THE COST-TO-QUALITY EVALUATION AND OPTIMIZATION OF THE HEAT POWERED SYSTEMS

Ion IONITA

"Lower Danube" University of Galati Romania, Str.Domneasca nr.47, 6200 Galati, Romania

ABSTRACT

The paper deals with cost-to-quality ratio, as most comprehensive optimization criterion of the heat-powered systems. It is emphasised especially the role of the co-generation systems among heat powered systems.
The matter of the paper develops cost-to-quality ratio concept. The author considers that it is not enough to optimise a heat powered system using its thermodynamic efficiency. Most completely is to use economic efficiency, this the last taking into consideration not only the cost of the consumed fuel, but also the investment cost and operation-maintenance cost.
All this study is accomplished using only the exergy-based analysis.

KEYWORDS

Exergy analysis, exergo-economics, cost-to-quality optimisation, co-generation systems, tri-generation systems.

1. INTRODUCTION

It is well known that to optimize a mathematical function, in our case something about the studied thermal system, we need to establish only one value of optimization and not several, like thermal efficiency, weight, size, cost and so on. In the field of the heat powered systems analysis often is used thermal efficiency as main optimizing criterion. But how about solar heater where the solar energy being free, we are not so much interested to obtain the highest value of thermal efficiency of this system? In this case we are more interested to have smaller investment cost and operation-maintenance cost. In other words, the solar energy is free but to use it in an industrial or domestic plant we have to pay for some land of placing and for raising of the industrial or domestic plant and then to exploit and maintain it in running conditions.

This introduction leads us to conclusion that it is necessary to combine thermodynamic analysis with economic analysis, so to obtain minimum cost of construction and operation of a heat powered system which is producing heat, electricity or cooling.

2. THE QUALITY OF THE ENERGY

Furthermore, we must have in view that any of the heat, electricity or freeze produced is a good or service, unavoidably characterised by its quality.

The heat is delivered to beneficiary using a matter or substance called thermal agent like water, steam or other fluid. This fluid is always characterised by its temperature and pressure. These two thermodynamic parameters can very well define the exergy, as qualitative measure of the energy.

The exergy of the heat is defined as the heat which can produce work, so we can evaluate it using so-called Carnot factor $\left(1-\frac{T_o}{T}\right)$, where T_o and T [K] are environmental and source temperature, respectively.

$$\dot{E}=\dot{Q}\left(1-\frac{T_o}{T}\right) \qquad (1)$$

Relation (1) shows that if we have at our disposal the heat flow rate $\dot{Q}$ [W], only a part of it is useful to produce work and this is the exergy flow rate $\dot{E}$

But, we know that electricity is pure exergy.

We know also that cooling is produced by electricity, or by heat at temperatures higher than the environmental one, that is, to produce cooling we have to consume exergy.

Carnot factor ($1-T_o/T$) on the right side of Eq.1 shows exactly the quality of the heat input.

Plotting the exergy of the heat input $\dot{Q}(1-T_o/T)$ versus T and rotating the figure in a convenient way, we obtain Figure 1, which represents two distinct energetic zones, which are separated by the Carnot factor curve:

- The upper left-hand zone is the exergy zone, where energy is available and is able to produce work. The higher the temperature of the working fluid, the larger its exergy $\dot{E}$, cf. Eq.1.
- The lower right-hand zone is the anergy zone, where the energy supply can be sizeable, but it is not able to produce work, its quality being unsatisfactory. This area is defined by equation:

$$\dot{A}=\dot{Q}\frac{T_o}{T} \quad [kW] \qquad (2)$$

For any temperature $T > T_o$ we have $\dot{Q}=\dot{E}+\dot{A}$.

Below T_o all the energy is anergy.

When $T = T_o$ we have $\dot{E}=0$ and $\dot{Q}=\dot{A}$.

In the limit $T \to \infty$, we note $\dot{E} \to \dot{Q}$, which means that entire energy is available. The higher the T, the more the energy is available and the higher its quality. In other words, the temperature T is the qualitative indicator of the energy quality and the T axis of the Figure 1 is the scale of energy quality.

To show the usefulness of the quality scale of the energy, in the Figure 2 were drawn the quality scales of the

Ion.ionita@ugal.ro

energy zones of the steam turbines cycle, gas turbines cycle and combined steam and gas turbine cycle. For this the author used the values of the reference [1]. In the first graph (ST) we can see that steam turbine cycle is using only the lower part of the exergy zone. This way the exergy destruction through heat transfer is very large.
In the second graph (GT) of the gas turbine cycle is used only the upper part of the quality scale of the energy. The lower part of it, below (550…600)^{o}C remains unutilised.
Only in the third graph (CCSGT), the quality scale of the energy shows us how useful is the combined cycle of steam and gas turbine, as we already know from practice.
I would like to go next underlining that the end user is willing to pay only the useful part of the energy, that is the exergy.

