

IRA-International Journal of Technology & Engineering ISSN 2455-4480
Proceedings of the
International Conference on Science & Engineering for Sustainable Development (2017)
Pg. no.295-317
Published by: Institute of Research Advances
<https://research-advances.org/index.php/IRAJTE>



Energy Environment Interaction Analysis in Thermal Power Plant: A Case Study of TPP with Energy Audit Approach in Indian Scenario

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Type of Review: Originality Check & Peer Review under the responsibility of the Scientific Committee of the Conference and The Institution of Engineers (India).

DOI: <http://dx.doi.org/10.21013/jte.ICSESD201729>

How to cite this paper:

Onkar, A., Dhomane, G., Moharil, R. (2017). Energy Environment Interaction Analysis in Thermal Power Plant: A Case Study of TPP with Energy Audit Approach in Indian Scenario. *Proceedings of the International Conference on Science & Engineering for Sustainable Development (2017)*, 295-317. doi: <http://dx.doi.org/10.21013/jte.ICSESD201729>

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ABSTRACT

*Engineering based on basic principle of combustion process ,associated thermodynamics,& basic engineering principles involved in optimization of **heat rate and in-house auxiliary consumption as energy input (i.e. coal consumption & in-house auxiliary consumption).**Strong theme behind this paper is actual implementation of academic knowledge with practical working experience in thermal power plant .whole paper is associated with reduction of coal, electrical energy input spent on in-house auxiliaries which ultimately reduces greenhouse emission & helps to maintain environment by upgrading knowledge & working experience of Engineer working with TPP.*

Keywords: Heat rate (kcal/kwh),calorific value(Kcal/kg),VFD(variable frequency Drive),CDM (Clean development Mechanism),PLF(Plant load Factor),TPP(Thermal power plant), CSTPS(Chandrapur Super Thermal Power Station), B.E.E(Bureau Of Energy Efficiency), MERC(Maharashtra Electricity Regulatory Comission),PAT (Perform Achieve & Trade),AVF(Avialable Factor).

Introduction

Availability of Power has a crucial rule in economic development of the country. In today's world energy is very precious. India ranks fifth in the world in total energy. A famous quote "Energy saved is energy generated" this shows that apart from increasing generation capacity at higher cost one must go for Energy Audit to save the electricity at much lower cost. A well done energy audit will always help owners to understand more about the ways energy is used in their organizations and help to identify areas where waste can occur. The Energy is the translation of conversation ideas and hopes into reality by leading technically feasible solutions. About 70% of energy generation capacity is from fossil fuels in India. India has been of the world's fastest growing energy markets due to rapid economic expansions. It is expected to be the second larger contributor to increase in Global energy demand by 2035. The world today acknowledges that the guiding concept for the future is SUSTAINABLE Development. Where industrial growth is linked to husbanding of the earth's resources. Negotiation on the Kyoto protocol to the United Nation Framework Convention on Climate Change (UNFCCC) were completed on December- 11, 1997 Committing the industrialized nation to specify legally binding reduction in emission of six greenhouse gases i.e. CO₂, NO_x, SO_x, HFCS, and PFCS & SF₆. The present study has been undertaken in such of reduction in specific coal consumption & Auxiliary Power consumption in Thermal Power Plant. Per capita GHG emissions of India are estimated to be 2.1 Tone of CO₂ in the year 2020 and 4.5 tone of CO₂ in the year2030. The key drives of the range of this estimated are the assumption on GDP growth rates. Penetration of clean energy assumed energy efficiency improvements. Present GHG emission is 2.61 billion tone of CO₂ (2016) will rise upto7.3 billion of CO₂e in 2031-32 and fall in CO₂ Intensity from 0.37kg of CO₂ to 0.28 kg of CO₂ per GDP from 2001-02 to 2031-32 as per TERI POZNAM model study which considered only limited improvement in energy efficiency based on past trends & expert judgment considering level of maturity of specific technology in India. But as per TERI MOEF model CO₂ intensity will fall from 0.37 kg CO₂ to 0.18 kg CO₂/GDP from 2001-02 to 2031-32. But this study considers energy efficiency improvement in specific technologies.[1,2]BEE launched the PAT program under NMEEE in 2012, as a part of CDM.

REVIEW OF PREVIOUS WORK

Environmental challenges to thermal power industries in India is already carried out [3]impact of advanced control solution & control loops is suggested in previous work [4] Use of data envelope Analysis (DEA) for calculating technical efficiency for decision making is suggested [5] study related to use of imported

coal & its impact on environment in Indian scenario is already studied [6] Model related to GHG emission calculation which provides useful tool for inventory preparation [7,9] problem related with fly ash & its utilization is discussed previously[8] Environmental benefit using supercritical Technology [10].In my paper actual problem related with work experience & its impact on input coal consumption with the help of engineering principles is discussed in detail .My paper is really helpful to fill the gap in literature review.

The PAT scheme currently identified 478 designated consumers from eight energy intensive industrial sectors namely Thermal Power Plant, Iron & Steel, Cement, Textiles, Chlor-Alkali, Aluminum fertilizers, pulp & paper. BEE has targeted 6.6 million mtoe to be saved by the scheme over the first cycle& multifold rise in saving expected in further cycles out to 2020. Thermal Power Plant are coming under the energy conservation act as a designated customer under the mandate of the energy conservation act 2001 the BEE is implementing various activities to provide momentum to the energy efficiency movement in the country with the view to enhance operating efficiency, reduce operating costs, minimize the emission of GHG and induce competitive cutting edge for the users.

Coal fired Thermal Power Plant unit enjoy lion’s share in Indian energy Scenario of the total 285173 MW. Maharashtra having Thermal installed capacity for generation over 26478 MW out of 40589 MW total installed capacity MERC approved normative parameters are Unit Heat Rate, Auxiliary Power, Specific Oil Consumption, and PLF. Energy efficiency is the least expensive way for power & process industries to meet a growing demand for cleaner energy. The IEA (International Energy Agency) 2006 energy technology perspectives model is a bottom up, least cost, Optimization program. The model was developed to describe the global potential for energy efficiency and CO₂ emission reduction in the period to 2050 particularly in Industrial Sector. As per this model CO₂emissions are stabilized globally in 2050 to 2005.level and world narrowly avoids a costly climate crisis.

