Identification of Key Parameters for Benchmarking of Combined Cycle Power Plants Retrofit

S. Sabzchi Asl, N. Tahouni, M. H. Panjeshahi

***Abstract*—**Benchmarking of a process with respect to energy consumption, without accomplishing a full retrofit study, can save both engineering time and money. In order to achieve this goal, the first step is to develop a conceptual-mathematical model that can easily be applied to a group of similar processes. In this research, we have aimed to identify a set of key parameters for the model which is supposed to be used for benchmarking of combined cycle power plants. For this purpose, three similar combined cycle power plants were studied. The results showed that ambient temperature, pressure and relative humidity, number of HRSG evaporator pressure levels and relative power in part load operation are the main key parameters. Also, the relationships between these parameters and produced power (by gas/ steam turbine), gas turbine and plant efficiency, temperature and mass flow rate of the stack flue gas were investigated.

***Keywords*—**Combined cycle power plant, energy benchmarking, modelling, Retrofit.

I. INTRODUCTION

POPULATION increment, urbanization, industrializing, and technologic development result directly in increasing energy consumption [1]. This rapid growing trend brings about the crucial environmental problems such as contamination and greenhouse effect [2]. Energy consumption is one of the most important indicator showing the development stages of countries and living standards of communities [1]. Efficient energy use, sometimes simply called energy efficiency, the goal to reduce the amount of energy required to provide products and services without lowering the products and services quality. We have two approaches to acquire the efficient processes; the first is the construction of new plants with new technologies and energy efficient processes, and the second is to retrofit the existing plants, with respect to new energy consuming standards. The first approach is not economical and requires a notable finance resources and new licenses, while the second approach is operational and appealing for employers. The efficient use of fuel in existing power plants is becoming more and more important, due to ever increasing need for electricity and the limited resources of primary energy [1]. Nowadays, modern technologies such as Pinch Analysis allow us to improve power plants efficiencies through retrofitting the thermal cycles. However, in general, the overall time and money required for retrofitting all existing plants would be a crucial question, in particular when governments and/or authorities intend to set up achievable targets for energy saving studies and financially support such projects. This is because conducting a full retrofit study for each single process is time consuming and costly. Employers decrease their energy costs in existing plants through energy management practices which evaluates energy performance, setting energy-savings goals, and regularly evaluating progress. To measure the effectiveness of energy management practices and management for continuous improvement, it is necessary to provide the reference points. Benchmarking creates these reference points and help organizations to specify the targets and successfully save energy [3]. Therefore, it would be a good practice to develop a benchmarking model for estimation of energy saving scope in a given process, as well as project economics, such as investment, saving and payback period, without doing full retrofit study.

Benchmarking is defined as an organizational process to evaluate and compare the services, products and processes with a recognized and accepted standard to facilitate the strategic outcomes [4]. In other words, benchmarking serves as a function, which receives the input variables, compares these inputs with a base case and gives a number of outputs [5]. Fig. 1 represents a schematic model of benchmarking function.

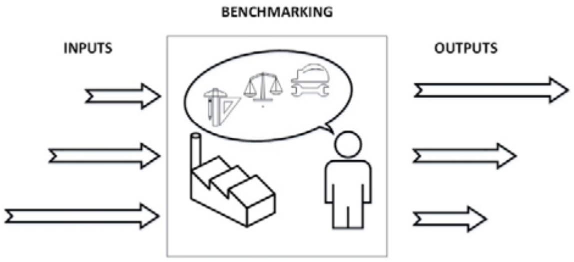

Fig. 1 A schematic model of benchmarking function

Benchmarking alarms organizations about how they use energy, where they use it, and what drives their energy use. Increasing profitability by lowering energy and operating cost is a key step in identifying opportunities. The main measure to evaluate the performance are identified through benchmarking, baselines are established, and goals are set. Benchmarking energy performance allows the energy manager to identify best practices that can be replicated. It makes reference points for measuring and rewarding good

---

S. Sabzchi Asl (MSc Student) and M. H. Panjeshahi (Professor) are with the School of Chemical Engineering, College of Engineering, University of Tehran, Iran (e-mail: saman.sabzchi@ut.ac.ir, mhpanj@ut.ac.ir).

