TECHNICAL AND FINANCIAL ANALYSIS OF COMBINED CYCLE GAS TURBINE

by

Muhammad Arshad KHAN

International Power Global Development, Ltd., Karachi, Sindh, Pakistan

Original scientific paper
DOI: 10.2298/TSCI110206039K

This paper presents technical and financial models which were developed in this study to predict the overall performance of combined cycle gas turbine plant in line with the needs of independent power producers in the liberalized market of power sector. Three similar sizes of combined cycle gas turbine power projects up to 200 MW of independent power producers in Pakistan were selected in-order to develop and drive the basic assumptions for the inputs of the models in view of prevailing Government of Pakistan's two components of electricity purchasing tariff that is energy purchase price and capacity purchase price at higher voltage grid station terminal from independent power producers. The levelized electricity purchasing tariff over life of plant on gaseous fuel at 60% plant load factor was 6.47 cent per kWh with energy purchase price and capacity purchase prices of 3.54 and 2.93 cents per kWh, respectively. The outcome of technical models of gas turbine, steam turbine and combined cycle gas turbine power were found in close agreement with the projects under consideration and provides opportunity of evaluation of technical and financial aspects of combined cycle power plant in a more simplified manner with relatively accurate results. At 105 °C exit temperature of heat recovery steam generator flue gases the net efficiency of combined cycle gas turbine was 48.8% whereas at 125 °C exit temperature of heat recovery steam generator flue gases it was 48.0%. Sensitivity analysis of selected influential components of electricity tariff was also carried out.

Key words: *combined cycle gas turbine, steam turbine, energy purchase price, capacity purchase price, efficiency, independent power producers*

Introduction

In growing economies where natural gas is available combined cycle gas turbine (CCGT) plant has been always a preferred option due to its high conversion efficiency of fossil fuel into electricity, flexibility of operation with lesser time of commissioning when compared to other similar size of electricity producing plants based on different technologies.

Leyzerovich [1] and Chase and Kehoe [2] reported that, overall efficiencies up to 50 to 60% of CCGT could now be achievable and this is due to improvement in design aspects of CCGT hardwares and efficient utilization of energy of heavy duty gas turbines (GT) exhaust gases for the generation of steam in the heat recovery steam generator (HRSG). Steam generated in HRSG is then used to drive the steam turbine (ST) for the production of electricity. The combination of GT, HRSG, and ST is called combined cycle (CC). Ragland [3] and Daycock *et al.* [4] also refer to availability of sophisticated technical softwares in the market for performing

Author's e-mail: drarsmkh@gmail.com

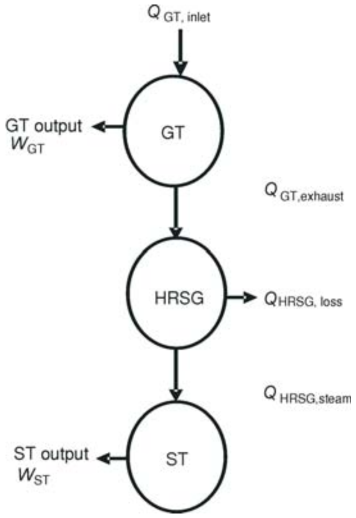

Figure 1. Model for predicting the performance of CCGT

the detailed analysis of various components of CCGT plants. Ahmed [5] and Brooks [6] provides the information about correction curves of different manufacturers of GT used to predict the performance of GT at mean site operating conditions *i. e.* other than ISO conditions.

In the present work, three models were developed to estimate the performance of GT along with one model for ST for the prediction of its output and efficiency. The output of selected GT and ST models were then used for the prediction of the performance of CCGT. General thermodynamic principles were applied to develop energy cascading model as shown in fig. 1.

In-order to evaluate the financial aspects for the installation of CCGT plant in Pakistan in view of Government of Pakistan's policy for power generating projects for the year 2002 [7] two financial models have been developed and discussed.

Description of technical models developed for the prediction of CCGT performance

Technical model comprises of the following models:
- technical models for predicting the performance of GT,
- technical model for predicting the performance of steam cycle, and
- technical model for predicting the performance of CC.

Technical models for predicting the performance of GT

The thermodynamic cycle of the GT follows the Brayton cycle. As a general guideline, the GT represents 66% of the CCGT electrical output whereas ST contributes up to 33%. For example for 200 MW CCGT plant, GT will supply 132 MW and selection of GT should be made accordingly.

The following simple model has been developed to predict the performance of GT at ambient conditions other than ISO ambient conditions. Although this is a simple model but provides fairly good estimation of GT efficiency and output at site conditions when compared with other models which are developed and discussed in this paper.

