2009 Annual Bulletin of the Australian Institute of High Energetic Materials v.1 (2010) pp. 163-170
USBN: 978-0-9806811-3-0
Available at www.ausihem.org

Optimal life cycle oriented design of a GT + 1PSH HRSG type CCGT power plant

Godoy E., Benz S. J.*, Scenna N. J.

Centro de Aplicaciones Informáticas al Modelado en Ingeniería,
Facultad Regional Rosario, Universidad Tecnológica Nacional, Argentina

Abstract:
In the present work, a life cycle oriented approach is used for designing power plants in a way they can satisfy the desired demand along the whole time horizon, while a selected performance indicator of the project is optimized. As case study, optimal design characteristics as well as optimal values of long term operation parameters of a GT + 1PSH HRSG Type CCGT power plant (*GT*: gas turbine, *1PSH HRSG*: 1 pressure with superheater-heat recovery steam generator, *CCGT*: combined cycle gas turbine) are obtained by means of a multiperiod mathematical model, seeing that the selected performance indicator is maximized. In addition, advantages of the life cycle oriented approach results are discussed when compared with a power plant design obtained by traditional methods.

Keywords: power plant, life cycle, multiperiod optimization

1. INTRODUCTION

A life cycle oriented approach, which makes decisions based on economic indicators that refer to the whole CCGT power plant life cycle, is critical under today's business conditions due to increased competition and market uncertainties, among others. Usually, a plant life cycle consists of several phases such as synthesis and design, construction, operation, and eventually disposal (Ishii et al., 1997). From the economic point of view, decisions made during the early stages of synthesis and design largely determine the economic performance of the plant across its entire life cycle. So, it becomes necessary to consider the capital investment and annual operative costs in front of variable demand conditions, and also, costs associated with the construction phase, start-up and shut-down periods, maintenance operations, etc.

Traditionally, power plants are designed for the maximum value of the expected demand, or even over-dimensioned with respect to such value, trying that way to secure they would be able to fulfil the power production requirement at any feasible scenario. Here, a multiperiod framework is proposed to be used to make decisions considering dynamic changes of external conditions through time, as risks associated to unforeseeable situations will became reduced by considering future scenarios within the model.

The aim of the present work is to determine characteristics of the equipment to be installed (design power of gas and steam turbines, exchange area of HRSG, etc.), and the operating conditions of the whole system (pressures, temperatures, flows, etc.) which represent the most effective way of meeting the expected demands over the entire life cycle of the facility. Two different performance criteria are here proposed to orient the search of the optimal design of the power plant. They are the net present value of the power plant along its entire life cycle and the thermal efficiency for evaluating the optimal thermodynamic performance over a long-term horizon.

Optimal values of design and operative variables of the power plant obtained through the multiperiod optimization model are reported considering the two different performance indicators previously described. Also, results obtained by means of the traditional approach are presented, in order to identify improvements for the design and operation of power plants offered by the here proposed multiperiod model.

2. MULTIPERIOD MATHEMATICAL MODEL OF A POWER PLANT

2.1. Case Study Schematic Description

A GT + 1PSH HRSG Type CCGT power plant is used as case study, which consists of a gas turbine, a single pressure level HRSG and a steam cycle. A schematic description is presented in Figure 1.

