

# *Exergetic, Thermal, and Fuel Savings Analyses of a 20.70-MW Bagasse-based Cogeneration Plant*

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## ABSTRACT

A thermodynamic study of a 20.70-MW bagasse-based cogeneration plant in the Indian sugar industry located in Belgaum is presented in this article. Analyses based on first and second laws of thermodynamics using actual operating data are presented first to acquaint the reader with plant's components and operation. The primary fuel energy savings achieved by the cogeneration plant in comparison with that of separate generation plants is determined and discussed. Secondly using the combustion, flue gas and environmental data from the plant, an irreversibility study is outlined that estimates the loss of exergy in the plant's components. The component contributing most to the overall plant inefficiency is pinpointed. The results show that the plant's cycle performs with an energy utilization factor of 69% and exergetic efficiency of 28%. Because of the inherent nature of combustion irreversibility, the largest fuel exergy loss (about 70%) is noticed in the boiler.

**Keywords:** Cogeneration, bagasse, exergy, efficiency.

## Nomenclature

$\epsilon_b$	Exergetic value of bagasse
$\eta_1$	First law efficiency
$\eta_2$	Second law efficiency
$\eta_{ex}$	Exergetic efficiency

$\eta_B$	Heat only boiler efficiency
$\eta_{th}$	Thermal efficiency
$\eta_C$	Conventional power plant efficiency
$\lambda_{CG}$	Heat to power ratio produced
B2	Boiler No. 2
Cv	Calorific value
CF	Centrifugal
CEST	Extraction condensing steam turbine
cond	Condenser
$E_f$	Chemical exergy of fuel bagasse
EUf	Energy utilization factor
$F_{CG}$	Cogeneration plant fuel consumption
FESR	Fuel energy savings ratio
HP	High pressure
HT	High temperature
LHV	Lower heating value
mb	Mass flow rate of bagasse burned
PH	Process heater
$Q_{NU}$	Non-useful heat rejected
$Q_U$	Useful heat
rej	Rejected
SG	Separate generation
tcd	Tons of cane crushed per day
tch	Tons of cane crushed per hour
tph	Tons per hour
$w_s, w_1$	Steam flow rate

## INTRODUCTION

The results of an ongoing thermodynamic study of an existing 20.70-MW modern bagasse-based cogeneration plant located in Belgaum, India are presented. Although the sugar industry is a seasonal industry, the cogeneration plant is designed to generate 20.70 MW of power throughout the year using bagasse generated during crushing season and using bagasse saved and purchased from the nearby non-cogenerating sugar factories during off-season. The (50% moisture) mill-wet bagasse obtained is directly burned as a fuel in the specially designed boilers to generate steam at the designed pressure and tem-

perature [1]. For the analysis reported within this article, the calorific value (LHV) and the chemical exergy of mill-wet bagasse are assumed to have an average value of 7650 kJ/kg and 9890 kJ/kg respectively [2,3,4,5]. Modern bagasse-fired boilers operate with 80 to 85% efficiency under optimum conditions [6].

The research reported here includes the results of thermodynamic analyses of the cogeneration plant cycle and processes. Analyses based on the first and second laws of thermodynamics are first presented to acquaint the reader with the plant's components, and operation data used in the calculation are based on the actual operating data obtained at the cogeneration plant during a thermodynamic study conducted in the year 2007. Although, the first and second law analysis of cogeneration plants is not new, the application of this concept to analyze the actual bagasse-based plant in the sugar industry and the conclusions emerging to form the analysis may provide some guidelines in the design optimization of new HP/HT cogeneration plants, which will yield the best thermodynamic advantage. The data are average values and are indicative of plant's base load operating state. If cogeneration is to be the rational choice from the primary energy savings point of view, it must save considerable fuel over separate generation [7,8]. Therefore, the fuel energy savings study is also included in the analysis.

Secondly, the exergetic efficiency of the cogeneration plant as a whole is determined using the chemical exergy of fuel as input [9]. The design optimization of the cogeneration plant from exergetic and thermal efficiency [10] point of view is discussed. Using the concept of physical exergy associated with the combustion products, flue gas, steam/water flows and environmental data from the plant, an irreversibility study is outlined that estimates the loss of physical exergy in the various components of the plant. The component contributing most to the plant's overall inefficiency is pinpointed [11]. The exergy study is further extended to determine the second law efficiency of major power producing/consuming components [12] of the cogeneration plant.

