REPOWERING OF THERMOELECTRICAL POWER PLANTS WITH CONVENTIONAL RANKINE CYCLE FOR COMBINED CYCLE USING HEAVY DUTY GAS TURBINES

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Abstract. *Several Thermoelectric Power plants installed in Latin American countries between the 60´s and the 90´s, most of them using fuel-oil, these days are working with low thermal efficiency and high pollutant emissions. The present paper presents the results of the possible approaches, the existing technological alternatives and the implication of repowering these units, focusing on the increasing of the installed capacity and improving thermal efficiency through its by then conversion to combined cycles. Based on the layout of a 73 MWe steam power plant of the end of the seventies and 30 years of continuous operation, six repowering options are evaluated: Option 1 – Simple combined cycle with two gas turbines (one of them new and the other just existing and operating only in peak regime), recuperative boiler and an additional steam turbine. The old steam boiler is removed. Option 2 – Only one gas turbine and a recuperative boiler, keeping the old steam turbine. The old steam boiler is removed. Option 3 – The same arrangement as option 2, but including water injection in the gas turbine combustion chamber. Option 4 – The same arrangement as option 2, but including steam injection in the gas turbine combustion chamber. Option 5 – A parallel combined cycle using natural gas, both in the old steam boiler and in the gas turbine. The old steam cycle is maintained and a gas turbine with a recuperative boiler is added. Option 6 – The same scheme as in option 5, but using fuel-oil in the conventional boiler and diesel fuel in the gas turbine. All the repowering cases are higher efficient when compared with the base case. Option 2 is the most efficient (50 % versus 28 % for the base case). The economic analysis for a 15-year period indicates that the lowest total present value (TPV) is for the option 2. An evaluation of* CO_2 *specific emissions shows that the best results are for option 4. For all analyzed cases, with the exception of option 6, the* CO_2 *specific emissions are reduced in about 40 %. It is concluded that the repowering is a thermodynamically, economically and environmentally feasible option for the extension of the useful life of old steam power plants.*

Keywords*: thermoelectric power plants, repowering, economic analysis, gas turbines*

1. INTRODUCTION

Thermoelectrical power plants repowering can be based on the analysis of three basic principles: the thermodynamic study of the different technological solutions, the economical evaluation of the several models and the smallest environmental impact produced by the decrease of the pollutants generated during the electricity production.

There is no general procedure for the repowering study. The selection of the most economical configuration depends on many factors, such as: type of fuel, operation mode, design of the steam system, environmental applications, useful life of the equipments and the economical factors.

If the residual life of the main equipments of a power plant is less than 15%, a good assumption is the scrap of the existent installation, the re-utilization of the auxiliary systems and the construction of a new combined cycle power plant or other type of plant. If the residual life of the main equipments is more than 15%, one may choose several thermal configurations. Other technological options may indicate the use the old main and auxiliary equipments: steam turbine, condenser, feed water heating system, feed water pumps and other. Addition of gas turbines and the use of their exhaust gases in the heat recovery boiler, that substitutes the conventional boiler for the steam generation, transform the old installation into a new combined cycle power plant.

Conventional steam generators/steam turbines, in parallel with gas turbines and heat recovery steam generators, constitute in a second source of high pressure superheated steam for the steam turbines. The extractions of steam from the steam turbine are reduced and the feed water heaters are used partially to increase the exit power of the turbo-generator. This results that in a very high efficiency repowered cycle with operational flexibility, allowing the power plant to operate as two individual systems, as combined cycle or hybrid system.

Selection of the best repowering alternatives parameters must be considered for best efficiency: the power plant thermal balance, the technical limits of the old and future equipments under the new configurations and the estimates of the most economical costs. Such a study is only possible if specially developed computer programs for the evaluation of different operational characteristics of the repowering solutions.

An important feature of the repowering study is cost-benefit analysis of one technology compared with other available options in the field of the electricity generation. The evaluation must consider fundamental economical parameters such as the investment cost, the operation and maintenance costs, and the operational flexibility of the repowering power plant compared with other options; as well as the operation of existing units in the interconnected grid system. The repowering will produce an impact in the programmed expansion of the installed generation capacity because it can reduce future needs of the installed electricity power; besides reduction of fuel consumption, operation and maintenance expenses, due to the decrease of the heat rate and greater operational efficiency of the installation.

