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Energy flow analysis in pulp and paper industry

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This work analyzed the energy flow of the pulp and paper industry in Taiwan. The potential technology options that were examined focus on how to capture some of the energy currently lost in the processes and then identifying the areas with energy-saving potential that could also have large impacts across a variety of industries. In addition, the energy-saving potential of these options was evaluated. The energy-saving potential of the pulp and paper industry would be around 6939.9 KLOE/M. The greatest energy-saving potential lies with improving energy distribution and equipment efficiency, which would together potentially comprise 86.8% of total energy conservation. This analysis can serve as a benchmark for current pulp and paper making operations, and as a base case for stimulating changes toward more efficient energy utilization in the pulp and paper industry.

1. Introduction

The GOV (gross output value) of the Taiwanese pulp and paper industry is around ten million NT dollars, and accounts for 3.9% of the total GDP (gross domestic product) in the Taiwanese manufacturing sector. There are 101 firms involved in the pulp and paper industry, and the quantity of pulp output and paper or paperboard output is about 380 kT and 43 kT, respectively. The pulp and paper industry is a large user of fossil energy in the Taiwanese manufacturing sector, and the concentration of greenhouse gases (GHG) from manufacturing factory activities and vehicle emissions has increased significantly. Improving the energy efficiency of industrial processes is the most significant option for lowering greenhouse gas emissions [1]. Consequently, energy research institutes and governmental energy departments from various nations have all committed to developing methods for assessing energy efficiency which can then be used as references for policy-making. Additionally, the energy utilization status of each of the different countries can be compared so that their common aim of reducing greenhouse gas emissions can be achieved. Numerous analytical studies have been undertaken on energy conservation for different industries, such as the iron and steel industry [2–6], cement industry [7,8], textile industry [9], petroleum/chemical industry [10–12], pulp industry [13] small and medium scale industries [14–16], manufacturing industry [17–21] and industrial/commercial/residential sectors [22–29]. There have been additional studies which have shown improved energy efficiency with the help of energy conservation techniques [26,30,31] or through a heavy investment in infrastructure [32]. Increasing energy efficiency is the most direct means of reducing GHG emissions. Little or no investment is needed to achieve a 10–30 percent reduction in greenhouse gas emissions [33,34]; while if energy users are willing to adopt improved technology or if government incentives are implemented, emissions can be even further reduced [15].

The pulp and paper industry uses energy which accounts for almost half of paper mills' cost [35]. Therefore, it is very important to analyze energy consumption flows, which include energy supply, energy distribution, energy conversion and energy end-use in the pulp and paper industry. According to analyzed results, enormous energy conservation potential can be obtained. There have been a number of prior efforts to study energy end-use in other manufacturing industries [36–39]. This paper describes the application of the energy flow model to the pulp and paper industry. The energy flow of the Taiwanese pulp and paper industry has been analyzed and the energy-saving opportunities and potential have also been identified.

2. Energy situation in Taiwan

2.1. Energy use structure

Taiwan has extremely limited coal and petroleum resources, although it does have abundant hydro resources and natural gas. New energy developments (including geothermal, wind, solar,

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Nomenclature

GOV	gross output value
NT dollar	new Taiwan dollar
GDP	gross domestic product
GHG	greenhouse gases
KLOE	kL of crude oil equivalent
NG	natural gas
KLOE/M	energy use per month
IR	infrared
PM	preventive maintenance
MIC	microbiologically influenced corrosion
NBKP	needle bleached kraft pulp
LBKP	leaf bleached kraft pulp
BLC	black liquor concentration

bio-energy, ocean temperature difference, and so on) cannot compensate for the lack of energy resources in Taiwan. Taiwan depends on imports for approximately 98% of its primary energy as rapid economic development has significantly increased energy and electricity demands. National total energy use was estimated at 104.9 million KLOE in 2009, an increase of 2.63% from the 2005 figure. The industrial sector accounted for 56.6% of national total energy use, and energy-intensive industries, such as iron and steel, chemicals, textiles, and electronics, accounted for 89.9% of total industrial sector energy use, as shown in Fig. 1.

