7	28.6	24.5	20.4	16.4	12.3	8.2	4.1							
36	37.4	33.2	29.1	24.9	20.8	16.6	12.5	8.3	4.2								
37	33.7	29.5	25.3	21.1	16.9	12.7	8.4	4.2									
38	30.0	25.7	21.4	17.1	12.9	8.6	4.3										
39	26.1	21.8	17.4	13.1	8.7	4.4											
40	22.1	17.7	13.3	8.9	4.4												
41	18.0	13.5	9.0	4.5													
42	13.7	9.2	4.6														
43	9.3	4.7															
44	4.7																

As shown in Fig. 2, a lower final moisture content of wood chips resulted in a greater truckload price and larger revenue for the supplier. Therefore, this analysis justifies the need to seek technological solutions that would decrease the truckload moisture content during transport.

If the mean moisture content of wood chips made from forest residues amounts to approximately 40%, as is the case in this paper (Fig. 1), then the supplier will be paid € 1,100 per truckload. A 4% to 7% decline in moisture content increases the truckload price to € 1,121 and € 1,136, respectively.

While these amounts do not seem to be high per truckload, one should consider this issue in the long term. As previously mentioned, the supplier delivers approximately 350 Mg of wood chips per day, which is equivalent to approximately 15 truckloads. Therefore, the supplier's daily profit due to reduced moisture content of wood chips during transport will be from € 53.6 to approximately € 450.0 or more, which could translate into tens of thousands of EUR annually.

The presented economic analysis of wood chip drying during transport is encouraging, indicating the need to investigate the technical possibilities of reducing biomass moisture content in the semi-trailer without supplying additional external energy.

In addition, the research team is working on a solution employing the waste heat generated by the internal combustion engine of the vehicle. One option involves the direct use of the warm air from the engine compartment (Fig. 3a), while in another option drying air is heated up by the exhaust gases (Fig. 3b). In the second solution, it is necessary to prevent two risks: accidental ignition of the transported biomass and its contamination with harmful particles from the fumes, which entails the installation of a heat exchanger so that the wood chips would not be directly exposed to exhaust gases. In that option, heated atmospheric air would be pumped into the semi-trailer through a special perforated double floor. The drying air would also pass through a control system limiting its temperature to approx. 40 to 50°C.

