Pure Energy Ratio of logging residua processing

Radomir Klvac
Faculty of Forestry and Wood Technology
Department of Forest and Forest Products Technology
Mendel University in Brno
Zemedelska 3, 613 00 Brno, Czech Republic
e-mail: klvac@mendelu.cz

Abstract:

This paper aims to determine the energy balance and efficiency of energy forest biomass production for different variations of technological chains. The assessment of logging technologies and wood raw material processing impact to environment comes from Energy Audit. The energy balance and efficiency assessment determination result from different technological procedures in energy biomass acquisition. Pure Energy Ratio (PER) of forest logging residues production and transfer is about 8 to 12 according to the specific technological chain. In combination with the final efficiency of the energy source combustion the PER value is significantly reduced. The lowest PER is achieved in large scale condensation power stations with the low co-firing (wood and coal) efficiency.

Keywords: slash, chipper, bundler, hauling, transport, biomass

1 Introduction

One of current key goals of the European Union (EU) is a requirement to reduce greenhouse gas emissions, which essentially affect the climate. As an EU member country, the Czech Republic pledged to cooperate in increasing the share of renewable energy sources (20/20/20), i.e. to reach a minimum proportion of renewable sources of primary energies in the European Union at 20% in 2020. Individual EU member countries committed to contribute to the total EU balance by different shares according to their actual conditions and possibilities. The government of the Czech Republic approved a 13% proportion of energy from renewable sources in 2020.

Pressure on using technologies in line with the principles of sustainable management has been increasing in not only the forest and wood sector, which brings various methods for the assessment of the impact of technologies on the environment at various levels of precision and with a different focus. One of methods to assess the effect of technology, product or service on the environment is Life Cycle Assessment (LCA method – ISO 14040-2), which constitutes a foundation for the evaluation based on the energy audit dwelling on the principle of establishing the amount of energy related to the assessed technology, product or service. This energy amount is free from the influence of economic (subsidies, currency strategies etc.), national and international policies and the results of such an assessment are therefore fully comparable. The comparison of possible technological processes of production is made by using unit energy (energy amount consumed per unit of production).

Advantageous in the assessment of energy source is to use the pure energy ratio, which is the ratio of acquired energy and consumed energy (invested into energy yield). Logging residues that are processed by various technological chains of different efficiency in terms of energy consumption for processing have become an important market commodity and a very frequently quoted renewable energy source. This is why the paper deals with the establishment of the pure energy ratio by using the technology of processing the logging residues for energy. By no means has it ambitions, however, to represent a single and versatile procedure in the selection of technologies appropriate for the processing of logging residues for energy purposes. Results obtained from the research should serve as one of criteria in the multiple criteria decision making for the selection of suitable technology.

The commercial use of Czech forests is considerably high at the present. Basic principles are sustainable forest management, nature conservation and environment protection. The current and future objective of forest experts is to identify the "safe" potential of forest biomass because its sources are not without limitations and the dynamic balance of natural ecosystems changed by man does not eliminate a risk of the negative deviation by possible ill-considered interventions.

Thinking about the timber use for fuel, we have to be aware of available dendromass sources and from where these can be obtained. Main sources are apparently the forest and the wood-processing industry. Logging residues of the character of small wood or to a lesser extent logging residues of the character of merchantable timber affected by rots represent biomass energy sources from the main felling. Forest biomass from tending operations is not much used because the cost of skidding small and scattered volumes is high. The Forest Management Institute in Brandýs nad Labem developed a methodology for the quantification of forest energy sources. Based on their identification, the utilizable logging residues amount to 317 thousand tons of total 511 thousand tons of dry matter these representing only the sources in which no risk exists of impairing the environment (Nikl et al., 2009).

The processing of logging residues involves a number of procedures such as timber felling, chipping or crushing and haulage. The processing itself involves various processing technologies and various machines. It is impossible to define which of the processing procedures is most suitable. A possible way to assess advantages of the processing procedure may be to establish the pure energy ratio. Terms "energy balance" or "energy ratio" are used to characterize relations between the energy input and output. Energy balance is a difference between the energy output and input. Energy ratio is a ratio between the energy output and energy input. (http://www.engineeringtoolbox.com/energy-ratio-d_1358.html)

$$dE = Eo - Ei \qquad (1)$$

$$ER = Eo / Ei \qquad (2)$$

where

dE - energy balance

Eo - energy output

Ei - energy input

ER - energy ratio

Studies published on the processing of logging residues were focused on some representatives of technologies for biomass processing in the Czech Republic. Klvač et al. (2009), Liška et al. (2009) and Liška et al. (2010) presented works assessing the John Deere 1490D slash bundler and the JENZ HEM 420 D chipper. Jiroušek et al. (2010) published some partial data on the large Peterson 2400A chipper.

A comparison of the individual technologies is still missing though. Therefore, the paper aims at comparing the efficiency of processing the logging residues by using different technologies where the efficiency of these technologies can be expressed by the pure energy ratio.

