

EXERGY MODELING AND PERFORMANCE EVALUATION OF PULP AND PAPER PRODUCTION PROCESS OF BAGASSE, A CASE STUDY

by

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Pulp and paper production industries are known as a renewable energy technology. In this research, exergetic analysis of pulp and paper production is presented. The system performance is evaluated based on the data of Pars paper industrial group, Iran, which is given as an illustrative example. An exergy destruction as well as exergy efficiency relation is determined for each section of the system components and the whole system to indicate the largest exergy losses and possibilities of improvement. It is found that the largest exergy losses occurred in the steam plant and soda recovery and these sections are highly exergy inefficient. Further it is observed that with decrease of excess air and preheating of inlet air the exergy efficiency of boilers is increased.

Key words: *bagasse, paper industry, exergy analysis*

Introduction

Pulp and paper industries have a high demand for both work and heat, which makes them suitable for exergy studies. An exergy analysis (or second law analysis) has proven to be a powerful tool in the simulation thermodynamic analyses of energy systems. In other words, it has been widely used in the design, simulation and performance evaluation of energy systems. It is employed to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. Many researchers and practicing engineers refer to exergy methods as powerful tools for analyzing, assessing, designing, improving, and optimizing systems and processes [1-3].

Many exergy analyses for industrial processes have been reported. To include the pulp and paper mills, Wall [4] discussed the simplicity and value of using the concept of exergy when analyzing processes to develop conventions and standards within the field. Gemci and Ozturk [5] performed exergy analysis of a sulphide-pulp preparation process in the pulp and paper in-

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dustry. Gong [6] studied exergy analysis of a pulp and paper mill and presented energy and exergy concepts to a Swedish pulp and paper mill. Hong *et al.* [7] 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 were evaluated. Sarimveis *et al.* [8] examined the utilization of mathematical programming tools for optimum energy management of the power plant in pulp and paper mills. The objective was the fulfillment of the total plant requirements in energy and steam with the minimum possible cost. Cortes and Rivera [9] studied the optimization of a pulp and paper mill with a co-generation plant. The optimization included the exergy, exergoeconomics, thermoeconomics, and pinch analysis. The proposed methodology was useful in determining not only the best plant operating conditions but also establishing the components or subsystems with the highest irreversibilities. Further Marshman *et al.* [10] studied energy optimization in a pulp and paper mill co-generation facility. They presented an energy optimization algorithm for pulp and paper mill co-generation system. The algorithm was applicable to a number of popular mill configurations, power sale contracts, and fuel purchasing scenarios. The method was also extended to address weather-dependent cooling limitations encountered by a mill cogeneration facility, in which case an iterative solution was proposed in order to maintain convexity of the optimization problem.

In this study, one of the Iranian pulp and paper industries is analyzed. Pars paper industrial group (PPIG) consists of two pulp mill and three paper mills and based material is bagasse. The main objective of this study is to conduct an exergy analysis as a thermodynamic consideration. Parameters such as fuel depletion ratio, relative irreversibility, productivity lack, exergetic factor and exergetic improvement potential are discussed for better understanding and modeling. Analysis of all subsection that affected on the process is performed to determine the most effective ways of improving the production of pulp and paper process from bagasse.

System description

The nominal capacity of PPIG is 350 tones/day but at the time of this study, the value of production paper was 146 tones/day. In the process of sugar production in Iran, bagasse is a disposed material. However the process of making paper from wood uses more energy than bagasse and bagasse is cheaper; it is an advantage to use bagasse as raw material. The production process of pulp and paper in PPIG consists of the following stages shown in fig. 1:

- *Depitting*. Pit of bagasse separated by means of impact depitter hammer and screened. Separated pit unused in process now, thus brought as a product. Depitted bagasse washed and mixed with water and pumped to pulp mill.
- *Digester*. Washed depitted bagasse pressed at first, so cooked in digester. In digester depitted bagasse cooked with white liquor (100 kg/m^3) and steam (785 kPa, 170 °C). Lignin content in bagasse dissolved in white liquor and useful pulp separated with lignin. Output of digester is mixed pulp and liquor and enters to blue tank for continuing of reaction.
- *Washing*. Mixed pulp and liquor washed in three rotational screen washers with weak liquor and warm water. Output weak black liquor of first washer pumped to recovery boiler for recovery of white liquor. In screen unit, pulp passes in screen at high pressure and separated residue lignin.

