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A techno-economic analysis of partial repowering of a 210 MW coal fired power plant

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Abstract. This paper presents a techno-economic analysis of a partial repowering scheme for an existing 210 MW coal fired power plant by integrating a gas turbine and by employing waste heat recovery. In this repowering scheme, one of the four operating coal mills is taken out and a new natural gas fired gas turbine (GT) block is considered to be integrated, whose exhaust is fed to the furnace of the existing boiler. Feedwater heating is proposed through the utilization of waste heat of the boiler exhaust gas. From the thermodynamic analysis it is seen that the proposed repowering scheme helps to increase the plant capacity by about 28% and the overall efficiency by 27%. It also results in 21% reduction in the plant heat rate and 29% reduction in the specific CO2 emissions. The economic analysis reveals that the partial repowering scheme is cost effective resulting in a reduction of the unit cost of electricity (UCOE) by 8.4%. The economic analysis further shows that the UCOE of the repowered plant is lower than that of a new green-field power plant of similar capacity.

Keywords: partial repowering; gas turbine; feedwater heating; specific CO_2 emission; cost of electricity

1. Introduction

Rapid industrialization and socio-economic growth is expected to dominate most parts the globe, especially the developing countries like India and China. World energy consumption is projected to increase by 56% by 2040 (International Energy Outlook 2013). Electricity is one of the major modes of energy consumption. 40% of the total worldwide electricity is generated from coal (International Energy Outlook 2013) and coal combustion results in huge amount of green house gas (GHG) emission into the atmosphere. Reduction in GHG emission from the fossil fuel based power plants is a major issue throughout the world nowadays because global carbon dioxide emission is projected to rise by 46% by 2040 (International Energy Outlook 2013). The necessity to satisfy the thirst of growing energy demand, coupled with different social and political issues associated with the construction of new power plants, has put renewed focus on repowering of old

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existing coal fired power plants to boost up their performance characteristics by enhancing the capacity, efficiency and by reducing GHG emissions in an economical way. Repowering can be done by various ways. Wolowicz *et al*. (2005) showed that improvement in power output and efficiency of a super critical power plant by 20% and 1%, respectively can be done by feedwater repowering using hot exhaust gas from a gas turbine (GT). Escosa and Romeo (2009) showed that 15% CO_2 emission reduction and 2.61% efficiency improvement of an existing power plant can be done by feedwater repowering whereas 23.17% CO_2 emission reduction and 3.62% efficiency improvement of the same existing plant can be done by parallel repowering by integrating GT with the existing plant. Karellas *et al*. (2012) made energetic, exergetic and economic analyses of feedwater repowering using GT exhaust and parallel repowering by GT and heat recovery steam generator. Carapellucci and Giordano (2013) made energy and economic performance analyses of feedwater repowering of an existing coal based power plant. A further study of the same author (2014) evaluated the effects of feedwater repowering operating conditions on energy, environmental and economic performances of a 600 MW coal fired power plant at different condenser overloads and boiler modes of operation. Tawfik and Smith (2010) addressed that hot windbox repowering and combined cycle repowering of an existing unit helps to increase in output by 49.2% and reduction in heat rate by 11.6%. Yilmazoglu and Durmaz (2013) showed that increase in net power output by 27% and decrease in specific CO_2 emission can be done by hot windbox repowering of a thermal power plant. Repowering by GT exhaust reburning in a combined cycle helped to increase the capacity and efficiency of Goi Thermal Power Plant the plant by 36% and 7.8%, respectively (Centre for the Analysis and Dissemination of Demonstrated Energy Technologies, 1996) Tucakovic *et al*. (2013) investigated the reconstruction of boiler of existing steam power plant for using GT exhaust by means of thermodynamic and economic analysis. Xu *et al*. (2013) addressed the effect of flue gas waste heat recovery on net work output and coal consumption of a typical 1000 MW coal fired plant in China. So it is seen from the above literature survey that various researcher have made investigation of repowering of existing power plant by using GT in different ways.

In this paper, a techno- economic analysis of a partial repowering scheme for an existing coal fired power plant, through GT integration and feed water heating using boiler exhaust, is reported. In this scheme, out of four coal mills, one mill is taken out from the existing boiler and equivalent energy is supplied by sending the GT exhaust into the furnace of the existing boiler. The residual oxygen content in the GT exhaust takes part in the combustion of coal, thereby reducing the boiler's secondary air requirement. Along with this, waste heated feedwater heaters are proposed to be installed after the existing air preheating section of the boiler for feed water heating by utilizing the waste heat of the flue gas coming out from the repowered plant's boiler.

