Integrated Assessment of a Combined Cycle Power Plant Using Experimental and Computational Energy Auditing Approaches

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Highlights

- Energy audits of combined cycle power plants was conducted.
- Compressors used up more than 60% of the energy produced by the turbine and 14% by the HRSG.

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Abstract: Combined cycle power plants are considered efficient for power generation and their higher thermal performance is of importance to reduce emissions. Energy audits are typically conducted as one-time estimates in developing regions, which don't provide useful information. Power plants in these areas also lack any specific energy management practices. This study involved conducting an energy audit of a combined cycle power plant and comparing the real data with results from an Aspen HYSYS model. The steam turbine's computed efficiency was found to be 30.4%, which is 27.61% less than its specified efficiency. A potential energy saving of 8–9% is predicted if variable speed water pumps are used to boost the efficiency of steam turbines by 5%. In the case of combined cycle operation, the combustion efficiency of the gas turbine is crucial for greater steam generation through the heat recovery in addition to increased turbine power output.

Keywords: Combined cycle power plant, energy auditing, Aspen HYSYS, plant efficiency

1. Introduction

Energy and environment are two main global concerns of current century. Greenhouse gas emissions is the main source of global warming. Carbon dioxide is considered as the major contributor and more than 40% of its emissions is from the power industry [1]. The use of non-renewable energy sources, particularly in emerging nations, is crucial to meeting the world's energy needs. Currently, Pakistan uses fossil fuel-fired power plants to generate about 80% of its electricity. There is a disparity between supply and demand due to the high cost of gasoline, the scarcity of petrol supplies, and the inefficient conversion of existing plants. The environment is negatively impacted by inefficient fossil fuel burning. In order to use fossil fuels efficiently and effectively, power plants can always be modified. There are serious energy losses which are posing great concern to the economic condition of the developing country.

Pakistan has a variety of power plants in operation, and among them, combined cycle power plants (CCPP) stand out for their high thermal efficiency and low carbon dioxide emissions [2]. Several countries like Singapore produces more than 90% of its electric power from CCPP. A thorough energy audit is frequently used to provide economic analysis in order to evaluate the improvement potential and identify the main energy-consuming subcomponents of a system [3]. The level for energy auditing varies from industrial audit to commercial audit and residential audit. Numerous criteria, such as the size and kind of the plant, the potential for energy savings, and cost reduction, affect the different types of energy audits [4]. Aminov et al. [5] reported a case study of a combined cycle gas turbine located at Tashkent with a focus to estimate amount of fuel savage and reduction in emissions. It was found that the efficiency of the plant can be raised from 34 to 58% using combined cycle than conventional cycle. Using sequential quadratic programming (SQP), Ahmadi et al. [6]

demonstrated the impact of fuel cost on the design parameters of a combined cycle power plant. Cihan et al. [7] conducted exergy analyses and proposed certain modifications in combine cycle to reduce exergy destruction in major parts i.e. gas turbine, combustion chamber and heat recovery unit which hold more than 85% of total exergy destruction. Kanoglu et al. [8] presented a detailed overview of various approaches used to calculate energetic and exergetic based efficiencies of power cycles with a focus to provide a practical tool for the improvement of plant through analysis and optimization. Dev et al. [9] developed a method to analyze the efficiency a combined cycle power plant to replace the conventional technique used to evaluate the thermal performance of the plant. An industrial combined CHP plant's dynamic process model was created by Kahlert et al. [10] and validated using operational data. The goal of this study is to determine how much a combined heat and power (CHP) plant's load may be decreased while still supplying process steam consistently.

Majority of the work has been reported on the energy efficiency of combined cycle power plant [2, 7, 11-14] but limited work on the plant energy audit [4]. Ahmad and Chattha [15] conducted an energy audit of combined cycle power plant (450 MW) just to point out locations which require improvement. No study has been reported on the use of computational and experimental approaches together to find out optimum operating conditions for the assessment of improvement potential. Regarding use of soft skills, Liu and Karimi [16] presented a method only to simulate an off-grid system of combined cycle gas turbine using Aspen HYSYS and compared the result with those obtained in Gate-Cycle. Hoang and Pawluskiewicz [17] modelled different pressure based combined cycles in Gate-Cycle to study the impact of different parameters and it was found that pressure ratio and temperature imparted significant influence on the system efficiency.

Energy audits are undervalued in developing nations like Pakistan because of their high initial costs, improbable performance gains, and unproven long-term advantages. Second, a barrier to commercializing energy-efficiency techniques is ignorance about the costs associated with energy audits and energy-saving tools used in plant operations [15]. In the current study, a 147 MW combined cycle thermal power plant underwent an energy audit, and the results were compared to those from a simulation of the same plant conducted using Aspen HYSES. Optimized operating conditions were defined by changing certain conditions to estimate the energy savage potential. The main objective was to drive the attention of authorities for the significance of conducting energy audit to provide a way forward to perform energy audit on existing power plant.