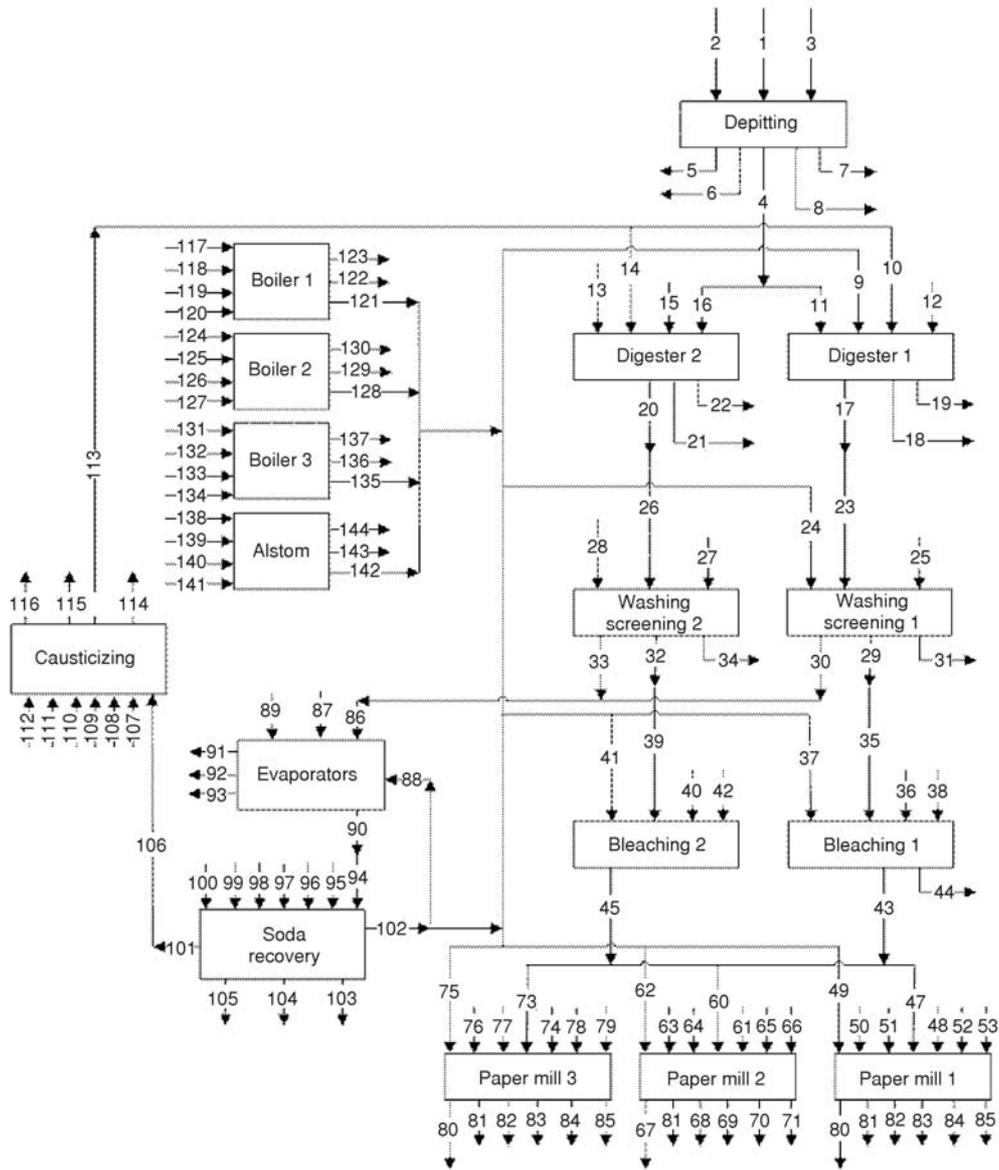


Figure 1. Production process in Pars paper industrial group

- *Bleaching*. Some time brown pulp should be changed into white pulp. In order to do this change, brown pulp is reacted in three stages with color, caustic, hypo, and finally named bleached pulp.
- *Evaporators*. Weak black liquor should be concentrated so that it can be used in recovery boiler. Evaporators include five effect (shell-tube) and concentrator in which weak black liquor evaporated to 45% dry content.

