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The Value and Profitability of Converting Sawmill Wood By-Products to Paper Production and Energy Generation: The Case of Poland

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Abstract

Analyzing the relationship between production of wood-based products and the production of paper and its derivatives ever more often attention is paid to complementarity of the processes of production, recovery and recycling of key raw materials and finally to their value and profitability of production. In this context, two main trends in converting wood by-products are noticed: paper production and energy generation. Development of market of sawmill by-products constitutes a challenge for wood industry, which requires determination of the most efficient means of utilizing those by-products. One of the crucial criteria of making business decisions is the value of wood by-products. A method of valuation of those sawmill by-products when converted into briquettes, pellet, or energy was presented. This method allows for multilateral analysis of profitability of various means of utilizing wooden by-products, on the example of Poland. Based on comparative analysis, recommendations for wood-based industry were formulated.

Keywords: paper production, sawmill by-products, wooden pellet, wooden briquettes, energy, wood market, economic efficiency, Poland

1. Introduction

The competitive position of the Polish wood industry is relatively strong. It is an effect of the domestic forest resources, the quantity and quality of round timber acquired from the national resource base, as well as continually growing significance of wood-based products

in global production and trade. The total forest area in Poland amounts to 9.2 thousands hectares, which means the afforestation rate is 29.5% (0.24 ha of forest per capita). Public forests hold a domineering position (80.8%), mainly those managed by National Forest Holding “The State Forests” (77%), which is a natural monopolist on the wood market. Polish gross wood resources amount to approximately 2.5 billion m³ of large timber (out of which almost 2.0 billion m³ belongs to The State Forests). The position of forest and wood-based sector in Polish economy is determined by key factors: forests cover about 30% of Poland’s territory, its share in GDP equals 2%, it creates workplaces and stimulates regional development. The contribution of forestry and wood-based sector to gross domestic product (GDP) in Poland amounts to: in case of forestry—0.3, and in case of wood industry—1.7%, which comes to an average share of forest and wood-based sector at the level of 2% (which is almost twice the world average) [1, 2]. Despite the imbalance in Polish wood- and wooden products market and the deficit of wood (a permanent phenomenon being an effect of the application of the principles of sustainable forest management), there is no threat for the development of wood-based industries in Poland [3, 4]. The following factors have a decisive impact on that: dynamic increase of demand for wood, wood being trendy and popular as an environmentally and human friendly raw material [5, 6]. A study of inter-sectoral cooperation seems justified with reference to the wood-based sector, especially owing to its territorial dispersion [7].

Polish wood industry plays an important role in the development of the national economy. The most important sectors based on wood include: sawmill industry, furniture industry, cellulose and paper industry, and market of wood-based panels. Coincidentally, it may be noticed that Polish market of wood by-products has developed dynamically. This industry is highly fragmented and focuses on small and medium-size businesses (with only a few large enterprises). A significant number of microenterprises (covering more than 30% of the entire sector) are not included in any official statistics. The share of wood-based industry in the production of the entire Polish processing industry is estimated at approximately 9%. Wood industry processes on average more than 38 million cubic meters of round timber per year, purchased mainly from National Forest Holding State Forests and worth more than 1.6 billion euro [8]. The potential of the wood sector is additionally confirmed by the level of employment—more than 260 thousand employees (including 125 thousand in furniture- and 50 thousand in paper industry). Value of production in wood-based sectors exceeds more than 20 billion euro (including 8 billion euro in paper industry and more than 7 billion euro in the furniture industry); here, the upward trend is maintained. The value of total export of wood industry products in Poland reaches more than 15 billion euro and there is a growing trend. Poland is the fourth largest exporter of furniture in the world (following China, Germany, and Italy), while other EU countries are the main recipients of Polish furniture [8]. Based on the case study of Poland, an attempt was made to evaluate the value and profitability of converting sawmill-wood by-products to paper production and energy generation. The aim of this study was to show a relatively easy method of verifying research hypothesis, which has assumed that the refining conversion of sawmill by-products, based on the example of selected new products processed in Poland enhances their value.

2. Paper and paper industry in Poland and its economic significance

Despite domination of electronic economy and sometimes forecast marginalization of paper, it remains present in a modern society as one of the basic products of everyday use. Paper and paper industry still plays a significant role in creating economy of products based on wood. Contemporary knowledge allows us to state that paper which has been used for over 2000 years still successfully competes with electronic media, as well as the most modern multi-component packaging materials made of plastic, etc.

The areas of main functional utilization of paper and cardboard along with an attempt to identify the most important tendencies in its development were shown in **Table 1** [9]. In case of an increment, the enhancement was estimated. Based on own research the level of changes was measured (using a 5-grade scale: very high, high, medium, low, and neutral enhancement). Analyzing the main fields in the functional usage of paper and cardboard, the following key developmental trends were identified: Packaging and Specialty—a great variety (average

Paper functional use	Types of paper	Ready made products made of paper	Developmental trends
Information: - collection - distribution - storage	Newsprint; Coated and uncoated magazines (SC and LWC); Coated and uncoated woodfree printing and writing	Newspapers; Journals-Books; Computer printouts; Xerographic copies; Inserts; Illustrations	Increased use of multicolor printing and copying; Electronic media taking over banking/trading docs; Increased recycling as raw material and use of additives (high enhancement)
Packaging: - transportation - distribution - protection	Liner; Sack; Corrugating medium Folding box board; Liquid packaging board; Wrapping	Bags Boxes Wrappings Containers	Increased: use for distribution of food and composites; General increase in recycling of packaging materials; (average medium enhancement)
Hygienic: - personal care - cleanliness - disease prevention	Tissue - dry crepe - wet crepe	Toilet tissue; Kitchen towels; Facial tissue Napkins; Hand towels; Hospital clothing; Wipers	Use increases with general living standard; End of chain for recycling of fibers; Use of virgin fiber for top-end products (high enhancement)
Specialty—a great variety	Official papers; Filter paper; Fire resistant papers	Notes; Stamps; Air filters; Coffee filters; Baking paper	An ever-increasing number of new applications (average medium enhancement)
Multi-functionality	All papers	Packaging labels (source of information and form of advertising); Printouts on sanitary papers. Multi-functional packaging	Trend towards multi-functionality takes multiple usage of paper products: new model of product life cycle and the cycle of usage of goods made of paper (very high enhancement)

Source: Own elaboration based on [9].

Table 1. Main fields of functional use of paper and cardboard.

medium enhancement); Hygienic and Information (high enhancement), and above all Multi-functionality (which appears to be dominant). Leading identified developmental trend is the emphasis on multi-functionality of paper products (very high enhancement). This trend accounts for not only versatile, but also multiple usages of paper products. It therefore results in creating a new model of product life cycle and at the same time a new model of cycle of usage of commodities made of paper, which aims at an attempt to develop a closed cycle of production and utilization of paper.

3. Poland as a consumer of paper and cardboard

One of the determinants of level and quality of life and simultaneously competitiveness of regions is the volume of paper consumption per capita [10–19]. Annual average paper consumption in Poland amounts to 130 kg per person per year (Figure 1).