2 Material and Methods

For calculating the pure energy ratio, it is first necessary to identify energy intensiveness of the procedure of logging residues processing. Klvač et al. (2003) claim that most energy intensive in fully mechanized technologies is the operational phase with approx. 80% of used energy. In order to simplify the pure energy ratio calculation, we therefore identified the energy intensiveness only for the operational phase of individual elements in the processing chain. The resulting value was multiplied by the coefficient of 1.2 and thus we received the energy intensiveness of all phases of the life cycle for the machines and equipments.

The methodology used for calculating the energy intensiveness of the operational phase was that of Klvač et al. (2003), based on the establishment of the consumption of working fluids (consumption of fuels, hydraulic oils, motor oils, transmission oils, oils to lubricate chains and other lubricants). The methodology also includes the determination of energies consumed for the manufacture of working fluids and energy contained in them (Tab. 1 and Tab. 2). No less important is to determine the machine productivity and some other characteristics needed to express in numbers the energy consumed per unit of production.

Table 1: Energy consumed to produce oils and energy contained in the oils (MJ.l^{-1}) (Våg et al., 2000)

Oil	Energy content	Energy consumption for production	Total
Mineral	38.5	45	83.5
Vegetable	36.1	12	48.1
Synthetic	36.1	22	58.1

Table 2: Energy consumed to produce fuels and energy contained in the fuels (MJ.l^{-1}) (Grägg, 1994, Altin et al., 2001, McDonnell, 1996)

Fuel	Energy content	Energy consumption for production	Total
Diesel	36.14	4.5	40.64
RME	33.1	15.6	48.70
Mixture 25 % RME and 75 % Diesel	35.64	7.07	42.74

RME – Rapeseed methyl esters

The energy audit of the operational phase is carried out as a sum of energy contained in fuels and energy required for their manufacture, and of energy contained in oils or lubricants and energy required for the manufacture of the working fluids.

Core procedures of processing the logging residues from planned main felling operations in the Czech Republic (Fig. 1) were identified and characterized for the purposes of comparison as follows:

Cutting of "merchantable timber" by power saw. Logging residues are dispersed and have to be concentrated by slash rakes; bundling, extraction of bundles, haulage of bundles to customers, crushing of bundles at the customer's.

Cutting of "merchantable timber" by power saw. Logging residues are dispersed and have to be concentrated by slash rakes, extracted by forwarders, with some logging residues left to dry at the roadside, chipping, haulage of chips.

Cutting of "merchantable timber" by power saw in the thinning operations, skidding of small wood (plus merchantable timber if economically inefficient) by animals or tractor, with some logging residues left to dry out at the roadside, chipping, haulage of chips.

Cutting of "merchantable timber" by harvester. Logging residues are concentrated in strips or piles, extracted by forwarder, left to dry out at the roadside, chipped and hauled.

Cutting of “merchantable timber” by harvester. Logging residues are concentrated in strips or piles, bundled, bundles extracted, hauled to customers and the bundles are crushed at the customer’s.

Based on the analyses of the individual junction points of the technology chain, energy intensiveness of these junction points was calculated and at all times converted per 1 ton DM so that individual chains in which different volume and weight units were used could be compared. The last step was the calculation of the pure energy ratio.

3 Results

3.1 The calculation of horse

The energy audit in horses slightly differs from the methodology originally developed for machines because their nature is different (living organisms). On the other hand, fossil energy sources are necessary for work with the horse as well, the energy being consumed to prepare fodder, to manufacture harness, horseshoes or other equipment used for skidding timber. Daily consumption was calculated separately for days of horse work and separately for days of horse rest. In practice there are usually two animals kept for the work, which take turns. Therefore, one horse was calculated with 150 working days and 215 rest days. The total consumption of energies was converted to a working hour with estimated 1000 of horse working hours per year. Energy consumed for the "manufacture" of the horse was calculated as a cumulative consumption of fodder in the period of three years, which was subsequently broken down to 10000 hours of horse life. Energy consumed for the harness (320 MJ) was spread to 5000 hours of harness service life and energy contained in horseshoes (4 kg by 30 $MJ.kg^{-1}$) was distributed to 500 hours of service life. The calculation did not include any energy related to stabling because the horses are in many cases kept in paddocks or in very simple shelters. Based on the above facts, total energy consumption in horses amounts to 13.7 $MJ.hour^{-1}$ (Magagnotti and Spinelli, 2011). The mentioned calculation was made for choker timber skidding. If other equipments are used such as hauling horse trailers, the resulting balance is considerably affected by the operation of those equipments, primarily in the field of indirect energies though. The most frequently occurring variant of using a horse for choker skidding is in the thinning of stands aged up to 40 years where wood is considered "non-economic" and its turn into cash on markets with roundwood or fibre assortments would not be worthwhile. The method is in general new in processing the wood raw material and the achieved productivity (ca $1m^3$) has not been verified yet by a sufficient number of studies and should be therefore considered of preliminary information character.

