Benchmarking Analysis of Energy Efficiency Indicators in Paper Mill

Yanzhong Zhang, Mengna Hong,* Jigeng Li, Xiaobin Chen, Zhiqiang Zeng, and Huanbin Liu

Paper mills consume a large amount of energy, which is an important factor restricting their sustainable development. Benchmarking is a critical method for discovering the energy-savings potential of mills. To address problems such as the absence of indicators for energy efficiency benchmarking, the influence of different basis weights on energy efficiency levels and on the estimation of energy-saving potential, this paper makes use of production line-based and process-based benchmarking in coated paperboard production. The indicator system is constructed to collect data and quantify the energy efficiency. K-means clustering is used to classify the basis weight and energy efficiency data for seven months and obtain the benchmark values. The results showed that the specific energy consumption (SEC) decreased with the increase in basis weight. An analysis of production line-based benchmarking for a paper mill in China indicated that energy efficiency reached the level of 5.92 to 6.94 GJ/t, which was 10.8 to 23.91% lower compared with the European Union best available energy level (7.78 GJ/t) and 6.28 to 24.6% higher compared with the energy consumption of American paper products integrated production units (5.57 GJ/t). These energy-saving measures should be taken into account in order to raise the energy efficiency in paper mills.

Keywords: Paper mill; Energy efficiency benchmarking; Energy-saving potential; K-means

*Contact information: State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Guangzhou 510640, P. R. China; *Corresponding author: femnhong@scut.edu.cn*

INTRODUCTION

As the propelling force in any paper mill, energy plays a fundamental role in driving all the unit processes and equipment. Improving the energy efficiency, in the theme of sustainable corporate behavior, is seen as a means of increasing global competitiveness in the future (May *et al*. 2005).

Appropriate performance indicators have been used to identify energy efficiency opportunities. The indicators calculated for assessing energy efficiency are different in different countries. Through a collaborative European effort, a common methodology adopted for assessing energy efficiency improvements has been discussed, and about 600 comparable energy efficiency indicators have been defined (Bosseboeuf *et al*. 1997). Within Asia-Pacific Economic Cooperation, a desire to promote the importance of energy efficiency policies and measures has been expressed, and strategies for assisting individual economies in increasing their economic efficiency through the wiser user of energy have been developed. Energy-intensive industries such as the paper industry need to take into account the relative economic significance of these strategies. Meanwhile, economic indicators have also been analyzed and their usefulness assessed (Yokobori

2003). Mesfun and Toffolo (2014) calculated the investment opportunity for the considered scenarios as an indicator of their economic convenience. Science and technology indicators based on empirical policy conclusions and further theorizing were produced and used, and these were shown to be insufficient for understanding and explaining industrial and technological change (Staffan 1998). Regarding energy efficiency improvement as the primary focus, Ruohonen *et al*. (2010) discussed the indicators used to make the evaluation, *e.g.*, the specific energy consumption or the fuel consumption in a mechanical pulp and paper mill, and identified great energy-saving potentials. Furthermore, another research team determined the changes in energy efficiency by calculating the SEC in a paper mill (Peng *et al*. 2005). Chu *et al*. (2016) investigated the removal efficiency of the chemical oxygen demand (COD) and color of effluent after treatment according to indicators of paper mill wastewater.

Many process integration and optimization techniques have been specified to enhance energy efficiency in paper mills. A holistic evaluation of the pulp-making and papermaking processes involved in the chain is crucial in order to investigate the potential for energy savings. Kubš *et al.* (2016) analyzed the energy efficiency of the milling of thermally modified and unmodified beech wood, taking into consideration the angular geometry of the cutting tool (milling cutter). A three-link model based on the second law of thermodynamics provides a scientific basis for understanding the energy system of the paper-making process and could help the mill implement the diagnosis and analysis from a systems point of view in order to achieve global optimization of energy systems (Li *et al*. 2010). Panepinto *et al.* (2016) evaluated the energy efficiency of a large wastewater treatment plant by a multi-step methodology in Italy. A set of comprehensive and detailed measures that improved energy efficiency were summarized by Kramer *et al*. (2009). Energy efficiency practices and technologies that could be implemented at the component, process, facility, and organizational levels were discussed. Additionally, a well-structured comprehensive review on emerging energy efficiency technologies for pulp and/or paper companies has also been provided (Kong *et al*. 2016). The energy-saving potential has been determined through a conventional analysis of energy balances (Utlu and Kincay 2013). The low energy-efficiency of the U. S. manufacturing sector, including paper mills, suggests that substantial opportunities for better industrial energy utilization still exist (Al-Ghandoor *et al*. 2010). These techniques focus on energy flow information and how to minimize energy consumption. However, the success of any study on process improvement depends on the quality of the available data and the way in which the specific characteristics are incorporated in the applied conceptual models (Savulescu and Alva-Argaez 2008). An Energy Management System (EMS) can be deployed to achieve the valuable fundamental energy data for the further energy analysis. An online energy supervisory evaluation was proposed based on the integrated energy information of an entire mill (Wu *et al*. 2012). The areas of power generation and energy recovery have been emphasized, including the process of implementing energy management functions with computers (Kaya and Keyes 1983). In order to achieve optimum energy management of the power plants in pulp and paper mills, production costs have been reduced by using mass and energy balances and a mathematical formulation of the electrical purchase contract (Sarimveis *et al*. 2003). How energy improvement measures would affect the operation of the powerhouse and how to quantify the potential economic advantage for kraft wood pulping mill were emphasized by Cakembergh-Mas *et al*. (2010).

As one of many techniques developed to help a company improve its efficiency, quality, and productivity, benchmarking was defined by the Xerox Corporation in the 1980s as, "searching for those best practices that will lead to the superior performance of a company" (Gannaway 1996). The ability to compare the energy consumption of different entities (for instance, production line, unit process, or equipment) and to normalize energy consumption into some key metric (such as GJ/t or kWh/t), allowing an "apples-to-apples" comparison between entities, is one key step in the benchmarking process (Van 2004). With regard to performance improvements in paper mills, significant opportunities still exist through application of the best practices and best available technologies (Bhutani 2015). Energy benchmarking comparisons were conducted in 23 Dutch paper mills based on industrial data on a detailed processing level (Laurijssen *et al*. 2013). Another benchmarking study found sources of wasted energy in a Canadian pulp and paper mill and revealed that the sector's best practices were near the theoretical minimums for certain process segments (PPIO Canada 2008). As such, the efficiency of the base-case process was given by a benchmarking analysis that globally assessed the current energy performance of the process and identified areas of inefficiency (Mateos-Espejel *et al*. 2011). Benchmarking encourages quantitative measurement, fosters communication between different roles, and creates an atmosphere in which proactive change is encouraged to identify specific goals as well as ways to potentially attain these goals (Gannaway 1996).