A. All India Installed Capacity of Power Station

All India installed capacity for coal based gas, diesel. Nuclear. Hydro; renewable energy by ministry of new and renewable energy (MNRE) as on 31.03.2016 is shown in Table I as per (CEA report 2016) and associated bar graph is also shown in fig.1

TABLE I
MODE WISE CONTRIBUTION IN PERCENTAGE (ALL INDIA)
AS ON 31.03.2016

TYPES OF GENERATION AND INSTALLED CAPACITY IN MW	
Coal Based	185172.88
Gas	24508.63
Diesel	993.53
Nuclear	5780.00
Hydro	42783.42
RES (MNRE)	42849.38
Grand Total	302087.84

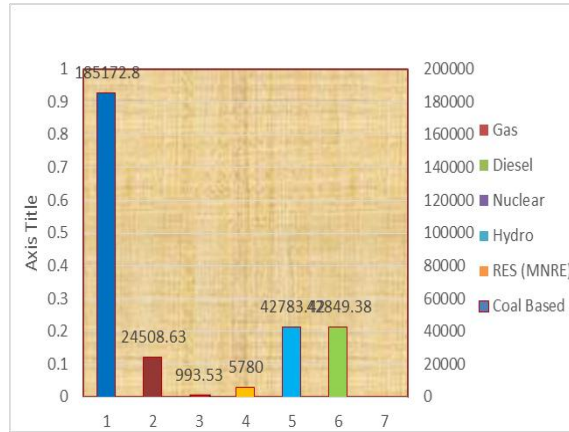


Fig 1. Bar graph for mode wise contribution in India

B. All Maharashtra State Installed Capacity of Power Station

Maharashtra state capacity for coal based, gas, diesel nuclear hydro & renewable energy as on 31.03.2016 is shown in table II as per (CEA report 2016) and associated bar graph is also shown in fig 2

TABLE II
MODE WISE CONTRIBUTION IN PERCENTAGE (IN MAHARASHTRA) AS ON 31.03.2016

TABLE 2 TYPES OF GENERATION AND INSTALLED CAPACITY IN MW	
Coal Based	26478.26
Gas	3475.93
Diesel	0
Nuclear	690.14
Hydro	3331.84
RES (MNRE)	6613.29
Grand Total	40589.46

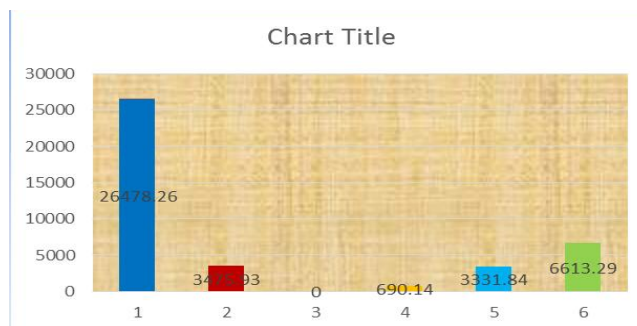


Fig2. bar graph for Mode-wise Contribution in Percentage (in Maharashtra)

C. Importance Of Energy Efficiency

The International Energy Agency’s “Accelerated Technology Scenario” suggests that Power Generation Efficiency can contribute significantly to the overall global effect to stabilize CO₂ emission by 2050 at or near to 2005 level model shows that “Power Generation Efficiency” alone which includes improved auxiliaries and other reduction measures has a larger climate impact than even nuclear power.

TABLE III

PERCENTAGE OF GLOBAL EFFECT TO STABILIZE CO₂

Table 3				
Product Efficiency	Energy & Feed stock substitution	CO ₂ Capture & Storage	Process innovation	Energy Efficiency
5%	20%	22%	4%	49%

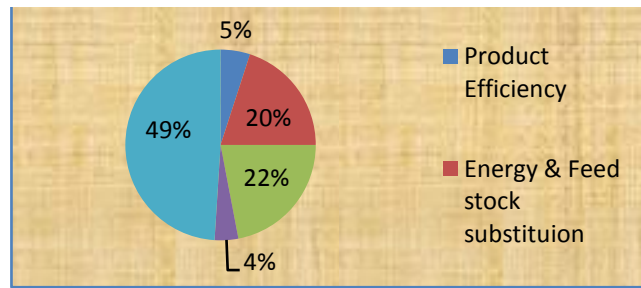


Fig 3. Piechart percentage of global effect to stabilize CO₂

POWER PLANT PROCESSES

In a thermal power plant various processes are carried out as shown in table IV. The coal is conveyed then it is crushed to a smaller size. Coal mills are provided to pulverize the coal to 200 mesh size and carried in a very fine powdered form to the boiler which produces steam. Feed water for boiler is preheated to get better cycle efficiency. Steam covering out from the boiler is super-heated before admitting to the turbine. After performing work in a high pressure turbine the exhaust steam is again reheated to 540 °C and then admitted in intermediate pressure turbine from intermediate pressure turbine steam goes to low pressure turbine and then exhaust steam is condensed to water and this water is again used as a feed water for the boiler.

Various activities is explained as follows

- 1) Conveying & preparing the fuel.
- 2) Moving necessary air to the furnace
- 3) Moving flue gas from the furnace
- 4) Returning the condensed water back to the steam generator
- 5) Maintaining the necessary cooling effect in the condenser
- 6) Operating various emission cleaning process

Pneumatic Control

D. Dynamic State Space Boiler Mode

INPUTS

SIG=Signal to fuel and air regulators

CV=Governor Valve flow area

PARAMETERS

T_w =Water wall time constant.

C_D = Drum storage capacitance

C_{SH}=Super heater storage capacitance

K =Friction drop coefficient

t_f = Fuel system dead time

T_f = Fuel system time constant

STATES

Q̇ = Furnace Heat release

ṁ_w =Mass flow rate of steam generated in water

Walls (riser) entering the drum.

P_T =Super heater steam pressure at governor valve.

P_D =Saturated steam pressure in the drum

Internal Variables

m = Mass flow rate of steam from drum to Super heater.