2.2. Energy utilization status in the Taiwanese pulp and paper industry

In 2009, the Taiwan pulp and paper industry consumed 1.29 million KLOE for its annual final product output. In comparison with 2008, there was a decrease of 7.60%. Meanwhile, the entire industrial sector consumed 59.35 million KLOE, a decrease of just 4.08%. Table 1 shows the recent energy consumption figures for the pulp and paper industry and the entire industrial sector. It can be seen that the energy consumption ratio of the pulp and paper industry to the entire industrial sector energy has decreased. Over the last five years, average energy consumption in the industrial sector increased 2.02%, while average pulp and paper industry energy consumption decreased 4.16%. Evidently, the energy consumption of the Taiwan pulp and paper industry has not increased at the same rate as that of other industries. In fact, energy consumption by the pulp and paper industry went from 2.82% of total industry energy consumption in 2005 to 2.17% in 2009.

3. Energy flow analysis methodology

Models, called “energy footprints,” showing the flow of energy supply, demand and losses for several US manufacturing industries, were created by DOE [35]. An energy footprint has the following characteristics [38]: (a) the overall energy footprint model represents the total energy input required to generate heat and power; (b) energy input is categorized into three components: fossil and biomass fuels, energy supply and utility/power plant; (c) fossil and biomass fuel input is given as one total input without showing the type of fuel individually; and (d) the energy footprint model provides motor losses and system losses associated with the machine drive, as well as electricity generation and transmission losses [35]. The energy flow analysis was referenced to the energy footprint model and used to map the flow of energy supply and demand in this study. The six steps of the study were questionnaire design and delivery, energy supply, central energy generation/utilities, energy

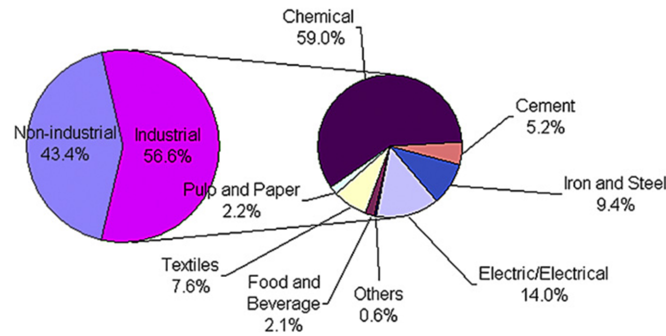

Fig. 1. 2009 energy use in Taiwan. Source: Bureau of Energy website.

distribution, energy conversion and process energy use, and they were used as the basis for the energy flow analysis. The energy flow analysis for the pulp and paper industry was set out as follows.

3.1. Step 1: questionnaire design and delivery

The purpose of the questionnaire as designed was to obtain valuable information about energy purchases, sales, utilization, energy demand, and equipment efficiency. The questionnaire response rate from the pulp and paper industries was almost 100%. Upon completion of the questionnaire survey and check, the energy raw data was obtained.

3.2. Step 2: energy supply

Energy supply means the sum of fuel consumption, purchased electricity, steam, biomass, and black liquor or byproduct fuels. It was found that the total energy use per month was equivalent to 95,230 MWh of electricity, 59,910.5 t of fuel coal, 7576.7 kL of fuel oil, 429 k m^3 of natural gas (NG), 31.9 kL of diesel oil, 8.5 kL of gasoline and 7800 t of renewable fuels. The total energy utilization (energy supply) was thus 91,657.6 kL of the crude oil equivalent per month (KLOE/M).

3.3. Step 3: central energy generation/utilities

This value represents the energy included in the energy supply mentioned in Step 2. In addition, power generation means the energy produced onsite by fuel, biomass and renewable energy which actually enter the plant.

$$\text{Renewable energy} = 7800\ \text{t} = 16{,}227.6\ \text{KLOE/M} \tag{1}$$

$$\text{Onsite power generation} = \sum(\text{electricity produced onsite by cogeneration} + \text{electricity produced onsite by conventional}) = 27{,}096.5\ \text{KLOE/M} \tag{2}$$

$$\text{Steam plant energy} = \text{fuel to boilers} \times \text{boiler efficiency} = 21{,}314.8\ \text{KLOE/M} \tag{3}$$

Table 1
Energy consumption summary of Taiwanese pulp and paper industry.