In this study, the production process of a paper mill in China whose leading product is high-grade brand coated paperboard was analyzed based on historical data. To make use of production line-based and process-based benchmarking, an indicator system was constructed. The whole data set was organized to illustrate the influence of different basis weights on the energy efficiency levels through K-means clustering. Finally, this paper analyzes the energy efficiency benchmarking process and explores the energy-savings potential.

EXPERIMENTAL

Indicator Construction

Energy efficiency measures how well the energy in a system is used to produce a relevant output (Yokobori 2003). The performance of certain indicators can be used to answer detailed or general questions related to energy efficiency, and, thus, the primary task of this research was to propose a framework for determining reliable indicators in a paper mill context. The following two guidelines were observed: (i) The selection of indicators was mainly determined by the object of evaluation and the goal of the application. These indicators might reflect not only the characteristics of one particular aspect, but also provide a comprehensive view of the overall energy efficiency at the production line level and the processing unit level. (ii) Using either a top-down or bottom-up approach, the connotation of each indicator, *e.g.*, the effective coverage range and unit of measurement, was taken fully into account.

The framework should cover the key unit processes that affect the energy efficiency level. For each different unit process in a paper mill, substantial amounts of equipment are utilized. In the interest of integrating qualitative and quantitative methodologies, indicators were chosen that accomplished a variety of functions, ranging from monitoring energy efficiency to guiding production and strengthening strategic management. Figure 1 shows that the indicators could be arranged in a hierarchical structure, and that all indicators could be quantified using different types of reliable statistical methods.

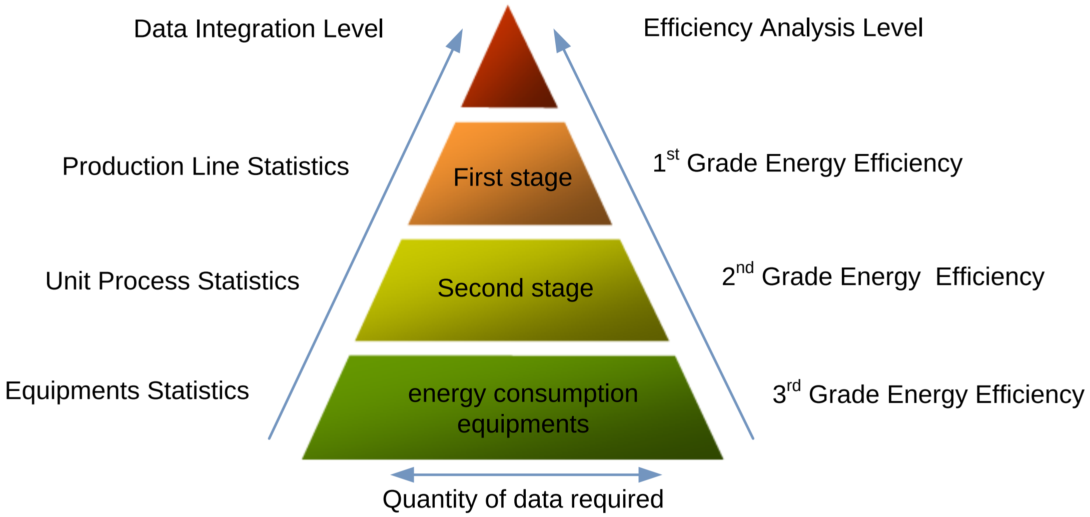

Fig. 1. Indicator hierarchy pyramid

An understanding of the implications of each indicator was necessary to conduct energy audits and quantify the energy efficiency of the system. The first step in drawing distinctions was to select an SEC to quantify the gap in different production lines and assess whether the energy efficiency was reasonable compared with the benchmark value of the enterprise itself or of international advanced values. The second step was to divide the production line, which consumes power and steam, into unit processes to evaluate potential energy savings by unit process. With respect to energy structure and usage efficiency, the sensors of the energy consumption equipment, which are designed to measure specific parameters such as electric current of exhaust fans, steam flow, steam temperature, steam pressure, and so on, was considered a useful tool for the integration of data from different sources and the quantitative analyses thereof. The availability of comprehensive and consistent data is an important foundation for the construction of more robust energy efficiency indicators. Therefore, the first step was to collect data from energy consumption equipment in accordance with the depth of analysis desired. The quality of the data required depends on the level of automation in the whole factory. As more detailed and comprehensive analyses are desired, the data requirements also increase.

K-means Clustering Algorithm

Considered one of the most important techniques of the Knowledge Discovery in Database (KDD), cluster analysis can be applied to many areas, including biology, market research, and medicine. K-means is the simplest and most basic algorithm of cluster analysis. The most obvious application of the K-means process the qualitative and quantitative evaluation of the large amounts of N-dimensional data by generation of reasonable “similarity groupings” or “clusterings” (Macqueen 1967). For a given data set $X = \{x_i | i = 1,2, \ldots n\}$, where each x_i is represented by $A_1, A_2, \ldots, A_d$ attributes. The similarity is given by the Euclidean distance between $x_i = (x_{i,1}, x_{i,2}, \dots, x_{i,d})$ and $x_j = (x_{j,1}, x_{j,2}, \dots, x_{j,d})$, and the formula is obtained as follows,

$$d(x_i, x_j) = \sqrt{\sum_{k=1}^{d} (x_{ik} - x_{jk})^2} \tag{1}$$

so that the squared-error objective function is defined as follows:

$$E = \sum_{i=1}^{k} \sum_{p \in X^i} \|p - m_i\|^2 \tag{2}$$

where X^i represents the cluster, m_i is the mean value in a cluster X^i, and p is a spatial point of X^i. The main steps of the K-means algorithm are as follows,

Step 1: set the appropriate k, $k = 1,2, .., n$;

Step 2: initialize the clustering centers $z_j = (z_{j,1}, z_{j,2}, \dots, z_{j,d})$, $j = 1,2 \dots k$;

Step 3: Compute the distance $d(x_i, z_j)$, $i = 1,2, \dots, n$, $j = 1,2, \dots, k$, and assign x_i to the nearest cluster. Finally, the average value of each cluster is calculated and regarded as the new clustering centers z_j;

Step 4: Calculate the squared-error objective function E and judge if $|E_{current} - E_{previous}| < \xi$, the algorithm stops; otherwise, return to step 3 until the termination condition is reached.

Validity Index

In K-means clustering analysis, it is necessary to choose a k number as the initial cluster centering and find a partition to minimize the sum of the squared error over all the k clusters. However, there is no perfect mathematical standard to ensure the k number. In this study, to minimize human intervention and satisfy the basic principles of the cluster algorithm, that the within-cluster difference is minimized and the between-cluster difference is maximized (Mishra *et al*. 2012), required use of the validity index $F(X, k)$ to confirm the optimal cluster number,

$$F(X, k) = \left| \frac{D_{in}}{D_{out}} - 1 \right| \tag{3}$$

where D_{in} is the within-cluster distance, and can be obtained approximately as below,

$$D_{in} = \sqrt{E} \tag{4}$$

and D_{out} is the between-cluster distance,

$$\mathrm{D_{out}} = \sum_{i=1}^{k} |\mathrm{m_i} - \mathrm{m}| \tag{5}$$

where m_i is the mean value in a cluster X^i, and m is the mean value in whole X.