## COGENERATION PLANT CONFIGURATION

The schematic of the cogeneration plant, both during season and off-season operation is shown in Figure 1 and Figure 3 and its representation on T-S diagram is included in Figure 2 and Figure 4, respectively.

These figures depict equipment and state point labels throughout the entire cycle and will be referred to frequently in the sections to follow. It is a 5500 tcd capacity sugar factory, meets its process steam demand from the exhaust of the mill turbine, and partially from the extractions drawn from the cogeneration plant's turbine.

The plant burns mill-wet bagasse directly in the spreader stoker furnace with a traveling grate, to generate 117 tph and 96 tph of steam at 65 bar and 495°C during season and off-season, respectively. The thermal energy of steam is converted into mechanical energy in one custom-built, multistage double-extraction condensing, impulse turbine [BHEL Make]. The turbine is coupled with a generator that converts mechanical shaft power into a base load of approximately 20.70 MW of electrical power.

The average steam to bagasse ratio is normally 2.25 for these pressure and temperature conditions [13]. The boiler furnace operates between 950°C to 1000°C and the exhaust flue gas temperature is limited to 150°C. The spreader stoker furnace permits reducing the normal excess air to 30% (instead of 40 to 50%) and consequently, improving efficiency substantially [14]. The electricity produced in the cogeneration plant is exported to the state grid after meeting captive requirements. Presently the plant is exporting 14.20 MW during season and 18.20 MW during

