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Impact of Structural Changes on Energy Efficiency of Finnish Pulp and Paper Industry

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Received: 20 August 2019; Accepted: 23 September 2019; Published: 26 September 2019

Abstract: A key challenge in prevention of global warming is how to increase energy efficiency, to be able to deal with increased fossil CO_2 emissions from rising energy usage. Increasing energy efficiency will decrease energy usage and is in a key role in emission mitigation. The focus is the pulp and paper industry, which is energy-intensive. Development of industrial energy efficiency has been studied before but the role of industrial transformation is still mostly unknown. The knowledge must be improved, to be able to predict future developments in the most effective way. In this research, impact of various production unit closures and start-ups on energy efficiency of the Finnish pulp and paper industry were studied utilizing statistical analysis. Results indicate that about 20% of the Finnish pulp and paper industry energy efficiency improvement between 2011 and 2017 is caused by the major structural changes. The rest, 80% of the progress, was mainly due to improved technology and more optimal operational modes. Additional findings suggest that modern mill start-ups have a significantly greater potential to reduce energy consumption than old mill closures.

Keywords: energy efficiency; pulp; paper; energy consumption; structural change

1. Introduction

World energy usage increases as a result from global population growth and increasing level of wellbeing [1]. Energy supply security, reduction of greenhouse gas emissions, and efforts to reduce global warming are the main issues acting as a driving force for changing our present energy usage [2]. Energy efficiency improvement has an important role in the cost-effective energy saving and in the sustainable development [3]. Energy efficiency means an ability to produce a high number of products with as low an amount of energy as possible. In addition to environmental advantages, enhancing energy efficiency lowers operating costs and consequently improves competitiveness [4]. Of the various sectors, industry was the largest energy consumer in the world in 2016: its share was about 30% of total consumed energy [5]. Therefore, significant results can be reached by improving industrial energy efficiency [6,7].

In Finland, industry and construction consumed 47% of total electricity in 2015 [8]. Inside the field of Finnish industry, forest industry was clearly the major consumer [9]. Production of pulp and, subsequently, paper requires significant amounts of energy. A high number of factors affect the energy consumption of pulp and paper industry mills, such as the type, size, age, and location of the mill, type of products, raw materials, and processes, as well as operational choices [10]. Even if energy consumption is measured to sufficient accuracy, evaluating the role of various changes to energy efficiency is challenging. Many factors have an influence on energy efficiency, but in many cases the size of the impact is unknown. By enhancing awareness about affecting factors, it is possible to develop mills and processes in an efficient way towards energy efficient operation. Several studies have been done relating energy efficiency measurement and improvement on industry [11–17]. Mostly, they concentrate on finding relevant energy intensity values [18,19]. Less attention has been paid to the effect of structural changes, i.e., retirements and additions of capacity.

The aim of this work is to study the impact of structural changes on energy efficiency of Finnish pulp and paper industry. EU (European Union) and IPPC (Integrated Pollution Prevention and Control) have called for intensification of energy usage [9]. At the same time, the business environment of pulp and paper industry is rapidly changing, and consequently pulp and paper industry has gone through a large structural change. Pulp and paper industry has been forced to implement notable changes to operate in a profitable way despite the challenging business environment. The demand for printing and writing paper is decreasing in EU, whereas an increasing amount of packaging materials is needed [20]. Thus, production grades are changing. Many mills have or are planning to enlarge their product portfolio towards new bioproducts, such as biofuels and biomaterials [21]. The major changes seen in Finland have been old unit closures, new unit start-ups and conversions of paper mills to products with increased demand, such as paperboard. It can safely be assumed that neither closed and nor started units have an average energy efficiency. Therefore, this study focuses on the effect of closures and start-ups on the pulp and paper industrial energy efficiency.

This paper consists of five parts. Section 2 introduces Finnish pulp and paper industry, especially developments in its production and energy consumption. Section 3 presents research methods and data gathering process. Results are shown in Section 4. Section 5 is discussion that considers received results. Finland was chosen as the target country of the research. It belongs to the major forest industry countries and the structural change has been significant in the past decade. The study is executed as a scenario analysis. Mill energy consumption data, gathered from various sources, is used for creating three scenarios, which are compared. The study focuses on energy aspects and for example economic measures are excluded.