By increasing the clustering number k, D_{in} was decreased but D_{out} was increased. When $\mathrm{F}(X,k)$ was close to zero, the effects on the clustering result coming from the difference between the within-cluster and between-cluster were well balanced, and the $\underset{k}{\mathrm{Min}}\,\mathrm{F}(X,k)$ was considered the optimal choice (Fig. 2.).

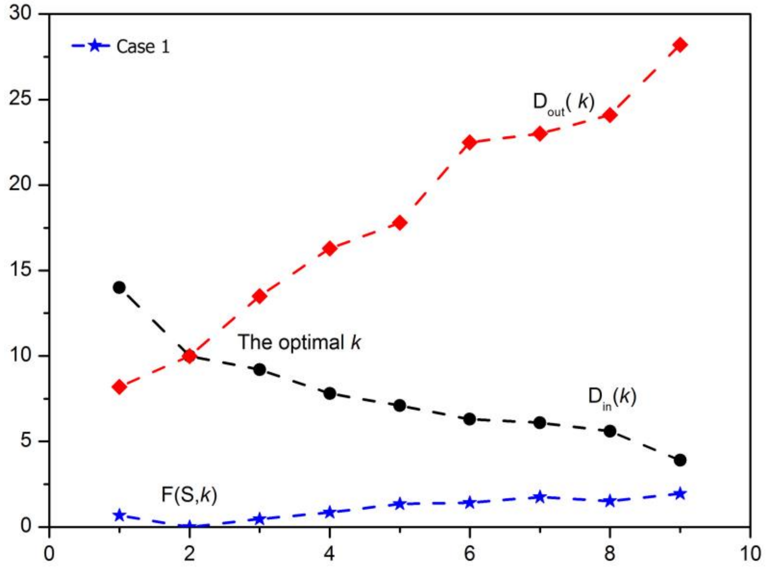

Fig. 2. Change of curves with k

Paper Mill Description

Zhuhai S. E. Z. Hongta Renheng Paper Co., Ltd. (Zhuhai, China) has three papermaking lines. The leading product is a high-grade brand coated paperboard whose base weight can be maintained in the range from 180 to 450 g/m^2. In this study, the third production line (abbreviated BM3) was investigated. The BM3 includes pulp-making and paper-making processes. The pulp-making process, which gets supplies of pulp board through purchase from other pulp mills, consists of raw material preparation, pulping, and washing and screening. The paper-making process consists of refining, approach system, forming section, press section, drying section, coating and drying, vacuum system, compress air system, calendaring, winding, rewinding, packaging, and the broke system. To drive the production line and make the material into the product, the primary energy source, mainly coal, was converted in a boiler system to steam at 5.2 MPa, and the high-pressure steam was decompressed to 0.5 MPa to provide heat for the production process and 1.1 MPa to generate electricity for the production line. Importantly, the 0.5 MPa steam and 1.1 MPa steam were adjusted to different pressures with differential pressure to meet the given heating curve.

To monitor the production process and ensure the quality of the product, a Quality Control System (QCS), Distributed Control System (DCS), and Web Inspection System (WIS) were employed. However, each system was highly independent, which made data sharing a very fragmentary process, generating a large information island.

Data Acquisition and Integration

To conduct the energy audit and quantify the energy efficiency, the SEC was regarded as a baseline of energy efficiency at the production line level. The key energy consumption unit processes, those that consume mostly power and steam, were used to show the distribution of energy efficiency. Table 1 shows that the indicator system consisted of two parts, giving a total of 16 items. Part I consists of three indicators: SEC, the total electricity consumption of production line, and the total thermal energy consumption of production line. Part II consists of 13 indicators: pulping, subsection I (raw material preparation and washing and screening), refining, approach system, forming section, press section, drying section, coating and drying, vacuum system, compressed air system, subsection II (calendaring, winding, rewinding, packaging, and the broke system), medium-pressure steam, and low-pressure steam.

Table 1. Specific Indicators for BM3*

No.	Operational Region	Indicator		Variable	Calculation
1	Production line	SEC (GJ/t)		$plsec$	$plsec = 0.0036 \times plec + pltc$
2		Electricity Consumption (kWh/t)		$plec$	$plec = \sum_{i=1}^{11} pu_i$
3		Thermal Energy Consumption (GJ/t)		$pltc$	$pltc = mth + lth$
	Unit process	Electricity Consumption (kWh/t)	Thermal Energy Consumption (GJ/t)		
4	Pulping	√		pu_1	
5	Subsection I	√		pu_2	
6	Refining	√		pu_3	
7	Approach system	√		pu_4	
8	Forming section	√		pu_5	
9	Press section	√		pu_6	
10	Drying section	√		pu_7	
11	Coating and drying	√		pu_8	
12	Vacuum system	√		pu_9	
13	Compressed air system	√		pu_{10}	
14	Subsection II	√		pu_{11}	
15	Medium-pressure steam		√	mth	
16	Low-pressure steam		√	lth	

*Depending on the specific situation in BM3, the information of 1.1 MPa steam and 0.5 MPa steam were obtained by intelligent instruments. No more details of steam could be provided on the unit processes.

Once the indicators were determined, EMS, which is an effective means of precisely tracking energy, was introduced for data collection. This provided the capacity to integrate the different running environments corresponding to each information island into a comprehensive one. Thus, numerous running parameters, including both analog and digital parameters, could be obtained securely. The data corresponding to these running parameters, such as the electric current of the exhaust fans, pulp flow, steam pressure, valve status, and so on, were sampled every second and stored in the historical database and relational database (SQL server) for further data processing and analysis depending on end-user requirement. The process of data collection lasted for nearly seven months, from September 1, 2015 to March 20, 2016. The following energy calculation was proposed in order to measure how well the energy was being used at each production line level and unit process level.

The actual paper production *G(t)* was determined by,

$$G = 0.06VB_{\mathrm{m}}qT \tag{6}$$

$$T = t_2 - t_1 - t_{\mathrm{b}} \tag{7}$$

where V (m/min) is the average speed of paper machine, B_m (m) is trim width, q (g/m^2) is basis weight, and T (h) is the operation time (not including paper break time t_b) from t_1 to t_2.

The energy of steam E_{s} (GJ/t) could be obtained by,

$$E_{\mathrm{s}} = \frac{(F_{\mathrm{s}}(t_2) - F_{\mathrm{s}}(t_1)) \times h_{\mathrm{s}}}{1000 \times G} \tag{8}$$

where $F_s(t_i)$ (t) is the cumulative flow of steam at moment t_i, $F_s(t_2) - F_s(t_1)$ is the total steam consumption from t_1 to t_2, and h_s (kJ/kg) is the specific enthalpy of steam.