The thermal efficiency of GT could be defined by eq. (1) with some assumptions like *i. e.* there is no pressure drop in the GT cycle with constant specific heat of the process fluid, where $\beta = (P_{\text{Comp, discharge}}/P_{\text{Comp, inlet}})^{(\gamma-1)/\gamma}$ is the ratio of GT compressor discharge pressure to inlet pressure, γ represent the ratio of specific heat at constant pressure to constant volume, $\eta_{\text{GT,isen}}$ and $\eta_{\text{Comp, isen}}$ are the isentropic efficiencies of GT and compressor of Brayton cycle, respectively [8]:

$$\eta_{\text{thermal}} = \frac{\dfrac{\eta_{\text{GT, isen}} T_{\text{GT, inlet}}}{\beta} - \dfrac{T_{\text{Comp, inlet}}}{\eta_{\text{Comp,isen}}}}{\dfrac{T_{\text{GT, inlet}} - T_{\text{Comp, inlet}}}{\beta - 1} - \dfrac{T_{\text{Comp, inlet}}}{\eta_{\text{Comp, isen}}}} \tag{1}$$

Similarly, to get the optimum pressure ratio (β_{opt}) of the cycle eq. (2) provides an accurate estimation [9]:

$$\beta_{\text{opt}} = \left[\left(\frac{T_{\text{Comp, inlet}}}{T_{\text{GT, inlet}}} \right) \left(\frac{1}{\eta_{\text{Comp, isen}} \eta_{\text{GT, isen}}} \right) \right]^{\left(\frac{\gamma}{2-2\gamma} \right)} \tag{2}$$

From the above equations, it is quite evident that compressor pressure ratio and GT inlet temperature plays important role in the selection of GT for CCGT. The referred eq. (1) presents quite reasonable estimation of GT thermal efficiency. Reference to tab. 1 site operating conditions, the thermal efficiency of GT comes out 32.90% at compressor optimum pressure ratio of 9.2, ratio of specific heat γ equal to 1.38 with assumed isentropic efficiency of 0.88% and 0.86% for turbine and compressor, respectively.

Table 1. ISO *vs.* mean site conditions of GT

Description	Units	ISO	Site
Ambient temperature	°C	15	25
Ambient pressure	bar	1.013	1.000
Altitude	m	0	400
Relative humidity	%	60	50
Compressor inlet pressure loss	mbar	0	10
GT exhaust pressure loss	mbar	0	34
LHV gas	MJ/kg	50	30
Water/fuel injection ratio		0	0
Steam/fuel injection ratio		0	0.5
Power supply frequency	Hz	50	50
Power factor		0.85	0.85
Turbine inlet temperature	°C	1060	1060

As GT is air breathing engine, its performance is changed by anything that affects the density and or mass flow of the air intake to the compressor and turbine. Air density changes with ambient temperature, relative humidity, and ambient pressure and altitude (*i. e.* operation of GT above sea level), the eq. (3) provide estimation of air density due to aforesaid weather conditions.

$$\rho_{\text{air}} = \frac{3.4848 \left\{ p_{\text{ambient}} - 0.0037960 RH \left[1.7526 \cdot 10^{8} \exp\left(\frac{-531556}{T + 273.15} \right) \right] \right\}}{T + 273.15} \tag{3}$$

where ρ_{air} [kgcm^{-3}] is the density of air, p_{ambient} [kPa] – the ambient air pressure, RH [%] – the relative humidity, and T [°C] – the ambient temperature [10].

The installation of GT at above the sea level or at higher altitude creates permanent degradation in the performance of GT which is merely due to reduction in air density at higher altitude. This drop in air density, is due to drop in barometric pressure at altitude above sea level, the eq. (4) presents the correction factor for GT output adjustment as a function of GT site elevation above the sea level in meters, whereas eq. (5) presents the adjustment of GT output in reference to ISO to site [11] conditions especially corrected to air density and elevation of site referred to tab.1:

$$cf_{\text{altitude}} = \left(\frac{288.15 - 0.0065 \times \text{Site elevation above sea level}}{288.15} \right)^{5.25} \tag{4}$$

$$MW_{\text{GT, corrected}} = MW_{\text{GT, ISO}} \frac{\rho_{\text{air, site}}}{\rho_{\text{air, ISO}}} \frac{cf_{\text{altitude, site}}}{cf_{\text{altitude, ISO}}} \tag{5}$$

$$\dot{m}_{\text{GT, exhaust, corrected}} = \dot{m}_{\text{GT, exhaust, ISO}} \frac{\rho_{\text{air, site}}}{\rho_{\text{air, ISO}}} \frac{cf_{\text{altitude, site}}}{cf_{\text{altitude, ISO}}} \tag{6}$$

$$T_{\text{GT, exhaust, corrected}} = T_{\text{GT, exhaust, ISO}} + (T_{\text{ambient, site}} - T_{\text{ambient, ISO}}) \tag{7}$$