Algebraic Equation

$$\dot{m} = K \sqrt{P_D - P_T} \tag{1}$$

$$\dot{m}_S = CV * P_T$$

Differential Equations

$$\frac{d}{dt} \phi = \frac{1}{T_f} [SIG (t - T_f) - \phi] \tag{2}$$

$$\frac{d}{dt} m_w = \frac{1}{T_w} [\dot{Q} - m_w]$$

$$\frac{d}{dt} P_T = \frac{1}{C_{SH}} [m - m_s] \tag{3}$$

$$\frac{d}{dt} P_D = \frac{1}{C_D} [m_w - m]$$

E. Outputs

ṁ_S = Superheated Steam mass flow rate to high pressure turbine stage from the above, by setting the state time derivatives to zero it is straight forward to obtain the condition for steady state equilibrium as.

H.Steady State Boiler Model

$$\dot{Q} = m_w = \dot{m} = \dot{m}_S = SIG$$

$$P_T = SIG / CV \tag{4}$$

$$P_D = (SIG/K)^2 + SIG/CV. \tag{5}$$

Main assumption and features of the model along with some components on these follow. [11, 12, 13]

1) Heat release in the furnace as a function of the fuel and air input signal is determined by the fuel system dynamics lags and dead-times associated with coal feeder and pulverizes.

2) The mass flow of steam from the drum to the super heater is proportional to the square root of the pressure drop between the drum and the Super heater.

3) The steam mass flow to the high pressure turbine stage is regulated by the governor valve.

E. Collection Of CSTPS Data

UHR = Unit Heat Rate (Kcal/Kwh)

η_0 = Overall Plant Efficiency

C1, C2, C3 = Capacity of the Individual unit or station (MW)

SHR= Station Heat Rate (Kcal/Kwh)

HR1, HR2, HR3 = Heat Rate of Individual Unit (Kcal/Kwh)

FO = Forced Outages

CF1HF1, CF2HF2 = Outage of Individual Unit

PM = Planned Maintenance

CH = Plant Installed Capacity in MW

AP= Auxiliary Power Consumption

% C = % Carbon in Coal

SEC = Specific Coal Consumption (Kg/Kwh)

Coal Consumption = Sp. Coal Consumption * Total Generation = (Kg/KWh) * KWh

TABLE IV

Year	Generation in MUS	Auxiliary Consumption in MUS	Net Generation in MUS	% Aux. Cons.	Coal consumed in (MT)	Spe. coal consumed (Kg/ Kwh)	% PL F	% AV F	Oil Con su. in (KL)	Spe.O il cons. (ML/ KWH)	CO2 emitted per year (M.T).
1998-99	13430.853	1080.8147	12350.03	8.1	9624798	0.72	65.5	80.45	32108	2.391	12030997.5
99-2000	15815.297	1199.632	15815.297	7.6	11099426	0.7	76.9	88.86	17664	1.117	13874282.5
2000-01	15555.586	1187.6788	14367.907	7.6	11049475	0.71	75.9	87.44	20997	1.35	13811843.5
2001-02	16227.276	1240.8251	14986.45	7.7	12061110	0.74	79.2	90.25	23900	1.473	15076387.5
2002-03	15179.486	1168.8033	14010.682	7.7	10899159	0.72	74.1	85.45	17965	1.184	13623948.8
2003-04	16227.416	1241.7805	14985.63	7.7	11656439	0.72	79	88.88	16676	1.028	14570548.8
2004-05	15923.74	1229.1063	14694.633	7.7	12237224	0.77	77.7	86.88	13466	0.846	15296530
2005-06	13987.194	1089.4513	12897.742	7.8	10284897	0.74	68.2	76.12	16181	1.157	12856121.3
2006-07	13160.881	1066.7697	12094.111	8.1	10302857	0.78	64.2	71.34	12708	0.966	12878571.3
2007-08	15861.574	1172.9946	14688.579	7.4	12513159	0.79	77.2	90.18	13109	0.826	15641448.8
2008-09	15004.081	1206.4956	13797.585	8	12177787	0.81	73.2	90.86	23606	1.573	15222233.8
2009-10	14622.743	1238.8508	13383.892	8.5	12024214	0.87	52.8	73.81	49121	4.535	15030267.5
2010-11	10832.377	1086.9732	9745.403	10	9461351	0.87	52.8	73.81	49121	4.535	11826688.8
2011-12	13515.866	1306.038	12209.828	9.7	11777672	0.87	65.8	86.14	21654	1.602	14722090
2012-13	14066.822	1320.2732	12746.548	9.4	11833865	0.84	68.6	90.58	21960	1.561	14792331.3
2013-14	11000.272	1082.4997	9917.772	9.8	9833638	0.89	53.7	77.36	33113	3.031	12292047.5
2014-15	12507.874	1122.0315	11385.842	9	11052068	0.88	64.4	88.73	16482	1.318	13815085
2015-16	12164.952	1006.2548	11158.697	8.3	10395323	0.86	59.2	77.05	9685	0.796	12994153.8

EARS CSTPS DATA

F. Regression Analysis

Descriptive statistics, correlation between various mentioned parameters, model summary, ANOVA coefficients a= Predictor (constant), specific oil consumption ml/kwh, Auxiliary consumption in mus,

Specific Coal consumption in Kg/kwh, Avf%, Plf % net generation in mus, oil consumption in kl, Coal consumed in mt. generation in mus.

b = depended variable – CO₂ emitted per year M.T.

Multiple Regression analysis was carried out to find out the equation for prediction between dependent & independent variables. The following have been the variables.

1. Independent Variable
2. Dependent Variable

Regression equation generated is as follows:-

CO₂ emitted per year in M.T. = 4.284 + (0.001 Auxiliary Consumption) + 5.841 * 10^{-0.05} (Net Generation) – 0.117 * % Auxiliary Consumption + 1.250 * Coal Consumed – 4.430 * (Specific Coal Consumed) + 0.004 * % PLF – 0.002 * % AVF – 2.133 * 10^{-0.005} + 0.267 * Specific Oil consumption

The value of coefficient of determination, R² is 1.0 and is adequate for acceptance of results.

The ANOVA analysis and 't' test carried out indicates the confidence level of 95%

Using the above equation the CO₂ emitted can be estimated if values and dependent variable are interrelated by controlling variable, CO₂ emission per year can be reduced which is helping to achieve greener Environment by reducing global warming impact.