2. Existing plant description

The schematic diagram of the existing plant is shown in Fig. 1. Here a 210 MW thermal power plant is considered. The figure shows all the major components of the plant and their configuration. The coal is burnt in the furnace (CC), and then the hot flue gas goes to the stack through induced draft fan (ID Fan) exchanging heat at evaporator (EVP), superheater (SPH), reheater (RH), economizer (ECO) and air pre-heater (APH) sections of the boiler. The forced draft fan (FD Fan) supplies the air, preheated at the air pre-heater (APH), to the furnace. The generated steam from the boiler is expanded high-pressure turbine (HPT), intermediate pressure turbine

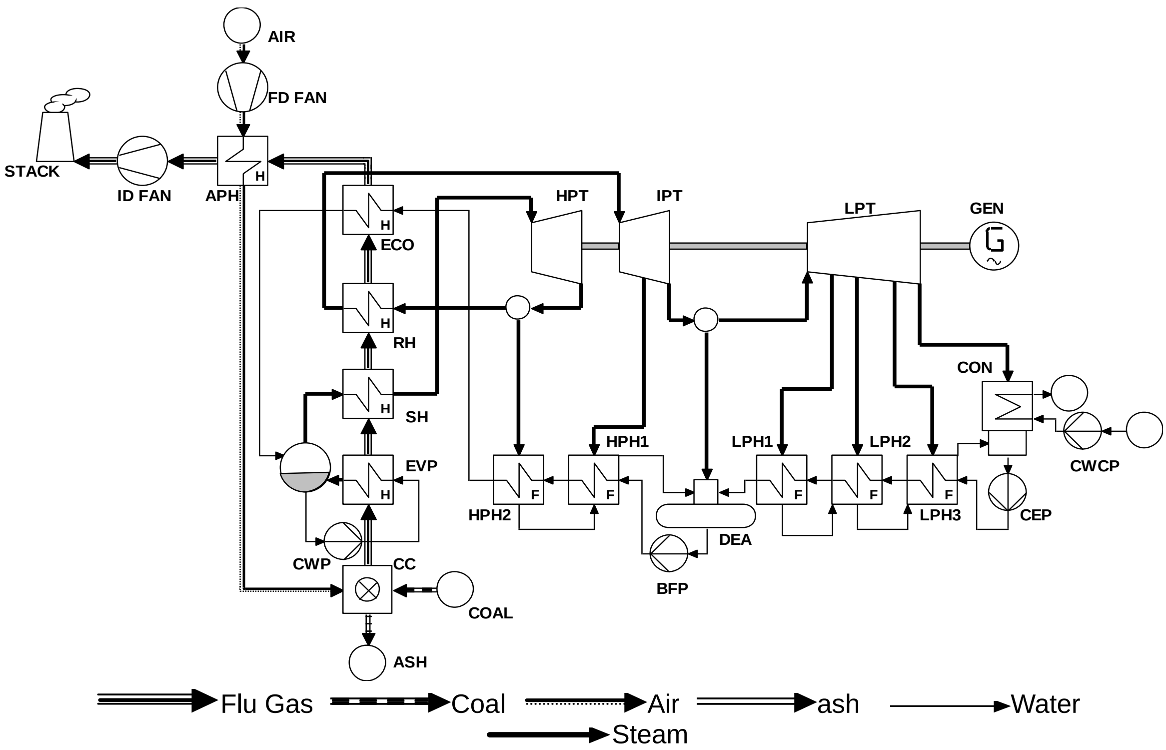

Fig. 1 Schematic diagram of the steam power plant in Cycle Tempo software interface

(IPT), low pressure turbine (LPT), which are connected to the generator (GEN) with a single shaft. There are two high pressure feed water heaters (HPH 1 & 2) and three low pressure feed water heaters (LPH1, 2 & 3). Some steam is extracted from the reheat line for heating purpose at HPH2 as shown in the Fig. 1. After being condensed in the condenser (CON), the LPT exhaust is fed to the deaerator (DEA) by the condensate extraction pump (CEP) through LPHs. Similarly the feed water from DEA is fed to the boiler through the high pressure heaters (HPH1 & 2) by the boiler feed pump (BFP). The feed water heaters are cascaded to each other. The condensate from the HPH is fed to deaerator and the condensate from LPH is fed to the condenser. The cooling water is supplied to the condenser by the cooling water circulation pump (CWCP). The circulation water pump (CWP) helps to circulate the water at the evaporator section of the boiler.

