# Energy Efficiency for Heat Engine Implementation into Systems of Cogeneration

ROXANA PATRASCU
Power Engineering Faculty
University of "Politehnica" of Bucharest
313, Splaiul Independentei Street
ROMANIA
op3003@yahoo.com

IOANA DIACONESCU
Engineering Faculty of Braila
"Dunarea de Jos" University of Galati
Calea Calarasilor nr. 29, Braila
ROMANIA
ioana.diaconescu@ugal.ro, http//www.ugal.ro

*Abstract:* - Cogeneration, the procedure of simultaneous and combined producing of two energies, makes a real saving of primary energy (fuel) in comparison with separate producing of these two energies. This fuel saving is found under the economic aspect into fuel expenses reducing and under the ecologic aspect into environment pollution reducing and primary energy resources increasing.
Cogeneration equipment with heat engines represents an energy efficiency increasing method itself if someone takes into account following technical economic points of view:
- the recovery of combustion gases heat before the evacuation into atmosphere;
- the recovery of cooling water heat of engine sub equipments;
- the electricity cost reducing under the National Grid cost, through elimination of all transporting and distribution taxes and also of intermediary companies taxes;
- the thermal energy cost reducing, much under the heat cost from centralized heat providing system. This type of energy is obtain from recovery and is based on produced electricity, so the only costs are parts of consumed elements (filters, supplementary water, so) costs and personnel salaries;
- total efficiency is superior to other power equipments, so $\eta_{gl} > 86$ %;
This paper underlines, using energy efficiency analysis methodology, the heat engine implementation into cogeneration systems and also energy, ecological and economic efficiency of cogeneration concept. Also, the methodology is validated through a case analysis.

*Key-Words:* - cogeneration, heat engines, balance, energy efficiency, indicator

## 1. Energy, ecologic and economic efficiency of cogeneration

The concept of efficiency consists in an action effects comparison, with necessary efforts for its fulfillment and someone can draw the conclusion that the economic efficiency expresses a complex structure of causality relations between positive and negative economic effects of one action finality.
Generally speaking, an activity is more efficient under energy aspect if energy loss from the thermodynamics boundary of that activity is smaller.
The concept of energy efficiency gets a specific meaning only if it is connected with a well defined boundary and with an activity which is running into an organized manner inside this boundary [1].
Energy efficiency involves many action ways, such as:
- The identification of all energy flows which are involved into the process realization;
- The identification of lost energy flows;
- The identification of the best advantageous measures for loss reduction taking into account their preliminary costs estimation in comparison with the profits result through energy efficiency growing;
- To apply the measures considered economic efficient, able to eliminate energy loss, the objective being to reduce energy costs and implicitly to grow the profitability.
The concept of energy efficiency has two meanings.

In a restricted way, energy efficiency concept has the meaning of energy performance. So that, energy efficiency growing in restricted way has as consequence the energy saving [2]. The final result of energy efficiency growing consists in energy bill or specific expenses reductions

Through its meaning, the cogeneration, the procedure to produce simultaneous and combined two different energy types, makes an effective primary energy saving (fuel) comparative with the measure which leads to greenhouse gases reducing, with a potential of 180 mil tones per year.