The energy of electricity E_{e} (kWh/t) can be determined by,

$$E_{\mathrm{e}} = \frac{F_{\mathrm{e}}(t_2) - F_{\mathrm{e}}(t_1)}{G} \tag{9}$$

where $F_e(t_i)$ (kWh) is the cumulative electricity consumption at moment t_i and $F_e(t_2) - F_e(t_1)$ is the total electricity consumption from t_1 to t_2.

Table 2. Experimental Data from 6 Samplings

Variable	2015/9/1 0:00	2015/9/1 8:00	2015/9/1 16:00	2016/3/20 0:00	2016/3/20 8:00	2016/3/20 16:00
$plsec$	8.257	8.219	9.741	6.016	5.899	5.804
$plec$	529.142	519.673	623.582	278.342	272.341	265.567
$pltc$	6.352	6.348	7.497	5.014	4.919	4.848
pu_1	23.580	20.074	23.529	13.109	14.217	13.546
pu_2	90.471	85.855	108.007	53.285	52.662	51.881
pu_3	203.411	199.243	244.315	92.950	87.790	81.979
pu_4	12.349	12.427	15.288	8.176	7.876	7.794
pu_5	25.984	26.252	27.399	10.809	11.698	12.280
pu_6	11.136	11.248	11.748	5.470	5.617	5.847
pu_7	23.309	23.413	26.450	14.004	14.608	15.045
pu_8	11.461	11.415	13.661	6.542	6.264	6.271
pu_9	61.911	62.454	73.132	25.345	24.371	24.400
pu_{10}	21.992	22.985	27.797	16.252	15.473	15.774
pu_{11}	43.538	44.307	52.257	32.401	31.764	30.753
mth	1.715	1.700	2.017	1.076	1.049	1.028
lth	4.637	4.648	5.479	3.938	3.870	3.820

Table 2 shows the data set obtained based on these calculations, consisting of 460 samplings of energy efficiency indicators at the frequency of 1 sample/shift and 44160 sampling of basis weight at the frequency of 1 sample/5 min (see Fig. 3).

RESULTS AND DISCUSSION

Data Partitions

The distribution of basis weight reflected the different energy efficiency levels in the paper mill. When the basis weight was less than 180 g/m^2, the quality of the paper did not meet the standard. This part of the data should be eliminated in the following section. Figure 3 shows that the smaller basis weight occurred when processed by Kalman filter; as the weight increased, SEC also increased.

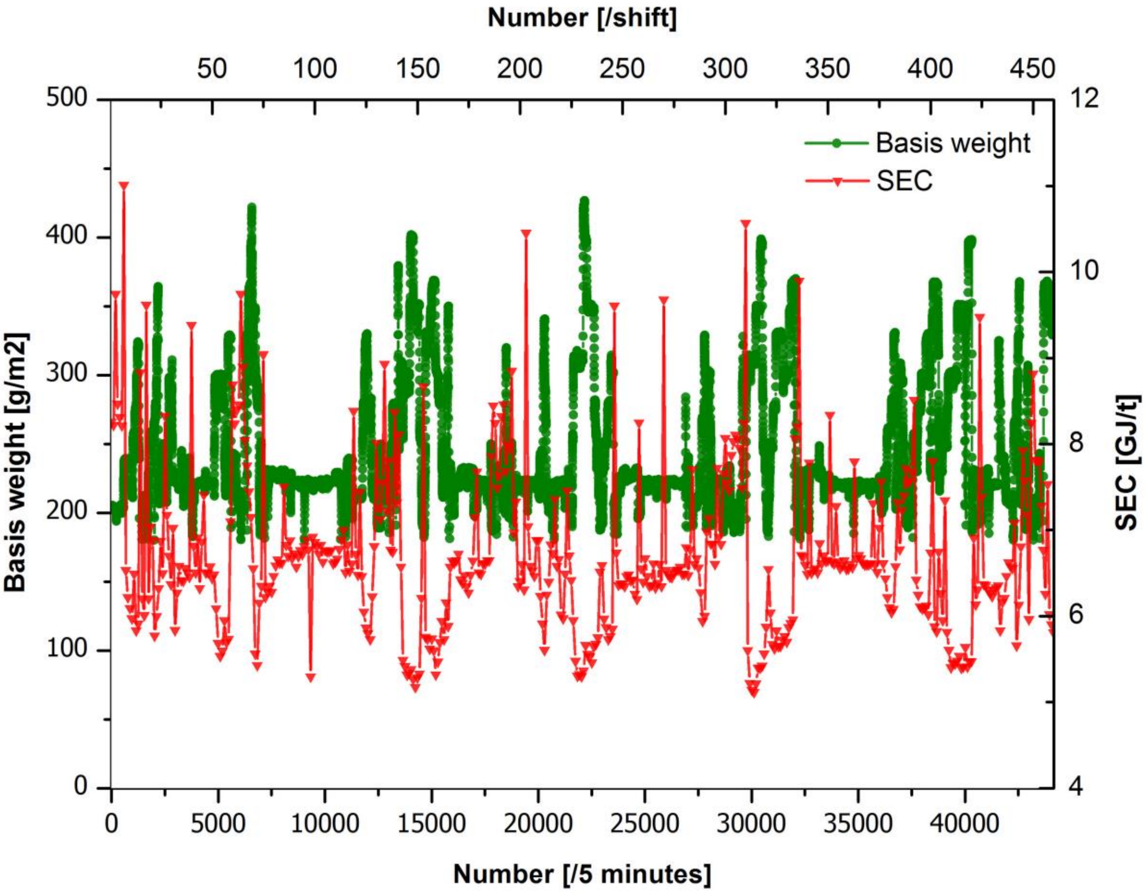

Fig. 3. Trend chart for basis weight and SEC

In order to identify different energy efficiency levels, K-means clustering was used to partition the basis weight samples into k clusters (k =2,3,...,9) (Mardia *et al.* 1979), and the validity index was used to determine the number clusters, k.

Table 3. Validity Index with the Increase of Cluster Number, *k*

	$k=2$	$k=3$	$k=4$	$k=5$	$k=6$	$k=7$	$k=8$	$k=9$
$\mathrm{F}(X,k)$	42.254	15.268	0.0148	1.543	0.631	0.109	0.143	0.351

Table 3 shows that when the number of clusters was set at 4, adding more clusters did not obtain a better effect. Therefore, a basis weight was set for the four clusters. Each cluster corresponded to a group of energy efficiency levels, and each group had a different centroid, which served as the benchmark of energy efficiency. Contrasting the sampling frequency, each sampling of energy efficiency indicators corresponded to 96 samplings of basis weight. It was necessary to convert the sampling data taken at different sampling frequencies and group them by applying the principle whereby the minority is subordinate to the majority to basis weight, *e.g.*, when the value of 30 samplings ranged from 180.23 to 239.48 and the value of 66 samplings ranged from 239.49 to 284.37 in 96 samplings of basis weight, the corresponded sampling of energy efficiency indicator belonged to the second group. The final results are displayed in Table 4.