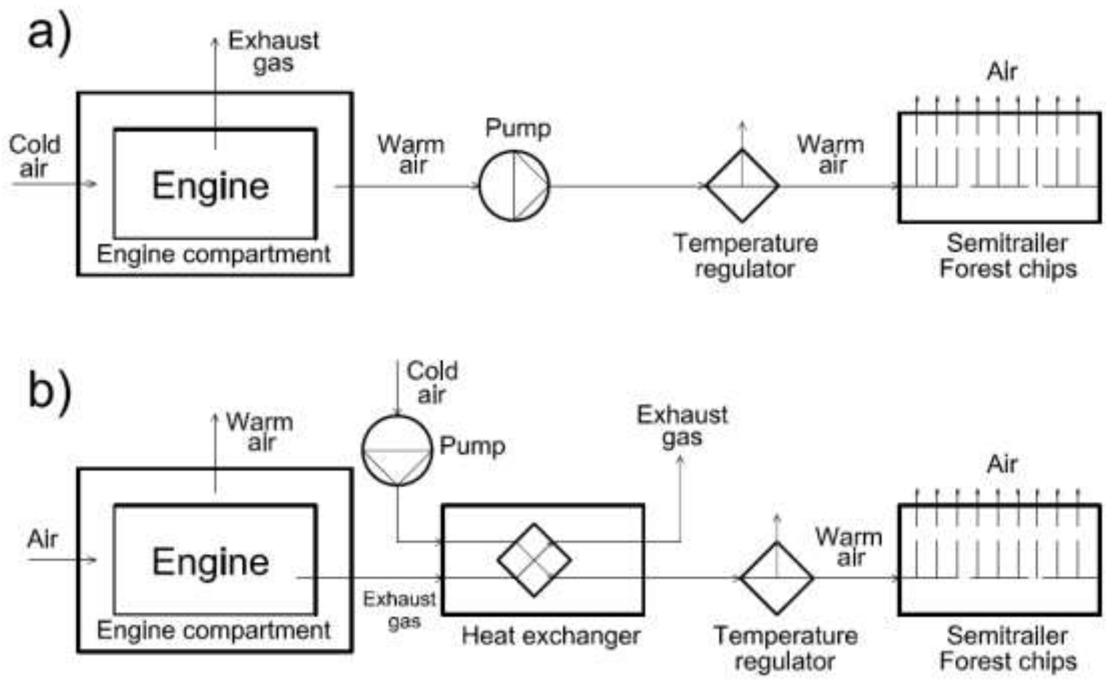

Fig. 3. General concept of utilizing waste heat for reducing the moisture content of forest wood chips: a) by recovery of heat from the engine compartment, and b) by recovery of exhaust heat using a heat exchanger

The considered transport time is too short for the spontaneous ignition of biomass, as it takes approx. 10 days for the temperature of a bed of wood chips to rise from approx. 12 °C to approx. 70 °C as a result of bacterial activity (Gierasimczuk 2009). In turn, an excessive increase in temperature caused by drying air can be prevented by the application of a temperature controller. Indeed, the blowing of warm air through a bed of wood chips would slow down microbial activity and dissipate excess moisture and heat.

In the presented concept, the tractor-trailer unit is modified by equipping the semi-trailer with a perforated double floor and by constructing a system for recovering warm air from the engine compartment, or alternatively, a heat exchange system for exhaust gases (Fig. 3). A preliminary cost analysis in the Polish market estimated the overall expenditure at approx. € 7500. The proposed heat recovery system does not cause a significant decline in engine power or increase in fuel consumption. In the case of waste heat recovery from the engine compartment, the cost of modification would amount to approx. € 4500. Given these assumptions, the investment would pay off, depending on the initial and final moisture content, after 260 to 790 truck trips in the case of an exhaust heat recovery system and after 150 to 470 trips in the case of an engine compartment heat recovery system, which corresponds to less than two years.

The phenomena analyzed in this article are used in the storage and transport of various products. In literature, references were found to similar solutions used to reduce the moisture of peanuts (Blankenship and Chew 1979). This process takes place on trailers; however, not during transport but during stops. Air heaters are used to feed hot air into the channels under the perforated floor of the semi-trailer (Lewis *et al.* 2017). Because of easy handling and relatively low investment costs, stationary drying containers are commonly used for chip drying in Germany. The moisture level of wood chips is reduced from approximately 50% down to approximately 10% within 3 days in the summer time, while output may decrease 50% in the wintertime when the ambient temperature reaches values below freezing (Walkiewicz *et al.* 2014). In the described case of the transport of wood chips, it was assumed that biomass drying took place during transport. As shown from the research discussed in the article, such a solution could bring benefits of increasing the value of transported cargo. Drying takes place during transport and the heat used comes from the vehicle, so the need for infrastructure (buildings, blowers, or heaters) in the storage area of wood chips is eliminated. Subsequent scientific studies will be devoted to the analysis of the possibility of heating the drying medium (air), for example by using heat taken from the exhaust system.

CONCLUSIONS

1. The moisture content of transported biomass had a dual effect on the final truckload price. While it increased the biomass amount by adding to its weight, it decreased its price by lowering its calorific value.
2. Mathematical analysis of both effects showed that despite weight loss, a decline in moisture content had a beneficial overall effect on the final truckload price.
3. A reduction in biomass moisture content from 45% to 25% could increase truckload price approximately € 65.5 (approximately 7%) given the initial truckload weight of 24 Mg and a unit energy price of 4.5 €/GJ.
4. One should take a long-term view on moisture reduction in wood chips during transport from forest areas to energy plants. While financial gains per truckload are not high (€ 3.6 to € 30.0), they may translate into tens of thousands of euros even more than € 23,810 over a year’s period.

5. Economic analysis results for wood chip drying during transport are promising and further study is needed to explore the technological possibilities of reducing biomass moisture in semi-trailers by recovering the waste energy generated by the truck engine.

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Article submitted: February 25, 2018; Peer review completed: April 9, 2018; Revised version received: April 21, 2018; Accepted: April 22, 2018; Published: April 26, 2018.
DOI: 10.15376/biores.13.2.4310-4322