3.2 The calculation of tractor

To calculate the energy use of tractors, we made use of one-year measurements conducted on the machine Model Zetor Forterra 8641 (Klvač et al., in press). The machine was used as a representative sample because it ranks with the medium performance class of tractors (engine output 60 kW). The machine was relatively new and used for heavy-duty work in harsh conditions. It is necessary to point out once again that skidding for fuel timber was conducted only by chokers in stands containing the "non-economic" timber with the machine being operated only in stands in which its efficiency could reach an adequate level. On the other hand, it is true that the technology was a pioneering one once again and there is not enough data to confirm its rating. The calculated values should be therefore considered of informative value only. Moreover, complementary technical equipment such as towed trailers may significantly affect the productivity.

Energy balance was calculated from the following values:

Fuel consumption: 1 – 1.2 $l.m^{-3}$

Transmission oil consumption: 6.7 $l.1000\ m^{-3}$

Motor oil consumption: 6.7 $l.1000\ m^{-3}$

Consumption of lubricants: 1.7 $kg.1000\ m^{-3}$

Lubrication spray: 1 *l*.1000 m^{-3}

The total energy consumed during the operational phase in the form of fuels and lubricants including energy required for their production, transport and distribution was calculated for two scenarios: Minimum fuel consumption (Scenario 1) of 41.9 $MJ.m^{-3}$ and Maximum fuel consumption (Scenario 2) of 50 $MJ.m^{-3}$.

The highest share of consumed energy in the operational phase was that of fuel (ca. 98%). Energy load from fuel consumption for Scenario 1 (fuel consumption 1 $l.m^{-3}$) and Scenario 2 (fuel consumption 1.2 $l.m^{-3}$) was expressed in numbers as 41 $MJ.m^{-3}$ and 48.8 $MJ.m^{-3}$, resp.

3.3 The calculation of slash bundle

Working widths of slash rakes range from 2.0 to 2.5 m and the length of raked small wood is about 5.0 m. The working speed depends on the terrain character and ranges from 4 to 7 km per hour. Output rate is 0.7 – 1.3 ha per shift.

The slash rake operates in the regime of the following three basic work procedures:

1 – Raking into strips; mounds are oriented along the longitudinal axis of the clearing at a distance of 20 – 50 m from one another; the slash is not burnt.

2 – Raking to stand margins – is used especially on the long narrow clearings where the strips of raked slash would be in the way. Working procedure would be as above; the work starts from the plot centre.

3 – Raking into piles – the slash rake moves across the site either in spiral towards an imaginary centre of the pile, or the slash is raked into strips and then divided into heaps.

Energy balance of using the slash rake was calculated from the following values:

Output per shift/hour: 65/8 m^3 (m^3 = FU)

Fuel consumption: 3.9 $l.h^{-1}$; 0.5 $l.FU^{-1}$

Consumption of oils: was not calculated

Energy intensiveness was calculated as 20.3 $MJ.FU^{-1}$ based on the consumption of fuels per each raked spatial meter of logging residues.

3.4 The calculation of forwarder

Fully mechanized technologies recorded an unusual growth in the last decade. In 2001, the proportion of timber processed by the fully mechanized harvester technology in the Czech Republic was approx. 5% while in 2009 it amounted to 30%. Forwarders are used not only for skidding the round wood but also in other forest operations such as slash removal. Technical parameters of these machines are diverse and there is a wide range of them fit for various operational conditions. For a better orientation of customers, the machines are divided into classes by their performance; however, classifications presented by individual authors differ.

The machine output considerably differs for individual classes. As a relatively close dependence has been demonstrated to exist between the engine output and the average fuel consumption in the fully mechanized technologies, skidding distance and loading area size markedly affect the unit energy intensiveness. The relation between fuel consumption (in litres per hour) and engine output (in kW) can be estimated according to the following exponential equation:

$$y = 16.005337 \cdot \left(1 - e^{-0{,}014162224 \cdot x}\right) \quad (3)$$

where x is engine output and y is fuel consumption per hour. Standard error was established as S=2.096 and correlation coefficient as r=0.919 (Klvač and Skoupy, 2009).

Bulk material is transported on classical forwarders or on forwarders with extended loading area. According to the loading area size, the capacity of forwarders ranges from 4 – 7 stacked cubic metres (steres) of logging residues. Output per hour fluctuates in dependence on the logging system (preparedness of the site) and average skidding distance. Following motor-manual felling when the to-be-removed material is dispersed across the logging site, the productivity ranges from 5 to 7 m^3 per hour (for skidding distances of 400 and 50 m) and decreases with the increasing skidding distance. Following the fully mechanized felling by harvester when the to-be-removed material is in piles, the hourly capacity of forwarders is by approx. 10% higher. Most demanding in terms of time consumption is the phase of material loading. The above productivity values apply to machines of higher classes and decrease with the decreasing machine class. For the purposes of this study, we used average values.

