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# Exergy Evaluation of Renewable Use in the Pulp and Paper Industry

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***Abstract*--Papermaking industry has energy-intensive installations that consume high amounts of energy but at the same time produce steam and electrical power on site by use of regenerative fuels. Black liquor and bark result from the technological. These renewable sources usually are burnt to recover chemicals and energy. In this paper there is presented a methodology for evaluation of renewable use in the pulp and paper industry. After that, there are presented numerical results from a pulp and paper mill, standing out fuel saving and reduction of pollution cost**.

***Index Terms*—cost, fuel, paper industry, power plant, renewable source**

## I. Nomenclature

c specific cost ($/GJ)
C cost (thousand $)
E exergy (TJ)
EP electricity purchased (MWh)
FD relative fuel difference (%)
FC fuel consumption (thousand mc)
FS fuel saving (thousand mc)

***Greek symbols***

ε exergy efficiency (%)
α exergy renewability (%)

***Subscripts***

c consumed
e electricity
f fuel
fep fuel electricity pollution
l losses
p pollution
r renewable
s steam
u useful

## II. Introduction

THE pulp and paper industry is energy-intensive, requiring large amounts of steam and electricity to process wood into paper and paper products. Pulp and paper mills also utilize significant amounts of self-generated fuels. For this industry, the main raw material is a renewable resource (wood). From the technological process results two sources of biomass: black liquor and bark. These renewable sources usually are burnt to recover chemicals and energy. Three main types of boilers are used in the own power plant of pulp and paper mill: the *recovery boiler*, which recovers chemicals and energy from spent kraft cooking chemicals, the *bark boiler* which recovers energy from bark and wood wastes, and the *power boiler*, which generates heat using a variety of fuels. For this industry, improvement efficiency of its energy production, the switch from using fossil fuels to biomass in order to minimize costs and environment impacts is a necessity. The exergy is a measure of potential harm from production and consumption material wastes which are disposed into the environment. From this reason, power plant exergy efficiency analysis can help a pulp and paper mill improve its exergy efficiency and reduce its emissions and production cost.

## III. Exergy Evaluation of Renewable Use

We estimate some indices for exergy evaluation of whole process to conversion of fuel to energy. For that, we develop a simulation model using fundamentals of thermodynamics, mass and energy conservation and existing process data. The exergy balances equations are used for estimation of exergy losses.

The exergies are calculated using standard method, [1].

For evaluation of *exergy efficiency*, the following indice, $\varepsilon$, is used:

$$\varepsilon = \frac{E_u}{E_c} \cdot 100 \qquad (1)$$

where $E_u$ is useful exergy (sum of exergy of supply steam and generated power); $E_c$ – consumed (chemical) exergy of all consumed fuel in the steam boilers.

For evaluation of renewable use, Zvolinsky proposes, *exergy renewability*, (α), [2], which considers the consumed exergy of renewable resources compared to the total of all consumed exergy.

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$$\alpha = \frac{E_r}{E_c} \cdot 100 \qquad (2)$$

where: $E_r$ – chemical exergy of renewable.

The unitary fuel cost, unitary cost of electricity which is purchased from public grid and emissions tax are known. In order to reduce energy costs and emissions cost, quantities of them must be reduced. If a part of fossil fuel is replaced with biomass then fuel cost and emissions cost are reduced. If all technological steam is provided by the bleeder turbines or by the backpressure turbines then more electricity is generated and electricity cost decreases. Thus, we estimate a coefficient which takes account of these costs and of the useful exergy, *specific fuel electricity pollution cost:*

$$c_{fep} = \frac{C_f + C_e + C_p}{E_u} \qquad (3)$$

where: $C_f$ is fuel cost (natural gas, oil), $C_e$ –cost of electricity which is purchased from the public grid, $C_p$ – cost of pollution due to all consumed fuel, [3], $E_u$ is useful exergy (sum of exergy of steam and generated electricity) The purpose is to minimize this coefficient.