- *Soda recovery*. Strong black liquor resulting from evaporators is then evaporated in cyclone evaporator to 60% dry content. Then strong black liquor enters the recovery boiler through the black liquor burner. Organic substances are combusted in recovery boiler. Non-combusted substances as melt enter the dissolving tank and they dissolve into weak wash liquor and named green liquor. Soda recovery boiler generates high pressure steam (2945 kPa, 320 °C).
- *Causticizing*. In causticizing unit green liquor converts to white liquor. Sodium carbonate is reacted with lime (produce in lime kiln) at temperature of 100 °C. When reaction is complete, sodium hydroxide is produced and calcium carbonate is removed. Reaction in lime kiln follows:

$$\text{CaCO}_3 + Q \rightarrow \text{CaO} + \text{CO}_2 \quad (1)$$
 Reaction in slacker is:

$$\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 \quad (2)$$

$$\text{Ca(OH)}_2 + 2\text{Na}_2\text{CO}_3 \rightarrow 2\text{Na(OH)} + \text{Ca(CO}_3) \quad (3)$$
- *Paper mills*. Three paper machines produce a number of different qualities paper. Saturated steam enters the cylinder in paper machines and heat is transferred to pulp and dries it to form paper. Almost 20% of all the pulp needed at mill is kraft.
- *Steam boilers*. Total steam in PPIG is provided with four oil boilers and a soda recovery boiler.

In order to conduct the exergy method, it is necessary to describe the composition of bagasse. The bagasse was analyzed for their composition and the data are presented in tab. 1. The heating value of bagasse varies with moisture content and ash of bagasse. Considering the bagasse used in this process, the heating value of bagasse is equal to 10500 kJ/kg. Table 2 gives the assumed chemical composition of the flows in the process.

Table 1. Average composition (ultimate analysis) of bagasse [11]

Substance	H	C	O	HHV [kJkg ⁻¹]	LHV [kJkg ⁻¹]
Bagasse	6.8 ± 1.3	45.3 ± 1.3	45.4 ± 1.7	16793 ± 244	6484 ± 568

Table 2. Chemical composition of substances in the pulp and paper mill [4]

Substance	H	H ₂ O	C	O	Na ₂ CO ₃	NaOH	Na ₂ S
Stripping liquor	0.6	85.8	4.7	3.9	0.9	2.5	1.6
Mixed liquor	0.9	76.2	7.4	6.4	1.7	4.5	2.8
Green liquor		80.8			14.0		5.2
Liquor	0.7	88.7	6.9	3.3	0.1	0.2	0.1
Pulp	0.8	87.1	6.3	5.8			
Pulp & liquor	1.4	78.0	12.4	7.6	0.1	0.3	0.2
Paper/kraft liner	5.8	7.6	45.0	41.6			
Waste paper	4.6	26.4	35.9	33.1			
Waste liquor	0.9	77.2	7.5	6.2	1.5	4.1	2.6
Weak liquor		95.9			3.0		1.1
Black liquor	3.3	39.6	18.8	16.3	4.2	11.5	7.2
White liquor	83.2	3.1	8.4	5.3			

Theoretical analysis

Unlike energy, exergy is not subject to a conservation law (except for reversible processes). Rather exergy is consumed or destroyed due to irreversibility in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibility associated with the process. The total exergy of a system can be divided into four components, physical exergy, kinetic exergy, potential exergy and chemical exergy as follows:

$$Ex = Ex^{PH} + Ex^{KN} + Ex^{PT} + Ex^{CH} \quad (4)$$

Only the physical and chemical exergy are considered in this study. Thus, the general exergy rate balance can be expressed as (fig. 2):

$$\dot{Ex}_{in} = \dot{Ex}_{product} + \dot{Ex}_{waste} + \dot{Ex}_{dest} \quad (5)$$

The exergy destruction is mainly made of irreversibility and the exergy of waste includes the solid and liquid waste, air emissions and follows:

$$\dot{Ex}_{dest} = T_0 \dot{S}_{gen} \quad (6)$$

The useful exergy is the exergy of the products. This can be calculated from the exergy balance:

$$\dot{Ex}_{product} = \dot{Ex}_{out} - \dot{Ex}_{waste} = \dot{Ex}_{in} - \dot{Ex}_{dest} - \dot{Ex}_{waste} \quad (7)$$

The specific physical exergy of flow i can be calculated from the equation:

$$e_{th,i}[(P_i, T_i), (P_0, T_0)] = (h_i - h_0) - T_0(s_i - s_0) \quad (8)$$

Here h is the enthalpy, s – the entropy, and the subscript zero indicates properties at the dead state of $P_0 = 101.325$ kPa and $T_0 = 298.15$ K.