2. Finnish Pulp and Paper Industry

Two-thirds of Finland is covered by forests [22]. Due to the ample resources Finland is one of the most important countries for the forest industry in the world. Forest industry was the second-largest employer in Finland in 2017 with 42,000 employees and accounting about 20% of both gross value of manufacturing and export [23].

Pulp and paper industry consumes most of the energy the forest industry uses. Mechanical forest industry is much less energy intensive. Its main products are sawn wood and wood-based panels. New forest industry bioproducts such as pellets, biogas, or biofuels are still of small volume. Wood pulp is the main virgin fiber material of paper. Also recycled or non-wood fiber is used. Chemical pulp is produced using sulphate process, sulphite process or other minor pulping processes. These processes are based on separating lignin from wood fibers by using alkaline chemicals in cooking. 80% of pulp produced in the world is produced by sulphate process [24]. In Finland, the sulphite process has not been used since 1992 [22]. Mechanical pulping consists of a grinding and refining processes, which utilizes mechanical energy to separate wood fibers. Many pulping processes accounted for as mechanical pulping are actually combinations of chemical and mechanical stages. Pulps produced by different processes have various properties and manufacturing costs. In addition to chosen process, properties are affected by treatment of fiber after pulping, such as bleaching. Paper is made in a paper machine that consists of forming, pressing, and drying sections. Different finishing processes like calendaring and coating can be utilized to achieve needed paper properties. The major paper grades are packaging papers and paperboards, printing and writing papers, and tissue papers.

2.1. Production

The major products of Finnish forest industry are pulp, paper, and mechanical forest industry products such as sawn wood and wood-based panels. In addition, a wide range of bioproducts is produced. Between 2010 and 2017, production of pulp and mechanical forest industry products has increased 336,000 tons and 2,350,000 m^3, respectively [20,25]. Paper production has been declining and in 2017 paper production was 1,462,000 tons lower than in 2010 [20]. Finland is an important exporter of pulp and paper products [26]. Exported pulp and paper were 3.7 million tons and 10 million tons in 2018, respectively [20].

Finnish forest industry has gone through a large structural change, which has modified product portfolios and production rates. Table 1 shows production volumes at the beginning and end of the decade. Production of printing and writing paper has decreased following the global trend. A main factor is the lowered demand for newsprint and magazine paper as a result from online publications. The production of paperboard has instead increased. As the level of wellbeing, especially in Asia, has risen, the demand for pulp and paper is increasing there [10]. Higher global pulp demand and favorable prices have increased chemical pulp production in Finland [26].

Table 1. Pulp and paper production in Finland in 2010 and 2017. Data from [20].

Grade	2010 (1000 t/a)	2017 (1000 t/a)	Change (%)
Paperboard	2830	3622	33
Other paper	1462	1232	−4
Printing and writing paper	7466	5422	−26
Chemical pulp	6733	7703	14
Mechanical and semi-chemical pulp	3775	3141	−13

Finnish pulp and paper industry consists currently of 17 paper mills, 14 paperboard mills, and 18 pulp mills [23]. Only few stand-alone pulp mills produce dried pulp that is delivered to paper mills. Over 80% of the pulp, as well as over 90% of the paper, is produced in integrated mills, as can be seen in Table 2. Integrated mill means that both pulp and paper are produced at the same site. Integration rate affects significantly the energy usage and the energy efficiency. Integrated mills produce pulp more energy efficiently than stand-alone mills, because they have no need for pulp drying and re-pulping and secondary heat can be used to preheat water needed in the paper machine. Practically all mechanical and recycled pulp units in Finland are integrated with a paper mill.

Table 2. Division of pulp and paper production in Finland. Elaborated from [9].