3. THE COST OF EXERGY

Depending on temperature as qualitative indicator (Eq.1) exergy has a cost. There is a direct connection between exergy and its cost.
Looking at exergy as a product that must be provided, we can use the economic analysis made by Tsatsaronis (1996) in the reference [2] for one co-generation system for heat and power. Extending the analysis to any co-or tri-generation system, we can speak about heat or electricity as delivering products or about cooling or chilling as some services done for an end user.
The total cost of an energetic product like heat or power or of a cooling service, is expressed by the equation

$$\dot{C}_P = \dot{C}_F + \dot{Z}^{CI} + \dot{Z}^{OM} \quad [\$/h] \qquad (3)$$

$\dot{C}_P$ [$/h] – the cost rate of the energy product like heat or power or of a thermal service as air-conditioning, cooling or heating.
$\dot{C}_F$ [$/h] – the cost rate of the fuel or electricity consumed to produce an energy product or a thermal service.
The values $\dot{C}_P$ and $\dot{C}_F$ are related to exergy, they are exergetic values.
$\dot{Z}^{CI}$ [$/h] – the cost rate of the capital investment expenditures, calculated by means of like cycle of the plant or of the engine.
$\dot{Z}^{OM}$ [$/h] – the cost rate of the expenditures made with:

- operation and maintenance of the plant or engine;
- the taxes and fees paid because of infringement of the environmental protection rules;

The values $\dot{Z}^{CI}$ and $\dot{Z}^{OM}$ are not depending directly of exergy, they are considered [2] non-exergetic values.
From Eq.3 we can see that thermal efficiency is related only with the value $\dot{C}_F$, the other two values ($\dot{Z}^{CI}$ and $\dot{Z}^{OM}$) not being at all influenced by it.
To argue that is better to use an engineering-economic approach, let's take the study of a marine co-generation system made by Gogan [3] in her doctoral thesis.
Before this we have to mention the Figure 3 – Thermodynamic efficiencies of different heat powered cycles: 1,2–steam turbines; 3,4–combined cycles of steam and gas turbines; 5-gas turbines; a-gas or liquid fuel; b-coal.
The main conclusion from this figure is that gas turbines cycles are working with high temperatures, that is with large exergies, that is in costly conditions, having instead lower or lowest efficiencies. This is our conclusion if we are applying only thermodynamic considerations. The exergoeconomic study made by Gogan [3] revealed that among five different Diesel-powered ship variants (the cases BC, A, B, C, D in the Figure 4) and the gas turbine powered ship variant (the case E), this the last is most economic, the total cost of heat, electricity and propulsion work produced by gas-turbine cycle representing 88,16% of the total cost for the base case BC (Diesel propulsion).
This above-mentioned study is one of the numerous arguments of exergoeconomic analysis applying advantage.

4. THE COST TO QUALITY RATIO (CQR)

Following the idea to have a most comprehensive evaluation of the efforts made to obtain an energy product or service, we have to mention that only the cost of a product is not enough to be used as comprehensive criterion. Anybody knows that a higher quality product is more expensive that one of lower quality. The reader can find a graph cost-to-quality in the reference [4].
The value that expresses the global amount of the features of a product, is the cost-to-quality ratio

$$CQR = \frac{\dot{C}_P}{Q} \qquad (4)$$

In Eq.4 the value Q represents the quality of the product. For energy products like heat or power, the quality is well expressed by their exergy (kJ for heat or kWh for power), the available part of the energy they are containing.
Therefore, for heat products like warm water or steam, CQR is measured in [$/kJ], while for electricity this value is expressed in [$/kWh]. Here we have to recognize just the taxation ways that are used now in practice, which encourage us to go this way for other applications, cooling for example.
The refrigerant plants or devices are delivering a service, which consists in extracting heat from some products and maintaining them at a constant temperature, bellow the environmental one. In this case the quality of the service is expressed in the cooling parameters, usually the storage temperature. To do this, the refrigerating plant is consuming electricity of some kW amount. This one is just the quality Q of the delivered service. The cost of this service $\dot{C}_P$ [$/h] can be evaluated using Eq.3. Therefore the cost-to-quality ratio of this service is $CQR = \dot{C}_P / Q$ [$/kWh]. This value is not a novelty, we can easily recognize in it the unitary costs, and long ago

practiced in our engineering-economic evaluations. Somehow new is only the approach to conduct the energy optimization using CQR as main criterion.