The chemical exergy of substance can be calculated as [12]:

$$Ex^{CH} = \sum_{j=1}^n y_j \overline{\varepsilon_j^{CH}} + RT_0 \sum_{j=1}^n y_j \ln y_j \quad (9)$$

where y_j is the mole fraction of component j , each component has molar $\overline{\varepsilon_j^{CH}}$ and R is the universal gas constant. Chemical data of substances can be taken from [1].

The exergy of the mixture is determined by its nature. In an ideal mixture the enthalpy can be calculated as the sum of the enthalpies of its component. The entropy of a mixture, on the other hand, is determined by its nature. An ideal mixture is one where the elements are completely intermixed. The entropy of such mixtures is [12]:

$$S = \sum_i y_i s_i - R \sum_i y_i \ln y_i \quad (10)$$

where y_i is the molar ratio of component i , and s_i its entropy.

Exergy is lost when separated substances are allowed to form an ideal mixture. The mixtures occurring in this analysis are rather non-ideal mixtures. However, there is no general theory or unequivocal concept for non-ideal mixtures. Data on specific heats are generally only

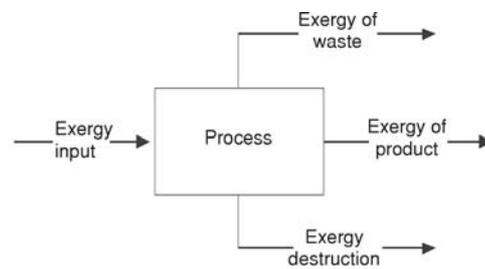


Figure 2. Exergy balance

available for pure elements and for specific chemical compounds such as oxides. Thus, the specific heat of a mixture is assumed to be the sum of the specific heat of the substances in relation to their proportion. This will generate incorrect values of thermal energy and exergy for mixtures where new phases appear. However, the impact on the final result from these errors is considered to be negligible in comparison to other errors, *e. g.* in the data for material flows and temperatures [4]. Change of entropy calculated for solids and liquids from:

$$s_2 - s_1 = c_{av} \ln\left(\frac{T_2}{T_1}\right) \quad (11)$$

In addition, for ideal gas:

$$s_2 - s_1 = \int c_p(T) \frac{dT}{T} - R \ln\left(\frac{P_2}{P_1}\right) \quad (12)$$

The efficiency of the process is then defined as the useful exergy of the total input exergy:

$$\eta_{ex} = \frac{\dot{E}x_{product}}{\dot{E}x_{in}} \quad (13)$$

The exergy loss can be calculated as:

$$\varepsilon_l = \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \quad (14)$$

For thermodynamics analysis of the system, the following parameters are used (see [12, 13]):

– for fuel depletion ratio:

$$\delta_k = \frac{(\dot{E}x_{dest})_k}{\dot{F}_{tot}} \quad (15)$$

– relative irreversibility:

$$\chi_k = \frac{(\dot{E}x_{dest})_k}{(\dot{E}x_{dest})_{tot}} \quad (16)$$

– productivity lack:

$$\xi_k = \frac{(\dot{E}x_{dest})_k}{\dot{P}_{tot}} \quad (17)$$

– exergetic factor:

$$f_k = \frac{\dot{F}_k}{\dot{F}_{tot}} \quad (18)$$

Results and discussion

The parametric analysis is performed to evaluate the performance – in terms of exergy – of the sub-process in PPIG and also to indicate the largest exergy losses and possibilities to improve them. Table 3 illustrates the description of the plant's flow and their thermodynamic properties. The material flows of every sub-process are given in ton per ton of produced paper (ton/tp) and the exergy flows in MJ/tp. In this study 1 kJ electricity is used as 1 kJ input energy to the process.