3. Configuration of the repowered plant

The schematic of the repowered plant is shown in Fig. 2. Here a natural gas fired GT block is added to the old plant. The air compressor (AC) compresses fresh air and sends it to the combustion chamber (CoC) of the GT. In the combustion chamber the compressed air reacts with standard natural gas, supplied by the fuel compressor (FC) and produces hot gas which expands in the GT. The compressor, turbine and the generator are mounted on a common single shaft. One of the existing coal mills is considered to be taken off and one-mill-equivalent energy is supplied through the GT exhaust into the furnace (CC) of the old boiler. The residual oxygen content of the

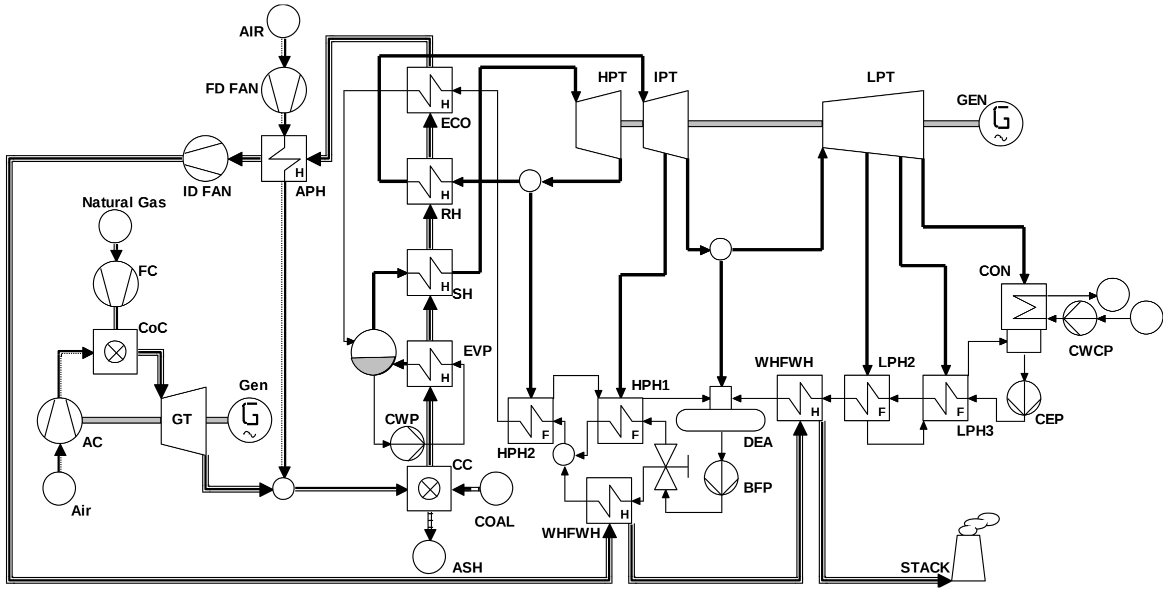

Fig. 2 Schematic diagram of the repowered power plant in Cycle Tempo software interface

GT exhaust aids in the combustion of coal in the boiler and helps in reducing the secondary air requirement. The boiler walls are assumed to be modified at the affected burner positions to provide the entry for the hot GT exhaust. Rest of the configuration of the old plant remains same as before, only the waste heated feed water heaters (WHFWH) are incorporated in place of two existing feed water heaters, HPH1 and LPH1, for waste heat utilization of the flue gas coming out from the boiler of the repowered plant.