Year	Energy type (KLOE) of pulp and paper industry					Industrial sector (KLOE)
	Electricity	Steam coal	Fuel oil	NG	Summation	
2005	938,174	322,077	268,558	6819	1,547,734	54,775,024
2006	957,505	284,764	245,566	7040	1,514,334	54,920,261
2007	946,197	276,089	253,462	7183	1,501,105	57,090,945
2008	889,600	261,073	222,547	6724	1,396,314	63,002,962
2009	806,920	276,736	185,871	4407	1,290,227	61,878,064

Source: AREMOS Data Bank.

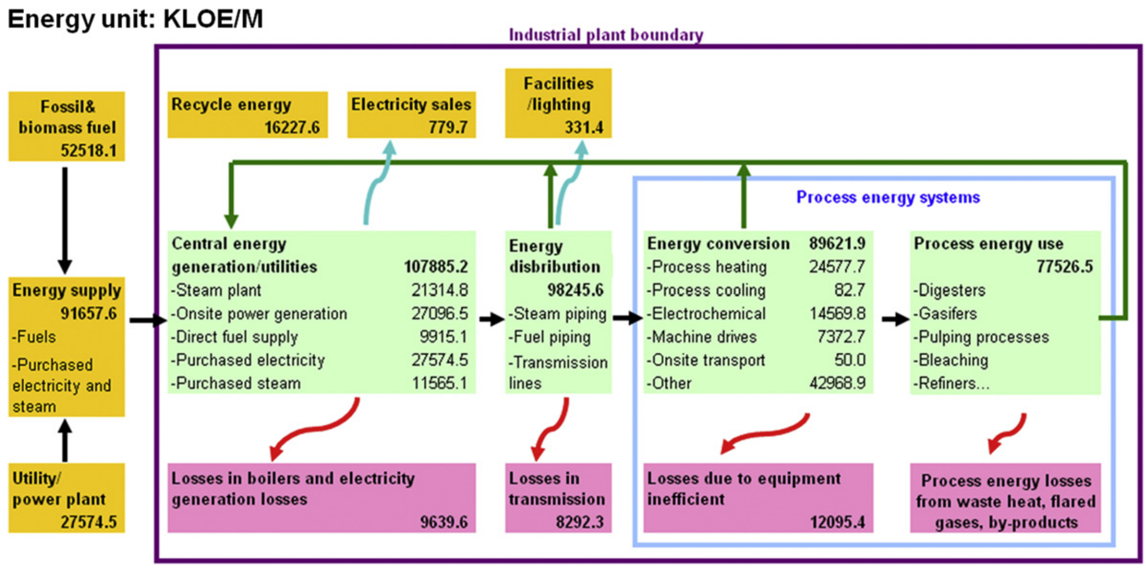

Fig. 2. Energy flow profile of Taiwanese pulp and paper industry (Energy unit: KLOE/M).

Losses in boilers and electricity generation = fuel to boilers − steam plant energy − onsite power generation − electricity sales = 9639.6 KLOE/M (4)

Direct fuel supply = energy supply − steam plant energy − onsite power generation − purchased electricity − losses in boilers and electricity generation = 9915.1 KLOE/M (5)

3.4. Step 4: energy distribution

This represents the energy which is distributed to the energy system processes. Energy distribution is obtained by subtracting the boiler and electricity generation losses in the pipes, valves, traps and electrical transmission lines from the central energy generation/utilities.

Energy distribution = central energy generation/utilities (from step 3) − losses in boilers and electricity generation = 98,245.6 KLOE/M (6)

Energy losses from pipes, valves, traps and electrical transmission lines were roughly estimated to be 5%–40%. The greater losses were in steam pipes (30% was assumed based on the experience of the pulp and paper industry) and small losses incurred in other fuel transmission lines (3%) and electricity transmission lines (3%) for this calculation.

Steam pipes losses = steam plant energy × 30% = 6354.7 KLOE/M (7)

Fuel pipes losses = direct fuel supply × 3% = 297.5 KLOE/M (8)

Electricity lines losses = (utility power plant + onsite power generation) × 3% = 1640.1 KLOE/M (9)

Total transmission losses = steam pipes losses + fuel pipes losses + electricity lines losses = 8292.3 KLOE/M (10)

3.5. Step 5: energy conversion

The available energy which can be used by motor-driven equipment, process heating and cooling units and other process equipment in this step is called energy conversion and is calculated by subtracting transmission losses and facility energy from the energy distribution systems.