2. Materials and Methods

In the current study, a 147 MW combined cycle thermal power plant in Faisalabad run by Pakistan's Northern Power Generation Company Limited (NPGCL) was chosen to determine its energy-saving potential. Four 25 MW gas turbines and one 47 MW steam turbine make up the plant. The plant is split into two halves called the topping cycle and the bottoming cycle. Topping cycle contains complete unit of gas turbine which consists of compressor, combustor and turbine itself. Compressor is a sixteen-stage axial flow type, which takes air at atmospheric temperature, filter and then compress it to high pressure. The outcomes related to operating conditions of compressor obtained during energy audit are shown in Table 1. For combustor, the performance depends upon detailed examination of the fuel using a gas chromatogram. The gross calorific value was found 12480 Kcal/kg giving combustion efficiency of 95% with fuel flow rate of 210.9 m^3/s (fuel gas density 0.802 kg/m^3).

Table 1: Gas turbine’s compressor operating parameters

Parameter	Unit	Comp-1	Comp-2	Comp-3	Comp-4
Ambient air pressure	Bar	1.003	1.002	1.005	1.004
Inlet air pressure	Bar	1.013	1.013	1.013	1.013
Discharge air pressure	Bar	9.62	9.63	9.62	9.625
Air inlet temperature	C	15	15	15	15
Air outlet temperature	C	320.2	319.7	320.1	320.3
Compression ratio	-	8	8	8	8
Isentropic efficiency	%	85.4	84.8	85.2	85.1

2.1 Topping cycle

In topping cycle, gas turbine is the core of the complete operation. Its performance is affected by the efficiency of allied components and inlet temperature of turbine. Temperature variation particularly in rainy and hot climate, effect its performance. Normally, it has been detected that during the operation, if the exit gas temperature is greater than combustion chamber, it has unfavorable effects on the overall turbine section. One of the important factors called surging needs to consider if it's come across more repeatedly. Especially in the hot weather, rises in inlet air temperature become more noticeable, and it causes a major decrease in power output of gas turbine. It happens because of the great specific volume of air drawn by the compressor and the output power is inversely proportional to the initial temperature. The output power and efficiency of gas turbines vary according to the initial conditions. Table 2 shows different parameters that were used during evaluation process of turbine performance. The operating efficiency of a gas turbine was calculated using equation [15]

$$\eta_{th} = \frac{(860)(W_{out})}{H_i} \qquad (1)$$

Where η_{th} is thermal efficiency of turbine, W_{out} stands for load of gas turbine (MW), Hi is the heat input (Kcal/h)

Table 2: Operating parameters accused for energy audit of gas turbines

Parameters	Unit	GT #1	GT#2	GT#3	GT#4
Relative humidity	%	61	60	60	61
Barometer pressure	mmHg	760	760	760	761
Rated power	MW	25	25	25	25
Power generated	MW	23.3	23.1	22.8	23
Fuel flow rate	Kg/s	15.2	15.3	14.9	15.3
Flue gas exit temperature	^oC	509	509	509	509
Compressed air discharge pressure	Bar	9.62	9.63	9.62	9.62
Compressed air discharge temperature	C	320.5	319.4	320.5	320.7
Gas turbine exhaust pressure	Bar	0.987	0.987	0.987	0.987
Air suction pressure	Bar	0.985	0.985	0.985	0.985
Back work ratio	-	0.63	0.63	0.63	0.63

GT stands for gas turbine

2.2 Bottoming cycle

Bottoming cycle consists of steam turbine, heat recovery steam generator (HRSG), and condenser. During bottoming cycle, the gas generates high amount of heat energy which is utilized in power generation from HRSG and generator. During auditing, the main goal in this section was to calculate steam turbine operating efficiency followed by measurements of condenser parameters and evaluation of HRSG section.

Steam turbine performs the core operation in bottoming cycle which depends on various design features. These features include exhaust condition, shaft orientation, extraction designations, pressure reheat designation, extraction type, turbine type and flow designation. All of the stated factors had been clarified for ease of understanding. The type of turbine in use shows the whole turbine mechanical arrangement and its mechanical efficiency. It also shows the shaft orientation which shows that whether the turbine arrangement is tandem or has arrangement of cross compound, which in turn concludes the turbines mechanical efficiency. Pressure heat up term defines the attainable portion of thermal energy that is accessible by the steam to the rotor of turbine. Flow term used to show whether the turbine is double flow or single flow type. This information is vital to be carried out for enthalpy calculations. The condition of exit flue gases is also key factor to the whole energy audit process. All these features used to calculate thermal, isentropic and adiabatic efficiency of the turbine. Moreover, accessibility theories of energy can be used to find out the total turbine cylinder efficiency. The efficiency of the whole turbine section can be calculated using equation [15]

$$\eta_{tcyl} = \frac{hin - hout}{hin - hs} \qquad (2)$$

The operating parameters of steam turbine used for energy audit are shown in Table 3.