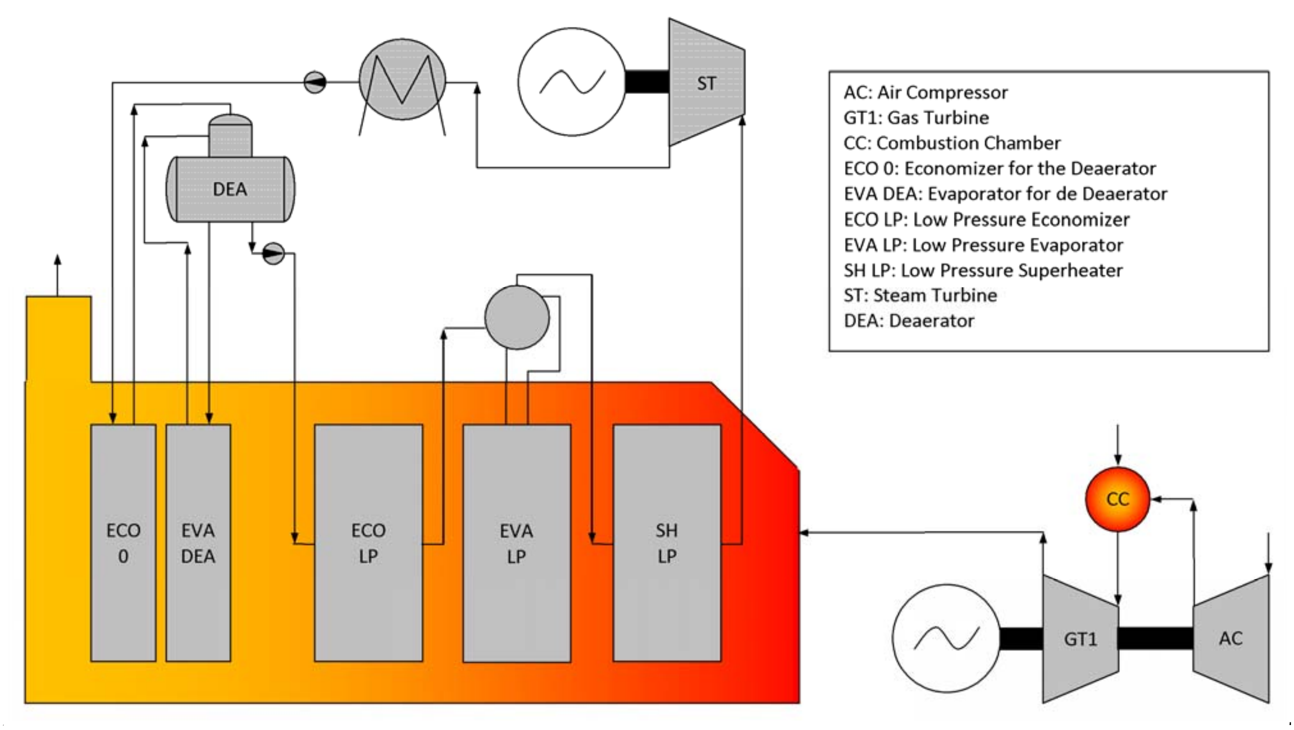

Figure 1: GT + 1PSH HRSG Type CCGT Power Plant Diagram

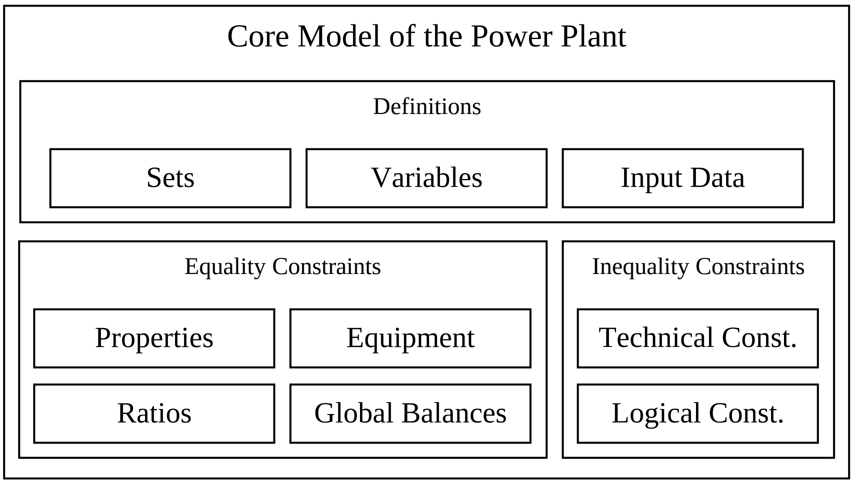

Figure 2: Modules that form the Core Model of the Power Plant

2.2. Core Model of the Power Plant

The mathematical model of the power plant is implemented in GAMS through a series of modules, as presented in Figure 2, which comprises the main characteristics of such systems (for further details, see Godoy et al., 2009; Valdés and Rapún, 2006).

2.3. Multiperiod Modelling Framework

Time Periods

The multiperiod modelling framework is defined as a set of periods *ti* which comprises the main stages of the plant life cycle (pre-operative phase, represented by the sub-set *pi*, when all the construction tasks are carried out; operative phase, represented by the sub-set *oi*, when the plant is operated at base and peak load; and post-operative phase, represented by the sub-set *li*, when the plant is dismantled) and accounts for the number of years the life cycle of the plant is intended to last.