II. ENERGY AUDIT METHODOLOGY

Energy audit is an engineering technique used to establish the pattern of energy use, level of operating efficiency, identify how and where losses are occurring, identify generic design deficiencies, identify process bottlenecks, identify performance deterioration, addressing technological obsolescence, addressing chronic operation and maintenance problems, suggest appropriate techniques to conserve energy along with economic implications and evaluation of performance efficiency helps for renovation and modernization, up gradation.

Energy Audit methodology consists of three phases.

- Preliminary Energy Audit
- Detailed Energy Audit
- Report Preparation.

This is explained with the help of following steps in fig 5

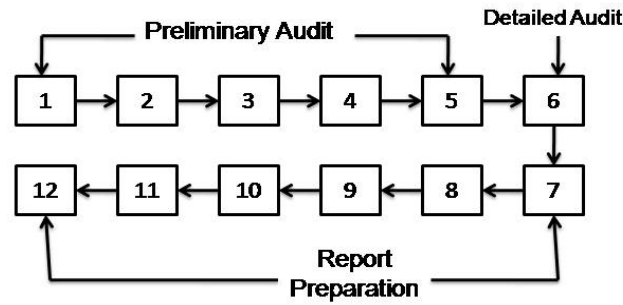


Fig.5 Flow Diagram For Energy Audit Methodology

1. Meeting and discussion with plant officials.
 2. Study of Process/ activity of the organization.
 3. Collection of technical details along with drawings.
 4. Collection of monthly post data (2 – 3 yrs.) on Electrical and fuel energy consumption.
 5. Action plan for detailed Audit.
 6. Performance evaluation of each utility and end use equipment by observation,
 7. Conducting tests and measurements.
 8. Data analysis, processing, computation, observation of result and comparison with design values.
 9. Identifying energy conservation measures and techno economic analysis.
 10. Recommendation for energy conservation and preparation of draft report.
 11. Submission of draft report to client.
 12. Receiving comments from client. & Submission of mutually agreed final report contains recommendation for improving.
- Energy efficiency with cost benefit analysis and action plan.

III. PERFORMANCE OPTIMIZATION PROGRAM METHODOLOGY FOR IMPLEMENTATION

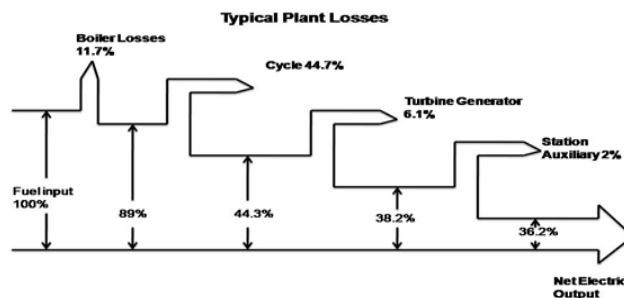


Fig 6. Sankey Diagram For Typical Plant Losses

A. Heat Rate:

It is a measure of how efficiency a Power Plant converts the chemical energy contained in the fuel into electrical energy. In each of sub-processes, some energy is lost to the environment. Some of the fuel is not burned completely; some of the thermal energy is lost out the stack and rejected to the cooling water, some of the kinetic and mechanical energy products heat instead of electricity, and last, some of the electricity that is produced is used by these sub-processes. Since chemical energy is usually measured in kilocalories (kcal) and electrical energy is usually measured in kilowatt-hours (kWh), the units of heat rate are normally kcal/kWh. If a power plant converted 100% of the chemical energy in the fuel into electricity, the plant would have a heat rate of 860 kcal/kWh

B. Factor Affecting Heat Rate

Actual or operating heat rate of a plant gets affected by following factors;

The Initial design. Such as number of stages of feed water heaters, steam driven pumps and fans instead of electric drives, higher initial steam temperature and/pressure are the major design factors which results in a lower heat rate.

- Ambient conditions such as Relative Humidity and Dry Bulb Temperatures affect the condenser cooling water temperature at the out let of cooling towers.
- Load Factor, Conventional power plants are most efficient at full load, and the efficiency decreases as the load decreases.
- The fuel supplied to Boilers. If the coal actually fed to the boiler is deviating from the design coal. This will adversely affect the heat rate.
- How well the plant is operated and maintained Power plants when operated with all the parameters maintained at design levels always operate at Optimum Heat Rate. Correction in Equipment deterioration, shutting off unnecessary auxiliary equipment etc. also improves the heat rate.

NEED OF OPTIMIZATION TEST

By performing an optimization test, the combination that results in minimizing the unit heat rate can be determined. The periodic performance tests are conducted to:

- Compare the current performance with expected performance
- Predict when and what, equipment maintenance or modification justified or required.
- Evaluate the effectiveness of maintenance work Validate the readings of 'on line' instruments.
- Determine the most efficient operating regime for equipment
- Account for heat rate losses (such as is due to poor turbine efficiency)

Following various tests are carried out

1. HP/IP Turbine Enthalpy Drop Efficiency Test: The purpose of HP/IP Turbine Enthalpy Drop Test is to determine the efficiency of HP and IP sections of the turbine, trend their performance and generate data to pinpoint the probable cause of degradation. The trends can then be used for determination of the optimum point at which the costs incurred due to performance degradation exceed the cost to be incurred for restoration of equipment. It is also used for validation of online instruments.

2. Condenser Performance Test: Condenser tests are done to assess the thermal and hydraulic performance of the condenser in terms of tube fouling, air-in-leakage and to optimize condenser-cleaning schedules. It is also used to trend the performance parameters and generate data to pinpoint the probable cause of degradation. The trends can then be used for deciding the future course of action like tube cleaning schedules, attending air-on-leakage, adequacy of Condenser CW flow, tube replacement programs etc.

3. Feed water Heater Performance Test: The purpose of Feed water heater tests is to assess the current performance and to provide data to assist in optimization of normal operation of the heater. Heater performance can be analyzed by calculating and monitoring Terminal Temperature difference (TTD), drain Cooler Approach (DCA), the pressure drop on the feed water side and the temperature rise across the heater. These parameters are trended over time for identification of abnormal changes in heater performance and to determine whether corrective action is required to maintain optimum performance.