N. Tahouni (Assistant Professor) is with the School of Chemical Engineering, College of Engineering, University of Tehran, Iran (corresponding author, phone: 98-21-66957788; fax: 98-21-66957784; e-mail: ntahuni@ut.ac.ir).

performance [3]. It identifies high-performing facilities for recognition and prioritizes poor performing facilities for immediate improvement. By evaluating trends and variability in energy use, benchmarking can improve management decisions on investments and payback period in energy-related projects. Nowadays, 80% of electricity over the world is approximately produced from fossil fuels (coal, petroleum, fuel-oil, natural gas) fired thermal power plants, while 20% of the electricity is compensated from different sources such as hydraulic, nuclear, wind, solar, geothermal and biogas. Power sector is highly capital intensive sector and has attracted attention of researchers from worldwide due to technical problems. Nevertheless, power sector retrofit has begun in most of the countries since last three decades. The energy supply to demand narrowing down day by day around the world, the growing demand of power has made the power plants of scientific interest [2]. The aim of this paper is to identify those inputs that might have significant impact on the model accuracy. In this benchmarking, the standard energy consumption level (base case) is determined.

Table I summarizes the most important benchmarking practices that have already been done on thermal power plants [6].

TABLE I
LITERATURE REVIEW OF BENCHMARKING IN POWER PLANTS

Author	Country	Power Plant	Inputs	Outputs
Liu et al. [7]	Taiwan	12 Power plants of Taiwan for period 2004–2006	Installed capacity Heating value of fuel Electricity used	Net electricity produced
Barros [8]	Portugal	25 Power plants of Portugal for period 2001–2004	Labor Capital Operational cost Investment	Energy production Energy sold Capacity utilization
Nakano & Managi [9]	Japan	10 Electric power generation companies of Japan	Number of employees Fuel in (MJ) Real capital stock	Production of electricity
Thakur et al. [10]	India	26 State Electricity Boards and State Electricity Departments of India for period 2001–2002	Total cost Number of employees	No. of customers Distribution line length Energy sold
Vaninsky [11]	US	Electric power generation of United States	Operating expenses Energy loss	Utilization of net capacity
Sarica &Or [12]	Turkey	65 power plants of Turkey period – 2001	Investment cost Construction time Fuel cost	Power produced Availability

II. SIMULATION AND MODELLING

To simulate the power plant cycles, we need the process operation data which vary with time. To solve this problem, the data in different time intervals were weighted and used as input data in simulation. For this study three similar units of combined cycle power plants (128 MW, 148.8 MW, and 160 MW) were studied. First, each unit including a gas cycle and a HRSG cycle was simulated using commercial simulation software. Fig. 2 represents a block flow diagram of the combined cycle power plant and Fig. 3 represents a gas cycle power plant separately.

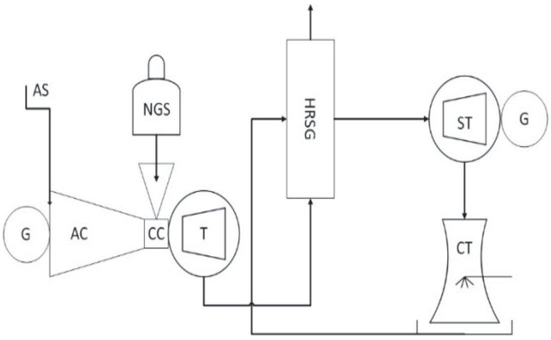

Fig. 2 BFD of Combined Cycle Power Plant, AC: Air Compressor, AS: Air Supply, CC: Combustion Chamber, CT: Cooling Tower, G: Generator, HRSG: Heat Recovery Steam Generator, NGS: Natural Gas Supply, ST: Steam Turbine, T: Turbine

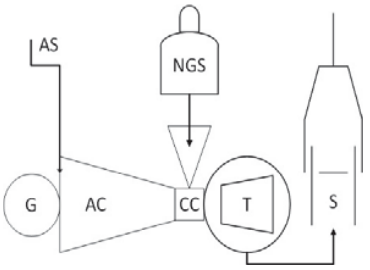

Fig. 3 BFD of Gas Cycle Power Plant, AC: Air Compressor, AS: Air Supply, CC: Combustion Chamber, G: Generator, NGS: Natural Gas Supply, S: Stack, T: Turbine