Environmental issues are very important factors in the energy businesses world, as well as in the daily life. The electricity generation is not exception; the effluents emissions generated by the thermoelectrical power plants are in the world focus. With the Protocol of Kyoto being enforced by an increasing number of governments, a strong pressure exists to reduce the emissions of the power plants. The repowering of old power plants with Rankine cycles burning solid or liquids fuels (coal, fuel oil) reduces the emissions of CO_2, SO_2 and NO_X drastically through the improvement of the existing power plant efficiency and of the new fuels option.

2. POWER PLANTS REPOWERING

2.1. Thermodynamic model

Usually, the steam turbines stay operational for several decades, allowing repowering, that is, the adaptation of an existing Rankine-cycle steam power plant into a combined cycle, by the addition of one or more gas turbines and heat recovery steam generators. As result one gets efficiency improvement and extension of the power plant useful life. Together with the increase of the generation capacity pollutants emission and losses of thermal energy by kWh of electricity generated are reduced.

To select the best repowering alternative for the new physical configuration of a plant, the efficiencies, the equipments definition and implantation must be considered. Several combinations of different equipments, with the help of thermal calculations, having as limit the imagination and the restrictions of the installation may be investigated. Table 1 shows just a few of the possible alternatives.

Table 1. Repowering options.

Option	Description	Δ Power (%)	Δ Efficiency (%)	Invest (%)[1]	Emissions Reduction (%)[2]	Time (months)
A	Combined cycle (GT+HRSG)	200	15 – 20	70 – 85	50 – 80	12 – 18
B	Hot Windbox (Boiler + GT)	15 – 30	8 – 10	20 – 30	50 – 80	8
C	Supplemental Boiler + Windbox	10 – 30	8 – 10	20 – 30	40 – 60	8
D	Feed Water Heating	10 – 30	8 – 10	15 – 20	10 – 20	2
E	Hybrid repowering	30 – 200	15 – 20	70 – 85	50 – 80	12 – 18

[1] Compared to the investment of a new combined cycle power plant of equal capacity.
[2] Compared to the reduction of emissions before the repowering.

In the numeric simulation of the steam processes expansion in a multi-stage steam turbine it is necessary to know the steam temperature, pressure and enthalpy at inlet; steam temperature, pressure and enthalpy at exit; extractions temperature, pressure and enthalpy; expanded steam mass flow, and the turbine isentropic efficiency. Using the First Law of Thermodynamics it is possible to determine the power developed by the steam turbine.

$$\dot{m}_s = \beta\sqrt{\left(P_1^2 - P_2^2\right)/T_1} \tag{1}$$

$$\sum\left(\Delta\dot{W}_{ST}\right) = \eta_i \cdot \left(\Delta H\right)_s \tag{2}$$

where:

$\sum\left(\Delta \dot{W}_{ST}\right)$	- Steam turbine power (MWe);
η_i	- Steam turbine isentropic efficiency (%);
$(\Delta H)_s$	- Enthalpy isentropic change (kJ/kg);
$\dot{m}_s$	- Flow mass of the steam (kg/s);
β	- Flow mass coefficient of the steam ($s \cdot m \cdot {}^{o}C^{0.5}/kg$);
P_1, P_2	- Pressure at the inlet and exit of the steam turbine (kPa);
T_1	- Temperature of the superheated steam at the steam turbine inlet (ºC).

According to the ASME PTC 4.1 – 1985 code the efficiency of a conventional boiler is calculated based on the total flow of the consumed fuel, specifications of the fuel mixture (Higher Heating Value), boiler geometric specification, excess air specification, feed water thermodynamic condition at boiler inlet and exit, heat transfer model specific data and steam generator constituent elements energy losses. The boiler global performance is given by:

$$\eta_B = 100 - L_R - \left[\frac{\Sigma P_B}{Q_{HHV}}\right] \cdot 100 \tag{3}$$

where:

η_B	- Boiler overall efficiency (%);
L_R	- Losses by radiation (%);
ΣP_B	- Main losses addition (kJ/s);
Q_{HHV}	- Fuel HHV (kJ/s).