An upward trend is observed with a declining rate of increase (Figure 2). Between 1995 and 2015, the ratio of annual paper consumption increased more than three times. It is the biggest growth among all European countries included in the survey. Further increase in paper consumption in Poland may be expected, as an average for countries of Western Europe, to be

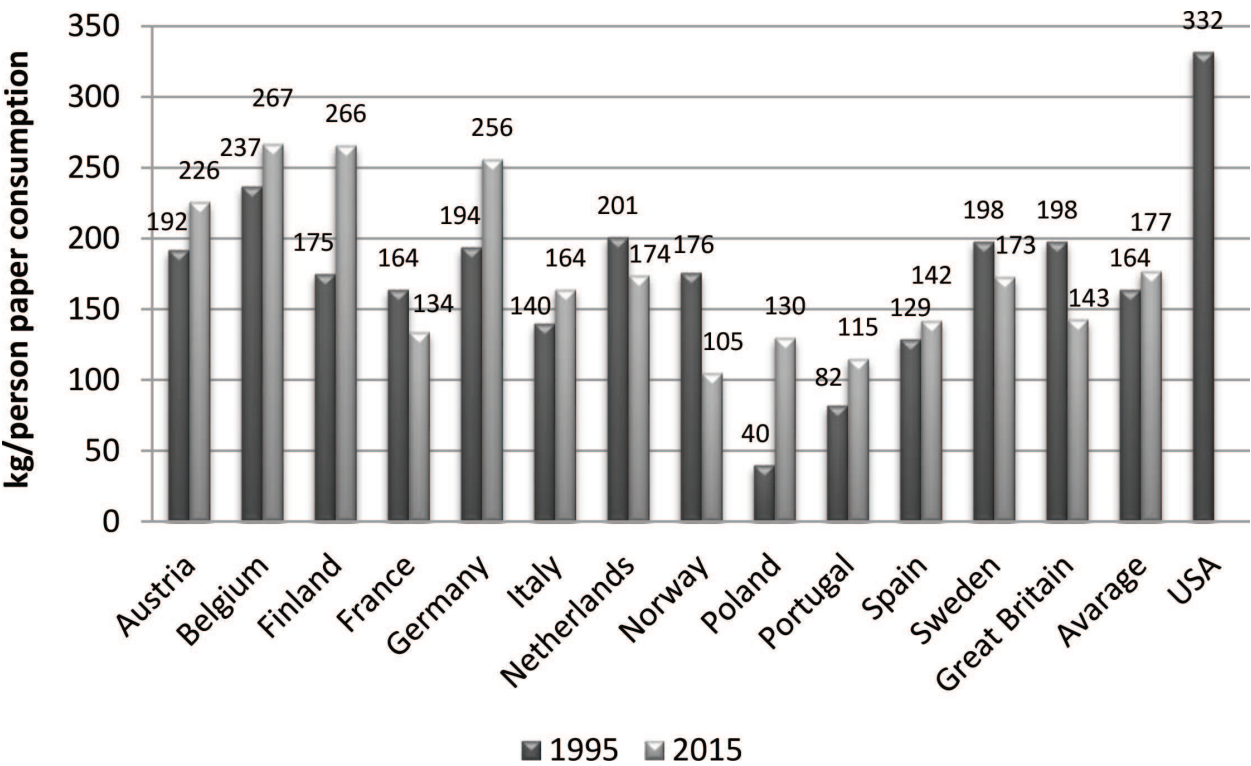


Figure 1. Comparison of paper and cardboard consumption in Poland and selected European countries in 1995 and 2015 [kg/person]. Legend: [X-axis label]: years 1995 and 2015; [Y-axis label]: kg/person paper consumption. Source: own elaboration based on [10, 11].

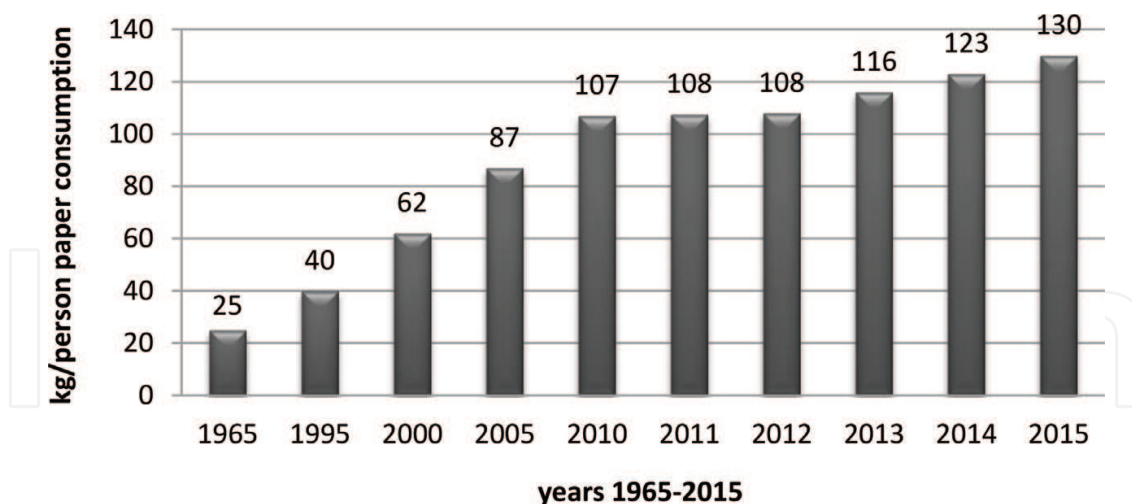


Figure 2. Paper consumption per capita in Poland [kg/person] in years 1965–2015. Legend: [X-axis label]: years 1965–2015; [Y-axis label]: kg/person paper consumption. Source: own elaboration based on [11–19].

177 kg per person. In some countries, the level of paper consumption is even two times higher than in Poland (Austria, Belgium, Spain, and Germany).

Even though a demand for newsprint decreases this trend is balanced by a growing demand for sanitary paper, packaging paper, and cardboard [20, 21].

4. Poland as a producer of paper and cardboard

Poland ranks eighth among CEPI member states as far as the production of paper and cardboard is concerned (the share of Poland is estimated at 5%) (**Figure 3**). Among the biggest paper industries or companies in Poland, there are [23]: Arctic Paper Kostrzyn SA GK with registered office in Poznan, Mondi Świecie SA GK in Świecie, International Paper-Kwidzyn sp. z o. o. in Kwidzyn, DS Smith Packing GK in Kielce, Polska Wytwórnia Papierów Wartościowych SA in Warsaw, and TFP sp. z o. o. in Kórnik.

In 2016, over 4.6 million tons of paper and cardboard was produced in Poland (**Table 2**), 5.6% more than in 2015. Transformation of Polish economy and direct foreign investments in paper industry led to 2.5 times increase in the volume of production, as compared to year 2000. Moreover, analyzing the dynamics of paper and cardboard production in Poland, one may indicate a steady upward trend in the period between 2006 and 2016 with a maximum reached in 2010 (13%) and high production ratios in 2009 and 2013 (over 7%).