Energy conversion = energy distribution (from step 4) − total transmission losses − non-process energy (facilities/lighting) = 89,621.9 KLOE/M (11)

Total energy conversion equipment losses = steam delivery systems losses + process heating systems losses + cooling systems losses + electrochemical systems losses + other energy losses = 10,202.3KLOE /M (12)

Total machine drive losses = pumps + fans + compressed air + refrigeration + others = 1893.1 KLOE/M (13)

Total equipment losses = total energy conversion equipment losses + total machine drive losses = 12,095.4 KLOE/M (14)

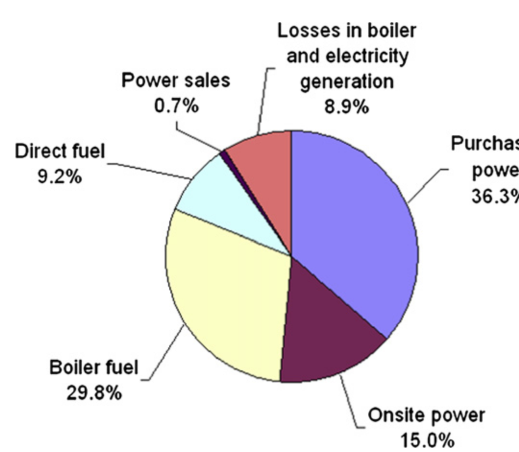

Fig. 3. Primary energy use distribution of Taiwanese pulp and paper industry.

Table 2
Primary energy use summary of Taiwanese pulp and paper industry.[a]

Purchased Energy	39,139.6
Onsite power	16,227.6
Boiler fuel	32,183.6
Direct fuel	9915.1
Power Sales	779.7
Losses in boiler and electricity generation	9639.6
Central energy generation/utilities	107,885.2

[a] Energy unit: KLOE/M.

3.6. Step 6: process energy use

Process energy use is estimated by subtracting energy losses due to equipment inefficiency from energy conversion systems to process energy use systems.

$$\text{Process energy use} = \text{energy conversion (from Step 5)} - \text{total equipment losses} = 77{,}526.5\ \text{KLOE/M} \quad (15)$$

By following these steps, the energy flow profile of the Taiwanese pulp and paper industry was established, as shown in Fig. 2. The energy flow profiles identified where energy was being lost and the areas with potential for energy savings.

4. Results and discussion

4.1. Energy use and loss analysis

The energy use and loss of the Taiwanese pulp and paper industry was analyzed in this study and the analysis results are described below. Primary energy, which includes purchased fuels/steam and electricity, byproduct fuels and the energy losses associated with offsite power generation and energy supply systems, provided a perspective on the total energy use associated with pulp and paper products [38]. The primary energy inputs in the Taiwanese pulp and paper industry are shown in Fig. 3. According to Fig. 3, over 1/3 of the energy used is contributed by purchased power, with boiler fuel comprising the primary energy source at 29.8%. According to the energy flow analysis methodology described in Section 3, the primary energy-use situation was as listed in Table 2.

The results of the energy loss analysis of the Taiwanese pulp and paper industry, as summarized in Table 3, showed that the total energy losses, from boiler and electricity generation losses, distribution losses and losses due to equipment inefficiency, were 30,027.3 KLOE. As determined from the energy flow analysis, the general energy flow and losses were as illustrated in Fig. 4. As Fig. 4 shows, equipment inefficiency accounted for an energy loss of 40.3%, boiler and electricity generation losses for an energy loss of 32.0% and distribution a 27.7% energy loss.

4.2. Energy conservation opportunities analysis

The energy flow analysis for the pulp and paper industry evaluated end-use and loss patterns to understand in depth the

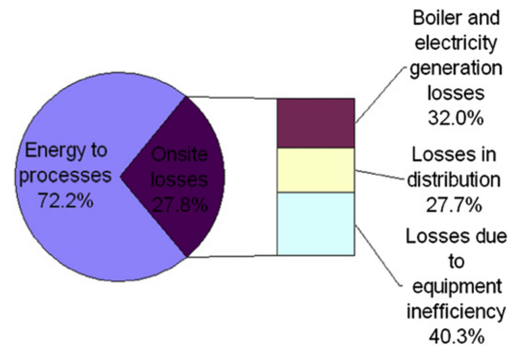

Fig. 4. Onsite energy loss profile of Taiwanese pulp and paper industry.

opportunities for energy conservation. According to the energy loss patterns, the energy conservation opportunities would be as follows.