Category	Share of Pulp Production (%)	Share of Paper Production (%)
Bleached chemi-thermomechanical pulp	4	-
Integrated recycled pulp and paper	2	3
Stand-alone chemical pulp	13	-
Stand-alone paper	-	6
Integrated mechanical pulp and paper	20	35
Integrated chemical pulp and paper	60	55

2.2. Energy Usage

Finnish forest industry consumed 19.7 TWh electricity in 2017, which is about one fifth of Finnish total electricity consumption [8]. Total energy consumption in Finland was 1352.3 PJ in 2017 [27]. Forest industry used 217 PJ fuels [8], which is a significant share of the total fuel usage. Forest industry is renewable-intensive, and it accounts for 45% of production and consumption of Finnish bioenergy [10]. During the 2010s, consumption of primary energy decreased only 0.3% Fuel consumption development towards fossil fuel-free operation is a significant change. The share of biofuels increased from 76% to 85% whereas the share of fossil fuels (natural gas, heavy fuel oil, and coal) decreased from 17% to 10%. Primary energy consumption in 2010 and 2017 is presented in Table 3.

Table 3. Primary energy consumption of Finnish forest industry in 2010–2017. Elaborated from [8].

Primary Energy Usage (1000 TJ)	2010	2017	Change
Biofuels, liquid	13,534	14,984	11%
Biofuels, solid	29,787	35,468	19%
Natural gas	30,820	13,248	−57%
Peat	12,649	7875	−38%
Heavy fuel oil	6217	5454	−12%
Coal	1048	2536	142%
Others	1910	2685	41%
Total	217,774	217,115	−0.3%

Table 4 presents electricity consumption development of Finnish forest industry in 2010–2017. Data utilized in the table is presented in Supplementary material. Pulp and paper industry consumes over five times more electricity than mechanical forest industry and production of bioproducts combined. That is because chemical forest industry utilizes processes with a high energy-intensity. On the other hand, chemical pulp mills produce a lot of energy from the combustion of their sidestreams. Modern pulp mills are able to produce much more heat and over double the electricity than their processes require [28]. The surplus energy can be sold. In addition to electricity consumption, pulp and paper industry is a significant heat consumer. It is challenging to study the heat consumption of Finnish forest industry. Mills do not record or inform their heat consumption precisely because heat is not as valuable a product for mills as electricity. Therefore, this paper does not present development of heat consumption for the lack of data, but heat saving due to structural changes will be calculated.

Table 4. Electricity consumption of Finnish forest industry in 2010 and 2017.

Electricity Consumption (GWh)	2010	2017	Change	Share of Total Consumption in 2017
Bioproducts	382	667	74%	3%
Mechanical forest industry	956	1138	19%	6%
Pulp and paper	20792	17819	−17%	91%
Total	22130	19624	−13%	

Finnish forest industry electricity consumption has been slightly decreasing during the last decade. The annual electricity consumption has decreased during 2010–2017 by 2506 GWh. Reduced production of paper has decreased electricity use. At the same time, the higher amounts of bioproducts, pulp, and mechanical forest industry products have increased the total electricity consumption. In addition, changes in the end products have affected the energy consumption. The part of the electricity consumption that is not attributed to production changes can be assumed to be caused by energy efficiency improvements.

Available high-quality data restricts the reviewed period to 2011–2017. Only electricity consumption statistics, including consumption of the total forest industry, are available [8]. Therefore, the consumption of pulp and paper industry must be calculated. The most accurate way for defining electricity consumption of pulp and paper industry is to subtract electricity consumptions of mechanical forest industry and bioproducts manufacturing from the total consumption. The electricity consumption (Figure 1) is estimated using several sources, which are introduced in Supplementary material. Annual electricity usage was 2336 GWh higher in 2011 than in 2017. A significant reason for electricity consumption decrease is the reduction of production rate and evolved product palette. Even if the chemical pulp production has increased, the paper production has decreased more, and consequently total electricity usage is currently lower than at the beginning of the decade. Based on gathered production data (Supplementary material) and typical electricity consumption values [29], the decrease caused by lower production rates and changed products is 1004 GWh (~5%). Therefore, an approximate

1332 GWh (~7%) decrease must be attributed to other reasons. The major factor for this decrease has been the energy efficiency improvement.