According to product criteria, the most dynamically developing segment of production is the segment of paper hand towels made from paper pulp, paper, cellulose wadding, or webs of cellulose fibers. In the decade under analysis, there has been a steady increase in the production with a maximum in 2012 (30%) and short-term slump in 2013 (decrease by 5.8%).

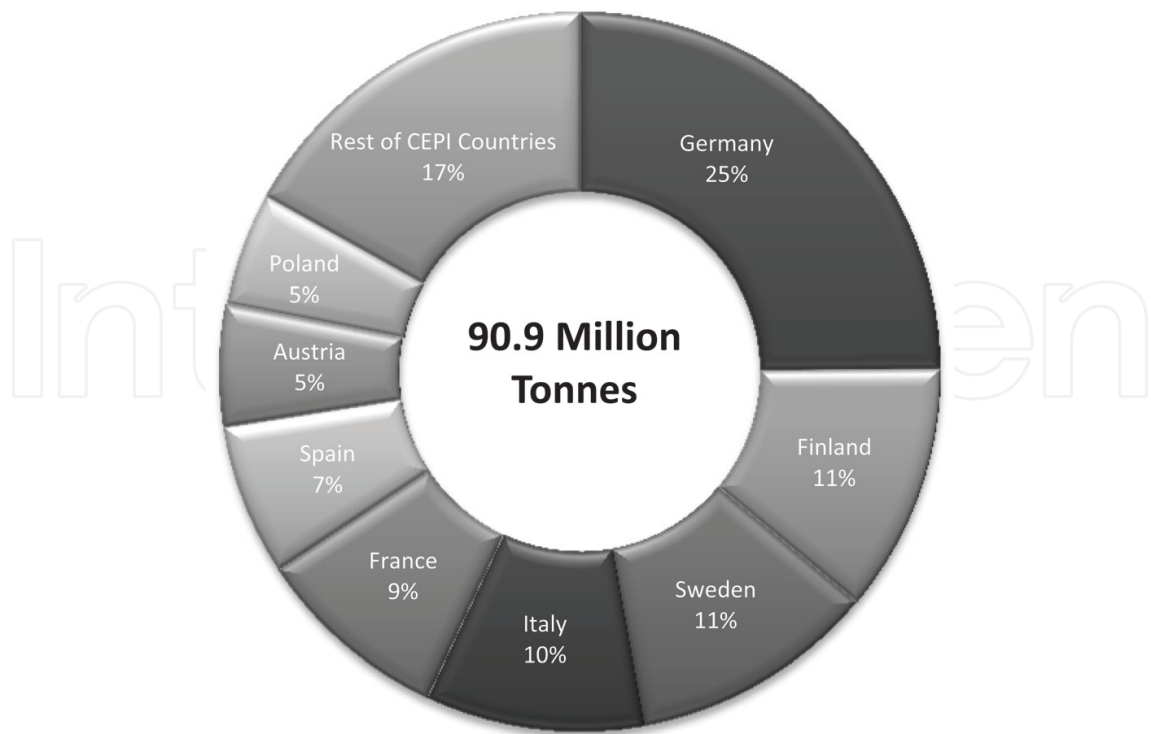


Figure 3. Major producers of paper and cardboard in Europe (2016). Source: own elaboration based on [22].

Production of corrugated cardboard increases from 3.3% in 2009 to 15.4% in 2011, subsequently reaching average values of 6% annually (2013–2016). Stable increase in the production is also observed in packaging segment including cartons, boxes, and cases made of paper and corrugated cardboard. An increase in the production of those commodities was noted from 4.5% in 2016 to 10.2% in 2012. The only decrease by 1.2%, took place in 2008.

Dynamic development of paper hand towels production as well as a steady increase in the production of cardboard and paper packaging compensates falls in the segment of newsprint in rolls or sheets.

Paper and paper-based products	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
	Units in thousands tons												
Soda or sulfate chemical woodpulp	751	802	825	814	820	826	881	894	848	881	881	873	877
Mechanical wood pulp*	244	249	345	353	331	319	299	307	304	306	301	286	303
Paper and paperboard/of which	1934	2732	2857	3005	3055	3275	3670	3756	3822	4106	4278	4399	4644
Newsprint	211	221	191	204	170	166	149	149	149	142	125	110	112
Graphic paper** and paperboard/of which	317	596	624	649	715	782	710	696	716	720	730	714	731
Graphic paper paperboard***	296	595	623	648	673	704	707	691	712	719	729	712	729
Uncoated, unbleached kraftliner	—	597	762	802	622	675	662	681	733	751	769	781	769
Semi-chemical fluting	—	136	189	180	185	280	178	188	178	180	178	154	170

Paper and paper-based products	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
	Units in thousands tons												
Uncoated Kraft paper and paperboard****	172	153	147	139	128	115	136	126	93	96	102	107	109
Corrugated paperboard	457	958	1054	1158	1210	1249	132	1528	1588	1703	1811	1933	2040
Sacks, bags of paper	83	90	104	117	102	126	124	126	115	113	121	124	131
Cartons, boxes of paper and corrugated paperboard	583	1155	1193	1417	1400	1523	1666	1747	1864	2010	2186	2408	2516
Toilet paper	116	215	208	219	237	259	255	268	297	298	304	330	367
Hand towels of paper pulp, paper, cellulose wadding, or webs	13	88	108	122	140	142	143	166	215	202	214	229	239

Source: own elaboration based on [24].

*Mechanical wood pulp; semi-chemical wood pulp; pulps of fibrous cellulosic material other than wood;

**Paper and paperboard of a kind used for writing, printing or other graphic purposes;

***Graphic paper and paperboard containing 10% and less by weight of the total fibers (by a mechanical process);

****Uncoated kraft paper and paperboard; sack kraft paper, creped or crinkled.

Table 2. Production of pulp and paper commodities in Poland (2000–2016).