For instance, using the operation parameters and calculated data of the co-generation (heat and power) system shown in Moran and Shapiro's book [5], the author obtained the Figure 5, in which the exergoeconomic parameters are the unitary cost of steam c_{st} = 7,2 ¢/kWh and the unitary cost of electricity c_e = 8,81 ¢/kWh.

These two exergoeconomic evaluating results depends on the specific cost of fuel c_F = 1,44 ¢/kWh, investment and operation maintenance costs of boiler $\dot{Z}_b$ = 1080 \$/h and of turbine $\dot{Z}_t$ = 92 \$/h.

To optimize this co-generation system means to change maybe the fuel unitary cost (c_F), to improve the cycle so to reduce $\dot{Z}_b$ or/and $\dot{Z}_t$. Doing like this, the reduction of CQR for steam (c_{st}) and for electricity (c_e) can maybe obtained.

The further approach is to use a general cost rate of the overall cycle [\$/h].

$$\dot{C}_{tot} = \dot{C}_e + \dot{C}_{st} = c_e \dot{W}_e + c_{st} \dot{E}_{st} \quad [\$/h] \qquad (5)$$

and to try reducing the total per hour cost and evaluating an optimal value for the delivered power $\dot{W}_e$ and heat $\dot{E}_{st}$.

For a plant in use the values $\dot{W}_e$ and $\dot{E}_{st}$ from Eq.5 are constant, they are contract requirements that must be kept untouched. In order to optimize the plant operation, that is to obtain minimum $\dot{C}_{tot}$, we can write

$$\dot{C}_{tot} = k_1 c_e + k_2 c_{st} \quad (k_1, k_2 = \text{const.}) \qquad (6)$$

To reduce the total cost $\dot{C}_{tot}$ maintaining the same quality, we have to accept all the solutions directed to reduce unitary costs of electricity c_e [\$/kWh] or of steam c_{st} [\$/kJ]. Among these solutions could be:

- The increase of the life cycle of the components, reducing this way capital investments $\dot{Z}^{CI}$ [\$/h].
- The improving of combustion processes and reducing this way operation-maintenance expenditures $\dot{Z}^{OM}$ [\$/h].
- The increase of the thermal efficiency of the plant and reducing this way fuel expenditures $\dot{C}_F$ [\$/h].

I think a complete list of the application solutions is hard to write, but from this enumeration we can see that any of the good solutions could contribute to total cost $\dot{C}_{tot}$ lowering.

CQR concept of evaluating and optimization of the heat-powered systems is not denying what is done now, when is evaluating and trying to minimize the total cost of the produced energy. More over, the prestigious works of Szargut [6] Tsatsaronis [7], Valero [8] make use of this concept without calling it when they are using the unitary costs expressed in \$/kWh or \$/kJ. In the above mentioned paper of Szargut as in many others, the reader can find numerous arguments supporting CQR concept, especially the relation (6) for unitary cost of the heat produced.

To understand better this concept the reader is invited to think that the quality of any energy product is unavoidably characterized by some contract parameters, as voltage (V) and frequency (Hz) for electricity, pressure (Pa) and temperature [K] of thermal agent for heat, the cooling storage temperature [K] for refrigeration service. All these products (electricity or heat) or services like refrigeration are accomplishing the quality requirements, delivering or consuming certain amount of exergy. That is just the quality of the delivered or consumed energy so to observe the contract requirements. These contract requirements, all of us know, must be kept constant and strongly observed during the product or service is delivered. CQR concept is including analytically the quality contract requirements in our engineering-economic evaluations, in order not to need remind them outside of mathematical model of production.

General conclusion CQR concept is wide comprehensive, it can be easily used in heat powered systems, where the quality of the products (heat, power, work) or of the services (heating, ventilating, air conditioning) can be well expressed by the exergy consumed to deliver them.

Acknowledgement
The author expresses all his gratitude to Professor Michael Moran, Ohio State University, USA, for wonderful Fundamentals of Engineering Thermodynamics book (2000) he wrote and presented him.

References

[1] Motoiu,C.,Darie,G.,Golovanov,N.,Goia,M.L. "Cresterea eficientei în producerea, transportul şi distributia energiei" (The efficiency improving of the energy production, transfer and distribution).Principii de management energetic (Principles of energy management) Editura Tehnica, Bucuresti, pp.349-380, Romania (1997) ISBN 973-31-1030-4.