Energy balance of using the forwarders was calculated from the following values:

Fuel consumption: 13.72 $l.h^{-1}$; 2.29 $l.FU^{-1}$

Consumption of oils:0.64 $l.h^{-1}$; 0.11 $l.FU^{-1}$

Energy intensiveness was calculated as 92.9 $MJ.FU^{-1}$ originating from the consumption of fuels and 8.8 $MJ.FU^{-1}$ coming from the consumption of oils. Total energy intensiveness of the operational phase of the forwarder life cycle in haulage was established as 101.7 MJ per each stacked cubic metre of removed logging residues. The value may range from 87.2 – 122 MJ per unit of production due to diverse conditions such as different skidding distance and natural conditions.

Bundles are hauled by the classical forwarders or by the forwarders with extended loading area. According to the loading area size, the capacity of forwarders ranges between 10 – 20 bundles (FU). The average daily productivity fluctuates in dependence on the average skidding distance. In this case, the productivity of forwarders is considerably higher than with the dispersed material because the loading time is minimized. For the purposes of this study, average values were considered and a forwarder of higher performance class was preferred, which is most frequently used.

Energy balance of using forwarders after bundler was calculated from the following values:

Fuel consumption: 13.72 $l.h^{-1}$; 1.25 $l.FU^{-1}$

Consumption of oils:0.64 $l.h^{-1}$; 0.06 $l.FU^{-1}$

Energy intensiveness was calculated as 50.7 $MJ.FU^{-1}$ originating from the consumption of fuels and 4.8 $MJ.FU^{-1}$ coming from the consumption of oils. Total energy intensiveness of the operational phase of the forwarder life cycle after bundler was established as 55.5 MJ per each removed bundle of logging residues. The value may range from 43.6 –76.3 MJ per unit of production due to diverse conditions such as different skidding distance and natural conditions.

3.5 The calculation of chipper

The calculation was made for a machine assembly containing the chipper JENZ HEM 420 Z (JH 420 Z) and the tractor FENDT 716 VARIO. The machine assembly was analyzed in operation under standard conditions of the Czech Republic and it was chosen as a representative of the medium performance class and because JENZ machines are commonly used in the Czech Republic. Lesy města Brna, a.s. (Forests of the City of Brno, joint stock company) purchased a mobile chipper JENZ Model HEM 420 Z and a tractor FENDT 716 VARIO with the intention to produce fuel chips from the forest dendromass (logging residues) from main and intermediate felling operations and from sawmill cut-offs. The supplies of chips were meant for the regional market in Brno and near surroundings. The machine was put into pilot and regular operation in December 2003 and in January 2004, respectively. The chipper dwells on a two-axle chassis and is equipped with a hydraulic arm for material feeding. The machine is fully controlled by a one-man crew from the driving unit (tractor) cab (Liška et al., 2011).

Energy balance was calculated from the following values:

Average production rate: 6608 tons (FU) per year

Number of working hours: 2702 PMH per year

Fuel consumption: 7.18 $l.h^{-1}$; 2.96 $l.FU^{-1}$

Consumption of oils: 0.06 $l.h^{-1}$; 0.026 $l.FU^{-1}$

Energy intensiveness was calculated as 144.31 $MJ.FU^{-1}$ originating from the consumption of fuels and 1.66 $MJ.FU^{-1}$ coming from the consumption of oils. Total energy intensiveness of the operational phase of the life cycle of the chipper and tractor machine assembly was established as 145.55 MJ per each manufactured ton of chips at a moisture content of 35%.

3.6 The calculation of slash bundler

The calculation was made for the John Deere 1490D bundler of logging residues based on data collected in two years (2007 and 2008) under standard conditions of the Czech Republic. The machine was purchased in June 2004 for processing the forest dendromass (logging residues) primarily after the main felling (Klvač et al., 2009). The bundler John Deere 1490D is designed as a machine of middle-to-higher class. The machine was nearly exclusively used for operation in stands after the main intentional felling. Following the felling by harvesters, the dendromass was concentrated in smaller piles depending on harvester travel and processing, which slightly increased the output of the bundler as compared with the situation when the logging residues are dispersed across the site. The bundler was occasionally used also in stands felled by the power saw technology where the dendromass was evenly distributed across the site and the machine production rate was reduced. Due to technological reasons the material was processed immediately after felling (dendromass was not intentionally left to dry out). Bundles were hauled by the forwarder to the main logging road and then they were supplied to the customer. The ratio of the processed coniferous and broadleaved forest dendromass was ca. 90:10.