## 2. Analysis of heat engine working in cogeneration

### 2.1. Useful data for energy analysis of heat engine in cogeneration

Heat engines used in cogeneration are using up fuel,

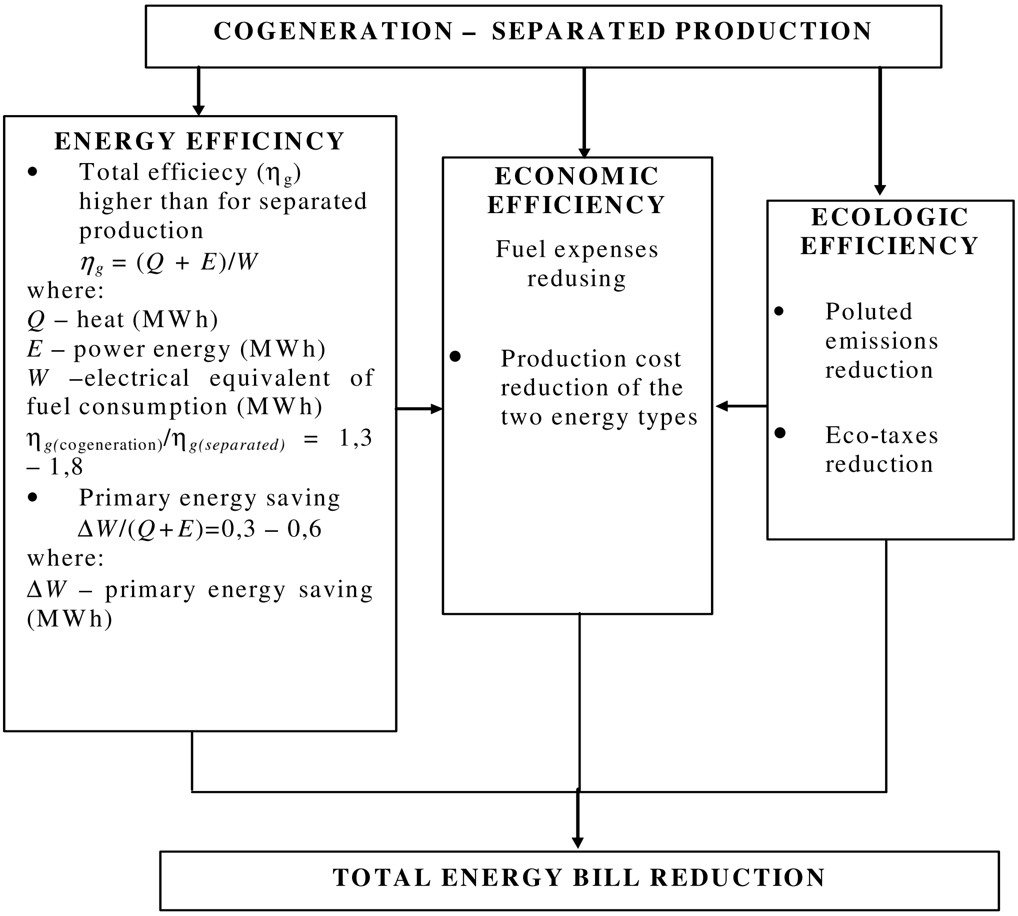


Fig. 1 Cogeneration efficiency in comparison with the two energy types separated production

separated production of mechanical work (thermo-electrical power plant) and heat (thermal power plant). This fuel saving can be found, economically speaking, into the reducing of expenses for fuel and ecologically speaking, into the reducing of environment pollution and of primary energy consumption. Energy, economic and ecologic efficiency of cogeneration in comparison with separated production is presented in figure 1 [3].

So, the cogeneration represents one of the most economically technologies for greenhouse gases reducing, fact which is official recognized by the EU together with renewable energy using. In the opening of the Kyoto Conference, the Council identified the cogeneration to be the most important usually as gas, liquid or dual and through a power generator action, these equipments are producing electricity. As a result of processes which are running in the motor thermodynamic cycle is also a heat amount from cooling system of the machine and from combustion gases. This heat amount is used into heat exchangers, into external technological processes, producing in combined way electricity and thermal energy (heat) generically named cogeneration. In some cases, when external consumption needs besides heat also thermal energy with low potential (air conditioning processes), heat engines can be very easy coupled with thermo chemical compression cooling equipments (absobtion or adsorption), carrying out the complex process of trigeneration [4].

Heat engines can be classified after their functionality as heat engines with alternating evolution and with rotary evolution.

For the analysis of heat engine in cogeneration systems it is necessary to have a data resource which contains the following:

-The combustion caloric value of fuel which guarantees performances, [kWh/($m^3_N$; kg)];
-Fuel consumption for different working conditions (50%; 75%; 100%), [($m^3_N$; kg)/h];
-Heat flow of fuel, [kW];
-Mechanic power at the engine axle, [kW];
-Electric power at the power generator clamps, [kW];
-Recovered heat flows from the different cooling zones of the engine, [kW];
-Total recovered heat flow, [kW];
-Total power (electric and thermal) for different working conditions, [kW];
-Fuel specific consumption expressed in power or physics units, [$m^3_N$; kg/kW or kWh/kWh];
-Lubrication oil specific consumption [kg/h, kg/kWh];
-Cooling water temperatures for different working conditions, at evacuation, [ºC];
-Cooling water temperature at admittance, [ºC];
-Cooling water flow, [$m^3$/h];
-Combustion gases temperature at evacuation, [ºC];
-Combustion gases temperature after heat recovery circuit, [ºC];
-Wet and dry combustion gases flow, [$m^3_N$; kg/h];
-Electric characteristics of power generator;
-Technical characteristics of the equipments used for system function monitoring;
-Technical characteristics of the environment pollution.