4. Pump Performance Test: BFP Performance tests are run to compare the current performance of the BFP to its 'expected' performance and also to compare its performance against similar pumps. The parameters to be determined include the total head developed by the pump, the balancing drum leak off flow and the efficiency of the 'train' (I.e. motor, hydraulic coupling and the pump) over the normal operating range. This information can be used to determine, if any corrective maintenance is required immediately or will be required in the future.

5. Turbine Cycle Heat Rate Test: The purpose of the Turbine Cycle Heat Rate test is to determine overall turbine cycle performance (both heat rate and capability) as well as component thermal performance and to provide a check of accuracy of critical station Instruments. It is used as guidance in scheduling, maintenance outages on the basis of performance trends. It is also used to evaluate major modifications of the turbine or turbine cycle, and changes in operating procedure.

6. Pulverizes Clean Air Test: The second test in a mill performance program is to check to see if each coal pipe is receiving the same amount of primary air. Clean airflow tests are also used to calibrate primary airflow measurement device wherever straight lengths are not available in P A ducting to the pulverizers.

7. Pulverizes Dirty Air/ Coal Flow Test:The dirty air/coal flow test is usually the third mill performance test (run after obtaining satisfactory results from both the primary air calibration and clean air tests. This test us used to:

- Detect imbalance, if any, in the air and coal flows between the discharges pipes of a Pulverized.
- Collect a representative, iso-kinetic, sample of pulverized coal from different pipes for determination of fineness fractions
- Cross-check the readings of the station Instrumentation e.g. primary airflow through the mill, mill outlet temperature, coal flow through the feeder etc.

8. Air Heaters: Purpose of monitoring of air heater performance is

- To determine air heater leakage rate (the amount of air that leaks to the gas side) which affects station service (fan power) and affects the “indicated” exit gas temperature used in heat rate deviation calculations
- To determine air heater x-ratio (which is an indication of boiler air infiltration, and a craver of AH efficiency)
- To determine air heater gas side efficiency (how well the AH is transferring heat from the gas side to the air side)
- To validate the station instrument readings e.g. air and gas temperatures, oxygen, air and gas side pressure drops etc.

A. Heat Rate Action Plan

This section discusses how to take that information and develop an action plan to:

- Ensure that necessary and cost beneficial improvement activities are carried out:
- Set “target” values for parameters (such as boiler outlet Tempand for their heat rate deviations for each unit.
- Predict future values for heat rate deviations and heat rates for strategic planning purposes for individual units, plants, and entire utility systems. Identifying and scheduling a new activity that will affect the heat rate
 - Changing the schedule for an activity already in the plan
 - If the same activity is planned for several units, after the completion of the first unit, the process indicator target and heat rate deviation target for the remaining units may need to be changed to reflect the values that were achieved.

B. Optimization of Boiler Performance

For getting optimum performance from the Boiler, it is necessary that controllable losses, such as Dry Flue gas loss and Loss due to incomplete combustion is minimized. Typical values of the losses in the Boiler (designed values) are as shown in table VI.

The effect on heat rate, due to deviation of important parameters from expected values, is listed below in table 7

TABLE: VI
BOILER LOSSES

Loss due to	% loss	Whether controllable
Dry Flue Gas loss	4.64	Controllable

H2O and H2 in fuel	5.60	Not controllable
H2O in air	0.18	Not controllable
Unburnt Carbon	0.60	controllable
Radiation	0.19	Not controllable
Unaccounted	0.40	Not controllable
Manufacturers Margin	0.50	Not controllable
Total Losses	12.11	
Efficiency	87.9	

TABLE: VII
DEVIATION IN HEAT RATE

Parameter	Expected	Actual	Excess Heat/kWh	Excess coal Consumption /kWh (C.V.3500 kcal/kg)	Excess coal consumption over the year, at PLF
Excess Oxygen	3.5%	4.0%	3.467	0.001	1600 Tons
Unburnt Carbon	1.0%	1.5%	3.782	0.0011	1700 Tons
FlueGas Temp	135	145	18.67	0.00533	7853 Tons
Moisture in coal	9%	11%	2.75	00078	1156

Mechanism Of Combustion Of Coal:

In Boilers, due to very high rate of fuel admission, average time a particle stays within the furnace is of the order of 1 to 2 seconds. Hence within this time all the coal particles should burn completely. Combustion is chemical reaction which progresses at a rate determined by

- Time required for combustion of volatile matter.
- Time required for combustion of Coal particle, devoid of volatile matter.

A Combustion of Volatile matter:

On admission of coal in the furnace, intense heat radiation present causes Coal particle temperature to increase rapidly, causing its expansion. The gaseous mater (i.e. the Volatile matter) comes out from the particle and on receiving Oxygen present in the Primary Air, burns out completely. In the process, Oxygen in Primary air gets consumed. The remaining particle, also called soot, now contains Carbon and Noncombustible. Time required for combustion of Volatile matter is 40 to 50 milliseconds. Reaction rate very fast owes to ease of Oxygen in air to mix with gaseous matter. For further combustion of soot particles, secondary air is supplied.

B Combustion of Solid fuel particles:

Soot, being a solid, cannot combine with Oxygen in air readily. In the furnaces, where temperature is above 1000⁰ C, the rate of combustion of soot particles is governed by the rate at which Oxygen in the

secondary air reaches to the surface of soot particle. The rate of reaction of coal Particle is given by Reaction Rate $q = K_{diff}P_s$

Where K_{diff} is called diffusional reaction rate coefficient and P_s is the partial pressure of Oxygen in the surrounding gas stream.

$$K_{diff} = 24 \phi D / X R' T_m$$

Where, $\phi = 1$ when CO_2 is transported from surface
 $\phi = 2$ when CO is transported from coal surface

D is diffusion coefficient of Oxygen in to the gas surrounding the coal particle

X is particle diameter in cm

R' is gas constant

Tm is mean temperature of the particle

The values of K_{diff} are given in following table.