Table 3. Exergy flow and other properties in PPIG (for state numbers refer to fig. 1)

State no. in fig. 1	Fluid	Mass flow rate [ton/tp]	Temperature [°C]	Pressure [kPa]	Exergy flow [MJ/tp]
1	Raw bagasse	2.69	25		26605.89
2	Water	23.52	35		34.34
3	Electricity	–	–		753.3
4	Depitted bagasse	2.33	25		23999
5	Pit	0.23	25		2185
6	Water	9.09	30		1.54
7	Waste water	14.51	30		2.32
8	Waste bagasse	0.13	25		1186.88
9	Steam	0.78	170	785	630.41
10	Caustic	0.97	25		1415.61
11	Bagasse	0.8	25		8240
12	Electricity	–	–		162.57
13	Steam	1.6	170	785	1309.72
14	Caustic	1.85	25		2699.87
15	Bagasse	1.53	25		15759
16	Electricity				169.31
17	Pulp and liquor	2.4	100		10200
18	Steam	0.1	150	100	49.02
19	Waste	0.05	100		24.51
20	Pulp and liquor	4.28	100		18190
21	Steam	0.6	150	100 kPa	294.15
22	Waste	0.1	150		49.02
23	Pulp and liquor	2.4	70		10200
24	Water	3.6	75		51.66
25	Electricity	–	–		325.15
26	Pulp and liquor	4.28	70		18190
27	Water	5.5	75		93.78
28	Electricity	–	–		470.18
29	Pulp	2	60		6202
30	Black liquor	3.7	60		4297.58
31	Waste	0.3	60		58.69
32	Pulp	3.75	60		11628.75
33	Black liquor	4.51	60		5238.41
34	Waste	1.52	60		147.95

Table 3. (continuation)

State no. in fig. 1	Fluid	Mass flow rate [ton/tp]	Temperature [°C]	Pressure [kPa]	Exergy flow [MJ/tp]
35	Brown pulp		50		
36	Hypo		75		
37	Saturated steam	0.24	130	270.1	151.21
38	Electricity	–	–		140.63
39	Brown pulp	3.67	50		11380.67
40	hypo	0.72	75		9.1
41	Saturated steam	0.48	130	270.1	280.93
42	Electricity	–	–		198.22
43	White liquor	1.42	40		4403.42
44	Waste materials	0.94	75		82.41
45	White liquor	3.27	40		10140.27
46	Waste materials	1.6	75		748.88
47	Pulp	1.83	35		2674.83
48	Waste paper	0.04	45		597.4
49	Steam	2.26	140	360	1521.4
50	Water	8.73	35		9.25
51	Water	0.9	55		5.34
52	Brought pulp	0.05	35		1108.85
53	Electricity	–	–		640.69
54	Paper	0.36	45		7983.72
55	Condensate	1	100		34.36
56	Water	4.05	35		2.83
57	Waste water	6.24	25		0
58	Water	0.9	45		2.41
59	Waste condensate	1.26	100		43.29
60	Pulp	1.51	35		4682.51
61	Waste paper	0.05	45		724.25
62	Steam	1.76	140	360	1185.06
63	Water	7.11	35		7.91
64	Water	0.8	55		4.74
65	Brought pulp	0.04	35		887.08
66	Electricity	–	–		714.42
67	Paper	0.29	45		6431.33
68	Condensate	1	100	100	34.36
69	Water	3.25	35		2.27
70	Waste water	5.17	25		0

Table 3. (continuation)

State no. in fig. 1	Fluid	Mass flow rate [ton/tp]	Temperature [°C]	Pressure [kPa]	Exergy flow [MJ/tp]
71	Water	0.8	45		2.14
72	Waste condensate	0.76	100	100	26.11
73	Pulp	1.68	35		5209.68
74	Waste paper	0.02	45		289.7
75	Steam	2.39	140	360	1609.26
76	Water	8.4	35		7.16
77	Water	0.4	55		2.37
78	Brought pulp	0.04	35		887.08
79	Electricity	–	–		975.65
80	Paper	0.35	45		7761.95
81	Condensate	1.8	100	100	61.85
82	Water	3.53	35		2.47
83	Waste water	6.66	25		0
84	Water	0.4	45		1.07
85	Waste condensate	0.19	100	100	6.52
86	Stripping liquor	8.2	60		9536
87	Water	1.99	30		40.59
88	Steam	2.62	141	375	1770.07
89	Electricity	–	–		89.77
90	Strong black liquor	1.56	102		8582.4
91	Water	1.99	50		10.65
92	Waste condensate	7.19	60	20	58.89
93	Condensate	2.08	90	70 kPa	55.83
94	Strong black liquor	1.56	95		8584.2
95	Water	6.83	120		354.66
96	Steam	1.2	207		1075.44
97	Fuel oil	0.36	65		1473.8
98	Air	8.48	25		0
99	Weak wash liquor	2.21	55		376.25
100	Electricity	–	–		601.95
101	Green liquor	1.7	95		1810.53
102	Steam	5.67	345	2945	6153.76
103	Exhaust gas	10.4	119		479.06
104	Water	0.7	210		635.74
105	Waste	2.17	274		594.58
106	Green liquor	1.7	90		1810.53
107	Water	1.24	50		5.11