(1) Boiler and power generation loss: Adding inverters to the boiler blowers would save electricity. Other energy conservation measures, such as controlling the discharge oxygen concentration and minimizing excess air, recycling the cooling water and waste heat, and lowering the discharge temperature to below the original design setting, would also be effective. Periodic inspection and cleaning are essential to improve the efficiency of the boiler and power generation system. In addition, if the boiler and power generation system equipment were upgraded, equipment efficiency would be improved.

(2) Energy distribution loss: Steam distribution losses due to heat transfer, ineffective steam traps, leaks etc. varied from 20% to 40% [40–42]. If these parts were upgraded, energy consumption and production costs would be reduced. The suggested energy conservation methods are as follows:
   (a) Install insulation and conduct a survey of the steam distribution to reduce the leakage of steam.
   (b) Steam traps:
      (i) If steam systems have not been adequately maintained, some of the installed steam traps may have failed. We recommend steam-trap testing intervals of weekly to monthly for high pressure (above 150 psig), monthly to quarterly for medium pressure (30–150 psig) and annually for low pressure (below 30 psig).
      (ii) Energy loss from the continuous discharge of condensation or the trap due to radiation, which will also increase condensate load. Regular systematic inspection, testing, and repair of steam traps should be established to reduce steam losses.

(3) Equipment inefficiency loss:
   (a) Pulping process:
      (i) Long periods of operation results in scale build-up inside the digester and a non-uniform temperature distribution. Since scales with low heat conductivity waste steam, they should be removed on a periodic basis to improve the efficiency of the equipment.

Table 3
Energy loss summary of Taiwanese pulp and paper industry.[a]

Boiler and electricity generation losses	9639.6
Losses in distribution	8292.3
Losses due to equipment inefficiency	12,095.4
Total energy losses	30,027.3

[a] Energy unit: KLOE/M.

Table 4
Total energy-saving potential for Taiwanese pulp and paper industry.

Energy saving items	Energy saving potential (KLOE/M)
Boiler and electricity generation	896.1
Distribution	2131.5
Equipment inefficiency	3739.7
Summary	6,767.3

(ii) Non-condensable gas produced during the reaction in the digester prevents the reaction from taking place. If the gas is removed, heat potential should be recovered by the heat exchanger.
(iii) The continuous digester has lower steam consumption but higher power consumption than the batch digester [43]. Ever since the yearly reduction of unit consumption for steam and electric power of the continuous digester, the use of the continuous type is preferred.
(iv) If the screening/cleaning and bleaching equipment were upgraded, the efficiency of bleaching would be improved and, thus, the steam consumption in the digester and the electricity used in refining and thickening would be reduced.
(v) Since the plate type of the black-water concentration evaporator has a lower pump power and higher operation efficiency than the tube type, the use of the plate type is preferred.

(b) Papermaking process:
(i) Preventive maintenance (PM) by the maintenance division: to prevent accidents and to repair or improve the equipment through periodic inspections.
(ii) Prevention of paper breaking: If a detailed analysis of the paper breaking were carried out, the problem would be readily solved.
(iii) Effective use of white water: If unique technologies, such as head-box temperature-setting optimization, recycle white water for effective reuse were established through the creative consideration of the current equipment, the use of new water would be reduced.
(iv) Dryer: The greatest heat consumer in the pulp and paper industry is the dryer and recovery from this part is necessary. If the uniform moisture profile in the cross direction of the dryer were obtained, the effective energy transfer to the wet paper and efficient evaporation would be possible.
(v) Paper machine: The paper machines process white water which contains sulfate and chloride with little or no recycling; the content of sulfate, chloride and the dissolved organic compounds increase and cause corrosion. To prevent general corrosion, fatigue failures, and MIC (microbiologically influenced corrosion) within the suction rolls, duplex stainless steels have been used [44]. Furthermore, the suction holes in the rolls would remain unblocked and the applied load on the rolls would not exceed the design load [45].

(c) Pulp refining process: Three types of refiners in common use are the conical type, drum type and disc type. The unit electricity consumption of the disc type refiner is lower than that of the other refiner types in NBKP (needle bleached kraft pulp) and LBKP (leaf bleached kraft pulp) and its use is recommended.