4. Assumptions

The following assumptions are made for the analysis.

i) The coal mills equally share the total coal flow rate in the existing plant.

ii) The isentropic efficiency values for the steam turbines, pumps, fans are 88%, 86% and 86%, respectively whereas the generator efficiency 95%.

iii) A typical Indian coal is assumed to be used in the existing coal fired plant. The following composition (by mass) of coal has been considered: 34.46% C, 2.43% H_2, 0.69% N_2, 6.97% O_2, 0.45% S, 12% H_2O and 43% ash (Suresh *et al*. 2012).

iv) The isentropic efficiencies of compressor and gas turbine are 87%.

v) The waste heat utilization is done by cooling the flue gas up to 100° C

vi) A GE H-series (Matta *et al.* 2000) gas turbine is considered to be used in the GT cycle where turbine inlet temperature (TIT) is taken 1300° C.

vii) The chemical composition of the natural gas is taken (Hazarika and Ghosh 2013) as CH_4: 0.8129, N_2: 0.1432, O_2: 0.0001, CO_2: 0.0089 and others higher hydrocarbons: 0.0349 (molar fraction), LHV: 38000 kJ/kg and HHV: 42107.3 kJ/kg.

5. Thermal modeling and heat balance calculations

Both the existing and repowered plants are modeled in Cycle Tempo (TU Delft 2005) simulation software. The operating parameters of the steam cycle are taken from existing plant data. The performance of the existing and the repowered plant are analyzed using first law analysis and heat balance calculations.

The net power output of the existing steam power plant is given as follows

$$\left(\dot{W}_{net}\right)_{st} = \dot{W}_{HPT} + \dot{W}_{IPT} + \dot{W}_{LPT} - \dot{W}_{CEP} - \dot{W}_{BFP} - \dot{W}_{CWP} - \dot{W}_{CWCP} - \dot{W}_{IDFan} - \dot{W}_{FDFan} \tag{1}$$

The net efficiency of the steam plant and plant heat rate (*HR*) is given as follows

$$\eta_{st} = \frac{\left(\dot{W}_{net}\right)_{st}}{\left(\dot{m}\right)_{coal} \times LHV} \times 100\% \tag{2}$$

$$HR_{st} = \frac{3600}{\eta_{st}} \tag{3}$$

The energetic performance of the repowered plant is also estimated by evaluating its major performance parameters.

The net power output from the gas turbine unit is given as follows

$$\left(\dot{W}_{net}\right)_{GT} = \left(\dot{W}\right)_{GT} - \left(\dot{W}\right)_{C} \tag{4}$$

where W_{GT} power developed by the gas turbine and W_C is the power consumed by compressor and they are determined by the following equations

$$\left(\dot{W}\right)_{GT} = \left(\dot{m}\right)_{flue\ \ gas} \int_{T_{Gout}}^{T_{Gin}} c_{p_{fluegas}}\, dT \tag{5}$$

$$\left(\dot{W}\right)_{C} = \left(\dot{m}\right)_{air} \int_{T_{ain}}^{T_{aout}} c_{p_{air}}\, dT \tag{6}$$

where T_{Gin} and T_{Gout} are the flue gas temperatures at gas turbine inlet and outlet, respectively and T_{ain} and T_{aout} are the air temperature at air compressor inlet and outlet, respectively.

The net power output of the repowered plant is given as follows

$$\left(\dot{W}_{net}\right)_{RP} = \left(\dot{W}_{net}\right)_{st} + \left(\dot{W}_{net}\right)_{GT} \tag{7}$$

The total rate of heat input for the repowered plant is given by the following equation.

$$\left(\dot{Q}_{in}\right)_{RP} = \frac{3}{4} \times \left(\dot{m}\right)_{coal} \times LHV + \left(\dot{Q}_{in}\right)_{GT} \tag{8}$$

The net efficiency and heat rate of the repowered plant are given as follows:

$$\eta_{RP} = \frac{\left(\dot{W}\right)_{RP}}{\left(\dot{Q}_{in}\right)_{RP}} \times 100\% \tag{9}$$

$$HR_{RP} = \frac{3600}{\eta_{RP}} \tag{10}$$

6. Estimation of CO_2 emission characteristics

Specific emission of CO_2 of the existing plant is calculated on the basis of simulated flue gas data analysis of the existing plant in Cycle Tempo interface. The rate of CO_2 emission from the existing plant can be expressed as follows

$$\left(\chi_{CO_2}\right)_{st} = \frac{\left(\dot{m}\right)_{Flue\ gas}}{\left(M\right)_{Flue\ gas}} \times molar\ \%\ of\ CO_2 \times M_{CO_2} \tag{11}$$

where, M is the molar weight.