If there are analyzed many solutions then following two coefficients are usefully:

- *Relative fuel difference, FD.* This variable expresses the relative decrease in fuel consumption between two solutions compared. This is expressed as

$$FD = \frac{FC_1 - FC_2}{FC_1} \cdot 100 \qquad (4)$$

where subscripts *1* and *2* refer to the solutions compared.

-The same, *relative pollution cost difference, RC*$_p$, is calculated.

## IV. CASE STUDY

A common approach to improve processes using simulation is to simulate a number of cases, and then select the best of these, [4].

In this paper is made exergy analyze of pulp and paper mill using the above simulation model. Purpose of this analyze is to identify possibilities for improving thermal processes. Figure 1 shows the simplified block flow diagram of pulp and paper mill with renewable resources: bark and black liquor.

The heat demand of the mill is split between two steam levels, medium pressure of 15 bar and low pressure of 5 bar. Combined heat power plant (CHP) uses fuels energy to provide useful heat as well as to generate electricity. This consists of 3 power boilers (PB) with natural gas and two recovery boilers (RB) feeding two backpressure bleeder turbines and two bark boilers (BB) of 15 bar technological steam.

CHP should ensure the supply of steam of 5 bar for three paper machines and steam of 15 bar for digesters and evaporation plant. In summer, the normal functioning of the CET is 1 gas steam boiler, 1 recovery boiler and 1 bark boiler. In winter, if all paper machines are in operation then the second gas steam boiler must be started.

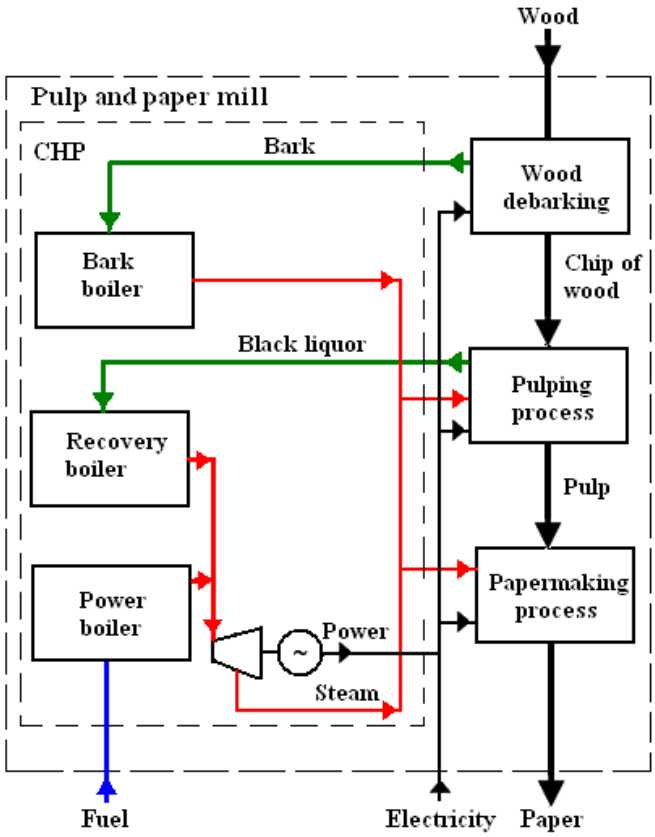


Fig. 1. Simplified block diagram of a pulp and paper mill showing renewable sources

The exergy analyze of CHP was made for a year period. The results are shown in the tables I…III.