Table 3. (continuation)

State no. in fig. 1	Fluid	Mass flow rate [ton/tp]	Temperature [°C]	Pressure [kPa]	Exergy flow [MJ/tp]
108	Natural gas	0.05	20		193.83
109	Sodium carbonate	0.13	65		1.23
110	Air	1.16	25		0
111	Water	0.19	25		0
112	Electricity	–	–		193.8
113	White liquor	0.8	90		1167.51
114	Weak wash liquor	1.72	55		296.23
115	Exhaust gas	1.53	536		451.61
116	Waste material	0.42	65		68.53
117	Water	0.86	108		33.15
118	Fuel oil	0.08	60		3274.72
119	Air	5.62	25		0
120	Electricity	–	–		71.8
121	Steam	0.69	280	785	621.71
122	Exhaust gas	5.7	188		669.81
123	Waste water	0.17	160		17.97
124	Water	1.11	108		43.29
125	Natural gas	0.07	20		3184.87
126	Air	2.1	25		0
127	Electricity	–	–		92.43
128	Steam	0.95	220	785	840.75
129	Exhaust gas	2.17	115		201.42
130	Waste water	0.16	164		46.45
131	Water	0.81	108		31.59
132	Natural gas	0.06	20		2725.75
133	Air	1.89	25		0
134	Electricity	–	–		131.7
135	Steam	0.71	220	785	628.3
136	Exhaust gas	1.95	126		147.65
137	Waste water	0.1	95		11.99
138	Water	9.98	120		570.72
139	Natural gas	0.55	20		25019.12
140	Air	9.49	25		0
141	Electricity	–	–		312.98
142	Steam	8.91	250	785	8524.28
143	Exhaust gas	10.04	224		1402.79
144	Waste water	1.07	95		137.08

The exergy efficiency, exergy destruction rate and some thermodynamic parameters for all the sub-processes are given in tab. 4. The highest exergy destruction occurred in soda recovery with relative irreversibility value of 33.98%. It is followed by Alstom boiler with 29.81%. The lowest exergy efficiency is in boiler 1. It is followed by boiler 3, boiler 2, soda recovery and Alstom boiler with 18.24%, 21.75%, 25.3%, 28.73%, and 32.91%, respectively.

Table 4. Exergetic and thermodynamics analysis data provided for sub-processes

Item no.	Component	Exergy of the fuel \dot{F} [MJ/tp]	Exergy of the product \dot{P} [MJ/tp]	Exergy destruction $\dot{E}x_{dest}$ [MJ/tp]	Exergy of waste $\dot{E}x_{waste}$ [MJ/tp]	Exergy efficiency η_{ex} [%]	Fuel depletion rate δ [%]	Relative irreversibility x [%]	Productivity lack ξ [%]	Exergetic factor f [%]
1	Depitting	27393.62	26185.45	18.97	1189.2	95.59	0.0091	0.03	0.01	13.15
2	Digester 1	10448.59	10249.02	175.06	24.51	98.09	0.0841	0.33	0.12	5.02
3	Washing 1	10576.81	10499.58	18.54	58.69	99.27	0.0089	0.03	0.01	5.08
4	Bleaching 1	5723.31	4403.42	1237.42	82.47	76.94	0.59	2.33	0.84	2.75
5	Digester 2	19937.9	18484.15	1404.73	49.02	92.71	0.67	2.64	0.95	9.57
6	Washing 2	18739.11	16867.16	1724	147.95	90.01	0.83	3.25	1.17	9.00
7	Bleaching 2	11868.92	10140.27	979.77	748.88	85.43	0.47	1.84	0.66	5.7
8	Paper machines 1	9539.77	8020.91	1469.33	49.53	84.08	0.71	2.77	0.99	4.58
9	Paper machines 2	8205.97	6467.96	1706.73	31.28	78.82	0.82	3.21	1.15	3.94
10	Paper machines 3	8980.9	7826.27	1141.45	13.18	87.14	0.55	2.15	0.77	4.31
11	Evaporators	11436.43	8648.88	2727.66	59.89	75.57	1.31	5.13	1.85	5.49
12	Soda recovery	27725.5	7964.29	18051.83	1709.38	28.73	8.67	33.98	12.21	13.31
13	Causticizing	2204.5	1463.74	221.36	520.14	66.4	0.11	0.42	0.15	1.06
14	Boiler 1	3379.67	616.7	2075.25	687.72	18.25	1.0	3.91	1.4	1.62
15	Boiler 2	3320.59	840.25	2232.47	247.87	25.3	1.07	4.2	1.51	1.59
16	Boiler 3	2889.04	628.3	2101.1	159.64	21.75	1.01	3.95	1.42	1.39
17	Alstom boiler	25902.82	8524.28	15838.67	1539.87	32.91	7.6	29.81	10.71	12.44