This tendency is driven by competition from electronic media; however, one cannot explicitly state that this trend is sustainable. Within the period under the study, there has been production decline in this segment by more than 10%; however, in recent years, an increase was recorded (including that of 4.1% in 2016). The changes in the dynamics of production of

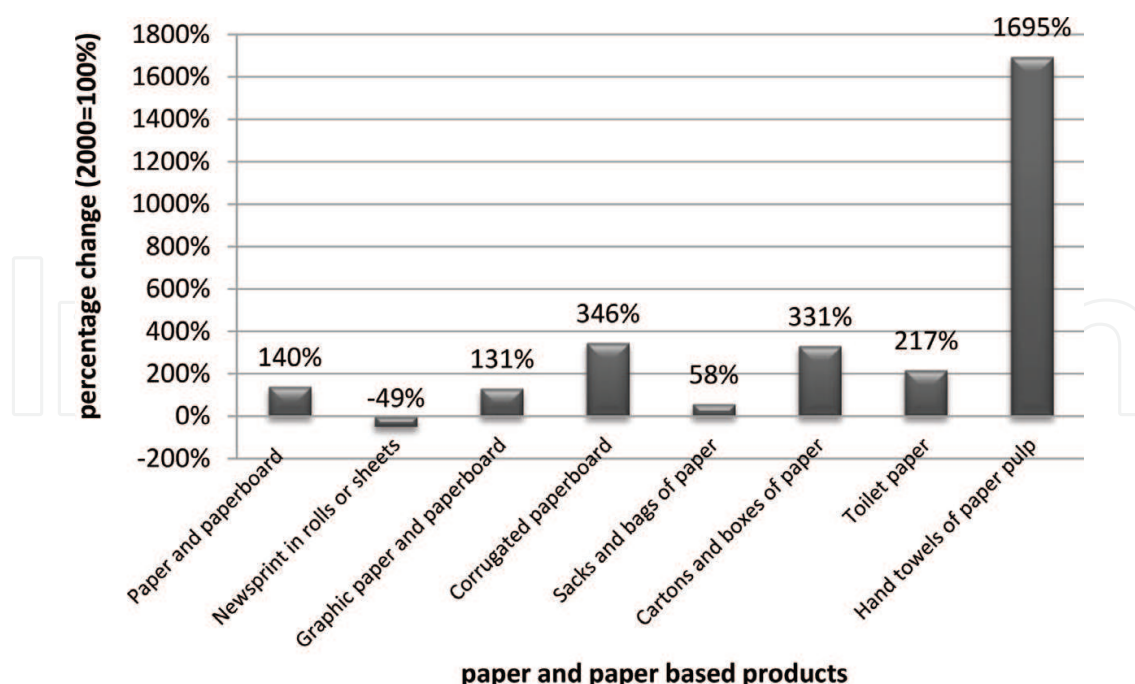


Figure 4. Dynamics of production of paper and cardboard and its different assortments in Poland in the period 2000–2016 (2000 = 100%). Legend: [X-axis label]: paper and paper-based products; [Y-axis label]: percentage change (2000 = 100%). Source: own elaboration based on [24].

individual paper, commodities were identified as a special example, which was also based on the carried out case study. It allows identifying the more important market trends with regards to products orientation. Analyzing changes in the total size of paper and cardboard production, as well as production broken down into the most important assortment groups in the period between 2000 and 2016 (**Figure 4**), the biggest growth (almost 18-times) was observed in the group of paper hand towels made of paper pulp, paper, cellulose wadding, or webs of cellulose fibers.

Also production of corrugated cardboard increased over four times, as well as the production of paper and corrugated cardboard packaging, such as cartons, boxes and cases. The smallest increase by “only” 60% was observed in the group of paper sacks and bags. While the production of newsprint in rolls or sheets dropped by almost 50%.

In a comprehensive approach as of year 2000 (that is within a period of 16 years, till year 2016), Poland recorded a total increase of 140% in the production of paper and cardboard.

5. The potential of Polish paper industry: international comparison

Presented results and conclusions were based on the data of Polish Main Statistical Office. Inclusion of international comparisons requires, at least within classification (assortment) used in Europe, adaptation of classification used by CEPI (**Table 3**). Structure by type of paper and cardboard production in CEPI member states (**Figure 5**) is dominated by graphic paper (39% share) as well as paper and corrugated cardboard (30% share).

In Poland, half of the production constitutes paper for corrugated cardboard production and the share of newsprint amounts to 20%, the next assortment group is sanitary papers with the share of 13% in the overall volume of paper industry production (**Figure 6**). The structure of Polish production is similar to the trends observed on paper and cardboard markets world-wide.

Analysis of CEPI statistics allows for a positive evaluation of the condition of European paper market, which in an analogical study period achieved better results than the USA or Canada [22]. In 2016, the total of 90.9 million tons of paper and cardboard was produced in Europe, which is a good result despite the 0.1% drop in overall production, as compared to year 2015. European market follows general trends of reducing weight of produced packaging materials, and most importantly focuses on efficient usage of resources [26]. In 2016, graphic papers production was limited (by 3.8%), and simultaneously there was an increase in the production of sanitary papers (by 1.1%) and packaging papers (by 2.4%). In the group of packaging papers, there has been an increase in the production of papers assigned for the production of corrugated cardboard (by 2.2%), used for manufacturing boxes (cartons) and other packaging used for transport purposes. Already, previously, indicated convergence of global trends with those observed on Polish paper and cardboard market, one may conclude that identification of economic tendencies for Polish case study concerning a selected Central and Eastern European country may be used as a source of forecast for the development of paper industry in other countries and the world regions.

CEPI paper assortment group	CEPI Countries Production (P) and consumption (C)				Poland Production (P) and consumption (C)			
	2014		2015		2014		2015	
	P	C	P	C	P	C	P	C
	Unit in thousands of tons							
Newsprint	7594	7061	7042	6606	126	9.6	110	—
Uncoated mechanical	5634	4684	5503	4623	0	275	0	247
Coated mechanical	7050	5142	6789	4926	0	266	0	239
Uncoated woodfree	9017	7149	8934	7036	730	239	714	287
Coated woodfree	7364	4938	7020	4754	0	248	0	285
Total graphic papers	36,659	28,918	35,265	27,946	856	1039	824	1052
Sanitary and household	7001	6700	7153	6925	562	418	568	414
Case materials	26,205	24,870	27,059	25,894	2044	1981	2166	2205
Carton board	8551	5744	8710	5891	239	474	265	517
Wrappings	4106	2994	4071	2866	89	269	95	276
Other paper & board for packaging	4591	4159	4733	4300	90	166	96	177
Total packaging papers	43,452	37,767	44,572	38,951	2462	2890	2622	3174
Other paper & board	3910	3642	3881	3594	399	355	385	346
Total paper & board	91,019	77,028	90,872	77,416	4278	4701	4399	4986

Source: own elaboration based on [11, 25].

Table 3. Paper and Board Production and Consumption in 2014 and 2015 (CEPI).