[2] Bejan,A,Tsatsaronis,G.,Moran,M. "Thermal Design and Optimization" John Wiley&Sons, New York (1996).

[3] Gogan,A.E. "Thermoeconomic Analysis and Optimization of Marine Cogeneration Systems". Ph-D thesis "Lower Danube" University of Galati, Romania, (2000).

[4] Ionita,C.I. "About the Application of Extended Exergy Analysis to the Optimization of Industrial Systems Using Cost/Quality Ratio" ECOS 2000 Proceedings, Twente, Nederland, pp.187-198, ISBN 9036514665, (2000).

[5] Moran,M.,Shapiro,H. "Fundamentals of Engineering Thermodynamics" John Willey & Sons, Inc, ISBN 0-471-31713-6,New York (2000)

[6] Szargut,J, "Cogeneration of Network Heat in the Set of a Humid Air Turbine" ECOS 2000 Proceedings,

Ion.ionita@ugal.ro

Twente, Nederland, pp.423-434, ISBN 9036514665, (2000).
[7] Tsatsaronis,G. "Design Optimization Using Exergoeconomics" Thermodynamic Optimization of Complex Energy Systems (A. Bejan and E Mamut eds) 1999 Kluwer Academic Publishers, pp.101-115, ISBN 0-7923-5726-4
[8] Valero,A.,Correas,I.and Serra,L. On-line thermoe-conomic diagnosis of thermal power plants". Thermodynamic Optimization of Complex Energy Systems (A. Bejan and E Mamut eds) 1999 Kluwer Academic Publishers, pp.117-136, ISBN 0-7923-5726-4.
[9] United Nations Economic and Social Commission for Asia and Pacific. Guidebook on Cogeneration as a Means of Pollution Control and Energy Efficiency in Asia.http/www.unescap.org/enrd/energy/co-gen.

Nomenclature

T_o – environmental temperature, [K];
T – source temperature, [K];
$\dot{E}$ - exergy flow rate, [kW];
$\dot{Q}$ - heat flow rate [kW];
$\dot{A}$ - anergy flow rate [kW];
ST – steam turbine;
GT – gas turbine;
CCSGT – combined cycle steam and gas turbines;
$\dot{C}_P$ - the cost rate of the energy product, like heat or power, or of a thermal service as air-conditioning, cooling or freezing, [$/h];
$\dot{C}_F$ - the cost rate of the fuel or electricity consumed to produce an energy product or a thermal service [$/h];
$\dot{Z}^{CI}$ - the cost rate of capital investment expenditures, calculated by means of life cycle of the plant or of the engine [$/h];
$\dot{Z}^{OM}$ - the cost rate of the expenditures related to:
- operation and maintenance of the plant, engine or device;
- the taxes and fees paid because of infrigement of the environmental protection rules;

CQR – cost-to-quality ratio [$/kWh; $/kJ];
Q – quality of the energy product;
c_{st} – unitary cost of steam [$/kJ];
c_e, c_{el} – unitary cost of electricity [$/kWh];
$\dot{c}_F$ - unitary cost of the fuel [$/kWh];
$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM}$ - the total non-exergetic cost rate of capital investments and operation-maintenance expenditures of the plant, engine or device, [$/h];
$\dot{Z}_t$ - the total non-exergetic cost rate of turbine [$/h];
$\dot{Z}_b$ - the total non-exergetic cost rate of boiler [$/h];
$\dot{C}_{tot}$ - the total cost rate of the co-generation plant [$/h];
$\dot{C}_e$ - the cost rate of the electricity produced [$/h];
$\dot{C}_{st}$ - the cost rate of the steam produced [$/h];
$\dot{W}_e$ - the power of the plant [kW];
$\dot{E}_{st}$ - the exergy flow rate of the steam produced [kJ/h].

Superscripts
CI – capital investments
OM – operation-maintenance;
Subscripts
P – product;
F – fuel;
st – steam;
e, el – electricity;
t – turbine;
b – boiler;
tot – total

Figure Captions

Figure 1 The quality scale of the energy
Figure 2 The quality scale of the energy zones of steam turbine cycle (ST), gas turbine cycle (GT) and combined cycle steam and gas turbine (CCSGT)
Figure 3. Thermodynamic efficiencies of different heat powered cycles: 1,2-steam turbine; 3,4-combined cycles of steam and gas turbines; 5-gas turbines; a-gas or liquid fuel; b-coal. (taken from [1])
Figure 4. Cost of all products C_{tot} [US $/h] for a marine tri-generation system (BC,A,B,C,D-different Diesel - powered ship variants; E-gas turbine powered ship variant) [3].
Figure 5. The schematic exergoeconomic flowsheet obtained with data of Moran and Shapiro's book [5] for a steam turbine co-generation system.