TABLE I
EXERGY ANALYSIS OF STEAM BOILERS

| Parameter | Symbol | Unit | Value | | | |
|---|---|---|---|---|---|---|
| | | | PB | RB | BB | Boilers hall |
| Consumed exergy | $E_c$ | TJ | 1832 | 1776 | 237 | 3845 |
| Useful exergy | $E_u$ | TJ | 487 | 467 | 52 | 1005 |
| Exergy losses | $E_l$ | TJ | 1345 | 1309 | 186 | 2840 |
| *Exergy efficiency* | $\varepsilon$ | % | *27* | *26* | *22* | *26* |

TABLE II
EXERGY ANALYSIS OF WHOLE CHP

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Fossil fuel exergy | $E_f$ | TJ | 1832 |
| Renewable exergy | $E_r$ | TJ | 2013 |
| *Total consumed exergy* | $E_c$ | *TJ* | *3845* |
| Useful exergy of steam of 4 bar | $E_{u,s4}$ | TJ | 318 |
| Useful exergy of steam of 15 bar | $E_{u,s15}$ | TJ | 247 |
| Total useful exergy of steam | $E_{u,s}$ | TJ | 565 |

| | | | |
|---|---|---|---|
| Generated electricity | $E_{u,e}$ | TJ | 216 |
| *Total useful exergy of CHP* | *$E_u$* | *TJ* | *781* |
| Exergy losses | $E_p$ | TJ | 3064 |
| *Exergy efficiency of CHP* | *$\varepsilon$* | *%* | *20.3* |
| *Exergy renewability* | *$\alpha$* | *%* | *52.4* |
| Fossil fuel saving | FS | thousand mc | 59700 |

TABLE III
COSTS

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Electricity purchased from public grid | EP | MWh | 149984 |
| Fossil fuel consumption | F | thousand mc | 54335 |
| NMVOC emissions | NMVOC | kg | 7328 |
| $NO_x$ emissions | $NO_x$ | kg | 183211 |
| $SO_2$ emissions | $SO_2$ | kg | 751 |
| Cost of electricity purchased from public grid | $C_e$ | thousand $ | 12340 |
| Natural gas cost | $C_f$ | thousand $ | 17189 |
| Pollution cost | $C_p$ | thousand $ | 2.3 |
| Total cost | C | thousand $ | 29532 |
| ***Specific fuel electricity pollution cost*** | ***$c_{fep}$*** | ***$/GJ*** | ***37.82*** |

In the table II, FS is natural gas saving which is obtained by using renewable and in the table III, emissions are due to the combustion natural gas in power boilers.

Note that more than half (52.4%) of fuel consumed in the manufacture of paper comes from own renewable source. However, after this analysis we sought solutions to improve the use renewable. Biomass (bark and black liquor) which result from the technological process can't be modified. But there are solutions for increasing of energy efficiency of recovery boiler: improving thermal insulation of the boiler, use of more efficient burners and adjust correct combustion. By applying these solutions can increase energy efficiency from 65% to 74% and the exergy efficiency from 26% to 30%. If technological installations require the same amount of heat that can be decreased consumption of natural gas in power steam boilers. The results of this simulation are shown in the following tables.

TABLE IV
EXERGY ANALYSIS OF STEAM BOILERS FOR SIMULATION

| Parameter | Symbol | Unit | Value | | | |
|---|---|---|---|---|---|---|
| | | | PB | RB | BB | Boilers hall |
| Consumed exergy | $E_c$ | TJ | 1585 | 1776 | 237 | 3598 |
| Useful exergy | $E_u$ | TJ | 422 | 532 | 52 | 1005 |
| Exergy losses | $E_l$ | TJ | 1163 | 1244 | 186 | 2593 |
| *Exergy efficiency* | *$\varepsilon$* | *%* | *27* | *30* | *22* | *28* |

TABLE V
EXERGY ANALYSIS OF WHOLE CHP FOR SIMULATION

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Fossil fuel exergy | $E_f$ | TJ | 1585 |
| Renewable exergy | $E_r$ | TJ | 2013 |
| *Total consumed exergy* | *$E_c$* | *TJ* | *3598* |
| Useful exergy of steam of 4 bar | $E_{u,s4}$ | TJ | 318 |
| Useful exergy of steam of 15 bar | $E_{u,s15}$ | TJ | 247 |
| Total useful exergy of steam | $E_{u,s}$ | TJ | 565 |
| Generated electricity | $E_{u,e}$ | TJ | 216 |
| *Total useful exergy of CHP* | *$E_u$* | *TJ* | *781* |
| Exergy losses | $E_p$ | TJ | 2817 |
| *Exergy efficiency of CHP* | *$\varepsilon$* | *%* | *21.7* |
| *Exergy renewability* | *$\alpha$* | *%* | *56.0* |
| Fossil fuel saving | FS | thousand mc | 59700 |