The gas turbines characteristic parameters are usually calculated at the ISO conditions (15ºC and 1 atmosphere). At off-design these parameters must be corrected. Initial evaluation requires several inlet data, among which: ambient temperature, compressor inlet pressure, inlet pressure loss, turbine inlet gas temperature and relative humidity. Those initial values determine the air mass flow and the compressor efficiency. The gas turbine thermal efficiency can be calculated by:

$$\eta_{total}^{GT} = 1 - \frac{\left\{\vartheta \cdot \left[1 - (\eta_{GT}) \cdot \left(1 - \frac{1}{\rho_{GT}}\right)\right] - 1\right\}}{\left[(\vartheta - 1) - \frac{(\rho_{comp} - 1)}{\eta_{comp}}\right]} \tag{4}$$

where:

η_{total}^{GT}	- Gas turbine overall efficiency (%);
ϑ	- Temperatures ratio (dimensionless);
η_{comp}	- Compressor isentropic efficiency (%);
η_{GT}	- Turbine efficiency (%);
ρ_{GT}	- Gas turbine cycle pressure ratio (dimensionless);
ρ_{comp}	- Compressor pressure ratio (dimensionless).

The heat recovery steam generators that were object of the present study are one pressure level, due to the physical configuration of the existing steam turbine in the U-2 power plant. For the numeric simulation of the recuperative boiler the models assumed:

- The approach temperature and the pinch point are given. The pinch point is between 8ºC to 10ºC and the approach temperature 14ºC;

- The gas turbine exhaust temperature leaving the recovery boiler stack is considered a control parameter. It should not be smaller than the fuel dew temperature. The natural gas (natural gas from Camisea - Peru) has a dew temperature of 93.33ºC and the fuel oil (Ecuador) 140ºC.

Some parameters of the performance cycle are defined using the First Law of Thermodynamics. The gas, steam and combined cycle thermal efficiency are calculated by:

$$\eta_{ter}^{GT} = \frac{\dot{W}_{liq}^{GT}}{\dot{m}_F \cdot LHV} \tag{5}$$

$$\eta_{ter}^{SC} = \frac{\dot{W}_{liq}^{SC}}{QS + Q_g} \tag{6}$$

$$\eta_{cc} = \frac{\dot{W}_{liq}^{GC} + \dot{W}_{liq}^{SC}}{QS + Q_{GC}} \tag{7}$$

where:

η_{ter}^{GT}	- Gas turbine thermal efficiency (%);
$\dot{W}_{liq}^{GT}$	- Gas turbine net power (MWe);
$\dot{m}_F$	- Fuel mass flow (kg/s);
LHV	- Fuel LHV (kJ/kg);
η_{ter}^{SC}	- Steam cycle thermal efficiency (%);
$\dot{W}_{liq}^{SC}$	- Steam cycle net power (MWe);
QS	- Supplemental burning (MWe);
Q_g	- Gas turbine exhausts thermal energy (MWe);
η_{cc}	- Combined cycle efficiency (%);
Q_{GC}	- Gas turbine fuel thermal energy (MWe).

2.2. Economic model

The methods used in the economical evaluation are presented in this item and used to find the best technical - economical alternative of the different repowering models studied for the conversion of an existing Rankine cycle with into combined cycle power plant.

2.2.1. Cost of the generated electricity

The cost of the generated electricity is related to the kWh of electricity produced, involving mainly capital, fuel and operation and maintenance costs. The electricity cost represents a key element In the electricity generation industry development, so that each power plant is designed for the least production cost. In this paper the electricity cost (US$/MWh) is calculated as follows:

$$C_{EG} = \frac{\psi \cdot C_0}{P \cdot H_{OP}} + \frac{\xi}{\eta_0} + \frac{U_{fix}}{P \cdot H_{OP}} + \mu_{\text{var}} \tag{8}$$

where:

C_0	- Total investment (US$);
ψ	- Annual factor (dimensionless); $\psi = \frac{q-1}{1-q^{-n}}$
n	- Depreciation (years);

P - Power produced (kW);
H_{OP} - Hours of operation (h);
ξ - Fuel price (US$/kg);
η_0 - Power plant average efficiency (kWh/kg);
U_{fix} - O&M fixed costs (US$);
μ_{var} - O&M variable costs (US$/kWh);
z - Discount rate (dimensionless); $q = 1 + z$

2.2.2. Present Value Method

In this method all of the annual costs (investment capital, fuel, operation and maintenance and others) anticipated for the life time of the project, are brought to the present time, using the present value factor (Γ). The Equation 9 that expresses this relationship is:

$$TPV = \sum_{i=1}^{n} \Gamma_i \cdot I \cdot \Lambda + \sum_{i=1}^{n} \Gamma_i A_{f,i} + \sum_{i=1}^{n} \Gamma_i A_{om,i} \tag{9}$$

where:
TPV - Total present value (US$);
$(\Gamma)_i$ - Present value factor (dimensionless);
I - Investment capital (US$);
Λ - Annual fixed cost rate (dimensionless);
$A_{f,i}$ - Fuel annual cost (US$);
$A_{om,i}$ - O&M annual cost (US$).