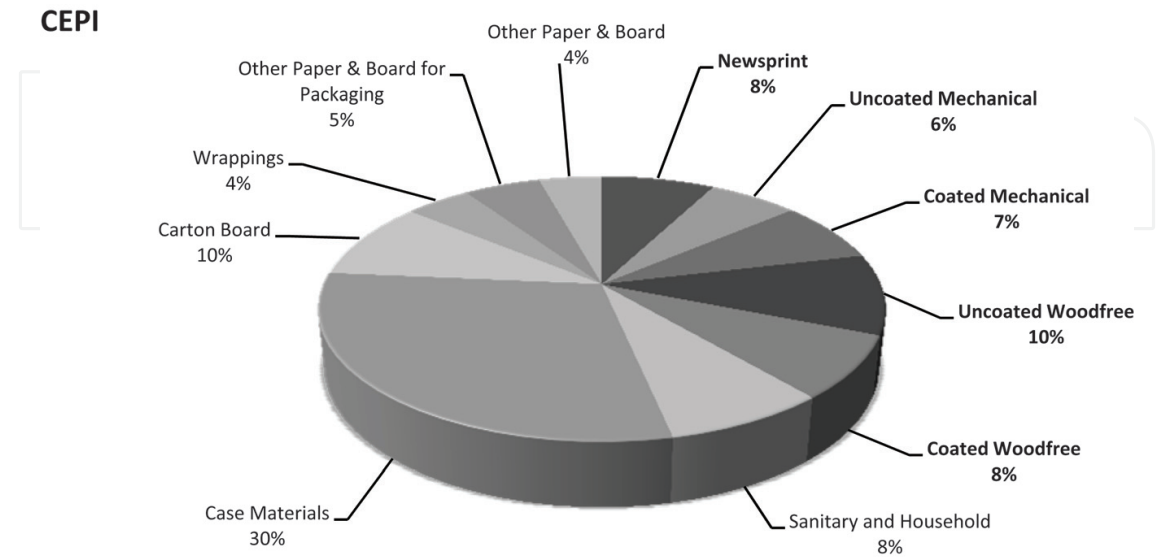


Figure 5. Structure of paper and paperboard production in CEPI countries in 2015. Source: own elaboration based on [11, 25].

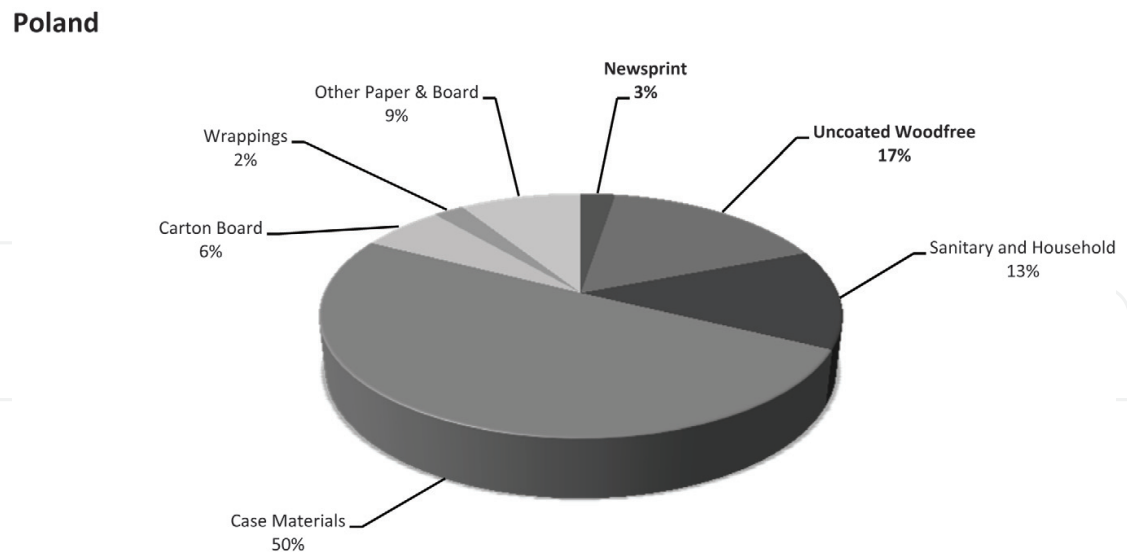


Figure 6. Structure of paper and paperboard production in Poland, in 2015 (CEPI). Source: own elaboration based on [11, 25].

6. Development prospects of paper and cardboard market

An attempt for identification of global development trends on the market of paper commodities based on a case study of local market (Poland), although seems to be a risky assumption, as reflected in the observations of consumers behaviors in Europe and world-wide. Those trends mainly concern two segments: paper and cardboard packaging (I) and sanitary papers (II). In the first case, development is determined by knowledge and belief of consumers regarding the endurance of packaging and the possibility of its recycling based on paper resources, while a growing demand for sanitary papers is determined by socio-economic factors related to the improvement in standard of living and demographic situation. China is a good example allowing us to draw conclusions that there is a link between growing GDP and an increase in the consumption of sanitary papers (**Figure 7**).

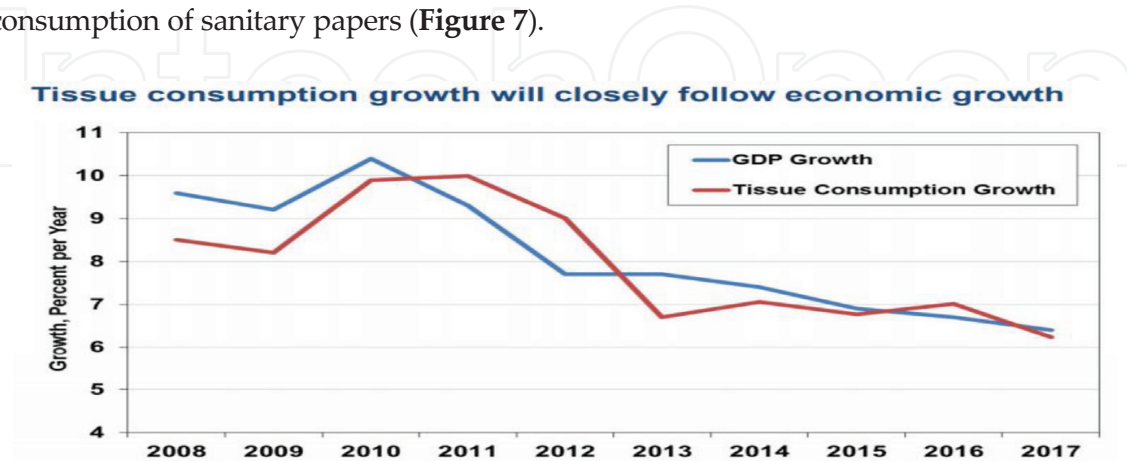


Figure 7. Comparison of GDP and tissue consumption changes in China (2008–2017). [X-axis label]: Years 2008–2017. Source: [27].

This trend is stimulated by other complementary factors: urbanization, growth of net income, as well as consumer spending and primarily standard of living, natural element of which is access to high quality paper sanitary products. Moreover, even in the group of graphic papers, which is threatened by a decreasing demand due to a partial substitution by electronic media, a domineering position of new technologies over paper is not yet sealed.