Similarly, eqs. (6) and (7) provides correction of GT exhaust mass flow and GT exhaust temperature in view of site air density and ambient temperature. Table 2 shows the result of the above explained simple GT model pertaining to *output, efficiency, exhaust temperature, and mass flow rate* of exhaust gases of GT at mean site operation conditions as given in tab.1. Two relatively complicated models were also developed based on manufacturers provided correction curves to perform the necessary correction to the operating mean site conditions from ISO conditions as given in tab. 2 on aforesaid four parameters. The corrected values of Site Model-I of tab. 2 were then used to subsequent run the model for the prediction of CCGT performance as discussed in next subsection.

Table 2. Correction of GT performance from ISO conditions to the mean site conditions

Description	Units	ISO	Simple model	Site model-I	Site model-II
Gross plant capacity of GT	MW	153.4	138.8	136.6	133.6
Gross efficiency of GT	%	34.3	32.9	33.5	33.2
Mass flow rate of GT exhaust gases	kg/s	510.0	462.8	471.5	489.4
Temperature of GT exhaust gases	°C	530.0	540.0	542.0	541.20

Technical model for predicting the performance of combined cycle

The description of cascaded energy flow model of CCGT has been illustrated in fig. 1 without supplementary firing of HRSG. The efficiency and output of ST and HRSG can be best estimated and optimized by having the information like ST exhaust annulus area along with terminal conditions of ST, number of pressure stages of HRSG, final feed water inlet temperature to economizer of HRSG, presence of sulfur contents in the GT burning fuel, *etc*. [12].

In order to estimate, the efficiency of ST, a separate model was developed which is discussed in next subsection. The estimation of final flue gases exit temperature of HRSG was done by considering the influence of sulfur contents in GT burning fuel *e*. *g*. natural gas and rate of conversion of sulfur dioxide into sulfur trioxide [13].

The following are the main set of governing equations based on general thermodynamic relationships. These equations were used to predict the performance of CCGT after estimating the performance of GT and ST:

$$\eta_{\text{GT}} = \frac{GT_{\text{output}}}{GT_{\text{heat input}}} = \frac{W_{\text{GT}}}{Q_{\text{GT, inlet}}} \tag{8}$$

After re-arranging eq. (8) $Q_{\text{GT, inlet}}$ becomes:

$$Q_{\text{GT, inlet}} = \frac{W_{\text{GT}}}{\eta_{\text{GT}}} \tag{9}$$

$$Q_{\text{GT, exhaust}} = Q_{\text{GT, inlet}} - W_{\text{GT}} \quad \text{(Reference fig. 1)} \tag{10}$$

By inserting W_{GT} from eq. (9) into eq. (10), $Q_{\text{GT, exhaust}}$ becomes:

$$Q_{\text{GT, exaust}} = (1 - \eta_{\text{GT}})\, Q_{\text{GT,inlet}} \tag{11}$$

$$\eta_{\text{HRSG}} \approx \left(1 - \frac{Q_{\text{HRSG, loss}}}{Q_{\text{GT, exhaust}}}\right) \text{ (reference fig. 1)} \tag{12}$$

In-order to find $Q_{\text{HRSG, loss}}$, simple thermodynamic relationship *i. e.* $mc_{\text{p}}\,\Delta T$ was used to quantify the contents of heat of the process fluid, where ΔT is the difference of HRSG exit temperature to the ambient temperature:

$$Q_{\text{HRSG,loss}} = \dot{m}_{\text{GT,exaust}} Cp_{\text{HRSG, exhauts}} \Delta T \tag{13}$$

$$\Delta T = T_{\text{HSRG, exit}} - T_{\text{ambient}} \tag{14}$$

The available heat to HRSG, *i. e.* hot flue gases energy of GT exhaust ($Q_{\text{GT,exhaust}}$) if multiplied by efficiency of HRSG then the output of HRSG ($Q_{\text{HRSG, steam}}$) could be estimated by eq. (15):

$$Q_{\text{HRSG, steam}} = Q_{\text{GT, exhaust}} \eta_{\text{HRSG}} \tag{15}$$

ST output (W_{ST}) could be found by multiplying output of the heat recovery steam generator, eq. (15), with $\eta_{\text{Rankine cycle}}$ as estimated by computational model as developed and discussed in next subsection:

$$W_{\text{ST}} = Q_{\text{HRSG, steam}} \eta_{\text{Rankine cycle}} \tag{16}$$

$$W_{\text{CC}} = W_{\text{GT}} + W_{\text{ST}} \tag{17}$$

The combined cycle efficiency is the ratio of addition of GT and ST output to the input to the cycle *i. e.* heat input to GT:

$$\eta_{\text{CC}} = \frac{W_{\text{GT}} + W_{\text{ST}}}{Q_{\text{GT, inlet}}} = \frac{W_{\text{CC}}}{Q_{\text{GT, inlet}}} \tag{18}$$