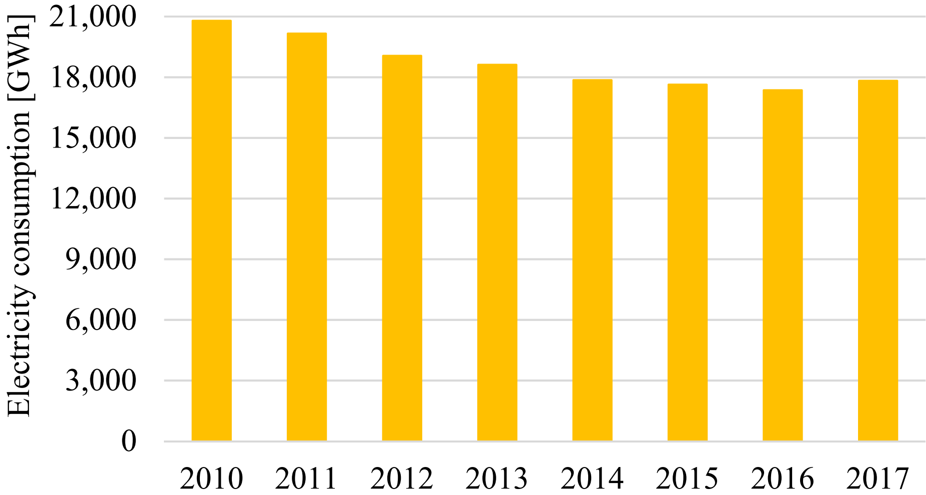


Figure 1. Pulp and paper industry electricity consumption in 2011–2017.

2.3. Structural Changes

Structural changes have been manifested in unit closures, unit start-ups and unit conversions to produce more profitable grades [9,29,30]. Changes in demand have led to significant reductions in pulp and paper production capacity [31]. In addition to whole mill closures and start-ups, major capacity increases and single machine upgrades have been taken into account in this study. In cases of conversions, old product is counted as a closure and new product is counted as a start-up. Table 5 presents closures during reviewed period. Paper production capacity removals have been 2,600,000 tons. Pulp capacity closures account to 530,000 tons. The largest wave of closures has occurred in printing and writing paper mills.

Table 5. Unit closures in Finland in 2011–2017 [9].

Unit	Capacity Decrease (t/a)	Product	Year of Closure
Myllykoski (UPM)	600,000	Magazine paper	2011
Myllykoski (UPM)	213,000	Groundwood	2011
Ääneskoski (M-Real)	200,000	Fine paper	2012
Rauma (UPM)	245,000	Magazine paper	2013
Veitsiluoto (Stora Enso)	190,000	Magazine paper	2014
Lohja (Loparex)	68,000	Other paper	2014
Kaukas (UPM)	270,000	Magazine paper	2014
Jämsänkoski (UPM)	270,000	Magazine paper	2014
Kauttua (Jujo Thermal)	10,000	Other paper	2015
Varkaus (Stora Enso)	285,000	Fine paper	2015
Kotka (Kotkamills)	185,000	Magazine paper	2016
Tervasaari (UPM)	100,000	Other paper	2016
Kyrö (Metsä Board)	105,000	Other paper	2016
Kyrö (Metsä Board)	74,000	Groundwood	2016
Äänekoski (Metsä Fibre)	500,000	Chemical pulp	2017

Table 6 shows the start-ups during reviewed period. During the 2010s, significant forest industry investments have been made in Finland: Reforms mainly concern enlargements in chemical pulp and paperboard production, but also biofuel mills have been built [32]. The increased demand for paperboard can be seen in the table. The number of unit start-ups is lower than the number of unit closures. There are three mills that were converted to produce paperboard, one totally new pulp mill, and three mills with a significant capacity growth. The capacity increase of paper and pulp has been 880,000 tons and 1,570,000 tons, respectively.

Table 6. Unit start-ups in Finland in 2011–2017 [9].

Unit	Capacity Increase (t/a)	Product	Year of Start-Up
Simpele (Metsä Board)	80,000	Paperboard	2011
Imatra (Stora Enso)	20,000	Paperboard	2015
Varkaus (Stora Enso)	380,000	Paperboard	2015
Kymi (UPM)	170,000	Chemical pulp	2015
Kotka (Kotkamills)	400,000	Paperboard	2016
Äänekoski (Metsä Fibre)	1,300,000	Chemical pulp	2017
Kymi (UPM)	100,000	Chemical pulp	2017

3. Methods

In this study, a method for analyzing structural energy efficiency changes was developed. Utilizing the method required gathering a high amount of individual mill energy consumption data from various sources. Both electricity and heat consumption data were gathered, verified, and analyzed.