Table 3 Operating parameters accused for energy audit of steam turbine

Parameters	Unit	Designed values
Rated output	MW	47
Rated steam flow	Tons/h	171
ST inlet pressure	Bar	39.5
ST inlet temperature	C	513
ST exhaust pressure	Bar	0.1
ST exhaust temperature	C	56
CW inlet temperature of condenser	C	28
CW outlet temperature of condenser	C	37
CW flow through condenser	Kg/s	2970
SH spray	T/h	4.81
Steam drum pressure	Bar	55

The Heat Recovery Steam Generated (HRSG) equipment, a steam recovering generator that uses gas turbine exhaust heat to make steam for a steam turbine, is the second major component in the bottoming cycle. To identify losses and assess the effectiveness of HRSG, an indirect auditing method was used. The losses, include loss due of carbon monoxide, moisture in fuel and air, loss because of dry flue gas, blow down loss and surface heat loss [18]. These calculations are helpful to understand quality of combustion in the combustor of the gas turbine unit. The loss because of moisture helps to know about the grade of fuel being burned. Relations used for calculating these losses are given below [13]

I. Dry flue gas losses

$$L1= \frac{m*Cp*(Tf-Ta)}{GCV\ of\ fuel} \quad (3)$$

II. Heat loss due to hydrogen in fuel

$$L2= \frac{9\ H2\ [584+Cp(Tf-Ta)]}{GCV\ of\ fuel} \quad (4)$$

III. Heat loss due to moisture in air

$$L3= \frac{AAS*humidity\ factor*Cp(Tf-Ta)}{GCV\ of\ fuel} \quad (5)$$

IV. Loss due to incomplete combustion

$$L4= \frac{\%CO*C}{\%CO+\%CO2} * \frac{5744}{GCV\ of\ fuel} * \mathbf{100} \quad (6)$$

V. Surface heat loss:

$$L\ surface= \mathbf{0.548}[\{(\frac{Ts}{55.55})^4 - \left(\frac{Ta}{55.55}\right)^4\} + \mathbf{1.957}(Ts-Ta)^{1.25} * \sqrt{\frac{(196.85Vm+68.9}{68.9}} \quad (7)$$

Performance assessment of condenser is very important parameter during the audit as it grasps much importance in the overall performance of power plant. Many factors are involved for the analysis of overall condenser performance but the main are the log-mean temperature difference (LMTD), condenser effectiveness ($\boldsymbol{\varepsilon}$), and condenser cleanliness factor which can be calculated as given below:

1) Condenser effectiveness

$$\boldsymbol{\varepsilon} = \frac{\Delta T}{Tsat - Tin} \quad (8)$$

2) Long mean temperature difference (LMTD)

$$\text{LMTD} = \frac{\Delta T}{ln\frac{(Tsat - Tin)}{(Tsat - Tout)}} \quad (9)$$

3) Condenser cleanliness factor

$$\text{CF} = \frac{\Delta Tactual}{\Delta Tdesign} \quad (10)$$

2.3 Power Plant Modeling and Simulation

For modeling of power plant, Aspen HYSYS is an effective tool. It is a process simulation which gives an industrial process design and helps in selecting suitable thermodynamic models. Mathematical models are also practiced in ASPEN to forecast the process performance. Then, this data could be utilized in a repetitive manner for design optimization. ASPEN doesn't design the process by its own. It takes a design given by user and simulates the performance of the process. So, a great understanding of the fundamental engineering principles is required to use suitable input parameters and to evaluate the appropriateness of the result obtained. In this study, models to symbolize a gas turbine process, steam turbine process and the cogeneration cycle (gas + steam cycle) were developed using Aspen HYSYS. All the designed models are dependent on the composition of natural gas (methane 91.69%, ethane 5.68%, propane 0.96%, i-Butachne 0.04%, n-Butane 0.03%, i-pentane 0.07%, n-pentane 0.07%, CO2 0.09%, N2 1.52%, and H2S 0.01%).

In ASPEN, important data relating to uncontaminated component and physical properties calculation are confined within the "Fluid Package". "Fluid Package" helps to use and assign all the necessary inputs. Different reactions take place in the combustor, where natural gas (CH_4) is blend with the incoming air from the compressor. "Peng-Robinson" thermodynamically model was used for simulation of power plant. In "Peng–Robinson" cubic equation which is used to state all thermodynamic possessions, consists of coefficient of vapor mixture fugacity, coefficient of liquid mixture fugacity excluding liquid molar volume. Molar volume of liquid both for simulated and physical components in Aspen-HYSYS is configured using "Rackett model". Overall, a section having possessions depend upon model of temperature for viscosity, heat capacity, vapor pressure, thermal energy of vaporization, density, surface tension, enthalpy, heat conductivity, Gibbs energy and entropy. This model is used mostly in processing plant, and petrochemical uses, crude towers and power plants.