The digester 1 and digester 2 are considered section digester. Similarly, washing screening 1 and washing screening 2 – section washing screening, bleaching 1 and bleaching 2 – section bleaching, paper mill 1, paper mill 2, and paper mill 3 – section paper mill, boiler 1, boiler 2, boiler 3, and Alstom boiler – section steam plant are considered.

The exergy flow diagram is drawn in fig. 3. This flow diagram includes utilized and unutilized outflows for all sub process in PPIG. It indicates that 73.73% (corresponding to about 60850.14 MJ/tp) of the total exergy entering the system is lost, while 26.27% is utilized. The highest exergy loss occurs from the steam plant with 29.85% (corresponding to about 24881.87 MJ/tp) of the total exergy input due to irreversibility of combustion and heat transfer. The second largest exergy loss (accounting for 23.7%) occurs from soda recovery. The steam plant and soda recovery have considerably larger exergy losses due to the production of steam.

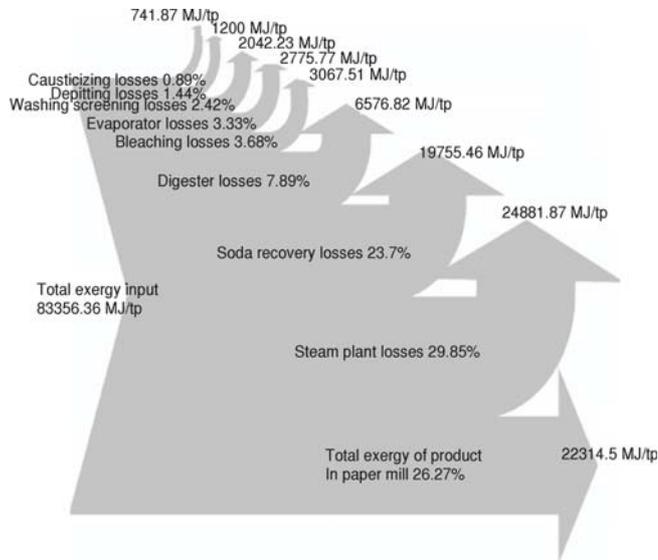


Figure 3. Exergy flow diagram for pulp and paper industry

The main cause of this low efficiency is the irreversibility of combustion and of heat transfer in the steam generator due to the low temperature output. The difference in temperature between the combustion gases and the working fluid is very large. Thus, in principal, it is possible to add a process that utilizes this temperature difference. Furthermore, the exergetic improvements potential of the steam plant and soda recovery is 15,595.49 MJ/tp and 12,864.95 MJ/tp, respectively, and these are high value in all sub process. Immediate efforts to improve the process should therefore be focused on these processes.

Table 5. Comparison exergy efficiency of PPIG with SCA-Munksund [4] and Skoghall [6]

Section	PPIG	SCA-Munksund	Skoghall
Depithing	95.59%	99%	97%
Digester	79.47%	99.7%	85%
Washing	93.35	99.1%	79%
Bleaching	82.67%	–	94%
Paper mill	83.5%	86.2%	89%
Steam plant	29.9%	31.3%	29%
Evaporator	69.47	97.1%	97.1%
Soda recovery	28.73%	36.3%	30%
Causticizing	66.4%	87.4%	87%

Boiler 1 and soda recovery are using fuel oil and boiler 2, boiler 3, and Alstom boiler are using natural gas. Exergy losses as waste flows are predominantly exhaust gases and damp air that are strongly linked to the steam plant and soda recovery. The percent excess air in com-