## 2.2. Methodology stages for the energy analysis of cogeneration systems with heat engines

To make an energy analysis for a complex cogeneration system with heat engine means to find the following:

a) Fixing the analyzed boundary

Analyzed boundary generally compounds physical limits of the equipment. In case when heat exchangers which recovery cooling system heat or combustion gases heat are placed to consumer, these exchangers will be included inside the boundary.

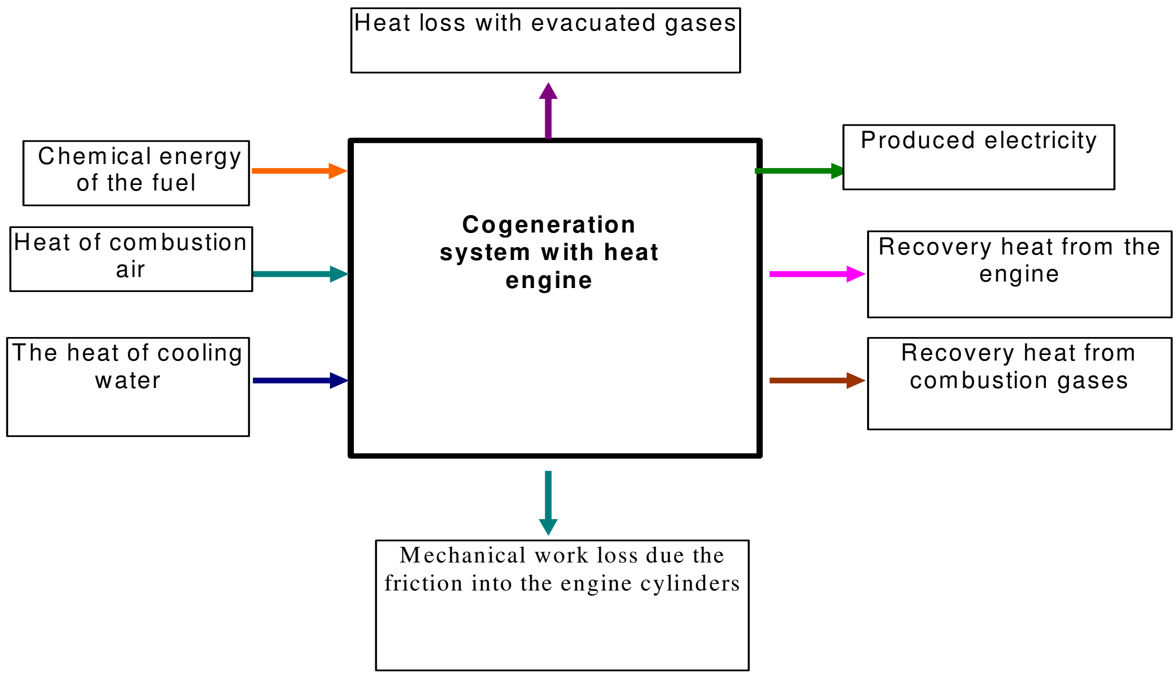


Fig. 2 The energy flow diagram of a heat engine in cogeneration solution

-Electric efficiency for different working conditions, [%];
-Thermal efficiency for different working conditions, [%];
-Total efficiency in cogeneration, [%];

b) Summary presentation of the inside boundary energies [5]

Heat engines used in cogeneration systems are producing the following types of energies:
-electricity;