(d) Fan, Pump and Motor: Electricity would be saved if the motor were switched to an energy-efficient motor-driven system. Moreover, variable frequency drives would be an excellent choice for adjustable-speed drive users because they allow operators to fine-tune processes while reducing costs for energy and equipment maintenance in the heating, ventilating and air-conditioning of buildings [46,47]. Electricity usage would be reduced if motors were combined with frequency control.

(e) Air Compressor System: A well-known problem with air compressor systems is leakage. Leakage means that the compressor has to work harder than necessary in order to maintain pressure in the compressed air line, which leads to higher than necessary electricity consumption [48]. When an air compressor system is converted to a system with electrically powered tools, an air-free chiller is installed and a screw-type air compressor is used to replace the centrifugal type, thus raising the coefficient of utilization.

4.3. Energy-saving potential evaluation

According to the Energy Management Law of Taiwan, energy users must observe the regulations promulgated by the central authority when conducting an energy audit, as well as setting an energy conservation target and creating an action plan [49]. According to the energy loss patterns discussed above, the potential energy-savings as determined by the evaluation are as follows:

(1) Boiler and power generation:
(a) Lowering the discharge temperature to below the original design setting and upgrading the equipment of the boiler and power generation system would increase equipment efficiency by 2%, equivalent to an energy saving of 230.1 KLOE/M.
(b) Recycling the cooling water and waste heat would increase the efficiency of the boiler by about 1.2%, equivalent to an energy saving of 319.7 KLOE/M.
(c) With periodic inspection and cleaning, the efficiency of the boiler would be increased by 1.0%, equivalent to an energy saving of 266.4 KLOE/M.
(d) An energy saving of about 79.9 KLOE/M (efficiency up 0.3%) could be realized by regulating and insulating the temperature in the boiler.

(2) Energy distribution: If steam distribution losses due to heat transfer, ineffective steam traps, leaks etc. were minimized, energy consumption would be reduced by 5–10% (2131.5 KLOE/M).

(3) Equipment inefficiency:
(a) Paper drying: Energy savings would approach 25% if thermal energy were captured from the steam or if advanced dryer control systems were utilized to optimize the drying process. In addition, if the motors of the fan and pump were switched to an energy-efficient motor-driven system, electricity usage would be reduced. The energy consumption would decrease 20%, equivalent to an energy saving of 1477.1 KLOE/M.
(b) Digester: Long operation over time produces scales inside the digester and can result in an energy loss of 1.0–7.0%. If the scales were removed on a periodic basis, equipment efficiency would be improved and energy saved (170.3 KLOE/M). Also, improving digester efficiency by capturing waste heat and using chemical pulping aids to help break down the wood chips into pulp would result in a 10–20% energy saving (425.6 KLOE/M) in the pulping process.
(c) Black liquor concentration (BLC): BLC is the process of evaporating water from black liquor to increase its solids content and to make the recovery boiler combustion process more efficient [50]. Martin et al. [51] estimated a steam saving of 0.76 MMBtu per ton of pulp [52]. The production of pulp in Taiwan is around one million tons per year, making the energy-saving potential from the perspective of BLC about 1666.7 KLOE/M.

In summary, the energy-saving potential of the pulp and paper industry would be 6939.9 KLOE/M, as listed in Table 4. According to Table 4, the greatest energy-saving potential lies with improving energy distribution and equipment efficiency, which potentially comprise 86.8% in total energy conservation.

5. Conclusions

Taiwan must conform to the Kyoto Protocol in the future and preparations must be made. The Bureau of Energy of the Ministry of Economics Affairs has taken substantial preparatory measures and established an energy analysis group to help energy users analyze energy flow profiles, enhance energy efficiency and reduce CO_2 emissions. This work has analyzed the energy flow of the pulp and paper industry in Taiwan and found that the main energy losses were from distribution, boilers and electricity generation and equipment inefficiencies. In addition, energy-saving opportunities and potentials were identified and evaluated. The energy-saving potential of the pulp and paper industry would be around 6939.9 KLOE/M. The greatest energy-saving potential lies with improving energy distribution and equipment efficiency, and potentially comprises 86.8% in total energy conservation. This study then developed a quantified list in terms of potential energy-saving opportunities for improving the efficiency of the pulp and paper industry. These analysis results can serve as benchmarks for current pulp and paper making operations and as a base case for stimulating changes of energy utilization in the pulp and paper industry.

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