In addition, each year is divided into four seasonal sub-periods *sti*, which allow modelling the variations some variables incur because of the seasons shift (Aguilar et al., 2007). As an example, Eq. (1) models the time-dependent trend of the power demand, as the real world variability of such variable is assimilated to vary in a discrete way (it is assumed that the mean annual power demand *Wo* increases a fixed percentage *ADG* each year, while seasonal variations *Woe* are also introduced).

$$Wo_{ti,sti} = Wo_{ti-1} \cdot (1 + ADG) \cdot (1 + Woe_{sti}) \qquad (1)$$

Similarly, variability of the parameters that define the multiperiod modelling framework is also considered, including for example seasonal changes of the ambient temperature, annualized increments of electricity prices and fuel costs, and so on.

As the life cycle of the facility is intended to last up to 30 years, and since each year is divided into 4 seasons, the multiperiod modelling framework includes 120 different scenarios which need to be optimized in order to obtain the optimal value of the objective function over the whole time horizon.

Coupling Constraints

A set of equality constraints is defined to couple the values of the design variables through the multiple scenarios included within the time horizon.

Transfer areas *A* of the HRSG sections (ECO: economizer; EVA: evaporator; SH: superheater) get coupled as values of these areas (identified by the subindex *Des*) are selected in a way they enable to operate the combined cycle at its optimal performance (Eq. (2)).

$$A^{j}_{oi,sti} = A^{j}_{Des} \quad , \quad j = ECO, EVA, SH \qquad (2)$$

Power generation turbines (GT: gas turbine; ST: steam turbine) are dimensioned (identified by the subindex *Des*) in a way they can deliver the desired amount of power *W* while operating within feasible technical limits (according to Eq. (3)). Then, turbines operative power, as given by their operative load *Load*, is able to vary from its nominal value to half such assess, which is also known as technical minimum. Also, an upper limit to the design power of gas and steam turbines (identified by the subindex *max*) is in place (Eq. (4)). In addition, as the present model handles only continuous variables, it is allowed that each turbine adopts any size below such upper bound.

$$0.5 \le \; Load^{j}_{oi,sti} = \frac{W^{j}_{oi,sti}}{W^{j}_{Des}} \; \le 1 \quad , \quad j = GT \, , ST \qquad (3)$$

$$W^{j}_{Des} \le W^{j}_{\max} \quad , \quad j = GT \, , ST \qquad (4)$$

3. OPTIMIZATION FORMULATION FOR LIFE CYCLE COSTING

Life cycle oriented design of a GT + 1PSH HRSG Type CCGT power plant is here optimized by using the multiperiod optimization model. The mathematical statement of the economic problem linked to the evaluation of the profitability of investment options, that allows selecting the project which yields optimal values of the financial indicators, here evaluated through its net present value *NPV*, is given by Eqs. (5-7).

$$\max_{x} NPV = \sum_{ti,sti} \frac{(Sales + SVFC + Dep)_{ti,sti} - (C_{Op} + IFC + IWC + NIT)_{ti,sti}}{(1 + ADR)^{ti}} \quad : \text{Objective Function} \qquad (5)$$

$$s.t. \quad f(x^{Op}_{ti,sti} \, , x^{Des}) = 0 \quad : \text{Equality Constraints} \qquad (6)$$

$$g(x^{Op}_{ti,sti} \, , x^{Des}) \le 0 \quad : \text{Inequality Constraints} \qquad (7)$$

$$x^{Op}_{ti,sti} \, , x^{Des} \in \Re \quad , \quad ti = \left\{ \underbrace{1\,,2}_{Pre-Operative} \; , \underbrace{3\,, \cdots, 29}_{Operative} , \; \underbrace{30}_{Post-Operative} \right\} \quad , \quad sti = \{\, Au \, , Wi \, , Sp \, , Su \,\}$$

NPV of the project is the summation of discounted cash flows; i.e. it is the summation of net cash flows discounted to present value according to the annual discount rate *ADR* desired by the investor. The net cash flow of the *ti-th* year of the project life cycle is the difference between net financial input and output that occurs during such period, including sales of electricity *Sales*, operative costs C_{Op}, investment on fix capital *IFC*, investment on working capital *IWC*, salvage value of fix capital *SVFC*, depreciations *Dep*, and taxes *NIT*.