-heat as hot water from surface heat exchangers (under 100 ºC);
-heat as steam, from combustion gases, in recovery heaters;
-both types of heats in combined equipments.
c) The diagram of inside boundary energy flows
d) Energy balance of cogeneration solution with heat engines (figure 2) [6]
Energy balance of cogeneration solution equipment uses mass conservation, energy conservation and impulse conservation equations.
The general energy equation shows the equivalence between primary energy, useful energy and lost energy:

$$Q_i = Q_u + Q_p = Q_{el} + Q_t + Q_p \text{ [kW]} \quad (1)$$

The energy flow of fuel is:

$$Q_i = D_{gn} \cdot P_{ci} \quad \text{[kW]} \quad (2)$$

where: $D_{gn}$ is fuel flow aspired by the engine, [$m^3{}_N$/s] ;
$P_{ci}$ is combustion caloric value, [kJ/ $m^3{}_N$]
Useful energy is compounded by electricity and heat produce by the engine:

$$Q_u = Q_{el} + Q_t \quad \text{[kW]} \quad (3)$$

Where electrical power $Q_{el}$ is measured and heat flow $Q_t$ is measured or is calculated using functioning parameters registration.
The most important energy loss is with friction or with evacuated combustion gases or with convection between no isolated constructive parts of the engine and environment.
e) Identification of heat engine specific energy indexes in cogeneration
*Mechanical efficiency of heat engine* is defined as ration between mechanical work and admitted energy:

$$\eta_m = \frac{Q_m}{Q_i} \cdot 100 \text{ [\%]} \quad (4)$$

*Electrical efficiency at the power generator clamps* is defined as ratio between produced power energy and mechanical work:

$$\eta_{el} = \frac{Q_{el}}{Q_m} \cdot 100 = \frac{Q_{el}}{\eta_m \cdot Q_i} \cdot 100 \quad \text{[\%]} \quad (5)$$

So, electrical energy at power generator clamps is:

$$Q_{el} = \eta_m \cdot \eta_{el} \cdot Q_i \quad \text{[kW]} \quad (6)$$

*Thermal efficiency of the cycle* is defined as a ratio between recovered energy (from cooling systems and evacuated combustion gases) and admitted energy:

$$\eta_t = \frac{Q_t}{Q_i} \cdot 100 = \frac{Q_i - Q_{el} - Q_p}{Q_i} \cdot 100 = \left(1 - \frac{Q_{el} + Q_p}{Q_i}\right) \cdot 100 \quad \text{[\%]} \quad (7)$$

Taking into account the above relations, *the total efficiency of the cogeneration system* becomes:

$$\eta_{gl} = \frac{Q_u}{Q_i} \cdot 100 = \eta_{el} + \eta_t \quad \text{[\%]} \quad (8)$$

*The heat engine specific consumption* is calculated like in below relation:

$$b = \frac{D_{gn} \cdot P_{ci}}{Q_m} \quad \text{[kWh/kWh]} \quad (9)$$

Where, combustion caloric value $P_{ci}$ is measured in kWh/ $m^3{}_N$
*Cogeneration index* is defined as the ration between electrical power and heat flow produced in cogeneration [7]:

$$y_t = \frac{P_e}{q_t} \quad (10)$$

where:
$P_e$ – electrical power, [kWe];
$q_t$ – heat flow, [kWt].

$$y_t = \frac{P_e}{Q_t} = \frac{P_e}{Q_{apa} + Q_d} = \frac{P_e}{Q_{apa} + Q_{g0}} = \frac{P_e}{Q_{g0}(r + x)} \quad (11)$$

where x is heat recovery index from combustion gases and r is recovery index for a specific engine.

$$r = \frac{Q_{apa}}{Q_{g0}} \quad (12)$$

for x = 1 results:

$$y_{t0} = \frac{P_e}{Q_{g0}(r+1)} \quad (13)$$

So that $y_{t0} < y_t$ and $z = \frac{Q_t}{P_e} = \frac{1}{y_t}$ (14)

where z is called structure index.

## 3. Solutions for heat engine energy efficiency growing

The main solutions for energy performances growing into cogeneration systems consist in two aspects:
- growing of equipment performances (heat engines, heat exchangers, energy transport and distribution systems);
- growing of electrical and thermal energies simultaneous using for as long time as possible in a year.
An important measure for engine thermodynamic efficiency growing is to grow up the cylinder filling level through overfeeding procedure.