For ensuring complete combustion before the particle leaves the furnace, time available is 1 to 2 seconds. Hence it is necessary that the rate of reaction must be maximum possible. For obtaining high reaction rate, it is therefore necessary that

- Particle size should be as small as possible
- Temperature of the furnace should be as high as possible
- Diffusion coefficient D should be as high as possible
- Concentration of Oxygen in the gases surrounding the particles should be maximum possible leading to maximum Partial pressure of Oxygen,

TABLE VIII
 VALUE OF K_{DIFF} FOR VARIOUS PARTICLE SIZE AND TEMPERATURE

Tm in ° K	Particle Diameter, micron					
	25	50	75	100	125	150
1000	.376	.188	.125	.094	.075	.063
1200	.423	.211	.141	.106	.085	.070
1400	.466	.233	.155	.117	.093	.078
1600	.510	.255	.170	.128	.102	.085

TABLE IX
 DIFFUSION COEFFICIENT D FOR DIFFERENT TYPES OF GASES

Temperature, K	Diffusion coefficient			
	O ₂ - N ₂	CO- N ₂	CO ₂ - N ₂	H ₂ O - N ₂
1000	1.61	1.60	1.24	2.15
1100	1.88	1.87	1.45	2.52
1200	2.17	2.15	1.68	2.92
1300	2.47	2.45	1.92	3.34
1400	2.79	2.77	2.17	3.78
1500	3.13	3.10	2.42	4.25
1600	3.49	3.46	2.69	4.73

It can be seen that, Furnace temperature has a limitation, as it should be below the temperature at which Ash melts. Particle size has a limitation from Coal Mill throughput and economy of pulverization, Diffusion coefficient is constant for the given gas mixture and for the given temperature.

Considering the above limitations, Flame Temperature is generally between 1200 to 1400° C for the Indian coal, Particle size is limited to 75 micron, (corresponding to 200 mesh size). The only factor that

can have some variations is concentration of Oxygen in the gases surrounding the particles. For maintaining the concentration of oxygen high, it is necessary that secondary air must enter at predetermined places and with the design velocity, which is 40 m/s, i.e. slightly higher than that of Primary air velocity:

C Primary Air Velocity:

Primary air velocity in a coal pipe should be such that, coal particles remain air borne and do not separate from the stream. Hence, velocity of 35 mtr/sec is the optimum velocity to ensure above mentioned requirements. Considering this, manufacturers specify the mass flow rate of primary air to mill, at different mill loading conditions.

Air supply to boiler is such that Oxygen in flue gas is maintained at 3.5% on dry gas basis at APH outlet.

D Efficiency / Heat Rate Improvement With Available Instruments

In today's world of globalization, commercial aspects regarding any product should be given prime importance. Electrical energy is no exception to this. Cost of Coal is a major factor governing cost of electricity generation in coal fired power plants by optimizing the power plant's operation, with a focus on reducing Heat rate, cost of generation can be reduced to a great extent.

VII WHAT IS HEAT RATE

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$\text{Heat Rate} = \frac{\text{Heat input in Kcal}}{\text{Gross elect. Output in KWH}}$$

$$\text{Net Heat Rate} = \frac{\text{Heat input in Kcal}}{\text{Net elect. Output in KWH}}$$

Method of Calculation:

$$\text{Gross Turbine Heat Rate} = \frac{\text{Heat used in complete turbine cycle}}{\text{Gross Generation in MW}}$$

Where,

$$\text{Heat used in Turbine Cycle} = \text{Heat input at HP Cylinder} - \text{Heat in Feed water at Eco. Inlet} + \text{(Heat Added in Reheat Cycle)}$$

$$\text{Unit Heat Rate} = \frac{\text{Gross turbine Heat Rate}}{\text{Boiler Efficiency}}$$

Where,

Boiler efficiency is calculated by

- Loss Method
- Input / Output Method

Unit Efficiency= (860 /Unit Heat Rate) * 100

Savings: Typical Calculations

Considering Kcal/Kwh saved/Unit = 10 Kcal/kwh.

Average Maharashtra state (India) Thermal Generation / Day = 432 ×10⁶ Kwh

Average Coal calorific value = 3300 Kcal/kwh Average coal cost =

$$\text{Kg. Of coal saved /month} = \frac{10 \times 432 \times 10^6 \times 30}{3300}$$

$$\text{Tons of Coal saved /day} = \frac{10 \times 432 \times 10^6 \times 30}{3300 \times 1000} = 39273$$

Reduction of losses at above different stages will improve Heat Rate and Coal requirement of Utility.

Heat rate signifies heat input in Kcal for every unit generated. Improvement of even 25 Kcal/Kwh for a 210 MW unit amounts to saving of 4.66 crore per year as shown below.(Total energy requirement of Maharashtra state is 18000 Mw / day)

$$\text{Amount Saved/year} = \frac{\text{Heat Rate improved} * \text{KWH Generated / year} * \text{Coal Cost /ton}}{\text{CV} \times 1000}$$

$$= \frac{25 \times 210 \times 8760 \times 3350}{3300}$$

$$= 4.66 \text{Crore/ one 210 mw unit}$$

(Considering landed coal cost Rs. 3350 /- per ton & GCV = 3300 Kcal/Kwh)

As a part of CDM (Clean Development Mechanism) Maharashtra state (As well as in India) started heat rate optimization rigorously through Energy audit Program

TABLE X

Factor Affecting Heat Rate Deviation

Sr. No.	Factor	Design/Expected. Value	Deviation in Units	Heat Rate Deviation in Kcal/kwh (approx.,)
1	M.S. Pressure	130Kg.cm2	1 Kg/cm2	1.2
2	M.S.	535 ⁰ C	1 ⁰ C	1.2

	Temp.			
3	Hot R/H Temp.	535 ⁰ C	1 ⁰ C	1.8
4	Condenser Vacuum	660 mm. Hg	1mm	2.2
5	Eco. Inlet Temp.	251 ⁰ C	1 ⁰ C	1.77
6	Flue Gas Outlet Temp. AH-A	143 ⁰ C	1 ⁰ C	2.02
7	Flue Gas Outlet Temp. AH-B	143 ⁰ C	1 ⁰ C	2.02
8	Unburnt in Fly Ash	0.8%	1%	28.3
9	Unburnt in Bottom Ash	4.0%	1%	3.1
10	RH Spray Flow	0 Ton/hr.	1 Ton/hr.	4.0