Table 4. Partitioning Results

Cluster No.	Range of Basis Weight	Centroid of Each Cluster	Group No.	Samples of Each Indicator
1	[180.23, 239.48]	219.15	1	308
2	[239.49, 284.37]	259.83	2	58
3	[284.58, 335.69]	309.23	3	61
4	[335.76, 426.96]	362.20	4	33

Energy Efficiency Benchmarking

In this paper, first k value bounds were set such that $k \in \{2,3,4,5,6\}$, according to a simple rule of thumb sets the number to $k \cong \sqrt{n/2}$ with n as the number of objects (Mardia *et al.* 1979). A K-means algorithm was applied to different k values in each group, and a corresponding validity index was calculated, as shown in Fig. 4. The optimal choices for each of the four groups were: for $F(X_1, 5)$, 0.214; for $F(X_2, 3)$, 0.156; for $F(X_3, 4)$, 0.208; and for $F(X_4, 3)$, 0.072.

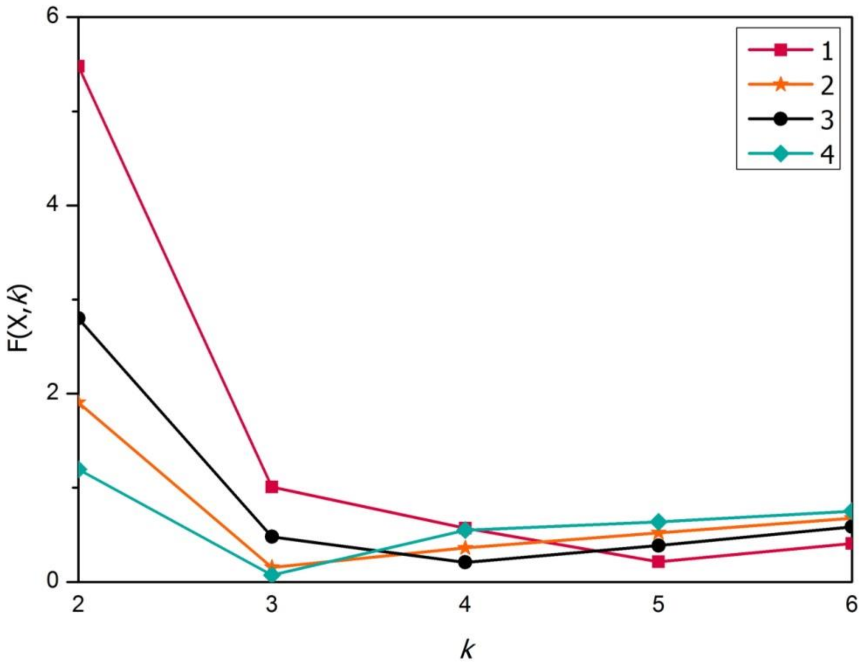

Fig. 4. Change in by different *k* in each group

In Tables 5 and 6, the results show the distribution of energy efficiency at the production line level and the unit process level. Three first-stage indicators were revealed through the qualitative calculation. Generally, SEC decreased with the increase in basis weight from group 1 to group 3. Meanwhile, the average contribution of thermal energy consumption to SEC increased (by 80.84%, 81.32%, 82.26%, and 83.28%). The highest range (5.96 to 11.02 GJ/t) of SEC was identified, and an abnormal SEC, which was equal to 11.02, was found in group 2 (see Fig. 6), because the no-load energy consumption accounted for about 40% of the total energy consumption in this shift. The refining process consumed most of the electricity at the unit process level, which accounted for approximately 30% of the total electricity consumption. Comparing the centroids of the different groups, the energy efficiency levels between group 3 and group 4 were very close. The total electricity consumption and the allocation to unit processes was reasonable, but that the total thermal energy consumption increased rather than decreased from group 3 to group 4. Particular attention needs to be paid to low-pressure steam consumption.

Table 5. Distribution of Energy Efficiency Levels: (1) Clustering Results at Unit Process Level based on K-means Algorithm and (2) Calculated Values for First-Stage Indicators. Results from Groups 1 and 2

	Group 1						**Group 2**			
Variable	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	Centroid	C_{21}	C_{22}	C_{23}	Centroid
$\boldsymbol{pu_1}$	19.73	14.47	23.53	13.39	17.12	**14.42**	24.44	12.87	15.63	**13.97**
$\boldsymbol{ot1}$	89.17	77.76	108.0	62.42	83.38	**69.70**	167.4	59.32	79.58	**67.82**
$\boldsymbol{pu_7}$	193.0	125.1	244.3	107.8	160.5	**122.6**	163.8	93.1	150.2	**113.0**
$\boldsymbol{pu_8}$	12.23	9.94	15.29	8.62	11.57	**9.46**	26.53	8.02	10.72	**9.22**
$\boldsymbol{pu_9}$	27.44	24.17	27.40	22.77	27.81	**23.94**	28.06	19.36	21.87	**20.33**
$\boldsymbol{pu_{10}}$	12.36	11.44	11.75	10.54	12.75	**11.10**	12.97	9.31	10.17	**9.66**
$\boldsymbol{pu_{11}}$	24.92	23.66	26.45	21.80	24.45	**22.69**	51.05	19.18	20.97	**20.32**
$\boldsymbol{pu_{13}}$	10.39	8.22	13.66	7.04	9.95	**7.84**	25.77	6.73	8.92	**7.77**
$\boldsymbol{pu_{14}}$	49.29	40.28	73.13	33.41	42.51	**36.87**	38.40	30.59	37.37	**32.94**
$\boldsymbol{pu_{15}}$	20.15	16.98	27.80	15.16	23.26	**16.86**	30.91	13.99	15.69	**14.84**
$\boldsymbol{ot2}$	42.06	36.20	52.26	31.80	42.36	**34.62**	66.10	26.44	35.43	**30.07**
$\boldsymbol{mth}$	1.69	1.34	2.02	1.17	1.57	**1.28**	2.08	1.04	1.43	**1.19**
$\boldsymbol{lth}$	4.94	4.47	5.48	4.10	4.94	**4.33**	6.65	3.84	4.55	**4.12**
$\boldsymbol{plec}$	500.7	388.2	623.6	334.8	455.7	**370.1**	635.4	298.9	406.6	**339.9**
$\boldsymbol{pltc}$	6.63	5.81	7.50	5.27	6.51	**5.61**	8.73	4.88	5.98	**5.31**
$\boldsymbol{plsec}$	8.43	7.21	9.74	6.48	8.15	**6.94**	11.02	5.96	7.44	**6.53**

Note: C_{ij} is the center of cluster j (the optimal clustering number in each group) in group i ($i = 1,2,3,4$)

Figures 5, 6, 7, and 8 show the histograms for each group corresponding to the production line level. The frequencies for the given ranges of actual SEC are shown in these graphs. The trend lines drawn on the bar charts show the frequency distributions. The centroid SEC and the minimum clustering center SEC (C_{14}, C_{22}, C_{31}, and C_{43}) of each group are marked, demonstrating the positions within the entire group. The minimum clustering center SEC of each group is in a relatively low position. The centroid SEC of each group is close to the mean of the actual SEC. It is reasonable that the centroid of each group could be regarded as the benchmark, which represents the mean level of energy efficiency.