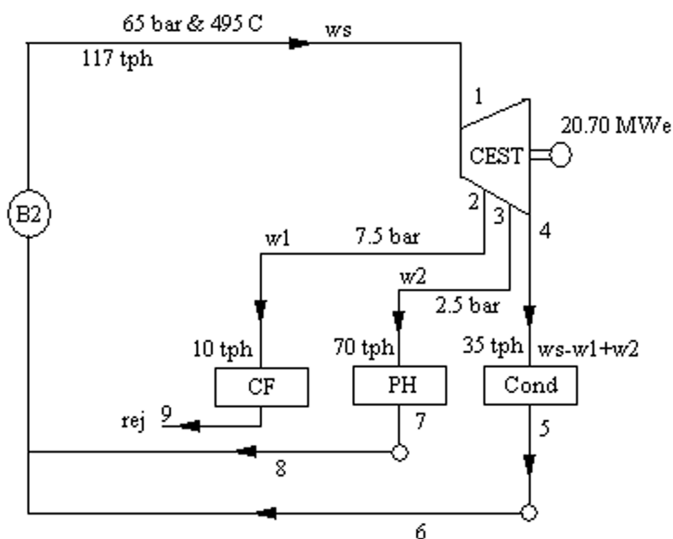


Figure 1. Cogeneration plant

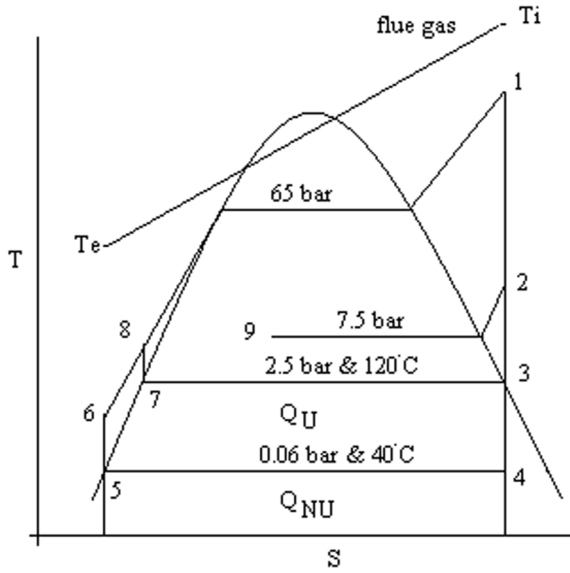


Figure 2. T-S diagram

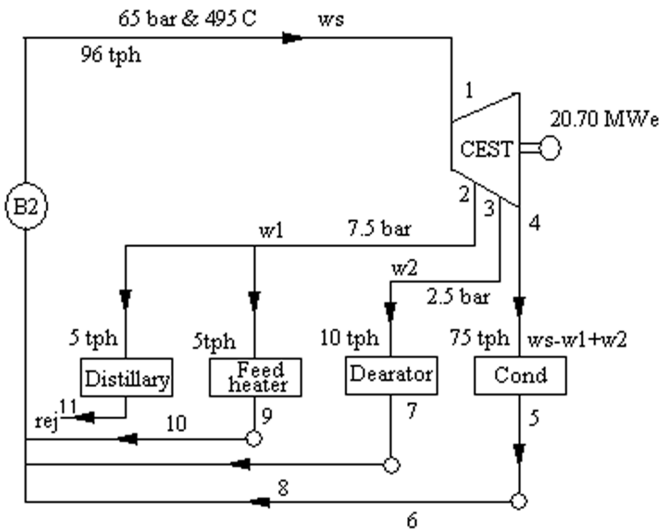


Figure 3. Off-season power plant

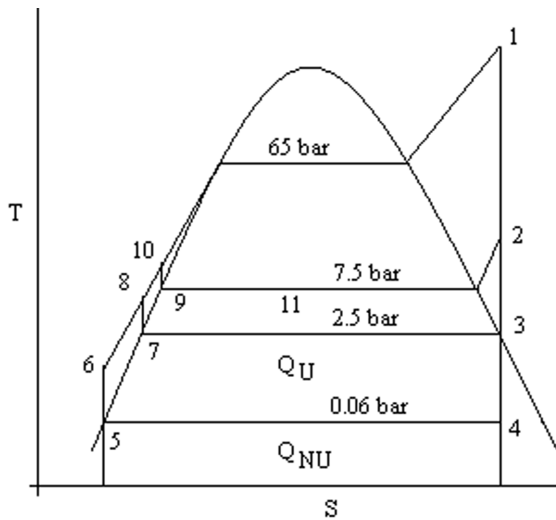


Figure 4. T-S diagram

off-season after meeting the captive requirements of 6.50 MW and 2.50 MW during season and off-season, respectively. The plant uses a cooling tower, and heating load as its condenser. To improve efficiency, the cogeneration plant is regenerative with inclusion of feed water heaters.

#### FIRST LAW ANALYSIS

The cogeneration plant is complex and includes numerous pumps, fans, and blowers that are not monitored for energy consumption. Therefore the boundary for this system is the entire plant. Applying steady flow energy equations and mass balance to each of the components and processes in Figure 1 and Figure 2 neglecting the changes in the kinetic energy and potential energy the work and heat quantities are evaluated. Thermal efficiency ( $\eta_{th}$ ) and energy utilization factor (EUF) or first law efficiency or total energy efficiency of the cogeneration plant are determined by

$$\eta_{th} = \frac{(W_{net})_{ST}}{F_{CG}} \quad (\text{Eq 1})$$

$$\text{EUF} = \frac{(W_{\text{net}})_{\text{ST}} + Q_{\text{CG}}}{F_{\text{CG}}} \quad (\text{Eq 2})$$

Where,

$F_{\text{CG}}$  is fuel energy supplied

Thermal efficiency expressed in Equation (1) has less relevance to a cogeneration plant, which provides process heat and generates electrical power. The better indicator of performance is the energy utilization factor (EUF) in Equation (2), which takes into account process heat produced [15]. The rate of turbine work produced  $(W_{\text{net}})_{\text{ST}}$  is calculated using an energy and mass balance around the turbine. The isentropic efficiency for the data based on manufacture's data is 85%. Using the known output of the turbine/generator set as well as generators efficiency the heat loss from the turbine is

$$Q_{\text{turbine}} = W_{\text{turbine}} + \sum_{\text{exit}} mh - \sum_{\text{in}} mh \quad (\text{Eq 3})$$

The rate of heat into the boiler is determined by multiplying the average (lower heating value, LHV) calorific value of the wet bagasse by the mass flow rate of the bagasse

$$F_{\text{CG}} = mb C_v \quad (\text{Eq 4})$$

However, not all the energy provided during the bagasse combustion process is transferred to the steam. The heat available to the steam,  $Q_{\text{steam}}$ , can be calculated using an energy balance at the boiler

$$Q_{\text{steam}} = \sum_{\text{exit}} mh - \sum_{\text{in}} mh \quad (\text{Eq 5})$$

From which the efficiency of boiler can also be calculated

$$\eta_{\text{boiler}} = \frac{Q_{\text{steam}}}{F_{\text{CG}}} \quad (\text{Eq 6})$$