The specific CO_2 emission rate of the existing steam plant is given as follows

$$\left(\xi_{CO_2}\right)_{st} = \frac{\left(\chi_{CO_2}\right)_{st}}{\left(\dot{W}_{net}\right)_{st}} \tag{12}$$

The rate CO_2 emission from the GT unit is estimated from the simulated gas composition data of Cycle Tempo analysis and can be expressed as

$$\left(\chi_{CO_2}\right)_{GT} = \frac{\left(\dot{m}\right)_{GT\ exhaust}}{M_{GT\ exhaust}} \times molar\ \%\ of\ CO_2 \times M_{CO_2} \tag{13}$$

where, M is the molar weight.

The total rate of CO_2 emission from the repowered plant is given as follows

$$\left(\chi_{CO_2}\right)_{RP} = \frac{3}{4} \times \left(\chi_{CO_2}\right)_{st} + \left(\chi_{CO_2}\right)_{GT} \tag{14}$$

The specific CO_2 emission rate from the repowered plant is given by the following equation.

$$\left(\xi_{CO_2}\right)_{RP} = \left(\frac{\chi_{CO_2}}{\dot{W}_{net}}\right)_{RP} \tag{15}$$

7. Economic analysis

The effect of this partial repowering is also assessed from an economic point of view. Here the attention is focused on the unit cost of electricity (UCOE) produced from the repowered plant. The UCOE is calculated and compared with the existing plant and new green-field plant of same capacity.

The unit cost of electricity is estimated by the following equation

$$UCOE = \frac{COE_{CAP} + COE_{O\&M} + COE_{FUEL}}{E} \tag{16}$$

where, E is the annualized delivered electricity.

The annualized delivered electricity from the power plant is estimated by the following equation.

$$E = W \times 8760 \times CUF \times (1 - a) \tag{17}$$

The different component of the unit cost of electricity is estimated by the following equations.

$$COE_{CAP} = TOC \times CRF \tag{18}$$

$$COE_{FUEL} = C_{FUEL} \times HR \times E \tag{19}$$

The total overnight capital cost (TOC) and capital recovery factor (CRF) are estimated by the following equations.

$$TOC = CC \times W_{net} \tag{20}$$

$$CRF = \frac{d}{\left(1 - (1 + d)^{-n}\right)} \tag{21}$$

The UCOE of the existing plant is estimated as follows

$$UCOE_{EP} = \frac{(COE_{CAP})_{EP} + (COE_{O\&M})_{EP} + (COE_{FUEL})_{EP}}{E_{EP}} \tag{22}$$

The unit cost of electricity of the repowered plant ($UCOE_{RP}$) is estimated as follows

$$UCOE_{RP} = \frac{(COE_{CAP})_{EP} + (COE_{CAP})_{GT\,unit} + (COE_{CAP})_{HX}}{E_{RP}} + \frac{(COE_{O\&M})_{EP} + (COE_{O\&M})_{GT\,unit} + (COE_{O\&M})_{HX}}{E_{RP}} + \frac{(COE_{FUEL})_{EP} + (COE_{FUEL})_{GT}}{E_{RP}} \tag{23}$$

The capital cost of the GT unit is estimated (Carapellucci and Giordano 2013) by the following equation.

$$(COE_{CAP})_{GTUnit} = 4424 \times P_{GT}^{0.78} \tag{24}$$

Table 1 List of assumptions for economic analysis

Name of the parameters	Existing plant	GT cycle
Plant life(Years)	30	15
Yearly operating hours(h)	8760	8760
Discount rate (%)	12	12
CRF	0.124	0.147
Capital cost ($/kW)	1000	800
Fuel cost ($/GJ)	3.2	4.8
CUF (%)	85	85
Auxiliary consumption (%)	4	4

Table 2 Major operating and performance parameters of the existing steam power plant

Parameters	Description	Quantity	Units
HP steam parameters	Pressure	147	bar
	Temperature	540	℃
Steam flow rates	HP turbine	179.2	kg/s
	IP turbine	162	kg/s
	LP turbine	142.15	kg/s
Rate of Energy Input	Coal flow rate per mill	8.34	kg/s
	No. of mill operating	4	
	Total rate of input energy	620124	kW
Air requirement	Primary	33.06	kg/s
	Secondary	221.14	kg/s
Gross Power	Steam Generator	219014.84	kW
Auxiliary Power Consumption	BFP	4141.4	kW
	CEP	156.27	kW
	CWP	224.04	kW
	CWCP	3047.1	kW
	FD Fan	708.05	kW
	ID Fan	737.91	kW
Net power		210000.08	kW
Efficiency	Net	33.86	%

where *P* is the power developed from the *GT* unit in *MW*.