2.3.1 Gas turbine model

Figure 1 shows gas turbine model developed using Aspen HYSYS. The stream from the compressor enters in the combustion chamber which is modeled with the help of Gibbs reactor where the different reactions occur. It calculates the exit gas compositions and chemical equilibrium. Both compressor and turbine (expander) models are aligned with one shaft. Connecting compressor and turbine (expander) in ASPEN means the speed of each connected unit process is similar and the sum of duties of each connected expander or compressor equals to zero. In Aspen HYSYS compressed air pressure is calculated with the help of programmed mixer pressure project by picking "Equalize" all in the design mixer parameters. Desired target variable values can be set using "Adjust" too in ASPEN and identifies an adjusted value can also be identified which helps to achieve the target value. Gas turbine model efficiency has been expressed as:

$$\eta_{GT} = \frac{Egt - Ecomp}{mNG * [LHV]NG} \quad (11)$$

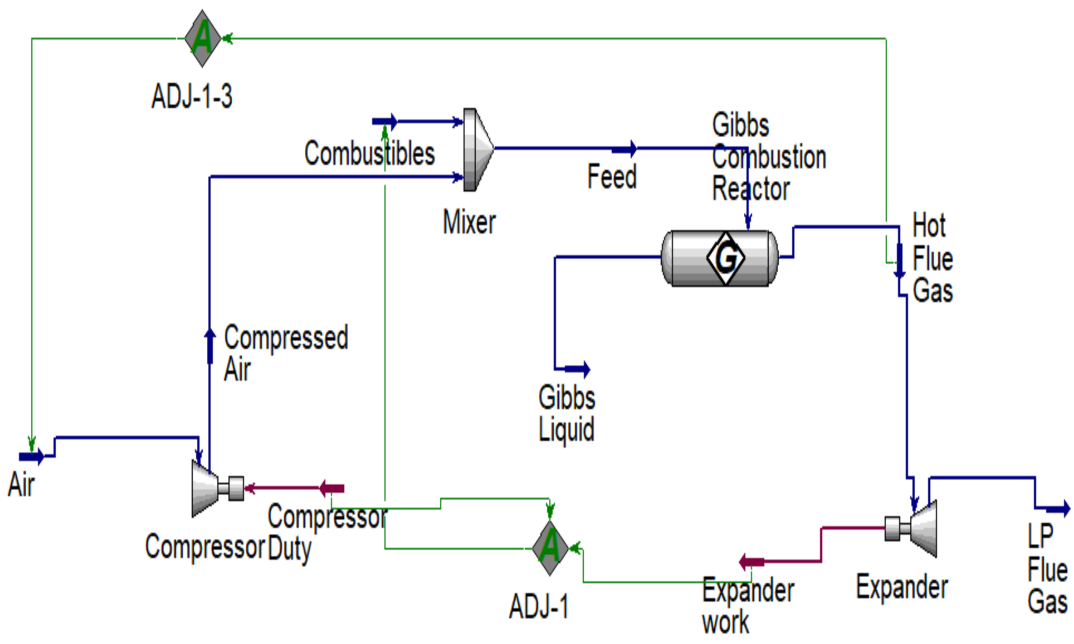

Fig 1. Gas turbine model using Aspen HYSYS with block flow diagram displaying various parts.

In case of multivariable inputs "Steady State Optimizer" is very powerful tool in Aspen HYSYS to optimize the functional conditions that maximize or minimize an "Objective Function". The acquisitive strategy in ASPEN makes this tool very powerful, meanwhile it has access to an extensive variety of values for the optimization research. "Hyprotech SQP" is used by the optimization solver which means Sequential Quadratic Programming (SQP) optimization solver. This procedure certifies that the estimation of model is done only at realistic point with the variable limits. Their main purpose is to get suitable optimization conditions that are then evident to operators to obtain a better result standards. Gas turbine model used variables like natural gas mas flow rate, natural gas pressure and flow of air mass.

2.3.2 Steam turbine model

In an ideal Rankine cycle, the turbine and pump would be isentropic where in an actual Rankine cycle, compression of pump and expansion of turbine are non-isentropic, which means these processes are irreversible and entropy is raised through the two procedures. Model of steam turbine process developed in Aspen HYSYS has shown in Figure 2. This model stated the mass flow, temperature of superheated vapor, high pressure stream, pressure after steam turbine, and temperature of cooler. Keeping in view the safety of steam turbine material, the temperature of super-heated vapor considered in range of 550 - 565 °C (temperature limit stainless steel). This low temperature range in steam turbine as compared to gas turbine clarifies that why steam turbine cycle is used in the bottoming process in combine cycle system. In order to make an imperative analysis of parameters, 47 MW rated output was set with the help of "Adjust". Steam turbine thermodynamic efficiency has been defined as the fraction of rated power output to heat input, the duty needed by the pump is about 1% of the work output of turbine. Steam turbine model efficiency has been expressed as:

$$\eta_{st} = \frac{Est - Epump/0.60}{EHRSG} \qquad (12)$$

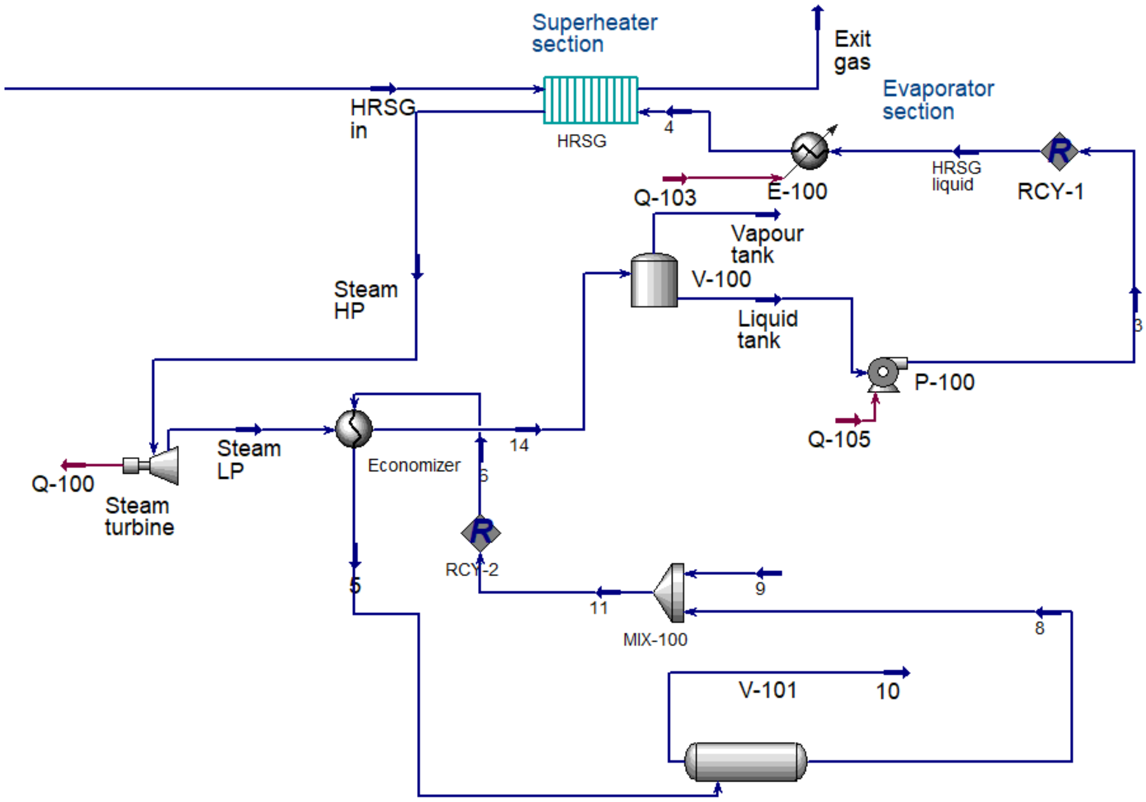

Fig 2. Steam turbine model produced by Aspen HYSYS with block flow diagram displaying various parts.

To examine the behavior of model, high- and low-pressure values used as independent variables. The method of optimization is same as in case of gas turbine but the variables used to optimize the steam turbine were pressure in high pressure stream, mass flow of water, superheated vapor temperature and pressure in low pressure stream.

2.3.3 Combined cycle model

In Aspen-HYSYS, the combined cycle is represented simply by using steam turbine and HRSG (heat recovery steam generator) as shown in Figure 3. In the steam turbine cycle, liquid water is pumped and heated through HRSG. After that in condenser, the low pressure steam changes its phase to liquid phase and then moved in to the tank to complete the process. The drained temperature of gas before the gas turbine should be less than 1200°C and the steam temperature after the HRSG should be less than 565°C.

The combined cycle's effectiveness can be calculated by

$$\eta_{cc} = \frac{(Egt - Ecomp) + (Est - \frac{Epump}{0.6})}{mNG * [LHV]NG} \quad (13)$$