By inserting eqs. (8), (11), (15), and (16) into eq. (18), the efficiency of combined cycle is presented in eq. (19):

$$\eta_{\text{CC}} = \eta_{\text{GT}} + (1 - \eta_{\text{GT}}) \eta_{\text{Rankine cycle}} \eta_{\text{HRSG}} \tag{19}$$

Net output and net efficiency of CC could be determined by subtracting works power consumption of the CC:

$$W_{\text{CC, Net}} = W_{\text{CC}} \left(1 - \frac{\text{Works power \%}}{100}\right) \tag{20}$$

$$\eta_{\text{CC, Net}} = \eta_{\text{CC}} \frac{W_{\text{CC, Net}}}{W_{\text{CC}}} \tag{21}$$

The efficiency of HRSG can also be estimated from the eq. (22) where λ presents heat loss factor and could be taken approximately equal to 0.99. The highest efficiency of HRSG that could be obtained either from eq. (12) or eq. (22) was used in the process of calculation of the CCGT performance. Table 7 exhibits the results of the CCGT model at two different exit temperatures of HRSG flue gases *i. e.* 125 °C and 105 °C where as the tab. 3 shows the input of CCGT model:

$$\eta_{HRSG} \approx \left(\frac{T_{\text{GT, exhaust}} - T_{\text{HRSG, exhaust}}}{T_{\text{GT, exhaust}} - T_{\text{ambient}}}\right) \lambda_{\text{HRSG}} \tag{22}$$

Table 3. Inputs for the prediction of the CCGT performance

Description	Units	Case-I	Case-II
Output of GT	MW	136.6	136.6
Efficiency of GT	%	33.5	33.5
Mass flow rate of GT exhaust gases	kg/s	471.5	471.5
GT exhaust temperature	°C	542.0	542.0
Ambient temperature	°C	25.0	25.0
HRSG exhaust gas temperature	°C	125.0	105.0
Efficiency of Rankine cycle	%	30.1	30.1
Works power consumption	%	3	3

Technical model for predicting the performance of steam cycle

In reference to CCGT cascaded model as illustrated in preceding subsection, the efficiency of steam cycle *i. e.* Rankine cycle could be estimated by following set of equations. The HRSG absorbs heat of the exhaust gases leaving the GT at its various stages and convert feed water into steam for the power generation in ST. After performing the useful work, the moist steam then condensed in the ST condenser and then flow back in HRSG.

Referring to eq. (23), the quantity of steam generation could be estimated by assuming terminal condition of steam of HRSG and *cf* which takes care of HRSG steam drum blow down and other miscellaneous steam losses in the cycle. The *cf* is considered as 0.90:

$$\dot{m}_{\mathrm{ST,\,inlet}} = \frac{Q_{\mathrm{GT,\,exhaust}}\eta_{\mathrm{HRSG}}}{h_{\mathrm{steam,\,inlet}}} cf \tag{23}$$

The isentropic efficiency which is ratio of actual enthalpy drop to the isentropic enthalpy drop across ST is illustrated in eq. (24) and assumed as 0.85 in this model:

$$\eta_{\mathrm{ST,\,isen}} = \frac{\Delta h_{\mathrm{actual}}}{\Delta h_{\mathrm{isen}}} \tag{24}$$

The eq. (24) can be re-arranged as:

$$\Delta h_{\mathrm{actual}} = \Delta h_{\mathrm{isen}}\eta_{\mathrm{ST,isen}} \tag{25}$$

The dryness fraction of mixture of steam (x_{isen}) at isentropic condition at ST condenser pressure (P_{c}) is determined by following equation where S_{f} and S_{g} are the entropy of mixture of steam at saturated water and saturated steam condition, respectively:

$$x_{\mathrm{isen}} = \frac{S_{\mathrm{isen}} - S_{\mathrm{f,P_c}}}{S_{\mathrm{g,\,P_c}} - S_{\mathrm{f,\,P_c}}} \tag{26}$$