Using descriptive approach, the following most important development trends of individual groups of paper products simultaneously reflect the formulated key trends in the development of the whole sector. Firstly, trends on the market of graphic papers were verified. Despite adverse opinions, the electronic media will not totally substitute paper as the medium of press, journalistic and scientific information as well as books and documents. Naturally, they will become a partial substitute facilitating and supplementing exchange of information on paper and communication. This investigation is supported by the following studies:

- The results of survey among office employees of 2400 small and medium-size enterprises from EMEA countries conducted on behalf of Epson Europe (2016–2017), which do not leave any doubts: pro-paper option dominates. 76% of respondents have an opinion that printing is a “very important” factor facilitating work and 75% states that “running paper-free office is unreal” (e.g., Poles print on average 29 pages a day) [28].
- 70% of Americans (including 69% aged 18–24) stated, in the survey conducted in September 2012 by Two Sides, that they prefer to read information printed on paper rather than displayed on a screen [29].
- Similar results were brought by research undertaken by Pew Research Center, which noticed that 6% of the respondents read books in digital format and 38% only in printed version. Hence, an imminent death of traditional books cannot be forecasted [30].
- Exchange-listed Association of German Book Sellers announced that in 2014, the existing buyers of electronic books ever more often read in printed formats (a drop in the number of e-book readers from 46% in 2013 to 33% in 2014) [31].
- A group of leading American companies removed advertisement promoting electronic invoices as more ecological. It has been justified by the statement that printing on paper has many unique features of environment protection (renewable resources), argument on rescuing forests is misconceived (more trees are planted than harvested), an actual cost of launching electronic documents is not known, while the majority still collects paper printouts of their e-documents for archive purposes [32].
- On the request of association of Consumers for Paper Options (CPO) in 2013, in the USA (and previously American post), it has been assessed that 80% of respondents are in the opinion that forcing clients to receive invoices (including those for energy consumption) only in electronic form is unacceptable [33].
- Scientists from McMaster University in Canada developed a method of printing on paper biosensors, which will be warning consumers against contaminated foods [34].

- At Bologna University, it has been proved that fruit sold on trays made of corrugated cardboard stay fresh for longer and are better protected than those sold on reusable plastic trays [35].
- Report “Paper and Productive Learning” [36] confirms domination of paper in academic education. 82% of students always or very often use paper when revising for exams, 74% uses paper for taking notes. Simultaneously, 64% of teachers are convinced that students better understand texts which are put on paper.
- Also, the study of artists’ opinions revealed their conviction about greater efficiency of art expressed via paper than in digital format [37].
- Finally, association of German paper mills (*Verband Deutscher Papierfabriken* (VDP)) using research method of interview and observation of usability of paper in everyday life of Germans identified a significant role of paper in context of hygiene (80% respondents), transport (69%), and information (66%). Paper environmental safety was recognized and 79% of respondents were for invoices and documents delivered in paper format [38].

Meanwhile, economies worldwide record decreases in the production of graphic papers; however, stating its imminent decline or total elimination from usage would be unjustifiable. A totally reverse trend is observed on the market of paper packaging including corrugated cardboard packaging. Demand for this product grows in BRIC countries (Brazil, Russia, India, and China). Already, over 65% of packaging in Germany is manufactured from corrugated cardboard. This market in Europe is considered to be a growth pole (the pace of growth is estimated at 4.8% annually). Over half of British consumers (57%) prefer to pack their fresh food products in paper bags [39], and similar preferences are declared by 68% of European consumers [40]. Development of corrugated cardboard is also stimulated by new products manufactured based on cardboard, including: ULD pallet with honeycomb structure [41], corrugated cardboard bicycle helmets for self-service bike rentals [42], and KarTent, manufactured entirely from cardboard designed by a Dutch start-up [43]. In reaction to those trends, some factories producing graphic paper change their profile and launch production of corrugated cardboard: (a) Pro-Gest is reconstructing newsprint mill in Mantua, Italy, planning the production of corrugated cardboard in 2018 [44], (b) a similar investment takes place in Heinzel factory in Laakirchen in Austria [45], (c) a change of profile for corrugated cardboard will be launched in Madrid by International Paper, following their acquisition of newsprint paper from Holmen [46], (d) new investments are also carried out by LEIPA in Schwedt [47], Mondi (Slovakia)—production of “Kraft top white” [48], in Poland Stora Enso in Ostrołęka [49], Prinzhorn group (Eurobox Polska) [50], and Schumacher Packaging Group in Myszków [51].

European tissue paper market is growing at a quite stable pace, on average by 2–3% per year. A decline was recorded only in 2009. Western European markets record lower increase rate (up to 2%), while developing markets of Eastern Europe including Russia and Poland constituting 60% of the market record higher which increases (up to 4–5%) [52]. Tissue paper market is steadily developing (13% of Polish market of commodities made of paper in 2015) [53], and consumers are looking for goods in both economy and, ever more frequently, premium

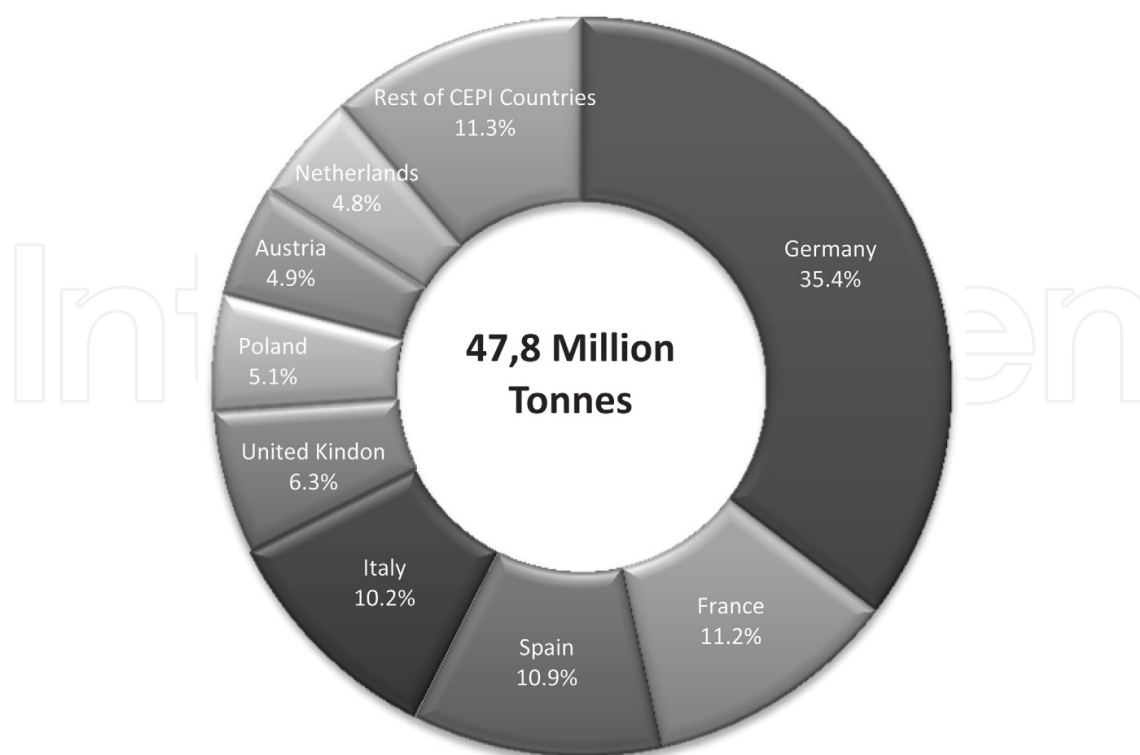


Figure 8. Use of recycled paper in CEPI countries in 2016. Source: own elaboration based on [25].

segment [54]. Along with the development of paper commodities market, one may also predict an increase in the usage of recycled paper. Currently this level is relatively stable with a slight growth in 2016 and amounts to 47.8 million tons (**Figure 8**). Collection of paper for recycling grew by 1% reaching the level of 56.4 million tons. Simultaneously, export of recycled paper increased by 5.6%, most of which was sent to Asian markets (91.7%). Level of recycling in EU countries, Switzerland, and Norway reached to 72.5% (increase by 0.7%).