### Fuel Energy Savings Ratio [FESR]

A cogeneration plant substitutes separate units of a conventional power plant of overall efficiency  $\eta_c$  and heat only boiler efficiency  $\eta_{B'}$

meeting the same loads of electricity  $W$  and process heat  $Q$  [7] than the fuel savings achieved by installing cogeneration plant is expressed as fuel energy savings ratio and is calculated as, assuming  $\eta_B = 0.85$   $\eta_C = 0.35$

$$FESR = 1 - \frac{1 + \lambda_{CG}}{EUF \left[ \frac{1}{\eta_C} + \frac{\lambda_{CG}}{\eta_B} \right]} \quad (\text{Eq 7})$$

Here,  $\lambda_{CG} = \left( \frac{Q_{CG}}{W_{CG}} \right)$  is the heat to power ratio provided by the cogeneration plant.

What it is important to remember here is that the FESR achieved by the cogeneration plant, as calculated using Equation 7, is relevant only if both separate generation plants and the cogeneration plant are burning the same fuel (bagasse). Otherwise to quantify the fuel savings, it is necessary to calculate fuel equivalent values, when two plants are consuming different fuels. FESR is the most relevant in the evaluation of performance assessment of the cogeneration plant as this can be used directly in the economic assessment of the plant.

The results are listed in Tables 1 and 2. The energy utilization factor of the plant is considerably high compared to its thermal efficiency, because low temperature steam is utilized in process heating. The cogeneration plant saves 14% of fuel compared to separate generation. However, it is worth investigating the magnitude of fossil fuel displacement by bagasse for power generation and its associated environmental benefits.

## SECOND LAW ANALYSIS

Exergy is a measure of energy quality, and exergetic or second law efficiency is the measure of perfectness of the system [16]. Exergy is not conserved but can be readily destroyed through the presence of irreversible process or transferred to or from a system through mass or energy flow [17]. In the present study, the following assumptions are made.

- (i) The chemical exergy of the fuel (bagasse) is considered an exergy input to determine the exergetic efficiency of the cogeneration plant as a whole.

**Table 1. Energy flow rates from the First Law analysis**

<i>Energy path flow</i>	<i>Power (kW)</i>	
	<i>Season</i>	<i>Off-Season</i>
Generator output	20,700	20,700
Captive consumption	6,500	2,500
Surplus power export to grid	14,200	18,200
Process heat rate	48,681	—
Energy utilized in steam generation	93,632	76,836
Fuel Energy input	110,925	90,652

**Table 2. Efficiencies from the First Law Analysis**

<i>Component</i>	<i>Value (%)</i>	
	<i>Season</i>	<i>Off-Season</i>
Boiler efficiency (calculated)	84	84
Turbine efficiency (manufacturer's data)	85	85
Generator efficiency (manufacture data)	92	92
Thermal efficiency (calculated)	24	33
Energy utilization factor (calculated)	69	—
Fuel energy savings (calculated)	14	—

- (ii) The physical exergy of the products of combustion, flue gas and steam/water flows is used to determine loss of exergy in the components of a cogeneration plant. The results are determined using the actual data available from the plant.

#### **Chemical Exergy of the Fuel and Exergetic Efficiency of Cogeneration Plant**

The chemical exergy flow rate of fuel (bagasse) is determined by multiplying the average exergetic value of wet bagasse by the mass flow rate of bagasse burned in the boiler.

$$E_f = m_b \varepsilon_b \quad (\text{Eq 8})$$

The exergetic efficiency of a cogeneration plant as a whole is determined as

$$\eta_{EX} = \frac{(W_{net})_{ST} + E_Q}{E_f} \quad (\text{Eq 9})$$

Where,

$E_Q$  is the exergy equivalent of process heat [18].