At known x_{isen} the enthalpy of steam at condenser steam pressure is presented in eq. (27) where $h_{\mathrm{fg,\,P_c}}$ shows the enthalpy of vaporization of steam at condenser pressure P_{c}:

$$h_{x\,\mathrm{isen}} = h_{\mathrm{f,\,P_c}} + x_{\mathrm{isen}}\,h_{\mathrm{fg,\,P_c}} \tag{27}$$

$$\Delta h_{\mathrm{isen}} = h_{\mathrm{ST,\,inlet}} - h_{x\,\mathrm{isen}} \tag{28}$$

The actual enthalpy drop across ($\Delta h_{\mathrm{actual}}$) ST is obtained by inserting eq. (28) in eq. (25). The enthalpy of mixture *i. e.* $h_{\mathrm{x,\,actual}}$ reference eq. (29) could be determined by subtracting eq. (25) from enthalpy of steam at ST inlet conditions. Equation (30) presents actual dryness fraction of mixture of steam which is also called as steam quality at condenser pressure P_{c}, for practical purpose manufactures of CCGT ST usually limit the droplet content of condensing ST to drop beyond 0.88% to avoid erosion of last stage components of ST [14]:

$$h_{x\,\mathrm{actual}} = h_{\mathrm{ST,\,inlet}} - \Delta h_{\mathrm{actual}} \tag{29}$$

$$x_{\text{actual}} = \frac{h_{x,\,\text{actual}} - h_{\text{f, P}_\text{c}}}{h_{\text{g, P}_\text{c}} - h_{\text{f, P}_\text{c}}} \tag{30}$$

ST work done and Rankine cycle efficiency are presented by eqs. (31) and (32):

$$W_{\text{ST}} = \dot{m}_{\text{ST, inlet}} \Delta h_{\text{actual}} \tag{31}$$

$$\eta_{\text{Rankine cycle}} = \frac{W_{\text{ST}}}{Q_{\text{GT, exhaust}} \eta_{\text{HRSG}}} 100 \tag{32}$$

Table 4 presents the result of Rankine cycle computational model. ST output of 68.66 MW and Rankine cycle efficiency of 30.10% were used for the prediction of the performance of CCGT.

Table 4. Results of computational model of ST performance

Description	Units	ST operational conditions		
Main steam flow rate	kg/s	59.67	59.67	59.67
Main steam pressure	bar	80.00	80.00	80.00
Main steam temperature (GT exhaust temp. –25 °C)	°C	510.70	510.70	510.70
Condenser pressure	bar	0.060	0.045	0.070
Dryness fraction	–	0.886	0.879	0.889
Work done ST	MW	68.66	70.30	67.75
Rankine cycle efficiency	%	30.10	30.81	29.70
Condenser cooling water temperature rise $\Delta T_{\text{CW, C}}$	°C	8	7	9
Condenser cooling water, $\dot{m}_{\text{CW, C}}$	m^3/s	3.82	4.34	3.41

The requirement of circulating cooling water to condense the moist steam in the condenser at saturated water temperature of P_c is illustrated in eq. (33) where $\Delta T_{\text{CW, C}}$ present the temperature rise of circulating cooling water of condenser:

$$\dot{m}_{\text{CW,C}} = \frac{\dot{m}_{\text{ST, inlet}} x_{\text{actual}} h_{\text{fg, P}_\text{c}}}{c_{p\text{CW, C}} \Delta T_{\text{CW, C}}} \tag{33}$$

Figure 2 shows the optimum efficiency of Rankine cycle as a function of steam quality of turbine exhaust steam *vs*. condenser vacuum of computational model at terminal condition of ST *i. e*. 80 bar and 510.7 °C with 0.85% isentropic efficiency of ST.

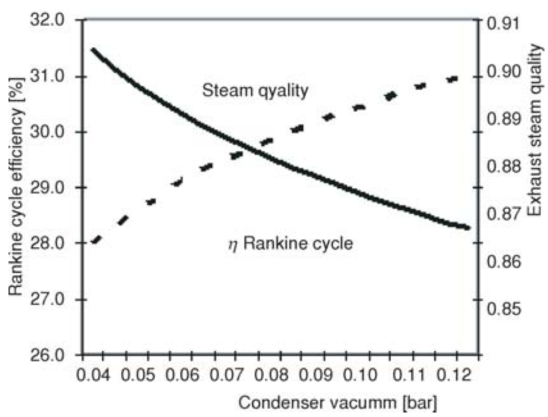

Figure 2. Rankine cycle efficiency [%] as a function of exhaust steam quality and condenser vacuum

Description of financial model for the prediction of electricity generation tariff by IPP

To develop the basic inputs that are required to run the financial model almost three similar size (200 MW) CCGT plants as shown in tab. 5, were selected from the recent agreements between the Private Power and Infrastructure Board and IPP. The electricity generation tariff of selected IPP power plants have been agreed for the life of the plant by the National Electricity Power Regulatory Authority (NEPRA). National transmission and dispatching company (NTDC), purchases electricity at high voltage (HV) side of the grid of IPP power plants and pay them according to agreed electricity generation tariff that is based on two major components *i. e.* Energy Purchase Price & Capacity Purchase Price. Table 6 shows the detail of these two components of tariff. In simple words, IPPs sell electricity according to the agreed generation tariff and NTDC buy electricity according to their needs.