Ion.ionita@ugal.ro

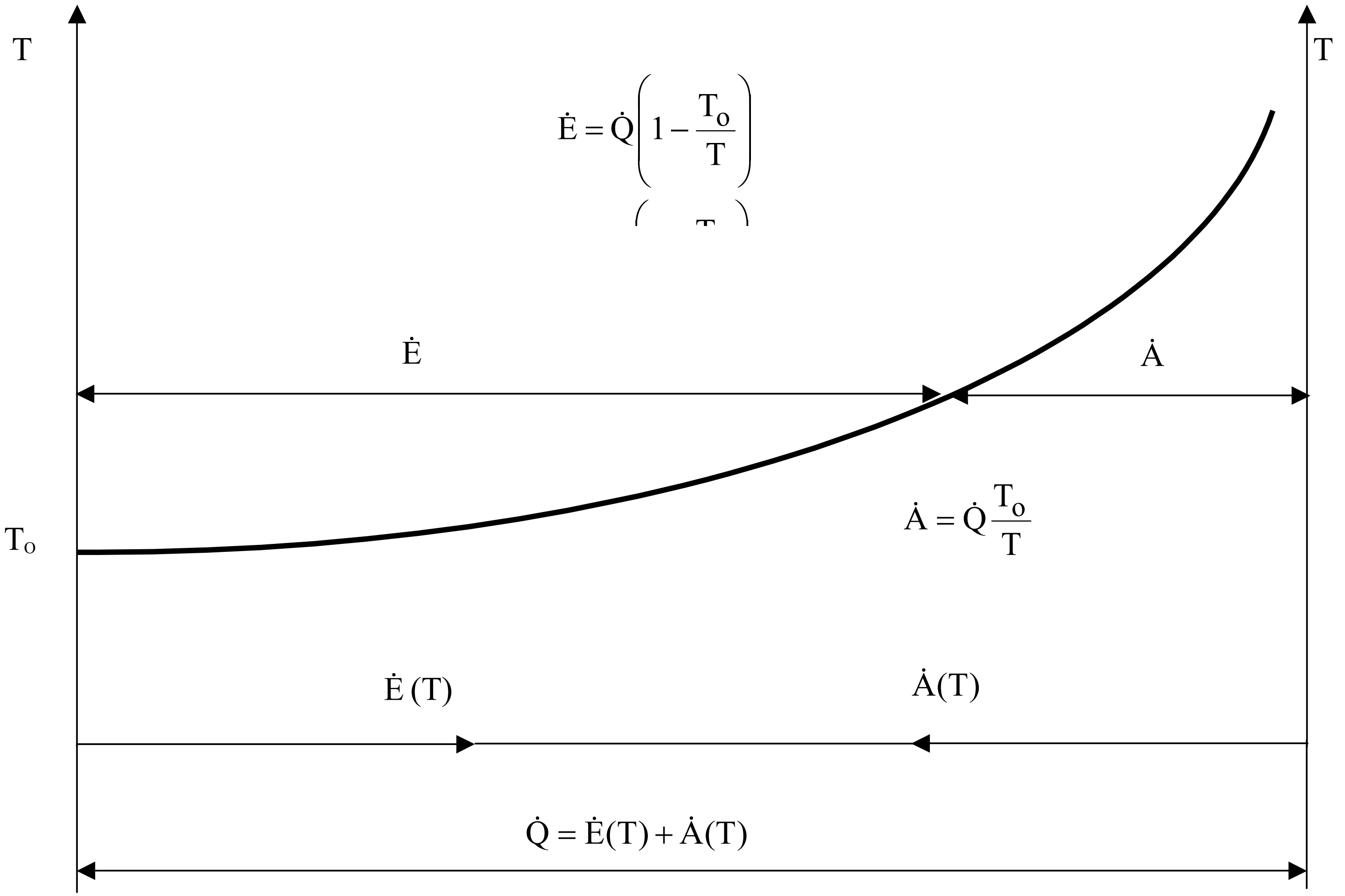
T
T
$\dot{E} = \dot{Q}\left(1 - \frac{T_o}{T}\right)$
$\dot{E}$
$\dot{A}$
T_o
$\dot{A} = \dot{Q}\frac{T_o}{T}$
$\dot{E}\,(T)$
$\dot{A}(T)$
$\dot{Q} = \dot{E}(T) + \dot{A}(T)$