3.1. Statistical Analysis

The study was executed as a statistical analysis. We derived energy utilization for Finnish pulp and paper sector as reference scenario one. Two additional energy consumption scenarios were made. The second scenario assumes that no units were closed but new ones were started. The third one assumes no new units were started but old ones were closed. Yearly production of all grades in each scenario was kept constant. Used method is presented step by step in Figure 2. Firstly, mills' heat and electricity consumption data, as well as mills' production rates, were collected and validated. To facilitate product division, all mills were categorized to groups introduced in Table 7. Mills' heat and electricity consumptions were decomposed to different products to enable comparing similar products. Energy consumptions of closed and started mills were compared with average existing ones. The average existing mill was defined using consumption values of at least five Finnish pulp and paper industry mills producing similar products as certain changed mill. Changes in energy consumption were calculated by assuming that average mills would replace the production of changed mills. Mills never operate with full capacity during the whole year due to maintenance stoppages etc. Calculations are done utilizing production rates 85% of the maximum capacity. Finally, obtained yearly energy consumption values were compared with statistical values.

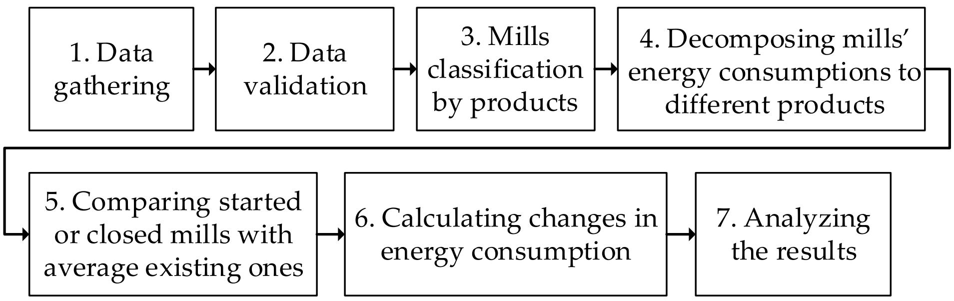


Figure 2. Utilized methodology step by step.

Table 7. Pulp and paper categorization groups.

Pulp	Paper
Chemical pulp	Paperboard
Groundwood	Magazine paper
Refiner	Fine paper
Semi-chemical pulp	Other paper
Chemi-mechanical pulp	
Recycled pulp	

Many Finnish mills are integrated, which makes evaluating energy consumption challenging. Mills reports usually the consumption of the whole mill, and therefore the consumption must be divided to different processes and products. The total energy consumption consists of the sum of consumption of every pulp and paper grade produced in the same mill:

$$E_{tot} = \sum_{i=1}^{n} P_i \cdot e_i \quad (1)$$

where E_{tot} is total energy consumption of the mill, P_i is production rate of the product and e_i is a weighting factor. The weighting factor is a typical specific energy consumption of the product. To be able to divide the consumption values to different pulp and paper grades, weighting factors presented in Table 8 are utilized.

Table 8. Weighting factors for dividing consumptions for different products. Data from [29].

Grade	Electricity Consumption (GJ/t)	Heat Consumption (GJ/t)
Chemical pulp	2.4	11.2
Groundwood	6.5	0
Refiner	5.5	−2.4
Semi-chemical pulp	1.6	3.6
Recycled pulp	1.4	0.2
Magazine paper	2.5	4.6
Fine paper	3.1	4.9
Fluting	1.2	5
Paperboard	2.4	5.6
Newsprint	2.1	4.7
Other paper	2.5	7.5