Table 5. Project cost of reference IPP plants under consideration

Description	Units	Plant A	Plant B	Plant C
Net capacity of the plant	MW	209.00	216.80	171.48
EPC cost	US$ per kWh	760.05	738.17	916.13
Total project cost	US$ per kWh	970.32	944.04	1145.72
Net CCGT efficiency	%	50.18	45.53	50.10
Fuel (gas)		Pipeline quality	Low BTU	Low BTU
Supplementary firing		No	Yes	No
Plant life	Years	30	25	25
Plant load factor (PLF)	%	60.00	60.00	60.00

Table 6. Detail of IPP electricity generation tariff structure

Components of electricity generation tariff								
Energy purchase price (EPP)		Capacity purchase price (CPP)						
Fuel	Variable O&M	Fix O&M	Insurance	Working capital	Return on equity	Return on equity (DC)	Withholding tax on dividends	Debt servicing

Energy purchase price

The first subcomponent of tab. 6 of EPP is fuel cost which is based on calculated fuel burn based on guaranteed efficiency of the plant at mean site operating conditions, calorific value and price of the fuel burn per unit of electricity sent out at HV terminal of grid to NTDC. The second sub component of EPP *i. e.* variable operation and maintenance (O&M) is based on utilization cost of consumables like lubricants, chemicals, spare parts, specialized technical services, contractual and mandatory inspections, and overhauls associated with plant operation [15, 16].

Capacity purchase price

CPP which consists of seven components as shown in tab. 6 has been worked out on annual basis and it depends on the availability of the plant by IPP. To bring EPP and CPP of the tariff on a common ground, CPP component of the tariff has also been calculated on per unit of electricity sent out at HV terminal of grid based on plant load factor. In general, plant load factor of 60% has been taken to perform this calculation.

The fixed part of O&M, does not depend upon energy generation of the power plant. It represents the fixed costs of all the staff for O&M, contractual service agreement, power plant administration, security, transportation, overheads, office costs and other costs as required to deal with day to day running of the project as well as some other fixed operational costs such as environmental monitoring, that do not change with plant export energy to grid and replacement of spares relating to ageing effects of plant [15, 16]. The remaining components are quite self explanatory.

In view of capital cost analysis of IPP projects under consideration the following are the two important estimates *i. e.* engineering, procurement, and construction (EPC) and total project cost.:

– EPC cost 750 US$ per kW
– Total project cost 950 US$ per kW

Based on the two important estimates, annualized electricity generation tariff was calculated in the table of Appendix – A along with the other estimates, as described in aforesaid description of the financial model and IPP under consideration.

Results and discussion

Table 2 shows the outcome and comparison of three models executed to predict the GT performance from ISO conditions to the mean site operating conditions (for reference see tab. 1). The impact of site operating parameters on the ISO rating is quite significant and has considerable impact on GT output and efficiency. Table 4 shows the model for the prediction of ST output and steam cycle efficiency and evaluate the condenser heat loss for the estimation of cooling water requirements at different condenser cooling water temperature rise and condenser vacuum.

The four corrected conditions of GT, Model-I of tab. 2, have been used as input to run model for the prediction of CCGT performance. The following is the outcome of the CCGT model at two different exit temperatures of HRSG flue gases based on input of tab. 3 as required to subsequent run the financial model. Table 7 shows the final outcome of the CCGT model executed with GT Model-I.

Table 7. Outcome of CCGT model at different exit temperatures of HRSG flue gases

Description	Units	Case I	Case II	Variance Case I & II
HRSG exit temperature	°C	125.0	105.0	20.0
Output of CCGT (Net)	MW	195.9	199.1	3.2
Efficiency of CCGT (Net)	%	48.0	48.8	0.8

Table 8. Comparison of output of financial models at 60% plant load factor with IPP plants under consideration

Description	Cents per kWh (levelized) Model-I	Cents per kWh (levelized) IPP Plant average	Cents per kWh simple model (Appendix – B)
Energy purchase price (EPP)	3.54	3.48	
Capacity purchase price (CPP)	2.93	3.05	–
Electricity generation tariff	6.47	6.53	6.01

Table 8 illustrates the important results of the financial model as executed after getting inputs information from CCGT model as shown in Case II in tab. 7.