Economic optimization is performed via the software GAMS, using CONOPT as NLP solver, in a personal computer with an AMD Athlon™ 64 Dual Core 4000+ 2.11 GHz processor and 1 GB DDR2 RAM memory. It can be observed that all the steps of the optimization procedure feature acceptable values of the resolution time and the iteration count, in spite of the complexity of the mathematical problem, as the number of variables and equations exceeds 15000 in all cases and many constraints are highly non-linear.

Table 1: Optimal Values of the Design Variables for the Economic Optima

Variable	Life Cycle Approach	Traditional Approach
GT Design Power (MW)	250.9	196.9
ST Design Power (MW)	76.2	130.2
Power Plant Production Capacity (MW)	327.1	327.1
Economizer Area (m^2)	12241	22185
Evaporator Area (m^2)	36489	45702
Superheater Area (m^2)	3870	5444
HRSG Exchange Area (m^2)	52600	73331
Area Distribution ECO : EVA : SH	0.233 : 0.694 : 0.073	0.303 : 0.623 : 0.074
Net Present Value (M$)	142.0	113.9

Optimal values of design variables associated to the multiperiod economic optimum obtained by means of the life cycle approach are reported in Table 1, including the power production distribution and the HRSG area distribution. These values are pared with the ones corresponding to the traditional approach, evidencing this way the improvements for the design and operation of power plants obtained with life cycle approach.

The design power ratio (relation of power produced by the gas turbine to power generated by the steam turbine) varies from 1.51 in the traditional solution to 3.29 in the economic optima, although the total power production capacity remains the same in both solutions. The HRSG exchange area associated to the economic optima is 28.3 % lower than the one obtained for a traditional based plant design. Then, a design based on a power ratio of 3.29 with gas and steam turbines of 250.9MW and 76.2MW, respectively, and a HRSG of 52600m^2 with an economizer:evaporator:superheater area ratio of 0.233:0.694:0.073, secures the best economic performance will be accomplished along the whole time horizon while maintaining the capital investment at the lowest feasible amount.

When the economic multiperiod optimization of the power plant is performed considering its whole life cycle, an optimal net present value of 142.0 M$ is obtained, as can be seen in Table 1. Since the value of the NPV corresponding to a traditional approach is 19.8 % lower, extra 28.1 M$ are gained when designing and operating the CCGT on its long-term horizon multiperiod economic optima.

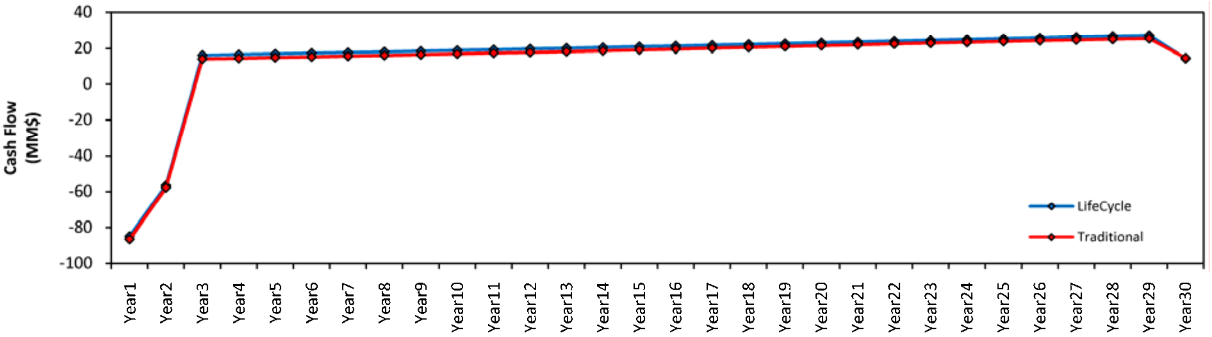

Figure 3: Cash Flows

Cash flows within each year along the plant life cycle are presented in Figure 3. During the pre-operative phase, negative cash flows occur because of investment on fix capital as the plant is built. Across the operative phase, increasing positive cash flows are obtained while satisfying the power demand; optimal economic results let state that the cash flow increases about 2.4 % on yearly basis in the first operative years, although such percentage decreases up to 1.7 % in the last ones. Finally, in the last year of the plant life cycle, the salvage value of the fixed capital investment originates a positive cash flow as the plant is dismantled.