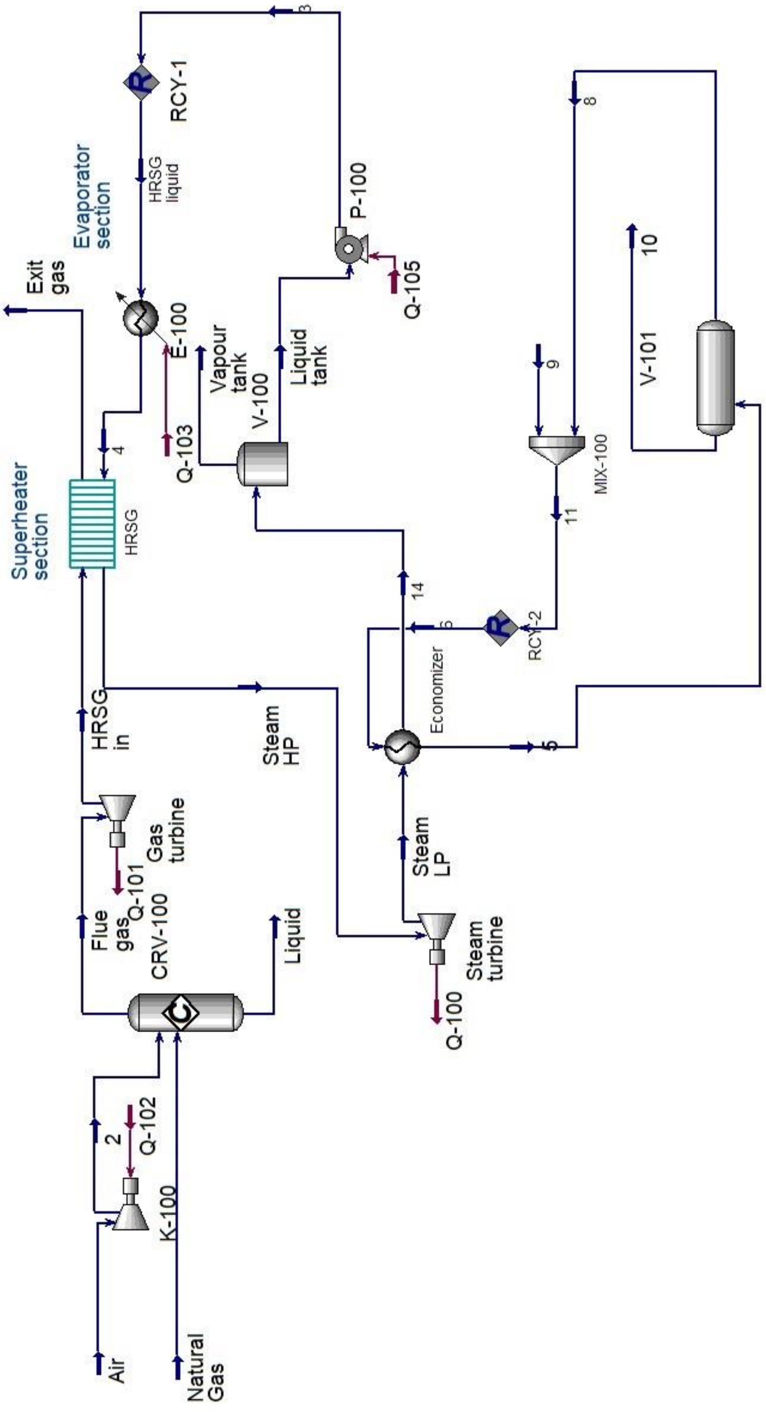

Fig 3. Combined cycle model using Aspen HYSYS with block flow diagram displaying various parts.

3. Results and Discussion

3.1 Gas turbine

The designed efficiency for all the four turbines was 27%. The actual efficiency for all the gas turbines were found low than those of their design efficiency (Table 4) due to low initial temperature, high energy consumption by compressor and poor plant condition. The inlet temperature of gas turbine can be increased by using heat resistance turbine materials or other option is to replace the parts that can withstand against the temperatures. Moreover, adding multistage compression with inter coolers for air compressor and multistage expansion with reheating, the efficiency of gas turbine could be increased by 4.6% which would reach near to its design value.

Table 4: Calculated heat rate and efficiency of gas turbines

Gas turbine	Load (W_{out}) (MW)	Design Heat rate (Kcal/kWh)	Heat input (H_i) (Kcal/h)	Efficiency (%)	Designed Efficiency (%)
GT#1	19	3083.17	69502339	23.51	27
GT#2	19.4	3083.17	69516666	24	27
GT#3	18.7	3083.17	70349956	22.86	27
GT#4	18.9	3083.17	70669565	23	27

Using Aspen HYSYS, a model of gas turbine was designed with same design conditions as of actual one (Fig.1). There are four gas turbines in power plant but the simulation was performed for a single turbine as all of these work under same conditions. The modelled (simulated), physically audited and optimized (using model) comparative outputs of different parameters are tabulated in Table 5. It can be observed that by increasing the compressed air temperature, the overall efficiency of gas turbine can be improved. The audited natural gas mass flow rate also reduced up to 15.44% and 18.20% in cases of modelled and optimized data respectively leading to less consumption of gas i.e. fuel economic. This could be achieved by installing multistage air compressor and multistage expansion for gas turbine leading to rise in turbine power output (up to 13.49% and 21.39% in cases of modelled and optimized data respectively) which ultimately lead to higher turbine efficiency i.e. close to its designed value.

Table 5: Comparison of gas turbine audit, simulation, and optimization findings.