2.2.3. Capitalized Cost Method

In this method a hypothetical capital value is referred directly to the initial investment, so that the fuel and operation and maintenance costs during the useful lifetime of the power plant are eliminated. It is calculated by Eq. 10:

$$ETC = I + \frac{C_f}{\Lambda} + \frac{C_{om}}{\Lambda} \tag{10}$$

where:
ETC - Evaluated total cost (US$);
C_f - Fuel leveling annual cost (US$);
C_{om} - O&M leveling annual cost (US$).

2.3. CO_2 emission model

The change of the original thermodynamic configuration of a Rankine-cycle power plant for combined cycle (pure or hybrid) aiming at improvement of its overall electricity production efficiency involves the use of other fuels. Today, fuel oil is burnt in a conventional boiler, whist the repowered plants will use natural gas from Camisea (pure combined cycle) and diesel oil + fuel oil (hybrid).

Equation 11 is used for the calculation of the power plant CO_2 specific emission (g CO_2 equiv/kWh generated):

$$DE_{CO_2} = \frac{1.000 \cdot HR}{\overline{\overline{HV}}} \cdot \sum_j \chi_j \left(F_j^{CO_2}\right) \tag{11}$$

where:

DE_{CO_2} - CO_2 specific emission (g CO_2/kWh);
HR - Fuel specific consumption (kJ/kWh);
$\overline{HV}$ - Heating value by mass of the fuels used (kJ/kg);
$F_j^{CO_2}$ - CO_2 emission factor (kg CO_2/ kg fuel);
χ_j - Mass fraction of each type of fuel burned (dimensionless).

3. CASE STUDY: "ENG. GONZALO ZEVALLOS (U2) POWER PLANT" IN GUAYAQUIL – ECUADOR

The technical characteristics of the oldest and less efficient of the electricity generating units of "Eng. Gonzalo Zevallos" facility, the U2 power plant, are indicated in Tab. 2:

Table 2. U2 Operational conditions (100% nominal power).

Equipment	Parameter	Values
Boiler	Feedwater temperature	217 °C
	Steam temperature	513 °C
	Steam mass flow	295 ton/h
Turbine	Angular speed	3,600 rpm
	Steam input pressure	88 kg/cm^2
	Nominal power	73,000 kW
Condenser	Cooling water mass flow	3,160 kg/s
	Vacuum	63.5 mm Hg.
Electric Generator	Apparent power	85,883 kVA
	Peak power	75,000 kW
	Power factor	0.85
	Field Voltage	13.8 kV

Both combined and hybrid cycles were investigated in the preliminary studies for the conversion of the U2 power plant. For the combined cycle model four types of thermal configurations were used: two gas turbines, one gas turbine, Feedwater injection into the gas turbine combustion chamber and superheated steam injection into gas turbine combustion chamber. For the hybrid repowering model, two thermodynamic arrangements were used: hybrid cycle with natural gas and hybrid cycle burning a mixture of fuel oil and diesel oil.

The thermodynamic properties of each U2 power plant thermal configurations (current condition and the repowering models) were obtained from numeric simulation using the commercial software GateCycle and the results are shown in the next section.

The methodology for the evaluation of the studied power plant (U2 power plant) and the repowering models are described below:

- Compilation of the actual Rankine thermal cycle data at peak, average and low load;
- Graphic programming of the thermodynamic configurations of U2 power plant for the current operation condition and the repowering models, using the commercial software GateCycle;
- Gathering of the operational parameters from performance analysis for:
  a) Rankine cycle modified (one model);
  b) Simple combined cycle (four models);
  c) Hybrid combined cycle (two models);
- Economical evaluation of the repowering models using standard analysis techniques aiming at determination of the viability of the power plants projects based on, among others: cost of the generated electricity, present value method and capitalized cost;
- Environmental evaluation using the CO_2/kWh specific emission parameterization of each one of the studied repowering models.

A synthesis of the applied methodology is presented in Tab. 3.

Table 3. Methodology synthesis applied to the power plant simulation.