As the comparison of figures shows gas cycle which is only comprised of gas turbine, is a part of combined cycle. On the other words, the model offered for the combined cycle will cover the gas cycle as well. A combined cycle is included of two separate cycles connected to each other through the stack flue gas from the gas turbine. Gas turbine is a standardized machine, made in factory, transmitted to the power plant, and used without any change. In the other words, no processional change (we do not mean structural changes like the coating of combustion chamber, the shape of the turbine blades and etc.) can be applied on the gas turbine to improve its function. The structure of steam cycle of combined cycle does not allow us to change the cycle, to increase the heat transfer area for more heat recovery in heat exchanger network (such as shell and tube heat exchanger in conventional steam cycle) to raise the amount of heat recovery and efficiency of the cycle. Also, environmental conditions have a great and direct effects on the function of gas turbine and consequently on steam turbine. Therefore, the influence of environmental factors on combined cycle function has been studied, and a model has been offered for the influence of these parameters on the function of these cycles, used as a standard to evaluate the similar cycles. Then, several parameters evaluated as candidate parameters (ambient temperature, pressure and relative humidity of the site, relative power in part load, IGV, inlet temperature of gas turbine (GT), number of HRSG evaporator pressure levels, etc.) are examined. The power production in gas and steam turbine, gas turbine and plant electrical efficiencies, temperature and mass flow rate of the stack flue gas were first measured in ISO condition. Table II represents ISO condition for thermal power plants.

TABLE II
ISO CONDITION FOR THERMAL POWER PLANTS

Parameter	A.T(K)	Altitude(m)	A.P(bar)	RH (%)	No.
Value	288.15	0	1.013	60	3

A.T = Ambient Absolute Temperature, A.P = Ambient Absolute Pressure, RH =Ambient Relative Humidity, No. =Number of HRSG Evaporator Pressure levels

Next, each input parameter, with respect to the initial ISO condition, was altered and the deviations of all output parameters were recorded. The results of the case studies and associated data were reconciled using commercial statistical analysis software. To do this, several regressions were implemented on each set of data (case study) between an input and all outputs separately. This procedure was repeated for all inputs. Afterwards, the weighted coefficients for these regressions were obtained from the combination of coefficients that generated in previous step for each set of data. The value for R-squared factors (above 0.99) in each step verified that the linear regression was appropriate.

III. RESULTS AND DISCUSSION

All specific characteristics related to GTs are usually measured and reported in ISO conditions in manufacturing plants. However, all these specifications in power plants' sites vary in their nominal values due to the deviation of ambient conditions from ISO conditions. According to the simulation results, the deviation of all candidate parameters from ISO values affected the amount of power production and efficiencies, temperature and mass flow rate of the stack flue gas, but impact of some parameters was negligible. Table III represents the results of benchmarking of gas cycle and the relationships between input and output parameters, respectively. A key point that must be mentioned is that all parameters are dimensionless, consequently the results can easily be applied to the similar case studies. Reports have been limited to the expression of important affecting parameters. Also, Table IV represents the results of benchmarking for HRSG cycle with association parameters.

Note that to determine the effect of deviation from ISO conditions, the ratio of each input parameter at desired conditions to the ISO value is substituted in relevant expression in associated model. Similarly, output is the ratio of that output parameter at desired condition to the ISO value.

To consider the effect of several input parameters simultaneously, the outputs of these functions for several different inputs can be multiplied to form an overall output for multi deviation situations. To validate and evaluate the accuracy of this model, a combined cycle power plant operation data was utilized as a case study. Table V represents the case study site data. Both part load and full load data were taken into account. Equations (1)-(11) show the calculation steps.