The detected average usability of the machine in actual conditions was 81.6% (Tab. 3). The value is relatively high and apparently indicates high experience of the operator and good preparedness of the dendromass for bundling. The usability factor value is nearly identical for the two studied years; however, the number of produced bundles was higher in 2008 by nearly 76%. The resulting production rate was calculated including the machine travel both within the given stand and between the sites when the machine does not produce bundles.

Table 3: Output units of the slash bundler John Deere 1490D

period	2007	2008
SMH	3389	3558
bundles (pcs)	10041	17647
Tons (1bundle = 340.85 kg)	3360,6	6015
Utilization	79,6 %	83,6 %
Productivity pcs.SMH^{-1}	3	5

SMH – Scheduled machine hour – working hour including breaks and timeouts

PMH – Productive machine hour – working hour without breaks and timeouts

Energy balance was calculated from the following values:

Average production rate: 13844 bundles (FU) per year

Number of working hours: 3474 hours per year

Fuel consumption: 7.3 $l.h^{-1}$; 1.83 $l.FU^{-1}$

Consumption of oils: 0.62 $l.h^{-1}$; 0.16 $l.FU^{-1}$

Energy intensiveness was calculated as 74.4 MJ.FU^{-1} originating from the consumption of fuels and 13.4 MJ.FU^{-1} coming from the consumption of oils. Total energy intensiveness of the operational phase of the life cycle of the slash bundler was established as 87.8 MJ per each manufactured bundle.

3.7 The calculation of haulage

Haulage of wood matter from the roadside landing entails various problems such as heterogeneity of the transported material, poor utilization of returns, seasonal character of work, impact of climate, causing a high share of "empty" travels. Data processing, optimization of transport and necessary flexible response to different situations impose high requirements on both the information system and managers steering timber haulage operations. Therefore, a "tailored" information system has been developed in response to the existing absence of information systems in the field of transporting timber, wood-based materials and sawn timber.

In 2005-2009, marked changes occurred in the fleet of logging truck-and-trailer units (TTU); old and obsolete TTUs were put out of operation and new ones were procured where necessary. Obsolete Liaz TTUs were taken out of service as first. Since the amount of data on these TTUs was not representative, this type of TTUs was not assessed in this study. TTU types evaluated in this study were as follows: Iveco, Tatra, Mercedes Benz Actros 3344, Mercedes Benz Actros 3341, Mercedes Benz Actros 2644 and Mercedes Benz Actros 3348.

The total number of records (monthly outputs of various TTUs) made in this study was 2548. The total number of studied TTUs operating in various parts of the Czech Republic in 2005-2009 was 134. In the study period, we recorded and evaluated more than 136 292 cases of transportation at which the TTUs covered more than 11 million km – primarily in the haulage of round timber. Diesel oil consumption in the study period amounted to 6.8 mil. litres without breakdown to consumption in the haulage of wood matter and to indirect consumption during travel to the working site or to repair. The average utilization of the fleet was 53%. The average consumption of all monitored TTUs was 67.4 *l*.100 km^{-1}.

The average utilization of individual types of truck-and-trailer units ranged from 46-60%. The average utilization was increasing in dependence on the average hauling distance, which made it easier for operations controllers to find suitable transportation means. Short hauling distances typically show one-direction haulage of wood matter and many a time it is impossible to find utilization of units for their return travels, which are furthermore loaded by travelling to the working site and to repair or maintenance. This shows in particular in special TTUs for disintegrated wood matter (e.g. chips, sawdust) and this is why the utilization of units on short hauling distances hardly reaches 50%.

According to Plzeňská teplárenská, a.s. (District Heat Company), an economically and logistically adequate circle for deliveries of chips has a radius of about 80-100 km. Plzeňská teplárenská, a.s. is the greatest customer for biomass in the region of South Bohemia. Chips are transported exclusively by road. Rail transport in wagons is profitable only over larger distances and is not used in practice, as it would be necessary to despatch a whole train. A truck is capable of transporting 35 stacked cubic metres of chips, a truck-and-trailer unit can haul ca. 70 stacked cubic metres of chips and a special "moving floor" truck-and-trailer unit can carry up to 90 stacked cubic metres of chips. The availability of the latter is limited, however, and this is why these special units are not used for transporting chips from the roadside landing. Customers require the moisture content in chips of up to 35% and this is why the logging residues are left to dry out at the roadside and subsequently chipped.

Mean hauling distance for the transportation of chips was considered as 50 km; therefore, the values on the basis of which the energy balance was calculated were as follows:

Average productivity: 35 and 70 stacked cubic metres per haulage (Scenarios 1 and 2)

Fuel consumption: 60 *l*.100 km^{-1} and 65 *l*.100 km^{-1}

Fuel consumption: 1.71 *l*.FU^{-1} and 0.93 *l*.FU^{-1}

Consumption of oils: 0.45 *l*.100 km^{-1}; 0.013 *l*.FU^{-1}

Energy intensiveness was calculated as 69.5 and 37.8 MJ.FU^{-1} for Scenarios 1 and 2 originating from the consumption of fuels and 11.4 MJ.FU^{-1} for the both scenarios coming from the consumption of oils. Total energy intensiveness of the operational phase of the life cycle of chips haulage was established as 80.9 and 49.2 MJ per each hauled stacked cubic metre of loose chips.