The outcome of financial model-I has been in close agreement with average rates of three similar sizes of IPP plants. The inputs used to obtain results presented in Appendix A were also used to run simple model. The simple model as illustrated in Appendix B also provides a good estimation of cost of electricity generation.

Sensitivity analysis of four selected influential elements *i. e.* efficiency, fuel cost, annual plant factor and EPC cost on electricity generation tariff was done in the range of ±15%. On total electricity generation tariff, the impact of fuel cost and EPC exhibits an opposite behavior as compared to the impact of efficiency and plant load factor with ±0.9 cents per kWh change in electricity generation tariff respectively.

Conclusions

This paper presents, discusses, and analyzes the outcome of technical and financial models developed in this study in line with the needs of IPP in the liberalized market of power sector and provides opportunity of evaluation of technical and financial aspects of CCGT power plant in a more simplified manner with relatively accurate results. The predicted output of the technical and financial models were found in close agreement with power plants under consideration in this study. Three technical models were developed which provide the opportunity to predict the performance of GT, ST, and CCGT in reference to mean site operating conditions *vs.* ISO rating whereas the fourth model *i. e.* the financial model which takes inputs from technical models and estimate the nine sub components of the two major components of electricity generation tariff *i. e.* EPP and CPP as illustrated in tab. 6, have been found in close agreement of IPPs projects under consideration in this study (refer tabs. 7 and 8).

In order to build 199 MW CCGT plant operating on gaseous fuel with net efficiency of 48.8% at mean site conditions, 189 mUS$ needs to be invested by the IPP. Power generation purchaser company has to pay 37.09 mUS$ on annual basis on account of EPP and 38.40 mUS$ for the period of 1-10 years and 14.31 mUS$ for the period of 11-25 years on account of CPP, respectively, at 60% plant load factor. At 60% plant load factor, levelized CPP component of project for the period of 25 years would be 2.93 cents per kWh. EPP of this project has been worked out at a rate of 3.54 cents per kWh. The total levelized electricity generation tariff would be 6.47 cents per kWh at 60% plant load factor, for reference see Appendix A.

Acknowledgments

The author wishes to express his gratitude to Mr. Akhlaq Ahmed Butt, Deputy Director, Wapda Power Privatization Organization, Wapda House, Lahore, Pakistan, and Dr. Amna Arshad, Professor, IQRA University, Karachi, Pakistan for their support and guidance during course of this study and completion of work. Moreover, author is also thankful to National Electricity Power Regulatory Authority for their permission to use their website contents.

Nomenclature

cf – correction factor, [–]
c_p – specific heat at constant pressure, [$\mathrm{kJkg^{-1}\,K^{-1}}$]
h – enthalpy [$\mathrm{kJkg^{-1}K^{-1}}$]
LHV – lower heating value of fuel, [$\mathrm{MJkg^{-1}}$]
$\dot{m}$ – mass flow rate, [$\mathrm{kgs^{-1}}$]
P – pressure, [1bar = 10^5 $\mathrm{Nm^{-2}}$ = 100 kPa]
PLF – plant load factor, [%]
Q – heat, [MW]
S – entropy [$\mathrm{kJkg^{-1}K^{-1}}$]
T – temperature, [°C]
W – work done, [MW]

Appendix A

Financial model output for annual and levelized electricity generation tariff calculated at 60% plant load factor

Description	Units	Parameters
Net capacity of plant	MW	199.10
EPC cost	US$ per kWh	750.00
Total project cost	US$ per kWh	950.00
Net CCGT efficiency	%	48.80
Fuel cost at LHV	US$ per mBTU	4.74
PLF	%	60.00
Plant life	Years	25
Debt discount rate	%	11.00
Debt period	Years	10
Project construction period	Years	2
Debt equity ratio		75:25
EPC cost	mUS$	149.36
Total project cost	mUS$	189.18
Energy components		
Fuel	mUS$	34.11
Variable O&M	mUS$	2.99
Total energy component (EPP)	mUS$	37.09
Capacity components		
Fixed O&M	mUS$	3.40
Insurance	mUS$	2.02
Working capital	mUS$	0.60
Return on equity	mUS$	7.10
Return on equity (DC)	mUS$	0.62
Withholding tax	mUS$	0.58
Debt servicing (10 years)	mUS$	24.09
Total capacity component (CPP)	mUS$	38.40
Levelized EPP (1-25 years)	cents per kWh	3.54
Levelized CPP (1-25 years)	cents per kWh	2.93
Levelized electricity generation tariff	cents per kWh	6.47

Appendix – B

Simple model for the determination of cost of electricity [17].