In this study the exergy efficiency of main section of pulp and paper production is compared with SCA-Munksund pulp and paper mill [4] and Skoghall mill [6] and is shown in tab. 5. Exergy efficiency values were obtained 95.59% for the depitting, 79.47% for the digester, 93.35% for the washing, 82.67% for the bleaching, 83.5% for the paper mill, 29.9% for the steam plant, 69.47% for the evaporator, 28.37% for the soda recovery, and 66.4% for the causticizing, while those were found 26.27% for the overall process. These processes generate steam and exergy efficiency is low. The

bustion of natural gas and fuel oil is efficient parameter to optimize exergy efficiency and decrease exergy losses in the process. Then, according to exhaust gas analysis of boilers the optimal decrease of excess air for fuel oil boilers and natural gas boilers are 25% and 10% respectively. Table 6 indicates the effect of decrease of excess air on efficiency of boilers. With decrease of excess air for boilers increases the exergy of boiler 1, boiler 2, boiler 3, Alstom boiler and soda recovery *i. e.* 16%, 3%, 2%, 1%, 2%, respectively.

Table 6. Effect of decrease of excess air on exergy efficiency of boilers

Component	Initial percent excess air [%]	Initial combustion efficiency [%]	Decrease of excess air [%]	New combustion efficiency [%]
Boiler 1	280	67.7	25	88.5
Boiler 2	100	75.4	10	87
Boiler 3	100	71	10	87.5
Alstom boiler	12.7	81.9	10	87.5
Soda recovery	33	84	25	87.5

Other efficient parameter for optimizing exergy efficiency is preheating of inlet air of boilers. It is observed with preheat air up to 100 °C to increase inlet air temperature of boilers increases the exergy efficiency. Further increases the efficiency of boiler 1, boiler 2, boiler 3, Alstom boiler, and soda recovery *i. e.* 3%, 4%, 4%, 2%, 2.5%, respectively.

By preheating combustion air and by decreasing excess air in the boilers it will be possible to save some fuel while generating the same quantity of steam. Table 7 illustrates the annual fuel saving for the operation.

Table 7. Annual fuel saving in boilers

Component	Fuel	Average fuel consumption [m ³ per hour]	Fuel saving [m ³ peer year]
Boiler 1	Fuel oil	0.8	824.1
Boiler 2	Natural gas	700	525660.8
Boiler 3	Natural gas	632.2	581133.8
Alstom boiler	Natural gas	3895.3	2001872.6
Soda recovery	Fuel oil	2.26	631.8

Conclusions

An exergetic analysis and performance evaluation of pulp and paper production in Pars paper industrial group (PPIG) in Iran is presented. In order to determine the most effective procedure to improve the production of pulp and paper process from bagasse, all subsection that affected on the process is analyzed. The highest exergy losses are occurred in the steam plant and soda recovery. The steam plant and soda recovery have considerably larger exergy losses due to the production of steam. Thus, it is possible to develop better technology for them. With decrease of excess air and preheating of inlet air, exergy efficiency of steam plant and soda recovery can be increased. Further annual fuel saving in boilers is estimated.

Nomenclature

c	– specific heat, [$\text{Jkg}^{-1}\text{K}^{-1}$]
c_p	– specific heat at constant pressure, [$\text{Jkg}^{-1}\text{K}^{-1}$]
$\dot{E}x$	– exergy rate, [kJ s^{-1}]
e	– specific exergy, [kJkg^{-1}]
F	– exergy rate of the fuel, [kJ s^{-1}]
f	– exergetic factor, [%]
h	– specific enthalpy, [kJkg^{-1}]
I	– rate of irreversibility, [kJ s^{-1}]
P	– pressure, [Pa]
\dot{P}	– exergy rate of the product, [kJ s^{-1}]
R	– molar gas constant (8.314), [$\text{kJkg}^{-1}\text{mol}^{-1}$]
S	– entropy rate, [kJ s^{-1}]
s	– specific enthalpy, [$\text{kJkg}^{-1}\text{K}^{-1}$]
T	– temperature, [K]
y_i	– mol fraction in the steam

Greek symbols

δ	– fuel depletion rate, [%]
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ε_l	– exergy losses
ε_j	– molar exergy of each component
η_{ex}	– exergy efficiency, [%]
ξ	– productivity lack, [%]
χ	– relative irreversibility, [%]

Subscripts

dest	– destroyed (destruction)
gen	– generation
i	– flow
in	– inlet

Component

k	– successive number of elements
out	– outlet
tot	– total
0	– dead (reference) state

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