TABLE III
BENCHMARKING MODEL OF GAS TURBINE CYCLE

INPUTS	OUTPUTS			
	GT.EF^	GT^	E.M^	E.T^
A.T^	-0.67101A.T^+ 1.675212	-1.95726A.T^+ 2.960542	-1.33551A.T^+ 2.339155	0.34058A.T^+ 0.657829
A.P^	0.028472A.P^ +0.971932	1.024597A.P^ -0.0248	1.013382A.P^ -0.01355	-0.00992A.P^+ 1.009851
RH^	-0.00173RH^+ 1.001733	0.002466RH^ +0.997511	-0.00369RH^+ 1.003761	0.001745RH^+ 0.998229
L^<0.5	1.198672L^+ 0.259977	L^	0.015094L^+ 0.676113	0.575363L^+ 0.700349
L^>0.5	0.319954L^+ 0.687785	L^	0.65566L^+ 0.341321	1

X^ = Ratio of X Parameter in Desired Condition to X Parameter in ISO Condition, A.T =Ambient Absolute Temperature, A.P =Ambient Absolute Pressure, RH =Ambient Relative Humidity, L =Gas Turbine Load, GT.EF =Gas Turbine Efficiency, GT =Gas Turbine Electrical Power, E.M =Gas Turbine Exhaust Mass Flow, E.T =Gas Turbine Exhaust Temperature

TABLE IV
BENCHMARKING MODEL OF HRSG CYCLE

INPUTS	OUTPUTS	
	PL.EF^	ST^
A.T^	-9.21974(A.T^).^3 + 28.20772(A.T^).^2 - 28.7019A.T^+10.71401	-0.22326A.T^+1.222248
A.P^	0.021991A.P^+0.978104	0.999973A.P^-0.00043
RH^	0.000231RH^+0.999769	0.007603RH^+0.992545
L^< 0.5	1.145279L^+0.362119	1.124876L^+0.083423
L^> 0.5	0.163969L^+0.83973	0.672499L^+0.324036
No.	-0.01063No.^3+0.080829No.^2-0.16384No.+1.05106	-0.03094No.^3+0.235512No.^2-0.47784No.+1.149396

X^ = Ratio of X Parameter in Desired Condition to X Parameter in ISO Condition, A.T =Ambient Absolute Temperature, A.P =Ambient Absolute Pressure, RH =Ambient Relative Humidity, L =Gas Turbine Load, No. =Number of HRSG Evaporator Pressure Levels, PL.EF =Plant Overall Electrical Efficiency, ST =Steam Turbine Electrical Power

Input Calculations:

$$A.T^{\wedge} = (287.15)/(288.15) = 0.99653 \tag{1}$$

$$A.P^{\wedge} = 0.918/1.013 = 0.905301 \tag{2}$$

$$RH^{\wedge} = 31/60 = 0.516667 \tag{3}$$

$$L^{\wedge} = 72/100 = 0.72 \tag{4}$$

$$\text{No.} = 3 \quad (5)$$

Output Calculations:

$$GT^{\wedge}_{A.T} = 1.010078 \quad (6)$$

$$GT^{\wedge}_{A.P} = 0.902773 \quad (7)$$

$$GT^{\wedge}_{RH} = 1.000002 \quad (8)$$

$$GT^{\wedge}_{L} = 0.72 \quad (9)$$

$$GT^{\wedge} = 1.010078*0.902773*1.000002*0.72= 0.910763 \quad (10)$$

After calculating the overall output coefficient for all output parameters using input site data and related models, these overall output coefficients were multiplied by ISO value of that output parameters to form the site value of that parameter.

$$GT = GT^{\wedge} * GT_{ISO} = 0.910763*164603 = 149914.3\text{kW} \quad (11)$$

Tables VI and VII depict the model results, the real operation data, and the deviation percent of site data from model results.

TABLE V
ENVIRONMENTAL SITE DATA OF CASE STUDY

Parameter	A.T(K)	Altitude(m)	A.P(bar)	RH (%)	No.
Value	287.15	850	0.918	31	3

A.T = Ambient Absolute Temperature, A.P = Ambient Absolute Pressure, RH =Ambient Relative Humidity, No. = Number of HRSG Evaporator Pressure levels

TABLE VI
FULL LOAD CASE STUDY (L=100%)

INPUTS	RESULTS		
	MODEL	OPERATION	DEVIATION (%)
GT (KW)	149914	148880	0.69
GT.EF (%)	34.77	34.62	0.44
E.M (KG/S)	483.9	480	0.74
E.T (K)	814.78	816	-0.2
ST (KW)	79188	79030	0.199
PL.EF (%)	51.78	51.75	0.07