The optimal economic solution is also constituted by optimal values of the operative variables, including pressures, temperatures, flow rates, and so on. As example, in Figure 4, optimal profiles of annual mean operative loads for the gas and steam turbines are presented, which assure an optimal performance from an economic aim is achieved at each scenario that the plant faces along its whole life cycle while satisfying the predicted increase on the energy demand. Annual mean operative loads for the gas and steam turbines, determined by the life cycle approach, increase year by year from a minimum of about 75 % to a maximum near to 100 %.

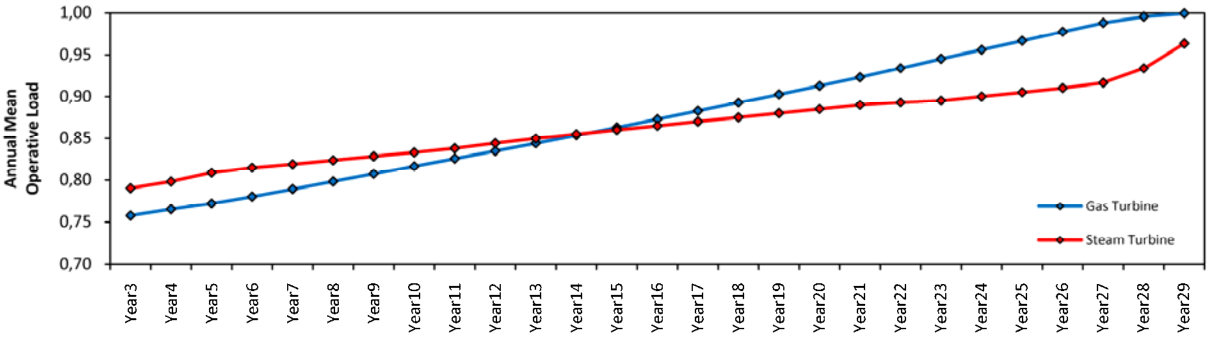

Figure 4: Annual Mean Operative Loads

4. THERMODYNAMIC PERFORMANCE EVALUATION OVER A LONG-TERM HORIZON

Evaluation of investment options by means of a thermodynamic aim may be used by itself in the preliminary stages of design, in order to identify trends and the existence of optimization opportunities (Godoy et al., 2009). Therefore, in the case of a life cycle oriented power plant design and considering the importance of its operative phase, it becomes interesting to search optimal designs characterized by the maximum thermodynamic performance averaged over a long-term production horizon.

The mathematical statement of the optimization problem that allows maximizing the power plant thermodynamic performance over a long-term horizon, here evaluated by means of the average thermal efficiency η_T, is given by Eqs. (8-10). Construction and shut-down periods are not considered for the thermodynamic optimization of the power plant, as the thermal efficiency can not be evaluated if the plant is not operating.

$$\max_{x} \eta_T = \frac{1}{N_{oi} \cdot N_{sti}} \cdot \sum_{oi,sti} \frac{Wnet_{oi,sti}}{mf_{oi,sti} \cdot LHV} \quad : \text{Objective Function} \tag{8}$$

$$s.t. \quad f\left(x^{Op}_{ti,sti}, x^{Des}\right) = 0 \quad : \text{Equality Constraints} \tag{9}$$

$$g\left(x^{Op}_{ti,sti}, x^{Des}\right) \leq 0 \quad : \text{Inequality Constraints} \tag{10}$$

$$x^{Op}_{ti,sti}, x^{Des} \in \Re \quad , \quad ti = \left\{ \underbrace{3, \cdots, 29}_{Operative} \right\} \quad , \quad sti = \left\{ Au, Wi, Sp, Su \right\}$$

The average thermal efficiency is computed as the arithmetic mean of the optimal values of the thermal efficiencies (calculated as the relation between the net power production *Wnet* and the fuel consumption *mf* multiplied by the lower heating value of the fuel *LHV*) corresponding to each scenario over the operative phase of the life cycle of the plant.

Thermodynamic optimization is performed via the software GAMS, using CONOPT as NLP solver, in a personal computer with an AMD Athlon^{TM} 64 Dual Core 4000+ 2.11 GHz processor and 1 GB DDR2 RAM memory. It can be observed that all the steps of the optimization procedure feature acceptable values of the resolution time and the iteration count, in spite of the complexity of the mathematical problem, as the number of variables and equations exceeds 15000 in all cases and many constraints are highly non-linear.