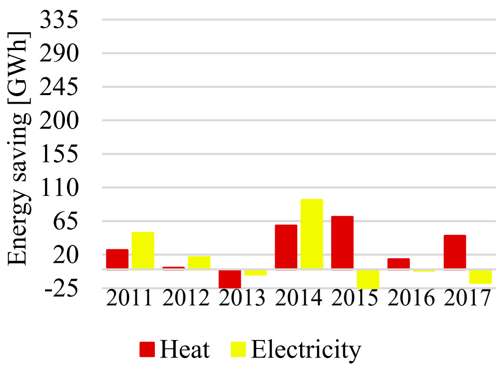
3.2. Data Gathering

Verifying and analyzing the results requires gathering reliable heat and electricity consumption data from every Finnish pulp and paper mill. In addition, the products and production rates of every mill must be known. The focus was on closed and started mills and mills similar with changed ones. Finding energy consumption data is difficult because most companies like to keep their consumption and production values as a trade secret for commercial purposes. A high number of sources, mainly environmental reports and permits, university theses dealing with energy use of individual mills, articles, and other publications, were utilized for assigning heat and electricity production and consumption values for each mill and each product. Gathered data and sources are presented in Supplementary material. Most of this work was started in a project for the Finnish Ministry of Environment [30]. Annual production rates for 2011–2017 were obtained from Finnish Forest Industries [33]. Occasionally, there was a high statistical difference with some of the values when compared with other similar mills. Clearly incorrect values were left out of the study or corrected to more reasonable ones.

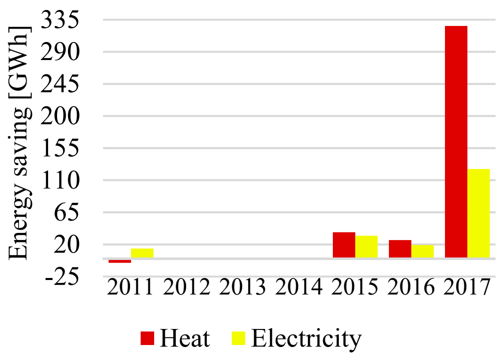
Gathering statistical data includes known sources of error. Mills do not necessarily measure and report their production and consumption values in a same way and the measurement devices and practices can be different. In addition, specific energy consumption in a certain mill varies significantly, for example due to capacity utilization rate or climate conditions (winter/summer). Some gathered values were reported several years ago which also increases the possibility of errors. However, utilization of individual mill values instead of statistical averages allows one to study the structural changes.

4. Results

Calculated results are shown in Figure 3a,b. Positive values define years with electricity or heat energy savings due to structural changes. Negative values indicate years when average of existing mills have been more energy efficient than started mills or less efficient than closed mills, and therefore the total energy consumption has increased. Figure 3a presents the impacts of unit closures on heat and electricity consumption. Heat is saved every year excluding 2013 when only one, relatively energy-efficient, paper machine was closed. Between 2015 and 2017, heat was saved but electricity consumption increased somewhat. Total heat and electricity savings due to closures were 193 GWh and 109 GWh, respectively. Figure 3b presents the effects of unit start-ups. New start-ups seem to improve the energy efficiency. The most significant savings occurred in 2017 when a modern pulp mill with a high capacity was started. In 2012–2014, no new mills were started. Total heat and electricity savings due to start-ups were 383 GWh and 191 GWh, respectively. Closures and start-ups together saved heat and electricity 577 GWh and 299 GWh, respectively. As many factors, especially the accuracy of data reported by mills, affect the results, they should be viewed as the best estimation with the gathered data and used assumptions.



(a)



(b)

Figure 3. (**a**) Energy savings due to unit closures. (**b**) Energy saving due to unit start-ups.

Figure 4 presents the changes in Finnish pulp and paper electricity consumption. Changed production volumes are the main reason for changes in electricity usage. The black line estimates electricity consumption of chemical pulp and paper industry if the units present in 2011 would have continued to produce each year's production. It can be seen that both unit closures and start-ups have decreased the electricity consumption. Therefore, it seems safe to say they have increased the energy efficiency.

Figure 5 sums up the results of the development of electricity usage over the studied period. Decrease of annual consumption in pulp and paper industry during reviewed period was 2336 GWh. Approximately 1004 GWh was accounted for by decreased production rate and changed production portfolio. Therefore, decrease of 1332 GWh has been due to various energy efficiency improvements. Structural changes have decreased the annual electricity consumption by 299 GWh, and therefore almost 22% of the energy efficiency improvement is accounted by unit closures and start-ups. The respective shares of the start-up and closures were about 8% and 14%. The majority, almost 80%, of the improvement is derived from other energy efficiency improvement projects. It was previously mentioned that production of changed mills is 85% of the total capacity. If the total capacities had been used instead, the structural changes' share of the energy efficiency improvement would have been 26%. These results are valid only with the assumptions used here. If production volumes or the mix of different products change, the results would change.