Despite the fact that paper sector has to fight myths, such as “paper production destroys forests and environment,” market of paper commodities is well perceived by consumers and will be developing. This development will include mainly those segments which are based on wood, and maximize the added value by trying to implement the principle of “zero waste.” It is therefore about the type of industry which facilitates multiple recycling and converts into energy only, the materials which cannot be reused.

7. The value of sawmill wood by-products

In Poland, the use of sawmill by-products, which share in the total supply of all industrial wooden by-products (including veneer sector) amounts to 60%, becomes even more significant [55]. The aim of this analysis was to show a method of verifying research hypothesis, which has assumed that the refining conversion of sawmill by-products, based on the example

of selected new products processed in Poland enhances their value. The research used the data related to the prices of sawmill by-products, which was obtained via questionnaire and in-depth interview carried out at sawmills in Poland in 2015. Sawmills were selected using nonrandom sampling technique, in accordance with the minimum size of the sampling and the verification of statistical correctness of selection [56]. Evaluation of the profitability of processing the sawmill by-products into bio-fuels and energy was proposed based on:

1. Determining the value of sawmill by-products in the given areas of application

a. Processing into bio-fuels [55]:

$$W_{pi} = \frac{1}{a_{pi}} \left[c_{jp} \left(1 - \frac{m_j}{1-P} \right) - k_{pi} - k_{ti} \right] \quad [\text{EUR/m}^3] \quad (1)$$

b. Processing into energy [55]:

$$W_{ei} = c_{je} g \frac{19,5 - 2,5w_o}{1 + w_o} \left(1 - \frac{m_j}{1-P} \right) - k_{pi} - k_{ti} \quad [\text{EUR/m}^3] \quad (2)$$

where W_{pi} is the value of wooden residue being processed into any wooden fuel [EUR/m³], I is the number of the type of by-product being converted, $i \in \langle 1, n \rangle$, P is the type of generated wooden fuel, $p \in \langle 1, n \rangle$, a_{pi} is the ratio of material intensity when processing the given by-product “ i ” into wooden fuel “ p ” [m³/t, mp/t], c_{jp} is the unit sales price of the fuel “ p ” generated while processing by-products [EUR/t], m_j is the assumed net profit margin level m_j ; {0.01; 0.05; ... 0.15}, P is the Corporate Income Tax (CIT), in 2015 = 0.19, k_{pi} is the cost per unit of processing wooden residue [EUR/t], k_{ti} is the cost of transporting a unit of wooden residue [EUR/t], W_{ei} is the value of a given type of by-product of “ i ” number converted into energy [EUR/m³], c_{je} is the unit price of selling energy generated from burning by-products [EUR/GJ], G is the bulk density of the type of by-product being burnt [t/m³], and w_o is the absolute moisture of the by-product being burnt.

2. Comparing the determined value with the sales price of unprocessed sawmill by-products [55, 57]. Determined value of various types of sawmill by-products being processed into pellet, wooden briquettes, and energy was estimated and presented in **Table 4**, along with the sales prices of the post-production by-products from which they were processed.

The presented data indicate that a significantly higher increase in the value of sawmill by-products is reached by the entrepreneurs who process them at the place of their creation; hence, they do not bear any transport costs. The highest here is the value of post-production by-products processed into wooden briquettes, and slightly lower, in case of those being processed into pellet. The least profitable is processing “by-products” into energy, yet not for all types of by-products. The formula rationalizing the utilization of the stream of sawmill by-products via determining the value of their individual types which facilitates the selection

Types of by-products		Sawmill by-product average price [EUR/m³]	Value of by-products in conversion divided into								
			Pellet with margin			Briquettes with margin			Energy with margin		
			0.05	0.10	0.15	0.05	0.10	0.15	0.05	0.10	0.15
			Without transport cost [EUR/ m³]								
			Including transport cost [EUR/ m³]								
Sawdust	MSTR = 10%	28.10	46.48	39.89	35.68	49.52	45.54	41.56	29.21	27.14	25.07
			36.92	32.72	30.75*	42.35	38.37	34.40	26.49	24.42	22.35
	MSTR = 50%	24.12	39.67	33.52	29.59	42.65	38.94	35.23	33.85	31.46	29.06
			30.36	26.43	24.60*	35.57	31.86	28.14	31.51	29.11	26.72
De-fibered chips	MSTR =25%	28.10	44.93	39.96	34.99	52.62	47.87	43.13	33.60	31.22	28.84
			39.33	34.36	31.00**	47.02	42.27	37.52	31.75	29.37	26.99
	MSTR =50%	28.10	37.13	32.94	28.76	43.59	39.59	35.59	40.62	37.74	34.87
			31.51	29.59*	23.14	37.97	33.97	29.97	39.10	36.22	33.35
Pulp chips	MSTR =25%	35.36	50.25	44.93	39.61	57.05	52.01	46.97	33.60	31.22	28.84
			44.65	39.33	36.85*	51.44	46.40	41.36	31.75	29.37	26.99
	MSTR =50%	35.36	41.63	37.15	32.67	47.31	43.07	38.82	40.62	37.74	34.87
			36.01	31.53	27.05	41.69	37.45	33.20	39.10	36.22	33.35
Waste wood MSTR = 25%		24.59	52.68	46.75	40.82	61.88	56.22	50.55	33.60	31.22	28.84
			47.11	41.18	35.25	56.31	50.64	44.98	31.75	29.37	26.99

Source: own elaboration based on [55].

MSTR, moisture content; *, bb—sales only in big bag; **, bulk—only bulk sales. In **bold**, values of those converted by-products which came out as lower than the average sales price of sawmill wood by-products.

Table 4. Value of wood-sawmill by-products converted into pellet, briquettes and energy including and excluding cost of transport in Poland (2015).

of the most profitable one, from the sawmill perspective, and the way of utilizing its post-production by-products.