Table 6. Distribution of Energy Efficiency Levels: (1) Clustering Results at Unit Process Level based on K-means Algorithm and (2) Calculated Values for First-Stage Indicators. Results from Groups 3 and 4

	Group 3					**Group 4**			
Variable	C_{31}	C_{32}	C_{33}	C_{34}	Centroid	C_{41}	C_{42}	C_{43}	Centroid
pu_1	13.08	12.87	14.82	15.26	**13.39**	16.37	13.31	13.62	**13.93**
$ot1$	49.61	60.12	68.09	69.80	**59.62**	76.23	58.52	50.82	**57.24**
pu_7	61.37	93.45	119.0	148.4	**93.40**	102.9	94.06	66.46	**81.17**
pu_8	7.16	8.00	8.33	8.94	**7.92**	10.43	8.20	7.34	**8.09**
pu_9	14.80	15.28	17.35	17.74	**15.66**	14.75	12.55	12.18	**12.69**
pu_{10}	7.33	7.71	8.79	9.37	**7.90**	7.98	6.37	6.01	**6.43**
pu_{11}	16.65	16.66	17.71	17.63	**16.90**	18.84	14.49	14.08	**14.94**
pu_{13}	6.24	7.05	6.80	6.94	**6.81**	8.56	6.81	6.54	**6.93**
pu_{14}	26.70	30.55	29.83	34.15	**29.72**	37.89	28.71	27.35	**29.40**
pu_{15}	13.99	13.96	11.59	14.07	**13.55**	20.51	14.26	12.28	**14.19**
$ot2$	27.70	27.66	27.23	27.96	**27.61**	40.57	30.51	24.76	**29.07**
mth	0.89	1.04	1.13	1.30	**1.04**	1.31	1.03	0.93	**1.02**
lth	3.59	3.83	3.96	4.39	**3.83**	5.01	3.86	3.62	**3.91**
$plec$	244.6	293.3	329.5	370.3	**292.5**	355.0	287.8	241.4	**274.1**
$pltc$	4.48	4.87	5.09	5.69	**4.87**	6.32	4.89	4.55	**4.93**
$plsec$	5.36	5.93	6.28	7.02	**5.92**	7.60	5.93	5.42	**5.92**

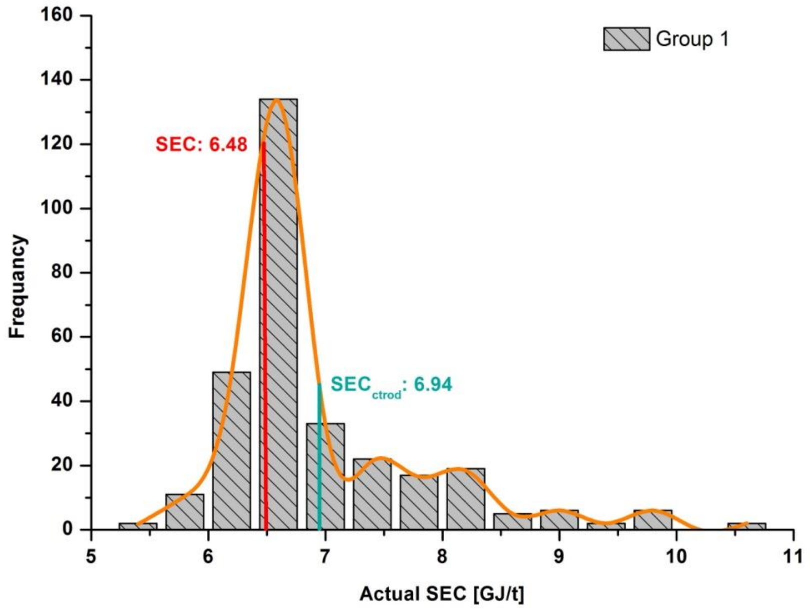

Fig. 5. Histograms of SEC in group 1

Once the benchmarks were determined, the differences between the production line itself and the international advanced values could be estimated using a Best Available Technology (BAT). In accordance with the research of the European Union and the American Institute, the two levels of best available energy consumption in coated paperboard production are 7.78 GJ/t and 5.57 GJ/t, respectively (Kinatrey *et al*. 2006; Kocabas *et al*. 2009).

The benchmarking SECs of the four groups were 6.94 GJ/t, 6.53 GJ/t, 5.92 GJ/t, and 5.92 GJ/t, which were 10.8%, 16.1%, 23.9%, and 23.91% lower, respectively, compared with European Union best available energy level and 24.6%, 17.2%, 6.28%, and 6.28% higher, respectively, compared with the integrated production unit energy consumption reported for American paper products. This indicated that the energy efficiency level of BM3 was lower than that of the European and higher than that of the American.