A calculation for different average hauling distances (see Tab. 4) was made to illustrate the considerable effect of average hauling distance on energy balance. The comparison of results for hauling distances 50, 100 and 150 km showed that energy intensiveness over a distance of 150 km was more than double as compared with the distance of 50 km that was recommended as optimal. The energy balance of small TTUs grew much more rapidly than that of heavy-duty large TTUs.

Table 4: Energy intensiveness of transportation over hauling distances of 50, 100 and 150 km

Average hauling distance	TTU type	Energy balance (MJ. stere^{-1}) from the operational phase	Energy balance (MJ.t^{-1} dry matter) from the operational phase
50	small	80.9	270
	large	49.2	164
100	small	133	443
	large	72.8	243
150	small	185.3	618
	large	98.4	328

Small is able to transport 35 stere units, large is able to transport 70 stere units

3.8 The calculation of haulage from the bundler

A decisive factor for profitable haulage is short hauling distance from the roadside landing to the customer. This is a problem so far in the Czech Republic in spite of the fact that the country is small because local incinerators are not prepared to burn bundles yet. The only firm capable of processing and buying out bundles is WOOD & PAPER a.s. residing in Štětí. Therefore, the bundles moved in a majority of cases within a reasonable travel distance from the customer or the bundles were exported to Austria (Gmünd) if the price calculation was more favourable. A truck-and-trailer unit can transport ca. 53 bundles. Customers were delivered bundles from two sample localities. Logging residues in one of the localities were bundled instantly after logging while logging residues in the other locality were bundled slightly dried out. Bundles delivered from the first locality amounted to 151 (av. moisture content 58.4%). Bundles delivered from the second locality amounted to 373 (av. moisture content 42.5%). Dry matter content of one bundle neared 179 kg in the both cases.

Thus, it is necessary to expect larger hauling distances for the delivery of bundles. In our case, the hauling distances were 206 and 114 km and this is why we considered mean hauling distances for the transportation of bundles to be 75 and 150 km and values on the basis of which the energy balance was calculated were as follows:

Average productivity: 53 bundles (FU) per haulage

Fuel consumption: 50 *l*.100 km^{-1}; 1.42 and 2.83 *l*.FU^{-1}

Consumption of oils: 0.45 *l*.100 km^{-1}; 0.013 *l*.FU^{-1}

Energy intensiveness was calculated as 57.7 and 115 MJ.FU^{-1} originating from the consumption of fuels and 11.4 MJ.FU^{-1} coming from the consumption of oils. Total energy intensiveness of the operational phase of the life cycle of slash bundle haulage was established as 69.1 and 126.4 MJ per each hauled bundle at hauling distances of 75 and 150 km.

3.9 The calculation of crusher

The calculation was made for the crusher Peterson 2400 A, which was employed throughout the year in processing the wood material of diverse origin. In one year, the machine worked 759 hours for 10 months.

Details of the machine employment in the processing of materials:

Logging residues – 308 hours

Pallets – 160 hours

Sawmill production residues – 145 hours

Whole trees from juvenile thinning of stands aged up to 40 years – 95 hours

Stem parts with soft rots – 51 hours

Average consumption of diesel oil per hour was 23.5 litres and included diesel consumed by the crusher, hydraulic crane and material feeder. The productivity of the crusher may reach up to 22 tons per hour; nevertheless, actual production rate ranged about 15 tons per hour. Thus, thanks to the high concentration, the average consumption of Diesel oil was approx. 1.6 litres per ton of the processed material, this corresponding to the energy consumption of 65 MJ per each ton of the processed material originating from the consumption of diesel oil. The value is rather informative as a sufficient amount of information concerning crushers of this class was not available and additional extensive measurements would be necessary (Jiroušek et al., 2010).

3.10 Pure Energy Ratio

The individual junction points of the technological chain were analyzed and their energy intensiveness converted to 1 ton of dry matter for the purposes of comparing chains in which different volume and weight units are used. It should be pointed out that the project did not include a detailed study of all theoretically available technological chains but only those that are most frequently used in conditions of the Czech Republic. It should be noted too that all calculations are based on average values and on model machines and if other machines are employed, their partial energy requirements may differ. We can state, however, that for the purposes of defining the pure energy ratio (PER), the results are sufficient. The pure energy ratio (PER) expresses in our study the ratio between the energy gained in chips supplied to the customer and the energy consumed during the whole process of the collection, processing and haulage of forest logging residues and chips.

Depending on the chosen technological chain, the pure energy ratio ranged from 8 – 12. With this multiple gain of energy, the used method of manufacturing and processing raw material for fuel (chips) can be considered highly effective and contributing to sustainable management.