TABLE XI
EFFECT OF TURBINE EFFICIENCY ON HEAT RATE

One % Improvement in Efficiency on	% Effect on Turbine Cycle Heat Rate	Effect on Heat Rate
HP Turbine	0.2% Heat Rate	5 kcal/kwh
IP Turbine	0.2% Heat Rate	5 kcal/kwh
LP Turbine	0.5% Heat Rate	12.5 kcal/kwh

A. Calculation Of Deviations In Heat Rate Due To Various Factors:

In table XI, various areas of heat losses are identified which are unavoidable. Loss on account of each factor is tried to be quantified and added to design heat rate for arriving practically achievable heat rate. Calculations are based on the design data for each unit & CSTPS as below

Design station heat rate =

$$\frac{(210 \times 4 \times 2363) + (2 \times 500 \times 2238) + (500 \times 2214)}{2340}$$
 = 2278 Kcal/kwh.

The design heat rate figures given by manufacturer are based on ideal conditions such as full/stable load, Design coal, No steam/water/Oil leakages, No routine operations like soot blowing, ash evacuation, blow downs, oil support, oil support, oil heating, Ageing effect etc. CHP losses are also not covered in

this heat rate. In practice however, all these losses are bound to be there and unavoidable. The quantum of these losses is worked out as below one by one.

TABLE XII
CALCULATION OF HEATRATE DEVIATION

Particulars	Unit-1	Unit-2	Unit-3	Unit-4	Unit-5	Unit-6	Unit-7	STN
Design performance								
a) Gross heat rate(Kcal/kwh)	2363	2363	2363	2363	2238	2238	2214	2278
b) Boiler efficiency (%)	86.32	86.32	86.32	86.32	88.10	88.10	88.00	87.40
c) Turbine heat rate(Kcal/kg)	2040	2040	2040	2040	1972	1972	1948	1991
d) CV of coal(Kcal/kg)	4313	4313	4445	4445	3750	3750	3500	3900
Sp. Coal cons(Kg/kwh)	0.548	0.548	0.532	0.532	0.597	0.597	0.632	0.584
Design Coal analysis	Unit-1&2	Unit-3&4	Unit-5&6	Unit-7				
Moisture (%)	8.65	8.65	8.0	10.0				
Ash (%)	30.5	35.0	40.0	42.0				
Volatile Mattel (%)	24.48	22.35	24.0	22.0				
Fixed carbon (%)	36.37	34.00	28.0	26.0				

B Loss Due To Poor Coal Quality:

Coal received at CSTPS is of E/F grade with average proximate analysis as below & quality is inferior as compared to design coal.

- GCV - 3625 Kcal/kg
- Moisture - 12 to 18% (depending on season)
- Ash - 40%
- Volatile matters - 22 to 24%

Hence, there will always be losses on account of poor coal quality which are mainly due high moisture, hydrogen and ash content in coal and coal mill reject.

C Loss Due To Moisture in Coal: Moisture in coal received is in the range of 12 to 18% depending on season/colliery. In rainy season, moisture is as high as 18 to 19 % i.e. about 10% more than design value.

Assuming coal factor as 0.72 kg/kWh,
Heat loss on account of additional moisture of 10%,

$(0.10 \times 0.72) \times (584 + C_p (T-t))$ where 584-Latent heat corresponding to Partial pr. of water vapor. $C_p=0.45$ (Sp. heat of S/H steam) T =Flue gas temp at A/H outlet (0c) T =Ambient temp. (0c)=0.072 \times (584+0.45(150-30))
=45.94 Kcal/kWh say 46kcal/kwh

D Heat Loss Due To Hydrogen In Fuel: Designer has given the loss due to hydrogen in coal as 3.96% for 210 MW units and 4.28% for 500 MW units. i.e. Average loss of 4.1% for station. If H2 content is worked out by back calculation from this loss i.e.

Loss due to H2 (%) = $\frac{9 \times H_2 \times (548 + C_p(T-t))}{CV \text{ of coal}}$

$$\begin{aligned} 0.041 &= \frac{9 \times H_2 \times (548 + 0.45(140-30))}{3900} \\ 0.41 &= 1.461 \times H_2 \\ H_2 &= 2.8\% \end{aligned}$$

In design coal analysis of unit-7, designer has mentioned H2 content of 2.8%, which matches with the H2% derived as above. Since, facility of H2 analysis is not available at CSTPS, H2 content in actual coal received, is derived by empirical formula as below.

H2% in coal = $VM \times (\frac{7.35}{24+10} - 0.013)$ (Gerhard's formula) VM+10

Where VM – Volatile matter in %

$$H_2 (\%) = \frac{24 \times (\frac{7.35}{24+10} - 0.013)}{100} = 4.88\%$$

Heat loss due to excess H2 in coal

$$= 9 \times H_2 \times (548 + C_p (T-t))$$

Where H2 – quantity of hydrogen = $0.72 \times \frac{(4.88-2.8)}{100}$

$$= 0.015 \text{ Kg/kWh.}$$

Heat loss due to excess H2 in coal

$$= 9 \times 0.015 \times (548 + 0.45(150-30))$$

$$= 86.13 \text{ Kcal/kWh say } \underline{\underline{86 \text{ Kcal/kwh}}}$$

4. Loss Due To Sensible Heat In Ash: Ash content in coal is about 40% as against design value of 30-35%, generating more ash and hence heat loss due to sensible heat of fly ash and bottom ash.

Design coal consumption is 0.548 Kg/kWh

With 35% ash content, ash generated will be $0.35 \times 0.548 = 0.2044 \text{ Kg/kWh}$

Actual coal consumption is 0.72 Kg/kWh and ash content is 40%.

Actual ash generated = $0.288 - 0.2044 = 0.0836 \text{ Kg/kWh.}$

Out of total ash generated, 80% is fly ash and 20% is bottom ash quantity.