Figure 1

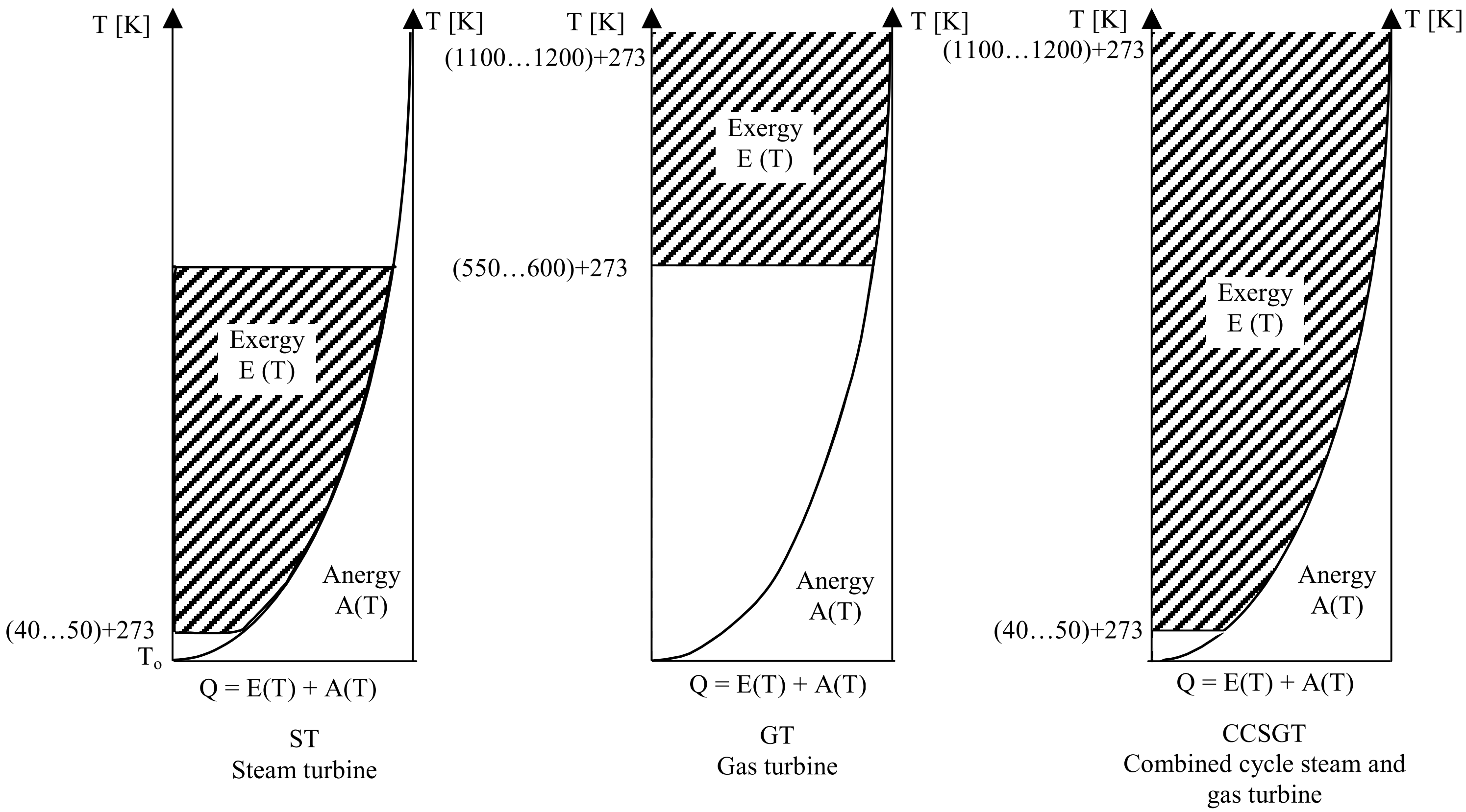
T [K]
T [K]
(40…50)+273
T_o
Exergy
E (T)
Anergy
A(T)
Q = E(T) + A(T)
ST
Steam turbine
T [K]
T [K]
(1100…1200)+273
(550…600)+273
Exergy
E (T)
Anergy
A(T)
Q = E(T) + A(T)
GT
Gas turbine
T [K]
T [K]
(1100…1200)+273
(40…50)+273
Exergy
E (T)
Anergy
A(T)
Q = E(T) + A(T)
CCSGT
Combined cycle steam and gas turbine