A comparison of the assessed chains in terms of their energy intensiveness and pure energy ratio is presented in Fig. 1. The ranking of the chains is as follows:

Most favourable in terms of energy consumption appears to be the chain consisting of "harvester – bundler – haulage - crusher", which exhibits the highest pure energy ratio thanks to its high efficiency. It should be noted that in this case, the operation of harvester has to be accommodated to the subsequent utilization of forest logging residues and to the fact that this variant of the processing has to do with green chips that are difficult to merchandize and not much sought. Energy intensiveness of this variant ranges from 1558 – 1941 MJ per 1 ton of chips DM.

The second energy-saving variant is the chain consisting of "harvester – forwarder - chipper" that makes use of the mechanized preparation of forest logging residues and high performance too. As compared with the above variant with the bundler, it is possible to split the phases of processing, to let the logging residues dry out, chipped and to haul a partly dried out material – brown chips. Energy intensiveness of this variant ranges from 1714 – 2258 MJ per 1 ton of chips DM.

The third variant in the rank of energy savings is a combination of "chain power saw – slash rake – slash bundler – haulage - crusher", which features some problem aspects such as twisting of tie cord during the disintegration by crusher or irregular drying out of bundles prior to crushing. Energy intensiveness of this variant ranges from 1812 – 2196 MJ per 1 ton of chips DM.

The fourth (less favourable) variant is represented by the chain consisting of "chain power saw – slash rake – forwarder - chipper" in which the output of the chain power saw and slash rake is lower as compared with that of the harvester in the second variant. Energy intensiveness of this variant ranges from 1968 – 2513 MJ per 1 ton of chips DM.

The relatively surprisingly least favourable in terms of energy consumption (highest energy intensiveness) was the chain consisting of "horse/tractor – forwarder – chipper - haulage", primarily due to the low performance of the horse and the high consumption of the tractor e.g. at skidding the forest logging residues in stands with dispersed (selection) felling. Energy intensiveness of this variant ranges from 2099 – 2644 MJ per 1 ton of chips DM.

In details the pure energy ratio is shown in table 5 and discussed below.

Table.5: Efficiency of using 1 ton of dendromass DM by different technologies

technology	En. content 1 t DM [GJ] Col. 1	En. use of processing* [GJ] Col. 2	en. content supplied to costumer** [GJ] Col. 3=1-2	Boiler efficiency [%] Col. 4	En. balance 1t DM [GJ] Col. 5	pure energy ratio Col. 6=1:(1-5)
(Local) district heat	19.2	1.8	17.4	85-93	14.79 - 16.2	4.35 - 6.4
Combined production (electricity and heat)	19.2	2.1	17.1	60-70	10.26 - 11.97	2.14 - 2.66
Large power plant (co-firing with coal)	19.2	2.5	16.7	23-27	3.84 – 4.5	1.25 – 1.31

Col. = Column

[*] Hauling distances are considerably shorter in district heat plants and energy consumption for haulage is therefore markedly lower (see Tab. 4). Large power plants require the collection of sources from longer distances and energy intensiveness ranges at the upper limit

[**] The longer the storage time, the greater the material degradation is (ca. 15% per month). This is why a higher degradation risk exists in large power plants due to the necessary advance storage of supplies.