TABLE VI
COSTS FOR SIMULATION

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Electricity purchased from public grid | EP | MWh | 149984 |
| Fossil fuel consumption | F | thousand mc | 47003 |
| NMVOC emissions | NMVOC | kg | 6339 |
| $NO_x$ emissions | $NO_x$ | kg | 158486 |
| $SO_2$ emissions | $SO_2$ | kg | 650 |
| Cost of electricity purchased from public grid | $C_e$ | thousand $ | 12340 |
| Natural gas cost | $C_f$ | thousand $ | 14870 |
| Pollution cost | $C_p$ | thousand $ | 2 |
| Total cost | C | thousand $ | 27211 |
| ***Specific fuel electricity pollution cost*** | ***$c_{fep}$*** | ***$/GJ*** | ***34.84*** |

Note, in the case of simulation, that by applying the proposed measures can achieve increased exergy efficiency boilers hall from 26% to 28% and for whole CHP, from 20.3% to 21.7%. Also increases and exergy renewability of 52.4% to 56% even though it uses the same amount of renewable. This may get the same amount of heat and electricity with a small quantity of natural gas. It can obtain such a gas saving by 7,332 thousand cubic meters, meaning a savings of 13.5% relative.

It is obtained and a corresponding decrease in emissions. But the emissions cost decreases with only 300 $, meaning a decrease of 13% relative, because pollution taxes are quite low.

The coefficient which takes account of energy-pollution costs and of the useful exergy, $c_{fep}$, decreases from 37.82% to 34.84%

## V. Conclusions

The use of the renewable sources leads to the fossil fuel saving and reduction of the pollutant emissions.

Pulp and paper mills are heat and power self-sufficient by using the heat value of the black liquor, bark and wood waste.

This paper includes an exergy analysis of the steam and power generation process for a pulp and paper mill. Following this analysis have been proposed solutions to improve utilization renewable. Exergy indicators and costs were estimated for both real and simulated case. Were emphasized fuel saving and reduce emissions. Thus, by applying measures to improve energy efficiency can achieve savings of 2,300 thousand $ per year and gas saving by 7,332 thousand cubic meters per year. The fossil fuel saving achieved by the use of renewables is 59,700 thousand cubic meters per year.

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## VII. Biographies

Prof. A. Hazi, PhD, graduated from Faculty of Electrotechnics of University Gh.Asachi of Iasi, specialization Industrial Energetics in 1982. In 1999 obtained the scientific title of doctor engineer of the University Politehnica of Bucharest, specialization Thermoenergetics.

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Doctor engineer since 1974, has an outstanding teaching, scientific and technical activity in the fields of heat transfer, thermal equipment and installations. Ph.D. coordinator since 1993, has managed to create in the university a strong school in the field of equipment and thermal installations with important collaboration in the country and abroad. Now, he is vice-rector of the University Politehnica of Bucharest.

Prof. Gh. Hazi, PhD, graduated from Faculty of Electrotechnics of University Gh.Asachi of Iasi, specialization Industrial Energetics in 1982. In 1997 obtained the scientific title of doctor engineer of the University Gh.Asachi of Iasi, specialization Electroenergetics.

Since 1990 teacher at the Department of Power Engineering, Faculty of Engineering of University of Bacau and has an intense teaching and scientific activity in the fields of networks, optimization and reliability of energy systems

Associated Professor, H. Necula, PhD, graduated from Faculty of Power Engineering of University Politehnica of Bucharest, specialization Industrial Energetics in 1993. In 1999 obtained the scientific title of doctor engineer of the National Institute of Applied Sciences in Lyon and the University Politehnica of Bucharest, specialization Thermoenergetics.

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