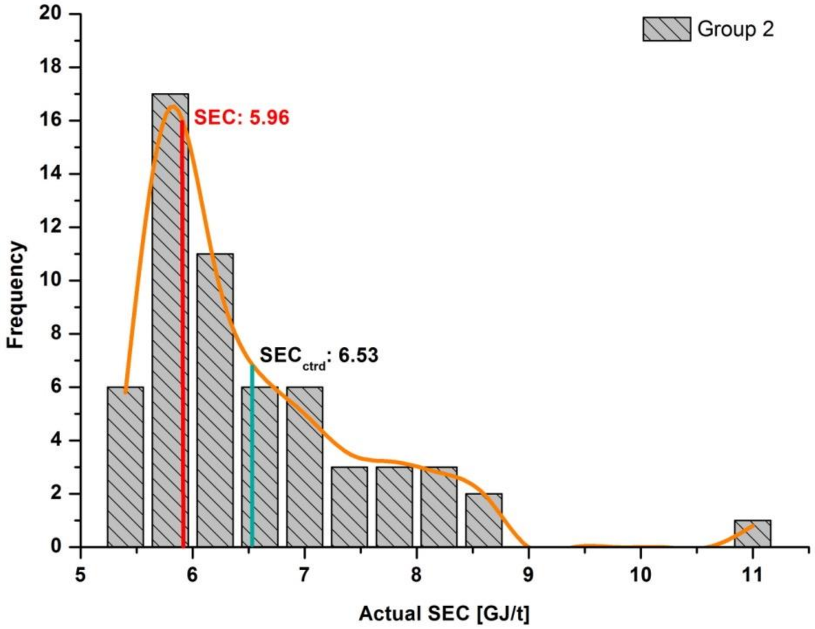

Fig. 6. Histograms of SEC in group 2

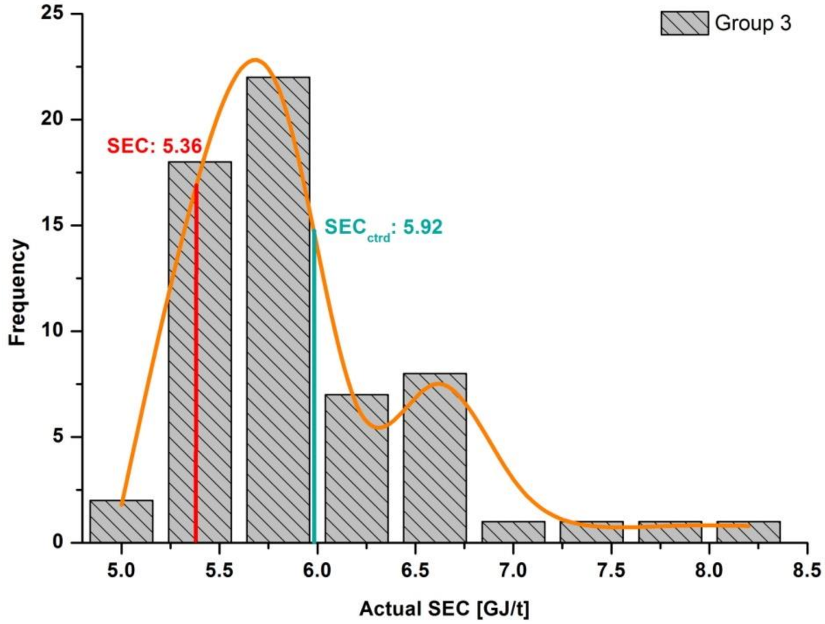

Fig. 7. Histograms of SEC in group 3

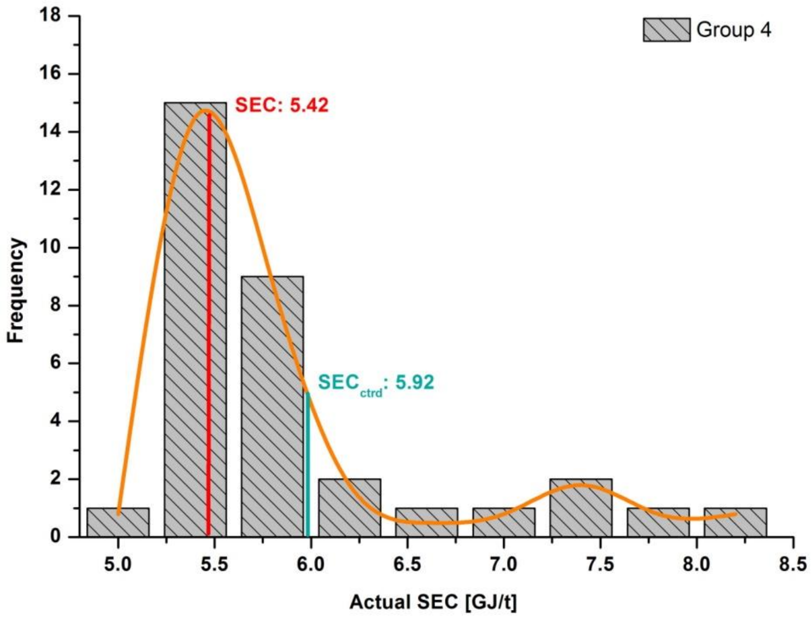

Fig. 8. Histograms of SEC in group 4

CONCLUSIONS

1. An indicator system for energy efficiency benchmarking was established at the production line and processing unit levels. EMS was introduced to collect data and quantify energy efficiency. K-means clustering was used to classify basis weight and energy efficiency data with the greatest possible distinction. The results showed that the basis weight was concentrated into four clusters: 180.23 to 239.48, 239.49 to 284.37, 284.58 to 335.69, and 335.76 to 426.96. Each cluster corresponded to a group of actual SECs, and each group had a centroid, which served as the energy efficiency benchmark. The benchmarking SECs were 6.94 GJ/t, 6.53 GJ/t, 5.92 GJ/t, and 5.92 GJ/t, respectively. This energy efficiency level was 10.8 to 23.91% lower compared with the European Union best available energy level (7.78 GJ/t) and 6.28 to 24.6% higher compared with the integrated production unit energy consumption of American paper products (5.57 GJ/t), which indicated that energy use could be reduced by strengthening the energy efficiency management, optimizing the production system, and updating technology implementation.
2. The average contribution of thermal energy consumption to SEC was more than 80%. Refining consumes most electricity at the processing unit level, which accounts for approximately 30% of the total electricity consumption. The SEC decreased with the increase of basis weight. However, the benchmarking SECs were equivalent from group 3 to group 4, because the total thermal energy consumption increased rather than decreased.
3. This paper provides insights into practical application that could quantify the energy efficiency and tap into energy-saving potentials for different basis weights. The selection of energy efficiency indicators still depends on the actual conditions of the paper mill. Case studies need to be performed to evaluate the applicability of this methodology in different paper grades.

ACKNOWLEDGMENTS

The authors are grateful for financial support from the National Natural Science Foundation of China (Grant No. 61333007), the Science and Technology Project of Guangdong Province (Grant No. 2015A010104004), the Science and Technology Project of Guangdong Province (Grant No. 2015B010110004), and the Science and Technology Project of Guangdong Province (Grant No. 2013B010406002). The authors also gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

REFERENCES CITED

Al-Ghandoor, A., Phelan, P. E., Villalobos, R., and Jaber, J. O. (2010). "Energy and exergy utilizations of the U. S. manufacturing sector," *Energy* 35(7), 3048-3065. DOI: 10.1016/j.energy.2010.03.046

Bosseboeuf, D., Chateau, B., and Lapillonne, B. (1997). "Cross-country comparison on energy efficiency indicators: The on-going European effort towards a common methodology," *Energy Policy* 25(97), 673-682. DOI: 10.1016/S0301-4215(97) 00059-1

Bhutani, N. (2015). "Case study for performance assessment and benefit estimation in paper machines by data mining," *Energy Procedia* 75, 1542-1548. DOI: 10.1016/j.egypro.2015.07.323

Cakembergh-Mas, A., Paris, J., and Trepanier, M. (2010). "Strategic simulation of the energy management in a kraft mill," *Energy Conversion and Management* 54(1), 988-997. DOI: 10.1016/j.enconman.2009.12.001

Chu, H., Wang, Z., and Liu, Y. (2016). "Application of modified bentonite granulated electrodes for advanced treatment of pulp and paper mill wastewater in three-dimensional electrode system," *Journal of Environmental Chemical Engineering* 4(2), 1810-1817. DOI: 10.1016/j.jece.2016.02.017

Gannaway, J. N. (1996). *Analysis of the Benchmarking process as a Potential Tool to Enhance Organizational Competitiveness*, Ph.D. Dissertation, Southern Methodist University, Dallas, TX, USA.