Optimal values of design variables associated to the multiperiod thermodynamic optima considering the long-term production horizon are reported in Table 2, including the power production distribution and the HRSG area distribution. These values are paired with the ones corresponding to the traditional approach, evidencing this way the improvements for the design and operation of power plants obtained with the life cycle approach.

Table 2: Optimal Values of the Design Variables for the Thermodynamic Optima

Variable	Life Cycle Approach	Traditional Approach
GT Design Power (MW)	248.5	236.1
ST Design Power (MW)	78.6	130.9
Power Plant Design Power (MW)	327.1	367.0
Economizer Area (m^2)	14388	22185
Evaporator Area (m^2)	36276	45702
Superheater Area (m^2)	4214	5444
HRSG Exchange Area (m^2)	54878	73331
Area Distribution ECO : EVA : SH	0.262 : 0.661 : 0.077	0.303 : 0.623 : 0.074
Thermal Efficiency (%)	52.17	47.11

The optimal thermodynamic operation of a life cycle oriented power plant design requires a power generation capacity 12.2 % lower than a power plant design based on a traditional approach. Furthermore, the design power ratio varies from 1.80 in the traditional solution to 3.16 in the thermodynamic optima, due mainly to the diminution of the design power of the steam turbine.

The HRSG exchange area associated to the thermodynamic optima is 28.3 % lower than the one necessary for a traditional based plant design. In addition, area redistribution among the HRSG sections also takes place, given that an additional 3.8 % of the total heat exchange area is assigned to the evaporator in detriment on majority of the economizer area.

Therefore, besides maximizing the thermal efficiency, thermodynamic optimization over a long-term operative horizon determines a large diminution of the design power of the steam turbine and considerable improvements in the associated HRSG design, both promoting a priori the reduction of the necessary capital investment. Even so, the optima and structural characteristics identified based on a thermodynamic oriented optimization procedure can be made more realistic through subsequent refinements based on cost minimization.

The average thermal efficiency associated to the multiperiod thermodynamic optima is 5.06 % higher than the one corresponding to the design and operation of a power generating facility by the traditional approach (see Table 2).

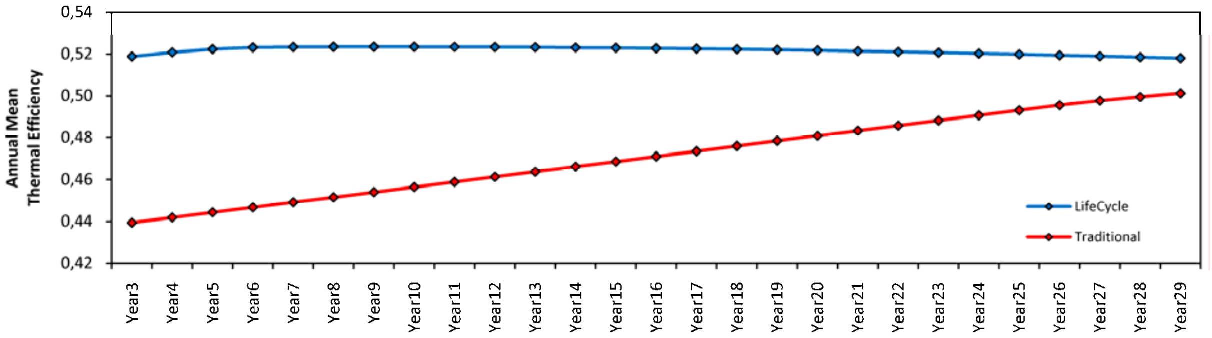

Figure 5: Annual Mean Thermal Efficiencies

In Figure 5, profiles of the annual mean thermal efficiency over the operative phase of the power plant life cycle are presented. For the optimized design parameters, the power generating facility reaches a maximum optimal performance in the seventh operative year, with a value of the annual mean thermal efficiency of 52.35 %; further ahead, the annual mean thermal efficiency decreases slightly year by year, though its value never drops below 51.81 %. On the other hand, a traditional plant exhibits a trend with an increasing thermal efficiency up to the last operative year, but with far lower values of this parameter (as in some years, the difference with respect to the maximum obtainable efficiency climbs up to 8 %).