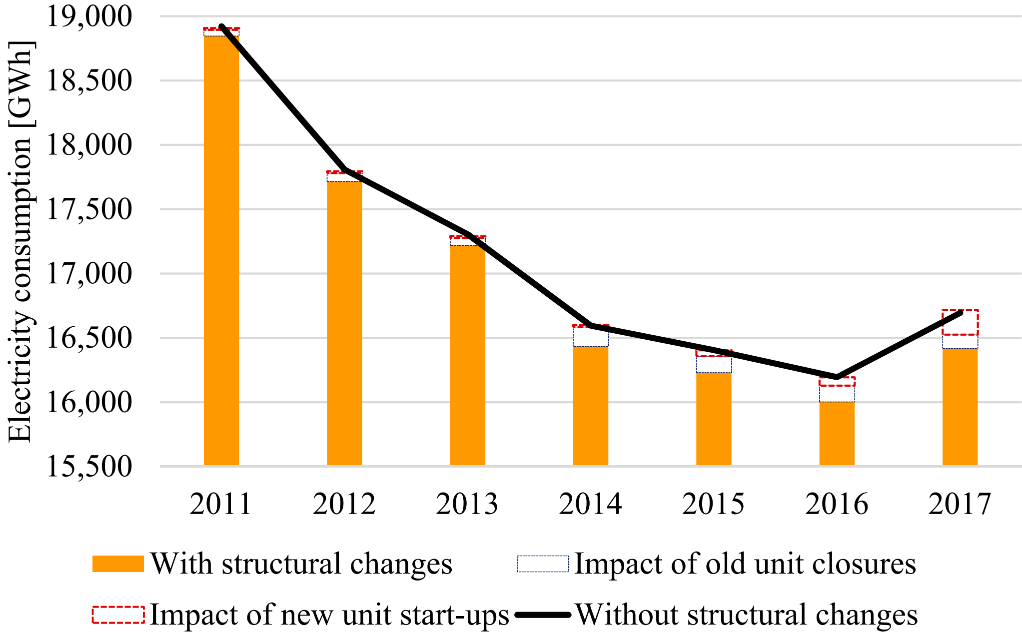


Figure 4. Effect of structural changes on electricity consumption.

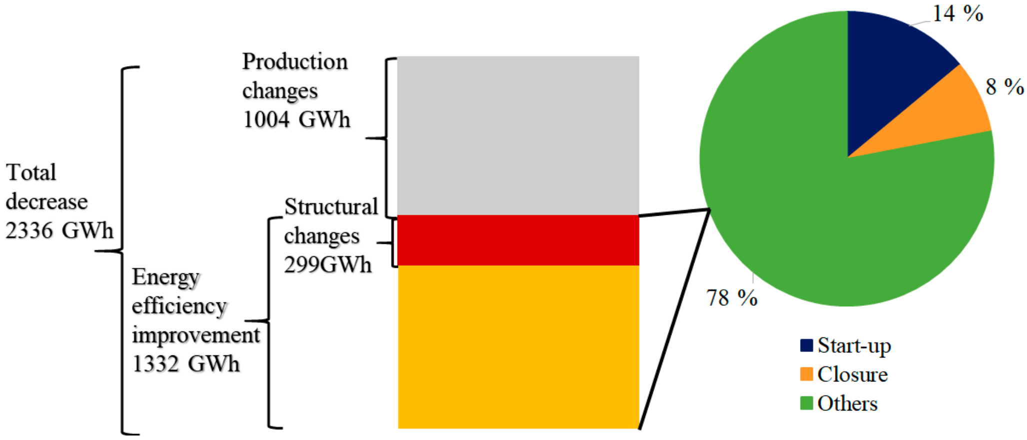


Figure 5. Division of electricity consumption changes in Finnish P&P industry in 2011–2017.

5. Discussion

The results indicate that, considering electricity, the structural changes had about 20% effect on the total energy efficiency improvement. With a moderate to high certainty, it can be stated that structural changes have improved the energy efficiency of Finnish forest industry. However, the structural changes explain only one-fifth of the improvement, and the remaining four-fifths must be explained with other factors. These major factors are changes in used technology and improved modes of operation. These technology changes include both small and large energy efficiency investments. Large investments, like modernizations of individual departments, improved utilization of secondary and waste heat or water cycle closures, can have significant impact on energy consumption.