Jigeng, L., Huanbin, L., Yongjun, Y., Jinsong, T., Lingbo, K., Yugang, L., and Jingjiang, J. (2010). "Energy system diagnosis and analysis with "Three-Links" models in pulp and paper mill," in: *International Conference on Renewable Energies and Power Quality (ICREPQ'10)*, Granada, Spain, http://www.icrepq.com/icrepq'10/290-Jigeng.pdf.

Kubš, J., Gaff, M., and Barcík, Š. (2016). "Factors affecting the consumption of energy during the milling of thermally modified and unmodified beech wood," *BioResources* 11(1), 736-747. DOI:10.15376/BIORES.11.1.736-747

Kaya, A., and Keyes, M. A. (1983). "Energy management technology in pulp, paper, and allied industries," *Automatica* 19, 111-30. DOI: 10.1016/0005-1098(83)90086-9

Kinstrey, R. B., and White, D. (2006). *Pulp and Paper Industry Energy Bandwidth Study*, TAPPI Engineering, Pulping & Environmental Conference 2(3), 837-865.

Kocabas, A. M., Yukseler, H., Dilek, F. B., and Yetis, U. (2009). "Adoption of European Union's IPPC Directive to a textile mill: Analysis of water and energy consumption," *Journal of Environmental Management* 91(1), 102-113. DOI:10.1016/j.jenvman.2009.07.012

Kong, L., Hasanbeili, A., and Price, L. (2016). "Assessment of emerging energy-efficiency technologies for the pulp and paper industry: A technical review," *Journal of Cleaner Production* 122, 5-28. DOI: 10.1016/j.jclepro.2015.12.116

Kramer, K. J., Masanet, E., and Worrell, E. (2009). "Energy efficiency opportunities in the U. S. Pulp and Paper Industry," *Energy Engineering: Journal of the Association of Energy Engineering* 107(1), 21-50. DOI: 10.1080/01998591009595081

Kramer, K., Masanet, E., Xu, T., and Worrell, E. (2009). *Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry*, Berkeley LAB, https://www.energystar.gov/ia/business/industry/downloads/Pulp_&_Paper_2009.pdf.

Laurijssen, J., Faaij, A., and Worrell, E. (2013). "Benchmarking energy use in the paper industry: A benchmarking study on process unit level," *Energy Efficiency* 6(1), 49-63. DOI: 10.1007/S12053-012-9163-9

Macqueen, J. B. (1967). "Some methods for classification and analysis of multivariate observation," in: *Proceedings of the 5th Berkeley Symposium on Mathematical Statistics*, L. L. Cam and J. Neyman (eds.), Berkeley, CA, pp. 281-297.

Mardia, K. V., Ken, J. T., and Bibby, J. M. (1979). *Multivariate Analysis. Probability and Mathematical Statistics*, Academic Press.

Mateos-Espejel, E., Savulescu, L., Marechal, F., and Paris, J. (2011). "Base case process development for energy efficiency improvement, application to a Kraft pulping mill. Part II: Benchmarking analysis," *Chemical Engineering Research and Design* 89(6), 729-741. DOI: 0.1016/j.cherd.2010.09.013

May, G., Barletta, I., Stahl, B., and Taisch, M. (2005). "Energy management in production: A novel method to develop key performance indicators for improving energy efficiency," *Applied Energy* 149, 46-61. DOI: 10.1016/j.apenergy.2015.03.065

Mesfun, S., and Toffolo, A. (2014). "Integrating the processes of a Kraft pulp and paper mill and its supply chain," *International Conference on Efficiency* 103, 300-310. DOI: 10.1016/j.enconman.2015.06.063

Mishra, B. K., Nayak, N. R., Rath A. K., and Swain, S. (2012). "Improving the efficiency of clustering by using enhanced clustering methodology," *International Journal of Advances in Engineering & Technology* 4(2), 415.

Panepinto, D., Fiore, S., Zappone, M., Genon, G., and Meucci, L. (2016). "Evaluation of the energy efficiency of a large wastewater treatment plant in Italy," *Applied Energy* 161, 404-411. DOI: 10.1016/j.apenergy.2015.10.027

Peng, L., Xiaoling Zeng, X., Wang, Y., and Hong, G.-B. (2005). "Analysis of energy efficiency and carbon dioxide reduction in the Chinese pulp and paper industry," *Energy Policy* 80, 60-75. DOI: 10.1016/j.enpol.2015.01.028

PPIO Canada (2008). *Benchmarking Energy Use in Canadian Pulp and Paper Mills*, Government of Canada Public Works & Government Services, Canada.

Ruohonen, P., Hippinen, I., Tuomaala, M., and Ahtila, P. (2010). "Analysis of alternative secondary heat uses to improve energy efficiency—Case A: Finnish mechanical pulp and paper mill," *Resources, Conservation and Recycling* 54(5), 326-335. DOI: 10.1016/j.resconrec.2009.07.002

Sarimveis, H. K., Angelou, A. S., Retsina, T. R., Rutherford, S. R., and Bafas, G. V. (2003). "Optimal energy management in pulp and paper mills," *Energy Conversion and Management* 44(10), 1707-1718. DOI: 10.1016/S0196-8904(02)00165-6

Savulescu, L. E., and Alva-Argaez, A. (2008). "Direct heat transfer considerations for improving energy efficiency in pulp and paper Kraft mills," *Energy* 33(10), 1562-1571. DOI: 10.1016/j.energy.2008.07.015

Staffan, L. (1998). "The relevance of science and technology indicators: The case of pulp and paper," *Research Policy* 27(4), 385-395. DOI: 10.1016/S0048-7333(98)00050-X

Utlu, Z., and Kincay, O. (2013). "An assessment of a pulp and paper mill through energy and exergy analyses," *Energy* 57, 565-573. DOI: 10.1016/j.energy.2013.05.054

Van, G. J. C. (2004). "Maximizing energy savings with enterprise energy management systems," in: *Proceedings of IEEE Conference Record of Annual Pulp and Paper Industry Technical Conference*, Victoria, BC, Canada, pp. 175-181. DOI: 10.1109/PAPCON.2004.1338378

Wu, B., Li, J., Liu, H., Liu, H., Zhang, Z., Zhou, Y., and Zhao, N. (2012). "Energy information integration based on EMS in paper mill," *Applied Energy* 93, 488-495. DOI: 10.1016/j.apenergy.2011.12.021

Yokobori, K. (2003). *Energy Efficiency Indicators Data Collection: A Study of Energy Efficiency Indicators for Industry in APEC Economies*, Asia Pacific Energy Research Center, Tokyo, Japan.

Article submitted: June 29, 2016; Peer review completed: September 4, 2016; Revised version received and accepted: September 20, 2016; Published: September 28, 2016.
DOI: 10.15376/biores.11.4.9723-9740