The physical exergy change associated with the mass flow rate of fluids through each component is dependent on the exergy in ( $E_{in}$ ), the exergy out ( $E_{out}$ ), and the exergy destroyed ( $E_{destroyed}$ ), during the process.

$$\Delta \epsilon = \epsilon_{in} - \epsilon_{exit} - \epsilon_{dest} \quad (\text{Eq 10})$$

By assuming a control volume of interest, this can be expanded into

$$\left[ \frac{dE}{dt} \right]_{cv} = \Sigma \left( 1 - \frac{T_o}{T_i} \right) Q_i + W_{CV} + m(\epsilon_{f_1} - \epsilon_{f_2}) - \epsilon_{dest} \quad (\text{Eq 11})$$

The change in exergy is  $\left[ \frac{dE}{dt} \right]_{cv}$ , therefore, a function of the heat, work, mass flow rate, and exergy destruction occurring within a component. The term  $Q_i$  is the heat transfer rate from the control volume at the location where  $T_i$  is the boundary temperature. The specific flow of exergy, term  $(\epsilon_{f_1} - \epsilon_{f_2})$  accounts for the exergy transfer rate associated with the mass flow into and out of the control volume [19].

$$(\epsilon_{f_1} - \epsilon_{f_2}) = (h_1 - h_2) - T_o (s_1 - s_2) + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2) \quad (\text{Eq 12})$$

The exergy destroyed is a function of entropy generation and the ambient air temperature ( $T_o$ ) surrounding the component. It is important to note that the surrounding temperature varies significantly from one component to another in the plant. For example, the temperature surrounding the boiler is much higher than the temperature surrounding the condenser.

The exergy concept is extended to determine the exergetic or second law efficiency of major components. This efficiency compares the

actual work produced/consumed by a device to the work interactions associated with a reversible device. The general expression for exergetic efficiency or second law efficiency of power producing/consuming device is

$$\eta_2 = \frac{W_{\text{act}}}{W_{\text{rev}}} \quad (\text{Eq 13})$$

while equations (14) and (15) are the expressions for the second efficiency of turbine ( $\eta_{2t}$ ) and boiler ( $\eta_{2b}$ ), respectively

$$\eta_{2\text{turbine}} = \frac{(W_{\text{net}})_{\text{ST}}}{ws (ef_1 - ef_2)} \quad (\text{Eq 14})$$

$$\eta_{2\text{boiler}} = \frac{ws[(h_1 - h_8) - T_0 (S_1 - S_8)]}{E_f} \quad (\text{Eq 15})$$

The cycle overall exergetic efficiency ( $\eta_2$  cycle) is determined as

$$\eta_{2\text{cycle}} = \frac{\eta_{\text{th}}}{\eta_{\text{rev}}} \quad (\text{Eq 16})$$

where  $\eta_{\text{th}}$  is based on the results of first law analysis and  $\eta_{\text{rev}}$  is based on the reversible heat engine operating between reservoirs at  $T_L$  and  $T_H$  (298K and 1273K, respectively)[20]. Table 3 and 4 show the results of the second law analysis. A remarkable difference is noticed between the first and second law efficiencies of the same plant. The results show that the turbine is the efficient component of the cycle, where as the boiler involves a great deal of exergy destruction. This is caused by the inherent nature of associated combustion irreversibility.

## CONCLUSIONS

A combined first and second law analysis of a 20.70-MW bagasse-based cogeneration plant in the Indian sugar industry is presented in this article. The plant functions as a cogeneration plant during (the on) season and as a independent conventional power plant during off sea-

**Table 3. Exergy flow rates from the Second Law analysis**

<i>Exergy flow path</i>	<i>Exergy flow rate (kW)</i>	
	<i>Season</i>	<i>Off-season</i>
Turbine net output	27234	29810
Process heater	12833	—
Exergy utilized in steam generation	42561	34926
Condenser	52	104
Fuel exergy input	142825	116723

**Table 4. Efficiencies from the Second Law analysis**

<i>Component</i>	<i>Value %</i>	
	<i>Season</i>	<i>Off-season</i>
Boiler efficiency (calculated)	30	30
Turbine (calculated)	61	82
Exergetic efficiency of plant (calculated)	28	26
Cycle efficiency (calculated)	31	43

son, using the same fuel bagasse during both the seasons. The results show that the plant performs with a thermal efficiency of 24% and energy utilization factor of 69% during season. The thermal efficiency of plant during off-season is 33%; this indicates the plant is optimized for its thermal efficiency for off-season functioning. The cogeneration plant saves 14% of primary fuel (bagasse) when compared to separate generation. However, it should be remembered that the fuel energy savings determined for cogeneration plant over separate generation is relevant only when both the plants are burning the same fuel. It is worth knowing the magnitude of coal displacement by bagasse for power generation and its associated environmental benefits. The exergetic efficiency of the plant is 28% and 26% during season and off-season, respectively. This is considerably lower than its thermal efficiency during off-season. This shows that the plant, as cogeneration system, is thermodynamically relatively less attractive over its functioning as power plant during off-season. However, the bagasse-based cogeneration plants in the Indian sugar

industries are economically and environmentally attractive because they burn (waste fuel) bagasse. The exergetic efficiency of the boiler is 30%, indicating the greatest fuel exergy destruction in it. Further research is still required to investigate the causes of irreversibility and to determine economic opportunities for reducing it.