*The overfeeding* practically consists into air specific mass growing or fuel mixture growing as a result of admission pressure growing [8].

*The admission pressure growing* is possible due the centrifugal, axial or volumetric compressors or due the turbo compressors and can provides a total overfeeding during the whole or partial time of admission phase. Through this method, the total engine thermodynamic efficiency is growing and in the same time with the electric efficiency through a power generator driving, to the values over 42-44 %.

There are many ways to provide the overfeeding, such as [9]:

- mechanic overfeeding, when compressor is direct driven by the motor shaft, solution which can be applied to motors where overfeeding pressure doesn't exceed1,5..1,6 bar;
- overfeeding with turbo ventilation, where is very well recovered the residual energy of combustion gases. The overfeeding pressure values are between 1.5...4 bar. In this case the compressor is driven by the same axle as a mini turbine which is working with the engine combustion gases. Due the very high turbine revolution (to the 60.000 rot/min), the transforming efficiency has also very high values providing an engine overfeeding for any working conditions.

Also, other method for thermodynamic cycle efficiency growing is engine volumetric compression ratio growing. This has a very practical connotation and involves a special engine construction.

Another total efficiency growing method is residual heat advanced recovery from cooling systems and also from evacuated combustion gases recovery.

Using all the sensible energy of combustion gases and also condensation latent heat of water vapors from combustion process the total efficiency can grow to the value of over 95 %. Such an equipment of 800 kW is already working in Germany for heat and electricity supplying of some botanic garden greenhouses.

Generally speaking, to get the desired results, the measures applied for heat engine boundary must to be accompanied by the energy efficiency measures for a larger boundary of taken over thermal and power energy systems of consumer equipments.

# 4. Energy analysis example for cogeneration equipment with heat engine working with gas fuel

To give an example for heat recovery of hot water 90/70 °C, from engine cooling system and combustion gases, it is shown below a practical application for a specific company.

## 4.1. Equipment general features

Cogeneration equipment has two heat engines with overfeeding which are working with gas fuel. The engines have to produce simultaneously electrical and thermal energies with parameters requested by the company.

The engines drive synchronous electrical power generators of 910 kVA each at 0.4 kV. The connection is made with two upper transformers 0,4/6 KV of 1000 kVA (one for each group). Monitoring complex system has an electronic equipment of ION type to follow consumed instantaneous power on each feeder, to avoid reverse power injection into power system [10].

Thermal energy is provided as hot water 90/70 ºC and is produced as heat recovery in surface heat exchangers from engines cooling system and combustion gases. This recovered heat is used for supplementary water pre heating and for technological utilities and indoor heating. General technical features for each cogeneration groups are:

- electrical power $P_e$= 601kWe/group and $P_e$= 1202 kWe/tot
- nominal heat power $P_t$= 732 kWt/group and $P_t$= 1464 kWt/tot
- noxious emissions at 5% $O_R$:
  - Nox < 250 mg/$m^3_N$;
  - CO < 650 mg/$m^3_N$;
  - NMHC < 150 mg/$m^3_N$
- fuel consumption per hour at nominal charge B=163 $m^3_N$/h;
- specific fuel consumption at nominal charge, for a combustion caloric value of de 9,5 kWh/ $m^3_N$, b=2,49 kWh/kWh
- group electrical efficiency at nominal charge $\eta_e$= 38,9 %;
- group thermal efficiency at nominal charge $\eta_t$ =47,4 %;
- group total efficiency at nominal charge $\eta_g$= 86,3 %;
- cooling water flow M= 31,5 $m^3$/h;
- evacuated humid gases flow $D_{ga}$= 3439 kg/h (2718 $m^3_N$/h)

## 4.2. Energy analysis of chosen boundary

Taking into account balance equations above presented someone could calculate electrical, thermal and total efficiencies and also specific combustion consumption for produced electricity. This calculation values are presented into below table, for 18 moth of functioning, starting with December 2006.