$$Y_{\mathrm{EL}} = \frac{TCR\,\psi}{PT_{\mathrm{eq}}} + \frac{Y_{\mathrm{F}}}{\eta} + \frac{U_{\mathrm{fix}}}{PT_{\mathrm{eq}}} + U_{\mathrm{var}} \tag{B.1}$$

where, U_{fix} [mUS$] is the annual fixed cost of operation, maintenance and administration, U_{var} [cents per kWh^{-1}] – the variable per unit cost of operation, maintenance and repair, P [MW] – the rated power output, TCR [mUS$] – the total capital requirement, T_{eq} [h] – the equivalent annual utilization at rated power output, Y_{F} [mBTU] – the price of fuel, Y_{EL}[cents per kWh] – the per unit cost of electricity, η [%] – the average plant efficiency, and ψ [N years] – the capital charge factor, based on discount rate (i) on the capital and the life of the plant.

Greek symbols

β – pressure ratio, [–]
γ – ratio of specific heats at constant pressure to constant volume, [–]
η – efficiency, [%]
Δ – difference, [–]
λ – heat loss factor, [–]
x – dryness fraction, [–]

Subscripts

c – condenser
Comp – compressor
CW – cooling water
f – saturated water
g – saturated vapor
isen – isentropic
Opt – optimum

Acronyms

BTU – British thermal units
CCGT – combine cycle gas turbine
CPP – capacity purchase price
CC – combined cycle
DC – during construction
EPC – cost???
EPP – energy purchase price
GT – gas turbine
HRSG – heat recovery steam generator
IPP – independent power producer
O&M – operation and maintenance
ST – steam turbine

References

[1] Leyzerovich, A., *Large Power Steam Turbines*, Design and Operation, Vol. l, PennWell Publishing Company, Tulsa, Okla., USA, 1997
[2] Chase, D. L., Kehoe,P. T., Gas Combined-Cycle Product Line and Performance Characteristics, GE Power Systems, GER 3574G – (10/00), Schenectady, New York, USA, pp. 3, 10-12 & 21
[3] Ragland, A., Stenzel, W., Combined Cycle Heat Recovery Optimization, *Proceedings*, International Joint Power Generation Conference 2000, Miami Beach, Fla., USA, IJPGC2000-1531, pp. 5-6
[4] Daycock, C., *et al*., Generation Cost Forecasting Using on Line Thermodynamic Model, *Electric Power,* (2004), pp. 5-7
[5] Ahmed, Combined Cycle Power Plant, Performance Evaluation under Specific Site Conditions, Rev.1 WAPDA, Pakistan, 2002
[6] Brooks, F. J., Gas Turbine Performance Characteristics, GE Power Systems, GER 356 7H – (10/00), Schenectady, New York, USA, pp. 8-10
[7] ***, Ministry of Water and Power, Pakistan, Policy for Power Generation Projects, 2002
[8] Ameri, M., *et al*., The Study of the Effects of Gas Turbine Inlet Air Cooling on the Heat Recovery Boiler Performance, *Proceedings*, ESDA04 7th Biennial Conference on Engineering Systems Design and Analysis, Manchester, UK, 2004, p. 2
[9] Boyce, M. P., *Gas Turbine Engineering Handbook,* Gulf Publishing Company, Houston, Tex., USA 1982
[10] Jones, F. E., Air Density Equation and the Transfer of the Mass Unit, *J. Res. Natl. Bureau Standard, 83* (1978), 5, pp. 419
[11] Harman, R. T. C., *Gas Turbine Engineering, Application*, *Cycles and Characteristics*, Macmillan Press Ltd., Hong Kong, 1981
[12] Gray, R. R., *et al*., *Power Plant Performance Monitoring*, R-Squared Publishing, Solvany, Cal., USA, 2004
[13] ***, NEPRA Pakistan, Engro Energy (Private) Limited, Case No: NEPRA/TRF-72/EEPL, Pakistan, 2007
[14] Gill, A. B., *Power Plant Performance*, Robert Hartnoll Ltd., Bodurin, England, 1984
[15] ***, NERPA Pakistan, Foundation Power Company, Daharki, Ltd., Case No: NEPRA/TRF-48/FPCDL, 2006
[16] ***, NERPA Pakistan, Sapphire Electric Company Limited, Case No: NEPRA/TRF-83/SECL, 2007
[17] Zhao, Y., *et al*., Modeling and Cost Optimization of Combined Cycle Heat Recovery Generator Systems, *Proceedings*, ASME Turbo Expo 2003, Atlanta, Geo, USA, GT 2003 – 38568, p. 2

Paper submitted: February 6, 2011
Paper revised: February 25, 2012
Paper accepted: March 11, 2012