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### References

1. Sai V Gollakota and P.R.K. Sobhanbabu. *Handbook on Sugar Mill Cogeneration in India*, New Delhi, Winrock International, 1st edition, 2002.
2. Charles Mbohwa and Suichi Fukuda. Electricity from Bagasse in Zimbabwe, *Bio-mass and Bioenergy*, Vol. 25, issue 2, 2003, pp 197-207.
3. Charles Mbohwa. Bagasse Energy Cogeneration Potential in the Zimbabwean Sugar Industry, *Renewable Energy*, Vol. 28, 2003, pp 191-204.
4. L.A.B. Cortez and E.O. Gomez, A Method for Exergy Analysis of Sugar Cane Bagasse Boilers, *Braz. J. of Chemical Engineering*, Vol. 15, issue 1, 1998, pp 1-13.
5. B. Vijayaraj, R. Saravanan, and S. Renganarayanan. Energy and Exergy Analysis of Sugar Cane Bagasse Drying, *Procee of Advances in Energy Research-AER-2006*, Chennai, Anna University, pp 77-82.
6. Surendra Prasad. Energy Aspects of Fiji's Sugar Industry: A Case for More Efficient Generation from Bagasse, *Fijian Studies*, Vol.1, No.2, Fiji Institute of Applied Studies, 2004, pp 243-264.
7. R.W. Porter and K. Mastanaiah. *Thermal-Economic Analysis of Heat Matched Industrial Cogeneration Systems*, Vol. 17, issue 2, 1982, pp 171-187.
8. www.educogen.com. *The European Educational Tool on Cogeneration*, 2nd edition, Dec 2001.
9. M.A.Korobitsyn. *Industrial Cogeneration*, University of Twente, Netherlands, 1998, pp 65-82.
10. Tamer Yilmaz. *Optimization of Cogeneration Systems Under Alternative Performance Criteria*, *Energy Conversion and Management*, Vol. 45, 2004, pp 939-945.
11. T.J. Kotas. *The Exergy Method of Thermal Plant Analysis*, London, Butterworths, 1st edition, 1985.
12. Margaret B. Bailey, et al. *Exergetic, Thermal and Exernalities Analysis of a Cogeneration Plant*, *Solar Energy Engineering*, Vol. 128, 2006, pp 98-103.
13. Mike Inkson and Mispion. B, Cogeneration Thermodynamics Revisited, *International Sugar Journal*, Vol. 107, issue 1279, 2005, pp 390-403.
14. E. Hugot. *Handbook of Cane Sugar Engineering*, Elsevier, 3rd edition, 1986.
15. J.H. Horlock. *Cogeneration-Combined heat and Power-Thermodynamics and Economics*, Malabar, Florida, Krieger Publishing Company, 12th edition, 1997.
16. A. Khaliq and K. Choudhary. Combined First and Second Law Analysis of Gas Turbine Cogeneration System with Inlet Air Cooling and Evaporative After Cooling of the Compressor Discharge. *International Journal of Engineering for Gas Turbine and Power*, Vol. 129, 2007, pp 1004-1011.

17. P.K. Nag. Basic and Applied Thermodynamics, New Delhi, TMG, 1st edition, 2002.
  18. Svein J. Nesheim and Ivar S. Ertesvag. Efficiencies and Indicators Defined to Promote Combined Heat and Power, *Energy Conversion and Management*, Vol.43, issue 3, 2007, pp 1004-1015.
  19. Ivar S. Ertesvag. Exergetic Comparison of Efficiency Indicators for Combined Heat and Power (CHP), *Energy*, 2007, Vol. 32, pp 2038-2050.
  20. Ahmet Erdil. Exergy Optimization for an Irreversible Combined Cogeneration Cycle, *Energy Institute*, Vol. 78, issue 1, 2005, pp 27-31.
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