Fly ash quantity = $0.0836 \times 0.8 = 0.06688 \text{ Kg/kwh.}$

*Heat loss due to sensible heat of bottom ash

= Bottom ash quantity \times Net temp. of ash \times Sp. Heat of bottom ash

$$= 0.01672 \times 600 \times 0.25 \text{ Kcal/kg/0c.}$$

$$= 2.508 \text{ Kcal/kWh.}$$

** Heat loss due to sensible heat of fly ash.

= Fly ash quantity Net temp of fly ash \times Sp. Heat of fly ash.

$$= 0.06688 \times 140 \times 0.2$$

$$= 1.873 \text{ Kcal/kWh.}$$

Total heat loss due to sensible heat of ash = $2.508 + 1.873 = 4.381 \text{ kcal/kwh.}$

Say 4Kcal/kwh.

6. Loss Due To Coal Mill Reject:

At CSTPS, percentage of coal mill reject generated to coal consumed varies from 0.8% to 1.8% with average 1.05 reject, quantity of reject generated per kwh,
 $=0.72 \text{ kg/kWh} \times 0.01$ where 0.72 is coal consumption rate.
 $=0.0072 \text{ Kg/kWh}$
 Calorific value of reject varies between 1000 kcal/kg to 1100 kcal/kg.
 Heat loss on account of reject $=0.0072 \times 1100$
 $=7.92 \text{ kcal/kwh}$ **say 8 Kcal/kwh.**

E Loss Due To Partial Loading Of The Units:

Design heat rates at partial loads are higher than design heat rate .Expected heat rates at partial loads for U-1 to U-7 enclosed herewith. Units do not run on full load throughout the year due to various constraints like ageing of the boilers. (18-20 years old units), grid problems, low system demand, wet coal/choking problem, poor coal quality, plant problems, startup/withdrawal of units. Actual average load of the CSTPS units was as below in table XIII.

**TABLE XIII
 DEVIATION DUE TO PARTIAL LOADING**

Factors	Uni t-1	Uni t-2	Uni t-3	Uni t-4	Uni t-5	Uni t-6	Uni t-7	ST N
Rated capacity (MW)	210	210	210	210	500	500	500	2340
Average load (MW)	171	169	189	201	454	420	472	2079
Heat rate expected at load at SN. 2 above	2378	2379	2372	2367	2258	2265	2222	2290
Design HR at rated capacity	2363	2363	2363	2363	2238	2238	2214	2278
Deviati on is expected H.R. due to partial loading (Kcal/k wh)	15	16	09	04	15	27	08	12

Thus, a deviation of **12 Kcal/kwh** should be considered in station heat rate due to partial loading of the units.

IV. OTHER LOSSES DUE TO PLANT PROBLEM

$$\begin{aligned} \text{Total heat rate deviation} &= A + B + C + D + E + F + G \\ &= 144 + 12 + 20 + 21 + 13 + 69 + 76 \\ &= 355 \text{ Kcal / Kwh} \end{aligned}$$

Hence, Best achievement heat rate of CSTPS is
 = 2278 + 355
 = 2633 Kcal / Kwh.
 Say 2635 Kcal / Kwh.

This figure fairly matches with the heat rate worked out as 2622 Kcal / Kwh based on the actual fuel consumption.

TABLE 19.
 LOSS DUE TO TYPICAL PLANT PROBLEM

S.N	Factors responsible for heat rate deviation	Deviation in Kcal/Kwh
A	Coal quality	1
	a) Loss due to moisture	4
	b) Loss due to hydrogen	4
	c) Loss due to sensible heat in ash	4
	d) Loss due to coal mill rejects	6
		8
		6
		4
B	Partial loading of units	1
		2
C	Ageing factor	2
		0
D	Aux. Steam / Steam, water leakages	2
		1
E	Radiation / unaccounted loss	1
		3
F	Coal handling losses	6
		9
G	Plant problems	7
	a) Condenser vacuum	6
	b) Dry flue gas loss	4
	c) MS / HRH temp	4
	d) MS pressure	1
		3.
		5
		1
	4	
	4.	
	5	

CONCLUSIONS

Factors Affecting Heat Rate Deviation

As per above discussion study my paper is based on energy Audit study, where suggestion for present energy use reduction on the basis of working experience in TPP is considered. Which shows increase in net generation of TPP and reduction in CO₂ emission factor. Actual or operating heat rate of a plant gets affected by following factors;

- The Initial design. Such as number of stages of feed water heaters, steam driven pumps and fans instead of electric drives, higher initial steam temperature and/pressure are the major design factors which results in a lower heat rate.
- Ambient conditions such as Relative Humidity and Dry Bulb Temperatures affect the condenser cooling water temperature at the out let of cooling towers.
- Load Factor, Conventional power plants are most efficient at full load, and the efficiency decreases as the load decreases.
- The fuel supplied to Boilers. If the coal actually fed to the boiler is deviating from the design coal. This will adversely affect the heat rate.
- How well the plant is operated and maintained Power plants when operated with all the parameters maintained at design levels always operate at Optimum Heat Rate. Correction in Equipment deterioration, shutting off unnecessary auxiliary equipment etc. also improves the heat rate.

Benefits Of Heat Rate Improvement

- Conservation of fuel takes place and money spent for fuel will be reduced. This lowers the cost of producing the electricity.
- The amount of emissions to the environment will be reduced. Improving the heat rate reduces the amount of greenhouse gas that is produced. Less fuel burned means less ash to be disposed of, and less particulate go out of the stack.
- Because less fuel is required to produce the same amount of electricity, the amount of energy on equipment such as pulverizers, coal pipes and nozzles, etc., is required. Also, along with reduced fuel flows, the air flow is reduced, reducing velocities through the boiler, resulting in less erosion and reduced fan power.
- Frequently, heat rate improvement (such as in the condenser pressure or auxiliary power use) results in an increase in the net generation of the unit, allowing the unit to run at a higher plant load factor. This advantage can be very valuable, especially in the summer when the condenser cooling water temperatures and ambient air temperatures are high, which sometimes results in generation being limited due to condenser pressure or running out of fan(s) capacity.

The Periodic Performance Tests Helps For Decision Making

- Compare the current performance with expected performance
- Predict when and what, equipment maintenance or modification justified or required. Evaluate the effectiveness of maintenance work Validate the readings of 'on line' instruments.
- Determine the most efficient operating regime for equipment
- Account for heat rate losses (such as is due to poor turbine efficiency) and gas side pressure drops etc.

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