Thermal Configuration	Characteristic	Fuel	Thermoenergetic evaluation	Economical evaluation	Environmental evaluation
Rankine cycle	Modified with superheating and regeneration	Fuel oil	• Off-design: 100, 75, 50, 25% • Water/fuel ratio: 0; 0.5; 1; 1.5 • Steam/fuel ratio: 0; 0.5; 1; 1.5 • Operational parameters and performances • Energy flows characterization	• Electricity cost (C_{EG}) • TPV Method • ETC Method • TRC Method	• CO_2/kWh specific emission • CO_2 emission factor from fuel oil • CO_2 emission factor from diesel oil • CO_2 emission factor from natural gas
Complete combined cycle (4 models)	HRSG + 2 GT	Natural gas			
	HRSG + 1 GT	Natural gas			
	HRSG +Feedwater Injection GT	Natural gas			
	HRSG +Steam Injection GT	Natural gas			
Hybrid cycle (2 models)	GT and conventional boiler: same fuel	Natural gas			
	GT and conventional boiler: different fuel	Boiler: Fuel oil GT: Diesel oil			

4. RESULTS

The results are analyzed and presented based on three topics: operational performance, economical analysis and CO_2 specific emission.

4.1. Operational performance

The off-design conditions numeric simulation for the current conditions of the U2 power plant was calculated varying mainly the thermodynamic parameters of the steam turbine, boiler, condenser, among other equipments. The off-design results for the models of combined cycle (simple and hybrid) were obtained reducing the load of the gas turbine, between 70 to 100% of the nominal power, maintaining constant the exhaust gas turbine temperature to minimize the impacts on the production of the quality of the steam supplied to the turbine.

Figure 1 shows the gas turbine net power as function of the combined cycle capacity factor, from which it is possible to observing a linear behavior of the load increment. The simple repowering combined cycle, with steam injection into the gas turbine combustion chamber, develops the largest net power, due to the addition of the superheated steam mass, which adds thermal energy to the combustion process and produces an increment in the exhaust gas turbine temperature as well as the combustion gases mass flow.

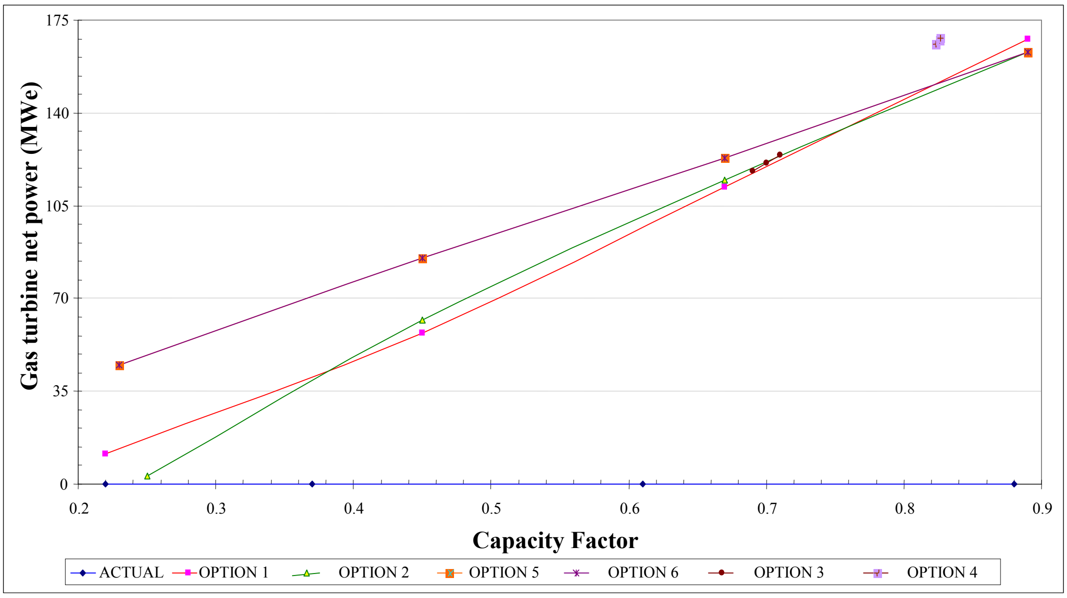

Figure 1. Gas turbine net power

For the hybrid model, when the gas turbine load is less than 50% of the nominal power, there is increase of the steam production in the conventional boiler, forcing the reduction of the combined cycle efficiency.