Table1. Efficiency hour values calculated for cogeneration equipment

| Parameter | | Value | | | | | |
|---|---|---|---|---|---|---|---|
| Measuring number | | 1 | 2 | 3 | 4 | 5 | 6 |
| Electrical efficiency | % | 37.78 | 38.45 | 38.51 | 38.23 | 38.45 | 38.42 |
| Thermal efficiency | % | 41.08 | 40.61 | 40.57 | 40.76 | 40.61 | 40.63 |
| Total efficiency | % | 78.86 | 79.06 | 79.08 | 79.00 | 79.06 | 79.05 |
| **Fuel specific consumption** | KWh/KWh | **2.620** | **2.601** | **2.597** | **2.616** | **2.601** | **2.603** |
| Parameter | | Value | | | | | |
| Measuring number | | 7 | 8 | 9 | 10 | 11 | 12 |
| Electrical efficiency | % | 38.42 | 38.26 | 38.42 | 38.39 | 38.37 | 38.41 |
| Thermal efficiency | % | 40.63 | 40.74 | 40.63 | 40.65 | 40.66 | 40.64 |
| Total efficiency | % | 79.05 | 79.00 | 79.05 | 79.04 | 79.04 | 79.05 |
| **Fuel specific consumption** | KWh/KWh | **2.603** | **2.613** | **2.603** | **2.605** | **2.606** | **2.604** |
| Parameter | | Value | | | | | |
| Measuring number | | 13 | 14 | 15 | 16 | 17 | 18 |
| Electrical efficiency | % | 38.71 | 38.64 | 38.36 | 38.35 | 38.51 | 38.48 |
| Thermal efficiency | % | 40.42 | 40.47 | 40.67 | 40.68 | 40.57 | 40.59 |
| Total efficiency | % | 79.14 | 79.11 | 79.03 | 79.03 | 79.08 | 79.07 |
| **Fuel specific consumption** | KWh/KWh | **2.583** | **2.588** | **2.607** | **2.607** | **2.597** | **2.599** |

The values measured into a short period of functioning time doesn't allow us to take the conclusion about the equipment functioning.

That is why, to take the conclusion about the cogeneration equipment functioning performances, recording results for 18 month of functioning were processed.

So, using the above balance equations, were calculated electrical and thermal efficiencies as monthly average values and also other indexes such as average powers, produced or provided energies, fuel specific consumption.

### 4.3. Conclusions regarding energy analysis of cogeneration equipment

From the analysis of energy balance results of cogeneration system someone can take the following conclusions:

a) for hour real measurements

- gas fuel consumption values related to physical normal state are between values from technical documentation, not more than the maximum consumption established for nominal charge;
- produced electrical power is at high values for measurements duration, between 950 and 1150 kW, which means an average loading of 96 %;
- provided heat power has values between 1050 and 1200 kWt, lower than nominal values, which means that taking percent is between 72 % and 82 % . This could be happened because of the environment conditions with high temperatures, situation in which heating flow request for winter time was low;
- electrical efficiency is between 40,5 % and 41,3% with an average of 40,7 %, values very close to maximum values of the equipment;
- thermal efficiency has values with 10 % lower than nominal values, between 37,8 % and 38,8 %. This is happened because of beneficiary reduced possibilities to take over the heat flow as hot water, especially because of high back temperature (over 70-75 ºC) from heating system. In this case is recommended another study for transporting net hydraulic equilibrium;
- talking about fuel specific consumption measured in energy units, this has values between 2,585 and 2,620 kWh/kWh and is perfectly situated in values domain of technical documentation.

b) for real monthly recordings from working process

- monthly active electric energy has values from 720 to 850 MWh/month, with an average of 800 MWh/month, which means a charging of 93% and monthly average electric efficiency of 40,3 %. Taking into account all of these someone can draw the conclusion that cogeneration equipment is working in optimal conditions. Power reducing is

justifiable especially through electrical consumptions on one of the feeders under the power generator nominal value, on Sundays and during the short stops for maintaining operations;
- thermal energy has different values from one month to another. So, in winter time the taken over heat reaches monthly values from 500 to 750 Gcal/month, because of heating consumption. In summer time, technological heat consumption is reduced to the value of 300 to 350 Gcal/month. All these lead to annual total efficiency reducing at the value of 73%, with over 13% less than equivalent value of nominal charge;
- regarding fuel average consumption, its value is found into the domain guaranteed by the technical documentation of the power generator groups.

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