L =Gas Turbine Load, GT =Gas Turbine Electrical Power, GT.EF =Gas Turbine Efficiency, E.M =Gas Turbine Exhaust Mass Flow, E.T =Gas Turbine Exhaust Temperature, ST =Steam Turbine Electrical Power, PL.EF =Plant Overall Electrical Efficiency

TABLE VII
PART LOAD CASE STUDY (L=72%)

INPUTS	RESULTS		
	MODEL	OPERATION	DEVIATION (%)
GT(KW)	107947	107205	0.69
GT.EF (%)	31.92	31.97	-0.13
E.M(KG/S)	398.11	390.28	2
E.T(K)	814.78	816	-0.2
ST(KW)	64002	63850	0.23
PL.EF (%)	49.6	49.73	-0.26

L =Gas Turbine Load, GT =Gas Turbine Electrical Power, GT.EF =Gas Turbine Efficiency, E.M =Gas Turbine Exhaust Mass Flow, E.T =Gas Turbine Exhaust Temperature, ST =Steam Turbine Electrical Power, PL.EF =Plant Overall Electrical Efficiency

IV. CONCLUSION

Produced power and efficiency of a combined cycle is directly related to production capacity of gas turbine and steam turbine. The produced power of gas turbine depends on the ambient condition and can be calculated using related relationships shown in Table III. Nevertheless, the produced power by steam turbine depends directly on the number of HRSG evaporator pressure levels, temperature, and mass flow rate of flue gas entering to the HRSG section and can be calculated using related relationships shown in Table IV. It seems that the comparison between real and estimated data by benchmarking method can make a good decision for implementing retrofit projects. The offered models as an important and efficient instrument could be employed as a measure and basis for evaluating and targeting in power plants.

REFERENCES

[1] S. C. Kaushik, V. S. Reddy, and S. K. Tyagi, “Energy and exergy analyses of thermal power plants: A review,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 4, pp. 1857–1872, 2011.
[2] H. H. Erdem, A. V. Akkaya, B. Cetin, A. Dagdas, S. H. Sevilgen, B. Sahin, I. Teke, C. Gungor, and S. Atas, “Comparative energetic and exergetic performance analyses for coal-fired thermal power plants in Turkey,” *Int. J. Therm. Sci.*, vol. 48, no. 11, pp. 2179–2186, 2009.
[3] S. Benchmarking, “Benchmarking for Success.” 2003.
[4] R. C. Camp, *Benchmarking: the search for industry best practices that lead to superior performance*. Milwaukee, Wis.: Quality Press; Quality Resources, 1989., 2013.
[5] N. Keren, H. H. West, and M. S. Mannan, “Benchmarking MOC practices in the process industries,” *Process Saf. Prog.*, vol. 21, no. 2, pp. 103–112, 2002.
[6] A. Lissitsa, T. Coelli, and D. S. P. Rao, “Agricultural economics education in Ukrainian Agricultural Universities: An efficiency analysis using data envelopment analysis,” in *Proceedings 11th International Congress of European Association of Agricultural Economists*, 2005.
[7] C. H. Liu, S. J. Lin, and C. Lewis, “Evaluation of thermal power plant operational performance in Taiwan by data envelopment analysis,” *Energy Policy*, vol. 38, no. 2, pp. 1049–1058, 2010.
[8] C. P. Barros, “Efficiency analysis of hydroelectric generating plants: a case study for Portugal,” *Energy Econ.*, vol. 30, no. 1, pp. 59–75, 2008.
[9] M. Nakano and S. Managi, “Regulatory reforms and productivity: an empirical analysis of the Japanese electricity industry,” *Energy Policy*, vol. 36, no. 1, pp. 201–209, 2008.
[10] T. Thakur, S. G. Deshmukh, S. C. Kaushik, and M. Kulshrestha, “Impact assessment of the Electricity Act 2003 on the Indian power sector,” *Energy Policy*, vol. 33, no. 9, pp. 1187–1198, 2005.
[11] A. Vaninsky, “Efficiency of electric power generation in the United States: analysis and forecast based on data envelopment analysis,” *Energy Econ.*, vol. 28, no. 3, pp. 326–338, 2006.
[12] K. Sarıca and I. Or, “Efficiency assessment of Turkish power plants using data envelopment analysis,” *Energy*, vol. 32, no. 8, pp. 1484–1499, 2007.