The tendency of the power produced by the steam turbine in the simple combined cycle models is different from the tendency in the hybrid cycles. With one gas turbine, the power ratio is inverted and, like this, the steam turbine power corresponds to 2/3 of the combined cycle power, instead of 1/3 as it happens when the overall power of the combined cycle is greater than 25% of the nominal power. When the combined cycle power is reduced to less than 25% of the nominal power, if there are two or more gas turbines, the power ratio $\left(\dot{W}_{ST}/\dot{W}_{GT}\right)$ stays in the 1/3 ratio.

An interesting feature in this results analysis is related with Fig. 2, where the original thermal cycle efficiency is improved from 28% to 50% (repowering complete combined cycle with one gas turbine).

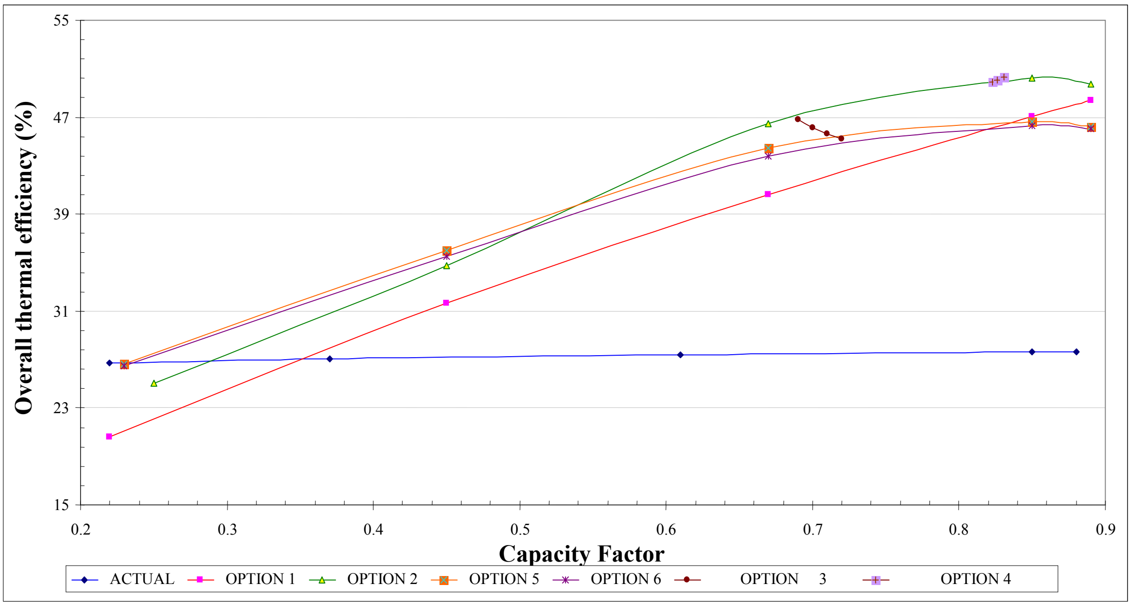

Figure 2. Overall thermal efficiency of the U2 power plant (currently and repowering)

4.2. Economical analysis

The economical analysis results of the different models are related to the Heat Rate incidence in the reduction of the expenses, the total cost evaluated and the change of the electricity price as function of the capacity factor.