Small changes, like repairing defective components or correcting operating practices, also have a clear influence on energy efficiency. Improvements in modes of operation consist of education and motivation of personnel as well as ensuring reliable data from processes is collected.

The results suggest that the size of heat savings was almost twice the size of the savings in electricity consumption. That finding meets the current trends. New technologies, for example, improved pressing and drying technologies, have increased the electricity consumption while they have decreased heat consumption [9]. In addition, modern devices for environmental protection have typically higher electricity consumption than older ones [10]. In summary, heat consumption of modern mills should clearly be lower than the heat consumption of older ones, and on the other hand, electricity consumption might be similar or even higher in modern mills in comparison to old ones.

Another interesting finding is that start-ups seem to improve energy efficiency more than closures. Start-ups have saved 70% more heat and electricity than closures, even if the amount of closed capacity was 30% higher than the started one. This finding can be explained by a high-level maintenance and regular upgrades of old mills in Finland. With good care, operating mills are kept in a good shape and the energy efficiency of them is thus not significantly lower than an average Finnish mill. On the other hand, this study indicates that modern mills have a high potential to reduce energy consumption of pulp and paper industry.

This study is valuable for policy makers, legislation, and industries. It indicates that structural changes have only a minor impact on the total energy efficiency and therefore results highlights importance of improving existing mills. Efforts used for energy efficiency improvement during recent decades have realized as significant results. On the other hand, a new large-size mill started in 2017 operates with high energy efficiency but its impact on total energy efficiency is low. The results encourages actors to invest in existing mills' improvement and maintenance. The Finnish pulp and paper industry has changed significantly during 2010s. The change has affected production rates and portfolio as well as energy usage and efficiency. Change will likely continue in the future. It is probable that new bio-based products reach an important position and even more printing and writing paper will be replaced with paperboard [29]. The changes will lead to modifications of pulp and paper making units. The results of this study can be used for estimating energy efficiency changes also in the future.

In further studies, it would be interesting to define the shares of other factors of energy efficiency improvement. Studying this topic would be difficult because a high amount of data about changes done in the mills, operational modes of the mills and energy consumptions should be made available. Also, the impact of structural changes on a global level should be examined. Varying structure of pulp and paper production as well as mill age will lead to changes in the presented results in every country. For example, countries with old mills operating with original processes probably save a high amount of energy by closing these old mills.

6. Conclusions

Finnish pulp and paper industry has gone through a large structural change that has manifested itself as several unit closures and a few new unit start-ups. In addition to changing production rate and product portfolio, structural changes have affected energy efficiency of the Finnish pulp and paper industry. The study was executed by collecting a high amount of mills' operational data and creating three scenarios. With the scenarios, energy efficiency improvement due to structural changes was estimated. Between 2011 and 2017, annual electricity consumption has decreased due to reduced production rate, changed products, and energy efficiency improvements. Energy efficiency improvements consist of several factors, such as structural changes, improved technology and processes, and more optimal operational choices. This study estimates that approximately 20% of the energy efficiency improvement is a result of structural changes. The remaining 80% is a sum of the other factors. The study also indicates that modern mill start-ups have a greater effect on energy efficiency than old mill closures. However, improving existing mills has a higher effect on total energy efficiency than closing old and starting new mills.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/19/3689/s1, Table S1: Products and production rates of Finnish pulp and paper mills. Table S2: Electricity consumption of Finnish pulp and paper mills. Table S3: Heat consumption of Finnish pulp and paper mills. Table S4: Specific electricity consumption of Finnish pulp and paper production. Table S5: Specific heat consumption of Finnish pulp and paper production. Table S6: Production rates of mechanical forest industry products. Table S7: Electricity consumption of mechanical forest industry products. Table S8: Production rates of bioproducts. Table S9: Electricity consumption of bioproducts. Figure S1: Electricity consumption of Finnish forest industry in 2010s.

Author Contributions: S.K. was responsible for the calculations and writing the manuscript. E.V. and T.L. made valuable comments and remarks during the process of writing.

Funding: The project has received funding from the Academy of Finland project "Role of forest industry transformation in energy efficiency improvement and reducing CO_2 emissions" which is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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