Parameter	Parameter symbol	Unit	Optimized results	ASPEN HYSYS result	Audited results
Air	Mass flow rate	kg/h	246601.7	245435.31	245435
	Pressure	bar	1.013	1.013	1.013
	Compressed air temperature	°C	419.42	423.79	320.2
Compressor	Isentropic efficiency	%	85	85	85
	Power consumption	kW	9894.76	10212.35	11970
	Polytropic efficiency	%	92.43	92.44	92.44
Natural gas	Mass flow	kg/h	4476	4626.93	5472
	Pressure	bar	8.021	8.53	9.625
Gibbs reactor	Temperature	°C	1200	1155	1000
	Pressure	bar	8.021	8.53	9.625
	Efficiency	%	99.9	99.9	-
Expander/ Turbine	Isentropic efficiency	%	75	75	75
	Power output	kW	23065.31	21563.84	19000.31
	Polytropic efficiency	%	80.42	79.32	69.89
Efficiency	-	%	26.85	25.1	23.51

3.2 Steam turbine and combine cycle

In order to measure the efficiency of steam turbine, the parameters tabulated in Table 6 are used. Using these parameters, the operation of steam turbine can be checked to find the possible energy saving potential.

Table 6 Steam turbine measured parameters

Parameter	Flow rate (tones/h)	Pressure (bar)	Temperature (C)	Enthalpy (Kcal/kg)
Main stream	171	39.5	513	3292
Steam turbine exhaust	169	0.1	55.6	2607
Feed water at economizer inlet	168	71.50	106	450

The steam turbine's computed efficiency was found to be 30.4%, which is 27.61% less than its intended efficiency (42%). It was brought on by the condenser's reduced steam pressure (39.5 bar), which was below the optimal level of 47.92 bar. This lowered pressure may be caused by a drop in steam condensation temperature, which causes a subsequent increase in the temperature differential during the operation. Adding a preheater to the steam turbine and employing a feed-water heating system could both increase efficiency. The efficiency of the turbine is also impacted by the types of feed and flow water pumps. Instead of adopting a variable speed water pump with adjustable frequency motors, which can boost the turbine efficiency by 5%, the plant under consideration used a throttle valve and a constant speed feed water pump to control the flow rate. As a result, when this measurement is taken into consideration, the potential for energy savings is projected to be between 8 and 9%, which is close to its design efficiency.

The efficiency of the steam turbine and combine cycle can be improved by some energy savings based on the audited, simulated, and optimized values of various parameters (Table 7). The turbine output power was determined to be 46.04MW (15% higher than existing), for optimized values, by lowering the temperature and pressure of exhaust flue gases up to 830.21°C and 8.021 bar while retaining the temperature and pressure of incoming flue gases at 500°C & 47.92 bar. The efficiency of the HRSG (77.33%) can be increased by optimizing the mass flow ratio and pressure level. Even though the condenser and pump are operating under better conditions, by lowering their power consumption to optimal levels—13% and 28% of current values, respectively—the overall turbine efficiency would rise by 19.27%, resulting in a 12.68% increase in combined efficiency.

Table 7 Comparing the outcomes of the combine cycle's optimization, simulation, and audit.

Parameters	Parameter symbol	Unit	Optimized results	ASPEN HYSYS results	Audited results
Exhaust flue gases move toward HRSG	Mass flow	ton/h	180.2	180.2	171
	Pressure	bar	8.021	8.53	9.625
	Temperature	°C	830.21	867.54	924.34
Heat recovery steam generator (HRSG)	Duty	MW	25.87	33.15	42.87
Steam	Temperature	C	500	505	513
	Pressure	bar	47.92	43.7	39.5
Turbine	Isentropic efficiency	%	75	75	73.6
	Polytropic efficiency	%	75	72.64	69.76

	Power output	MW	46.04	43.47	40
Condenser	Duty	MW	95.7	103	110
Pump	Pressure difference		50	50.1	51.4
	Duty	MW	1.075	1.252	1.5
	Adiabatic efficiency	%	75	75	75
Overall efficiency	-	%	36.26	33.14	30.4
Combined efficiency	-	%	43.87	40.23	38.93

Figure 4 illustrates comparative results from optimized and modelled (ASPEN) results for the system's major primary parameters (compressor power, gas flow, turbine outputs, pump power, overall and combination efficiency). It can be seen that the modelled values are nearly identical to the optimized values, demonstrating the model's ability to integrate with power systems and forecast their real-time performance in Aspen HYSYS.

In the case of combination cycle operation, the combustion efficiency of the gas turbine is crucial for greater steam generation through the Heat Recovery Steam Generator (HRSG) in addition to increased turbine power output. Various losses need to be calculated for understanding the quality of combustion in the combustor of the gas turbine unit. For example, loss due of moisture helps to know about the grade of fuel being burned. The calculated losses are tabulated in Table 8.