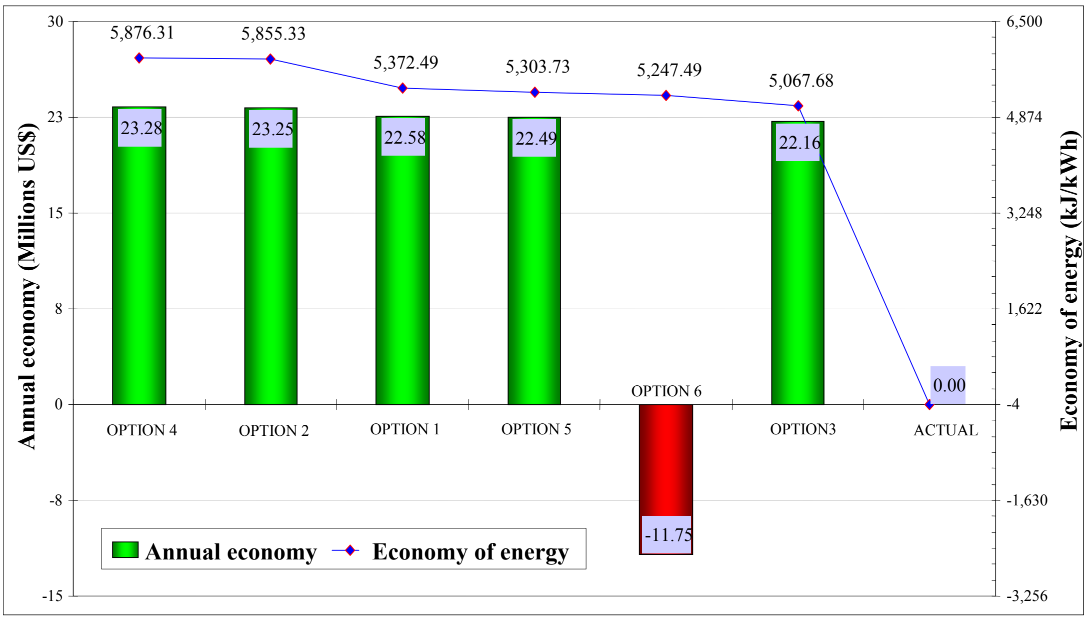

Figure 3. Economy of energy in function of the Heat Rate

One of the main improvement areas to reach in a repowering study is related to the reduction of the fuel specific consumption, a factor strongly decisive in the economy of the consumed fuel and cycle operation costs. This is clearly demonstrated in Fig. 3, where it can be determined that the economy in the energy primary consumption (Heat Rate) is between 5,067.68 and 5,876.31 kJ/kWh (39 – 46%) depending on the repowering model used.

The analysis of the results obtained for the Total Present Value (TPV) and the Evaluated Total Cost (ETC), shown in the Fig. 4, indicates that option 2 (complete combined cycle with one gas turbine) presents the best economical indices during the useful lifetime of all repowering models analyzed. Besides, the electricity price changes as function of the capacity factor and the production costs are reduced to about 50% (0.0745 to 0.0303 cent US$/kWh) when the power plant, operating as a modified Rankine cycle, is converted to a combined cycle (simple or hybrid).

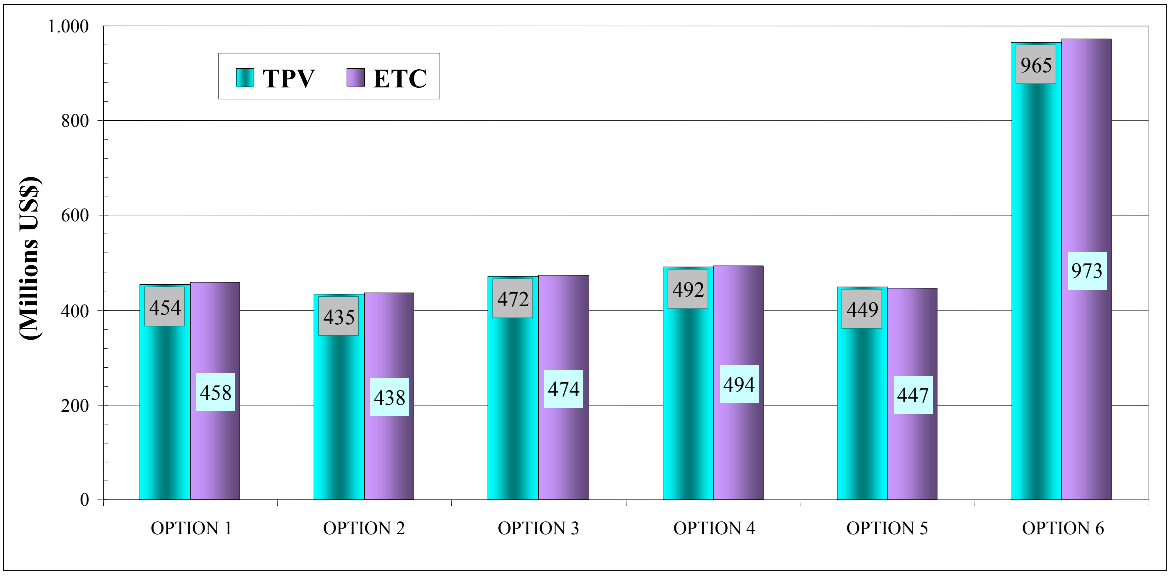

Figure 4. Total Present Value and Evaluated Total Cost for repowering models

4.3. CO_2 especific emission

Typically, the percentage of carbon by weight in fuel oil is 85%. Each kilogram of fuel oil produces 3.22 kg of CO_2 and each kilogram of natural gas produces 2.78 kg of CO_2. According to Fig. 5, in the actual operation conditions of the U2 power plant, the CO_2 specific emission corresponds to 800 - 900 g CO_2/kWh. When a Rankine cycle power plant burning fuel oil is converted to combined cycle burning natural gas, the CO_2 specific emission by kWh will be reduced to 400 - 500 g CO_2/kWh.