8. Criteria for evaluating profitability of processing sawmill wood by-products

Research attempts are taken to evaluate profitability criteria of converting the wooden by-products into wooden briquettes and pellets. Selected factors have been studied: namely threshold margin, maximum price (at which the raw material can be purchased for further

Type of wood by-product			Sawmill wood by-product average price [EUR/m ³]	Profitability of processing wood by-products generated as by-products and basic products						
				Break-even margin, m _{gr}		Maximum unit costs of conversion including transport	Maximum cost of transport per unit	Maximum distance from which raw materials can be transported*	Maximum purchase price of raw materials for conversion	Minimum selling price of finished product
				By-production	Basic production	k _{pmax} + k _{tmax} [EUR/t],[EUR/m ³]*	k _{tmax} [EUR/t]	l [km]	c _{pub} [EUR/m ³]	c _{min} [EUR/t]
			Pellet							
			Briquettes							
Sawdust	MSTR 10%	28.10	23.76	15.23	88.33	44.37	232.89	40.80	122.83	
			31.64	22.63	80.29	55.94	293.65	45.96	103.21	
	MSTR 50%	24.12	22.12	13.09	94.11	41.31	204.97	34.44	126.82	
			26.98	16.86	77.79	44.96	223.04	35.97	106.86	
De-fibred Chips	MSTR 25%	28.10	21.86	16.22	91.82	38.13	254.76	44.18	112.98	
			30.73	24.82	85.50	51.20	342.02	51.60	93.60	
	MSTR 50%	28.10	15.52	9.88	82.27	27.06	151.54	36.30	124.05	
			26.63	20.99	82.27	46.45	260.07	45.54	104.66	
Pulp Chips	MSTR 25%	35.36	18.93	12.66	89.04	35.35	236.16	48.79	127.63	
			26.41	19.79	81.00	46.69	311.95	55.24	108.24	
	MSTR 50%	35.36	11.68	5.41	77.02	21.81	122.13	40.17	141.17	
			18.75	12.13	68.98	33.16	185.65	45.57	121.78	
Waste Wood MSTR = 25%	24.59	28.69	23.99	105.14	50.05	400.30	33.60	53.06		
		37.34	32.42	98.81	61.70	493.48	31.75	60.98		

Source: own elaboration.

MSTR, moisture content; *, transport 25 m³, rate 1.06 EUR/km (In **bold** the highest values of: break-even margin level for various forms of utilizing sawmill-wood by-products); data presented excluding cost of transport.

Table 5. Profitability of processing wood by-products into pellets and briquettes and basic products in Poland (2015).

processing), maximum unit cost of processing (including and excluding cost of transport), and the minimum acceptable by the producer sales price of the wooden biofuel (Table 5).¹

Evaluation of profitability of processing sawmill by-products into ecological fuels and energy may be carried out in determining their value using the formula (3) [55], and then comparing it with the price of unprocessed “wooden residue.” Transformation of the formula given below (Eq. (3)), which allows to set down the maximum possible margin, costs of processing, or the price level of the “residue” up to which purchasing of it will still be profit-making:

$$W_{pub} = \frac{1}{a} \left[c_j \left(1 - \frac{m_j}{1-p} \right) - k_{jp} - k_{jt} \right] \quad [\text{EUR/m}^3] \quad (3)$$

where W_{pub} is the value of wooden residue being processed into any wooden fuel [EUR/m³], A is the amount of basic material necessary to generate one unit of a given wooden fuel [m³/t, mp/t].² c_j is the sales price per unit of a given wooden fuel [EUR/t], m_j is the target net profit margin m_j : {0.01; 0.05; ... 0.15}, P is the Corporate Income Tax (CIT), in 2015 = 0.19, k_{jp} is the cost per unit of processing wooden residue into a given wooden fuel [EUR/t], and k_{jt} is the cost of transporting a unit of wooden residue [EUR/t].

Comparative analysis used the data related to the prices of sawmill wood by-products, which was obtained via questionnaire carried out at wood processing plants (sawmills) in Poland in 2015. Analysis has embraced both companies (wood processing) which generated their own wood by-products as well as those which have to buy those (wooden) by-products (Table 5). Analysis of the juxtaposed values indicates that the most profitable form of processing wooden by-products is briquettes production and the highest margin level: 37.3% in case of the entrepreneurs who are in possession of those by-products may be obtained utilizing wood chips. The least profitable material for the production of briquettes is paper chips of 50% moisture content, due to their high price in the unprocessed form.

9. Conclusion

The formula rationalizing the utilization of the stream of sawmill by-products via determining the value of their individual types facilitates the selection of the most profitable, from the sawmill perspective, and the way of utilizing its post-production by-products. At the same time, it gives their owners the basis for choosing a versatile structure of their utilization. The above presented method may also be used when evaluating the profitability of production adopted as the main commercial activity by the entrepreneurs using the product available on the market.

¹For comparison, the current average exchange rate is 1 EUR = 4.2705 PLN (Table No. 078/A/NBP/2017 of April 21, 2017; Source: <http://www.nbp.pl/homen.aspx?f=kursy/ratesa.html> [Accessed: April 21, 2017]).

²The symbol “mp” means spatial meter in [mp/t] and [EUR/mp].

The following conclusions and recommendations were formulated:

1. The study showed that significantly higher increase in the value of further processed sawmill by-products is achieved by those entrepreneurs who process them at the place of their conversion without bearing any additional cost of transport.
2. Preferred and the most efficient way of utilizing wood by-products would be the sales of this raw material for further processing into paper and other derivatives (for example de-fibered chips), or alternatively direct utilization of solid pieces of wood assigned for a specific product which allows to gain added value, recycle, and reuse.
3. Only definite lack of resources primary usage should determine an optimum method of processing.
4. The highest value is characteristic for wooden by-products processed into briquettes, slightly lower for those processed into pellet. The least profitable is converting wooden by-products into energy.

In detail, it was identified that:

- The highest level of threshold margin is reached by the production of wooden briquettes utilizing wood chips (37.3%). The producer—who does not incur transport cost—may reach a higher margin, from 4.7% (wood chips) up to 9% (sawdust with 50% moisture content).
 - The maximum margin of net profit—determined for wooden pellet—is on average between 7.6 and 8% (including or excluding cost of transport) lower than in case of processing wooden by-products into briquettes.
 - Recommended for processing into pellet are: dry sawdust and paper chips—for which the average sales price may be higher.
 - The most profitable material—for briquettes production—constitutes de-fibered chips and wood chips (with moisture content of 25%), due to lower quality requirements concerning final product.
5. The descriptive analysis showed that significantly higher increase in the value of further processed sawmill by-products is achieved by those entrepreneurs who process them at the place of their conversion without bearing any additional cost of transport.
 6. Investigating the further processed sawmill by-products (i.e. the wooden by-products into ecological fuels) is of essential importance for the economic development of regions, especially for industries characterized by high territorial fragmentation, e.g., the forest and wood-based sector in Poland.

It needs to be highlighted that Polish wood market and derivative markets are determined by quasi-monopolistic organization of the market of wooden raw material. Institutional conditions of inter-municipal and inter-sectoral cooperation in Poland are concurrently an opportunity and a barrier for the establishment of partnerships with the participation of wood industry. Functioning of a secondary wood market, dispersed and territorially

diversified, is a subject to market mechanisms. It creates a new market for sawmill wood by-products, which is an opportunity for the development of small- and microenterprises in the forest- and wood-based sector in Poland.

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