Optimal values of the operative variables associated to the thermodynamic solutions obtained by the life cycle approach and by the traditional approach are also compared. As example, in Figure 6, evolution of the annual mean power ratio (relation of power produced by the gas turbine to power generated by the steam turbine) along the power plant operative phase is presented. In both cases, power ratio exhibit increasing trends; for the life cycle approach, annual increment of the power ratio is lower than 1 %; meanwhile, for the traditional approach, the power ratio increases between 1 % and 2 % on a yearly basis.

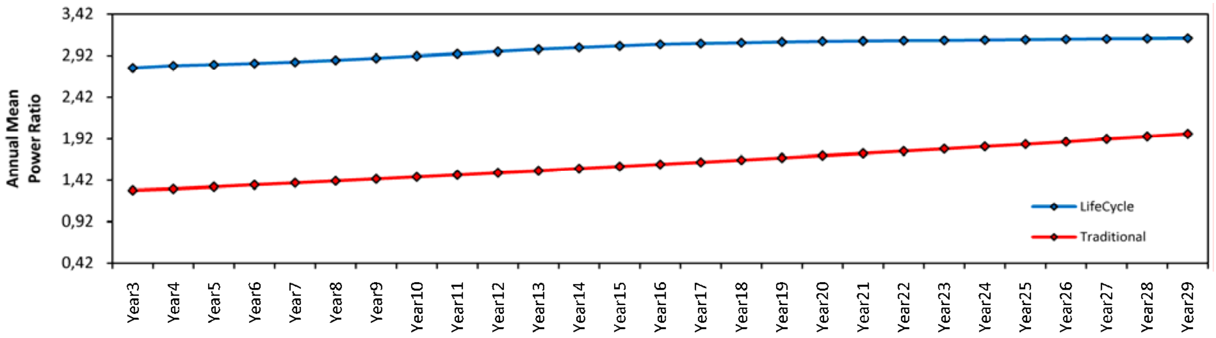

Figure 6: Annual Mean Power Ratios

5. CONCLUSIONS

Design and operation of a GT + 1PSH HRSG Type CCGT power plant is here optimized to meet the expected demands over the entire life cycle of the facility, including pre-operative, operative and post-operative phases. A long-term multiperiod optimization model is here presented to cope with this task. It constitutes a robust and flexible tool that provides insight of the multiperiod power plant design and operation.

Economic optimization along the power plant life cycle allows identifying optimal power plant designs taking into account variable costs associated to the operation phase, and the start-up and shut-down periods. On the other hand, thermodynamic performance optimization over a long-term horizon allows recognizing thermally efficient designs to operate along the power plant life cycle as well as new optimization opportunities.

Comparison with results obtained by the traditional approach (nominal condition design) shows improvements for the design of power plants offered by the here proposed life cycle oriented approach.

ACKNOWLEGEMENTS

The authors gratefully acknowledge the financial support of the Agencia Nacional de Promoción Cientifica y Tecnológica (ANPCyT) and the Universidad Tecnológica Nacional (UTN) from Argentina.

6. REFERENCES

Ishii, N.; Fuchino, T.; Muraki, M. Life Cycle Oriented Process Synthesis At Conceptual Planning Phase. Comput. Chem. Eng. **1997**, *21 (Sup 1)*, S953–S958.
Godoy, E.; Scenna, N.; Benz, S. Families of Optimal Thermodynamic Solutions for Combined Cycle Gas Turbine (CCGT) Power Plants. Appl. Therm. Eng. In Press, http://dx.doi.org/10.1016/j.applthermaleng.2009.10.022
Valdés, M.; Rapún, J. L. A General Method For The Optimum Design Of Heat Recovery Steam Generators. Energy **2006**, *31*, 3342–3361.
Aguilar, O.; Perry, S. J.; Kim, J-K.; Smith, R. Design And Optimization Of Flexible Utility Systems Subject To

Variable Conditions - Part 2: Methodology And Applications. Chem. Eng. Res. Des. **2007**, *85 (A8)*, 1136–1148.
Iyer, R. R.; Grossmann, I. E. Optimal Multiperiod Operational Planning For Utility Systems. Comput. Chem. Eng. **1997**, *21 (8)*, 787–800.

---

[*] Title and name of the corresponding author: Dra. Sonia Judith Benz (PhD)
Postal address: Zeballos 1341 – (2000) Rosario – Argentina
Telephone (incl. country code): +54-341-4484909
Fax (optional): +54-341-4484909
E-mail: sbenz@frro.utn.edu.ar