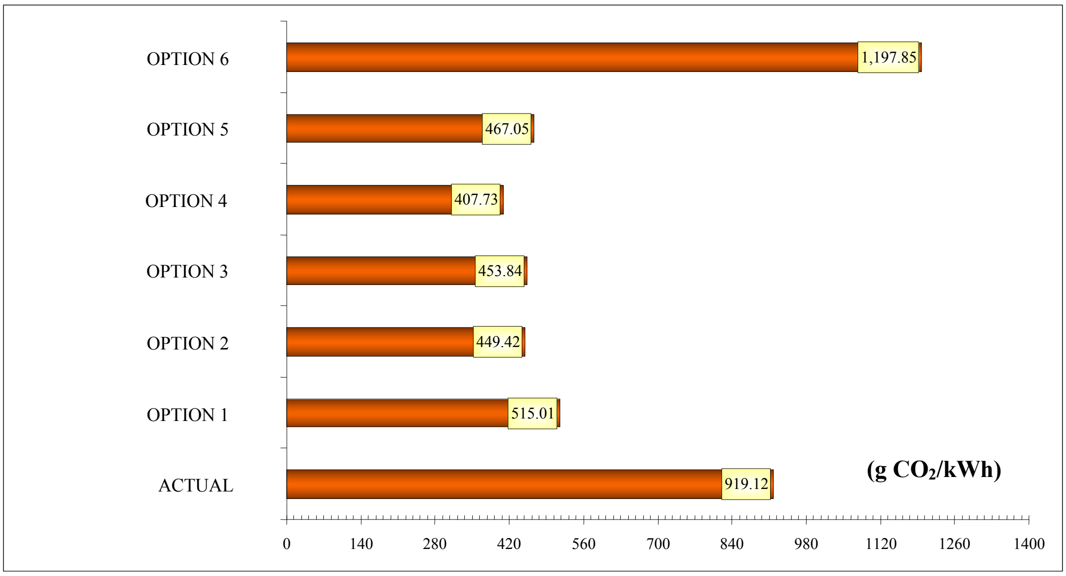

Figure 5. CO_2 specific emission by kWh generated of the U2 power plant (currently and repowering)

The U2 power plant at actual conditions has a specific emission of 919.12 g CO_2/kWh for a capacity factor of 65% with an average power of 53.16 MWe and Heat Rate of 13,037 kJ/kWh; when the U2 power plant is converted to a combined cycle, the best results for the reduction of the CO_2 specific emission are obtained with the simple combined cycle model with high pressure superheated steam injected into the gas turbine combustion chamber, for which the thermal model gives a specific emission of 407.73 g CO_2/kWh for a capacity factor of 83% with average power of 224.85 MWe and Heat Rate of 7,243.39 kJ/kWh.

5. CONCLUSIONS

The study for repowering existing steam power plants indicates the following advantages:

- Besides repowering being not new, It may be used for both new and existing power plants;
- Table 1 shows several of the repowering alternatives and Tab. 3 shows the repowering models applied in this study (option A and option E of Tab. 1).
- Upgrading older thermal power plants is often a cost-effective method for increasing the power output, improving efficiency and reducing emissions;
- Figure 2 shows how the option 2 is the most efficient of all repowering models studied in this work (approximately 50% in comparison to 28% for the base case);
- Figure 3 shows how the fuel specific consumption is a factor strongly decisive in the economy of the consumed fuel and cycle operation cost. Although option 4 is slightly best than option 2, an economic analysis for a 15 year period indicates that the lowest total present value (TPV) is for option 2 (Fig. 4);
- The amount of emissions from the repowering plants burning natural gas is small in comparison with the existing plant burning fuel oil ;
- Several commercially available gas turbines were used as flue gas sources. Generated power, fuel consumption, and flue gas temperature, at different loads, were known for these turbines and input to six repowering models;
- The comparison of several repowering solutions, complete combined cycle (four models) and hybrid combined cycle (two models) has shown a slightly higher energetic gain for the complete combined cycle model (with one old steam turbine, one new heat recovery steam generator and one new gas turbine burning natural gas).

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