Figure 2

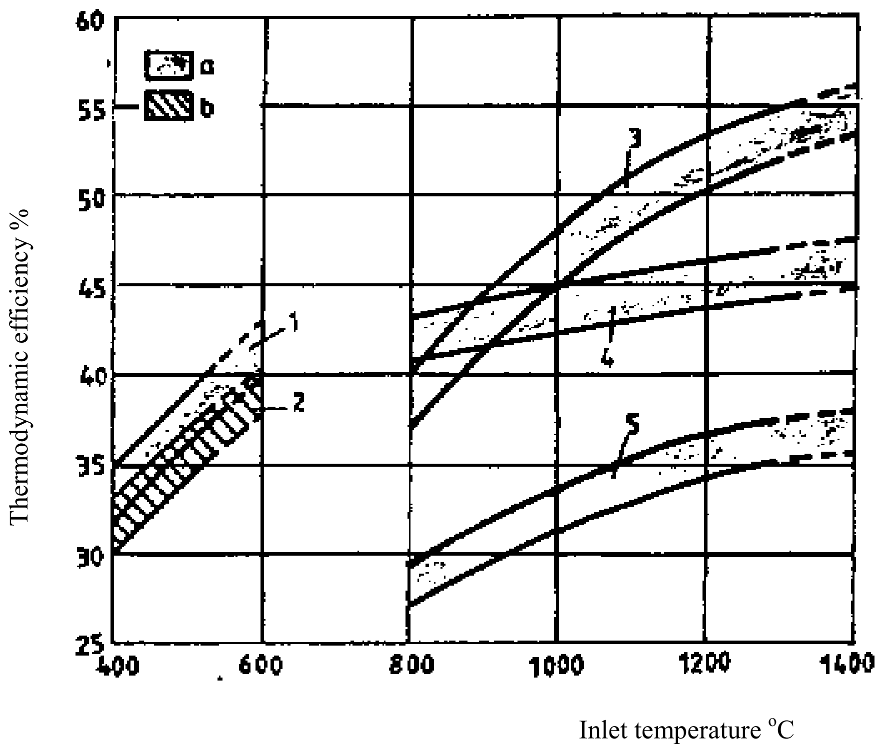

Figure 3

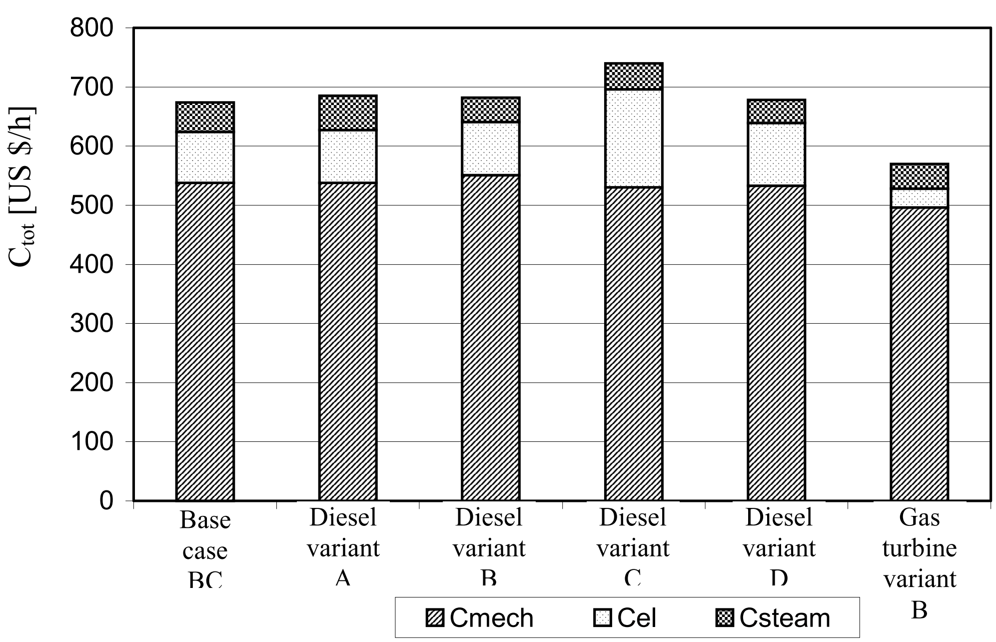

Figure 4

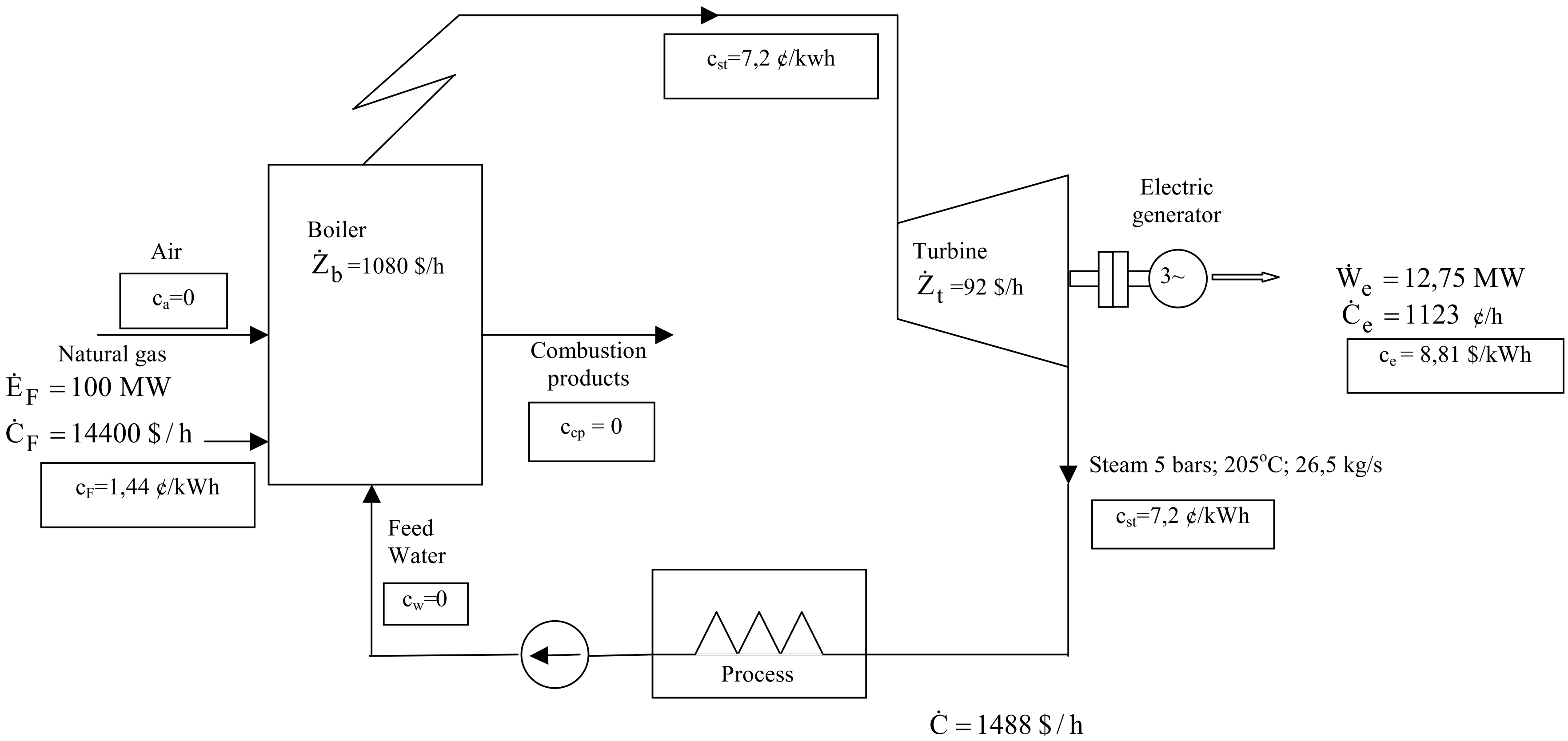
c_st=7,2 ¢/kwh
Boiler
Ż_b =1080 $/h
Air
c_a=0
Natural gas
Ė_F = 100 MW
Ċ_F = 14400 $/h
c_F=1,44 ¢/kWh
Combustion products
c_cp = 0
Feed Water
c_w=0
Process
Turbine
Ż_t =92 $/h
Electric generator
3~
Ẇ_e = 12,75 MW
Ċ_e = 1123 ¢/h
c_e = 8,81 $/kWh
Steam 5 bars; 205°C; 26,5 kg/s
c_st=7,2 ¢/kWh
Ċ = 1488 $/h

Figure 5