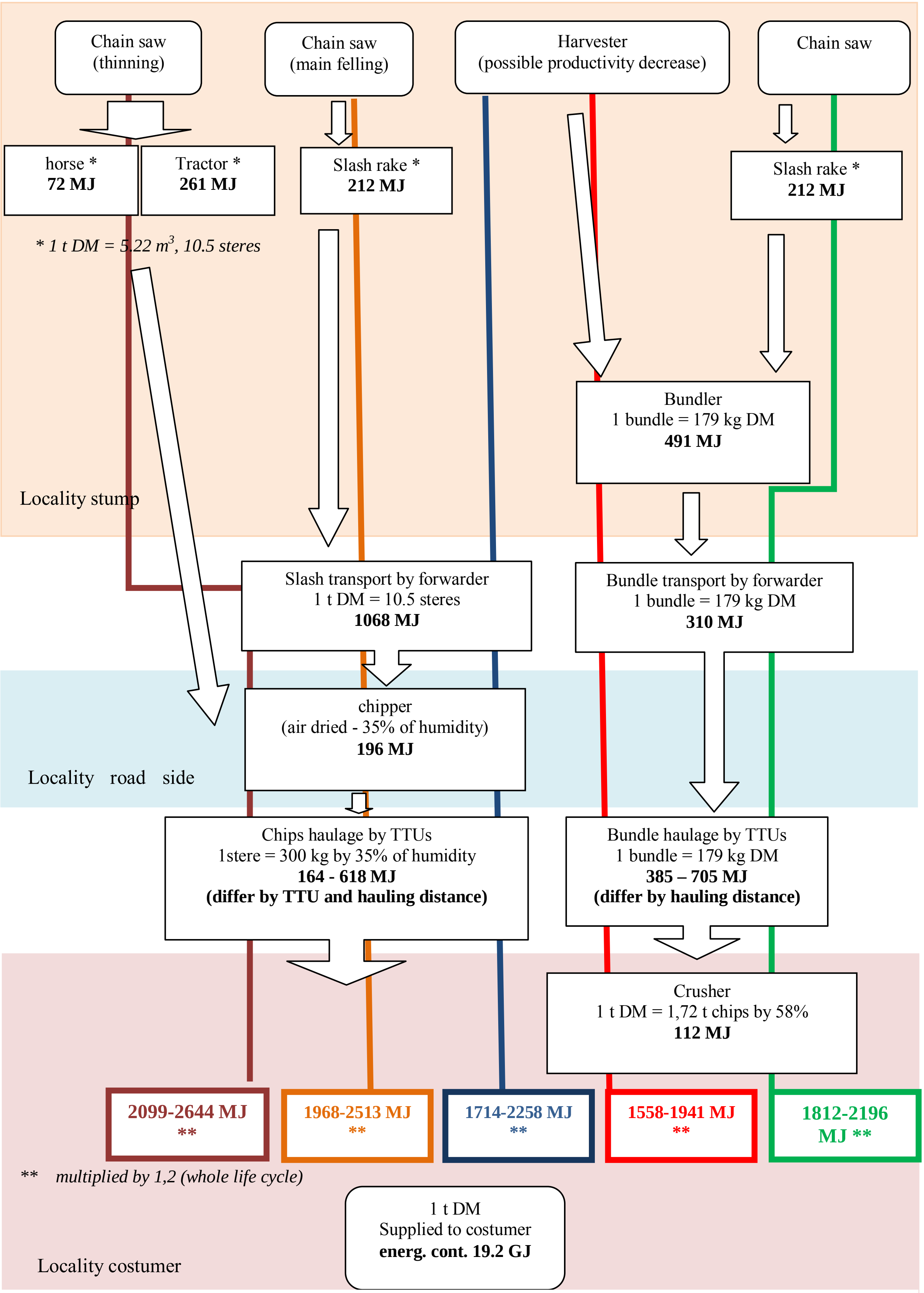

Figure 1: Energy use of logging residues processing chains (related to 1 ton of DM)

4 Discussion

The above calculations define the energy intensiveness of diverse methods through which forest logging residues can be converted into fuel chips. Nevertheless, the studied processing procedure ends in the customer’s stockyard or literally "in front of the boiler". At this stage we need to answer a question of how the renewable resources can be best utilized and if all the studied cases show a positive energy balance, how to manage these energy sources. There are a high number of technologies of various capacities and much diverse efficiencies used in the Czech Republic at present for the conversion of energy. One of the most discusses issues concerns the effective use of biomass. Power engineers agree that biomass use in generating electric energy by condensation methods is the least effective as the total efficiency of generation ranges between 23 – 27%. In the conditions of the Czech Republic, the biomass is mainly used for heating households as well as small- and medium-sized heat plants. The efficiency of current combustion plants ranges from 85 – 92%, which is most effective for the biomass use for energy. The efficiency of burning biomass in the local sources of family houses is 80 – 90%.

Table 5 characterizes a model use of 1 ton of dendromass DM by technologies currently used in the Czech Republic. The selected range represents the production of a smaller, high-efficiency heat plant of local significance, a medium-sized facility for the combined generation of electric energy and heat (KVET), and a large-scale electric power plant burning together biomass and coal as an example of the energy source with the lowest efficiency. The resulting energy yield (column 5) is the amount of energy that remains when the input energy content of dry matter (column 1) is reduced by energy intensiveness (en. costs of production) (column 2) and combusted in a boiler of given efficiency (column 4). By comparing the resulting energy gain with the input of energy DM content we obtain the pure energy ratio (PER). This pure energy ratio is to express by how many times more energy we gain as compared with the amount of energy expended for its gain. The ratio turns out best in the local heat plant where the energy gain is 4.35 – 6.4 times higher than the investment. The combined generation of heat and energy gives 2.14 – 2.66 times more. The generation of energy by combined coal and biomass burning in large condensation power plants gives the lower PER values (1.25 – 1.31 times more than energy investment). This shows that the amount of energy gained from the combined burning of coal and chips in the large condensation power plants is only by one fourth to one third higher than the amount of invested energy.

5 Acknowledgement

The research was supported from the Project no. MSM 6215648902 of the Ministry of Education of the Czech Republic, Project no. QH 71159 of the Ministry of Agriculture of the Czech Republic, Project COST OC10041 of the Ministry of Education of the Czech Republic, internal grant project IGA MENDELU Brno and Project no. 44892/ENV/10; 705/640/10 of the Ministry of the Environment of the Czech Republic.

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