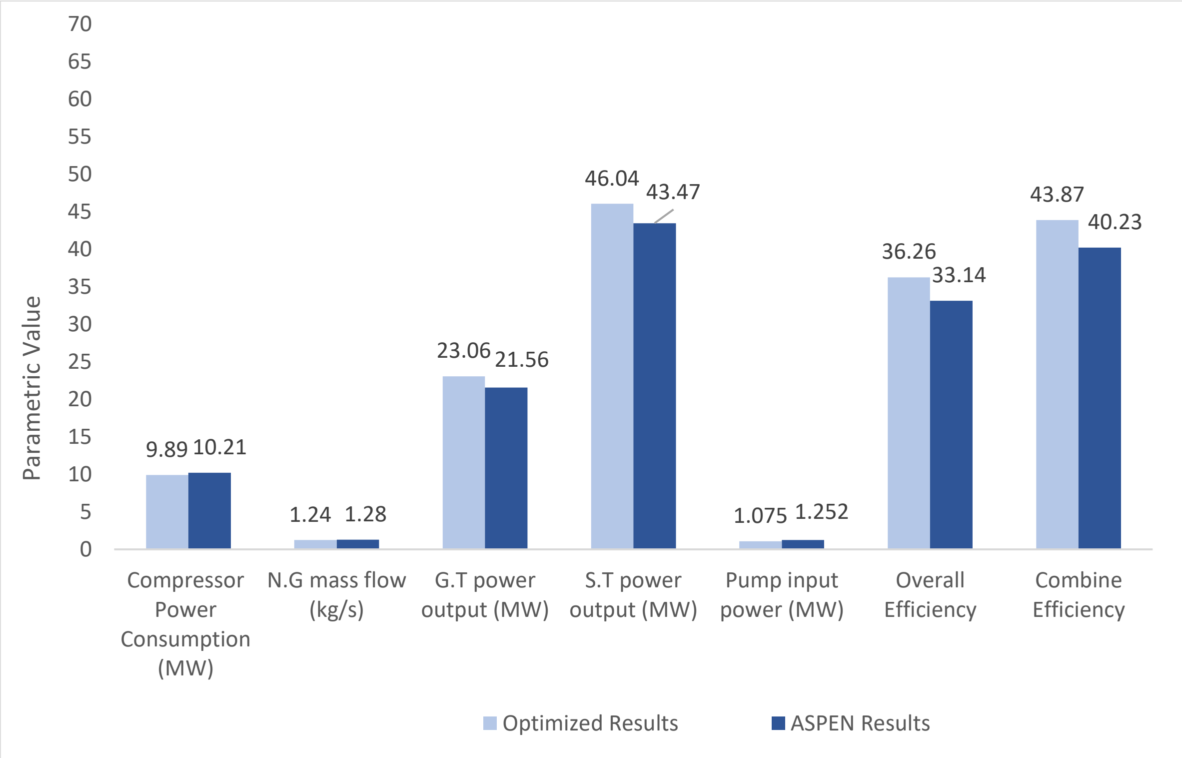

Fig 4. Comparison of the Optimized Results with the HYSYS Results for the Combine Cycle

Table 8: Loss calculation in HRSG

Input/output parameters	Percentage
Fuel heat input	100
Numerous heat losses in boiler	
Loss due to dry flue gas	5.42
Loss due to hydrogen in fuel	11.19

Loss due to moisture in fuel	0.0
Loss due to moisture in air	0.25
Loss due to incomplete combustion	3.77
Surface heat losses	2.23
Total losses	**22.86**
Boiler/combustion efficiency	**77.14**

As mentioned earlier, the use of Aspen Hyses for energy auditing of combined cycle power plants is very limited in comparison to its use for the performance analysis of plant components [15, 19]. When comparing results with some similar work, the size of the power plant, components conditions, and types of fuel used varies. Only one study could be found which directly reported the energy audit of power plant using Aspen Hyses and Gate Cycle software [16]. Liu and Karimi [16] reported use of Aspen Hyses and Gate Cycle for combined cycle power plants of 393 MW and 395 MW capacities respectively with respective plant efficiency of 56.14% and 56.49%. In the current study, the estimated plant efficiency was 40.23% (Aspen Hyses) with a plant capacity of almost 63% less than that reported by Liu and Karimi [16]. The results are quite in similar fashion with varying data depending on the size of plant and operating conditions.

4. Conclusions

The goal of the current study was to use empirical and computational methods to evaluate the energy savage potential and energy performance evaluation of a combined cycle power plant. A thorough energy audit was carried out, and by creating a virtual model of it in Aspen HYSYS, optimal operating conditions were discovered. It was found that the gas turbine, air compressor, and heat recovery steam generator (HRSG) all have an impact on the operation of a power plant. Compressors used up more than 60% of the energy produced by the turbine and 14% by the HRSG. HRSG is the ultimate source of energy in the bottoming cycle so it should be efficient.

Based on the optimized results, (a) variable speed water pumps can boost steam turbine efficiency by 5%, (b) efficient use of condenser must be considered as it plays very important role in efficiency improvement of the steam turbine, (c) efficiency of steam turbine can be improved by installing feed-water heating system and by adding preheater in steam turbine, (d) the overall improvement potential for combined cycle is estimated to be to 12.68%. The study offers a feasibility analysis to determine and calculate the cost of various energy inputs into and flows within a power plant over a specific time frame.

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Conflicts of Interest: "The authors declare no conflict of interest

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