The capital cost of heat exchangers (HX) for waste heated feed water heating is estimated by the following equation as suggested by Soltani *et al.* (2013).

$$\left(COE_{CAP}\right)_{HX} = 4122 \times A_{HX}^{0.6} \tag{25}$$

Where, the overall heat transfer coefficient (*U*) of the heat exchanger is considered as 0.029 kW/m^{2}K, assuming that the heat exchanger is made of stainless steel.The *UA* value is taken from the simulation result of the Cycle Tempo interface considering that the heat exchangers are of counter flow type.

The operation and maintenance cost is considered as 4% of the TOC. The other assumptions for economic analysis are summarized in Table 1. These assumptions are made on the basis of available data in literatures (Suresh *et al*. 2010, Banerjee 2014, Lako and Tosato 2010). A green field ultra supercritical power plant (USCPP) of similar capacity and efficiency has been also considered for comparison. The different components of the COE of the new USCPP are estimated using available data given in the literature (Mott MacDonald 2006, 2007).

8. Results and discussions

Table 2 presents the major performance and operating parameters of the existing steam power plant. The GT block is designed in such a way so that its exhaust gas would be able to supply the equivalent heat that was supplied from one existing coal mill of the steam plant. Keeping this in mind the mass flow rate of the GT exhaust is determined and finally the total mass flow rate of flue gas flowing through the repowered boiler is determined. As there is 13.16 % of O_2 present by mass in the GT exhaust, the secondary air supply to the repowered plant boiler is reduced. But, the amount of primary air supply per coal mill is kept constant. A comparison of different parameters of gas flow condition through the boiler before and after repowering is given in Table 3. Table 3 indicates that the temperature of the flue gas, coming out from the repowered boiler, is substantially high that is going to be wasted in the atmosphere. In this repowering scheme the waste heat of the flue gas is proposed to be utilized through WHFWH (gas to liquid heat exchanger) replacing one HPH (HPH1) and one LPH (LPH1) of the existing cycle. This arrangement helps to save bleed steam from IPT and LPT, leading to increase the specific work output from the steam cycle.

Table 3 Comparison between the conditions of gas flow through existing and repowered plant boiler

Parameters	Mass flow rate and Temperatures of air and flue gas before and after repowering	
	Before	After
Primary air	33.05 kg/s	24.78 kg/s
Secondary air	221.14 kg/s	100.22 kg/s
Exhaust gas from GT	NA	134.29 kg/s
flue gas through APH	273.2 kg/s	273.54 kg/s
flue gas before APH	398.94° C	347.24° C
flue gas after APH	135.17° C	219.2° C

Table 4 Comparison between the heating arrangements of FWHs of the existing and repowered plant

Feed water Heaters	Requirement of Bleed steam before and after repowering			
	Before		After	
	Heating Agent	Flow rate (kg/s)	Heating Agent	Flow rate (kg/s)
HPH2	Steam from reheat line	17.19	Steam from reheat line	17.19
HPH1	Bleed steam from IP	9.56	Bleed steam from IP	3.19
LPH1	Bleed steam from LP	7.307	NA	NA
LPH2	Bleed steam from LP	7.71	Bleed steam from LP	8.46
LPH1	Bleed steam from LP	3.22	Bleed steam from LP	3.38
Total		44.987		32.22

Table 5 Major operating and performance parameters of the repowered power plant

Parameters	Description	Quantity	Units
HP steam parameters	Pressure	147	bar
	Temperature	540	°C
Steam flow rates	HP turbine	179.2	kg/s
	IP turbine	162	kg/s
	LP turbine	148	kg/s
Rate of Energy Input	Coal flow rate per mill	8.33	kg/s
	No. of mill operating	3	
	Input from coal	465000	kW
	Natural gas flow rate	4.064	kg/s
	Input from natural gas	154453.91	kW
Air requirement	Primary	24.78	kg/s
	Secondary	100.22	kg/s
	Fresh Air for GT block	130.23	kg/s
Gross Power	Steam Generator	227165.50	kW
Auxiliary Power Consumption	BFP	4140.94	kW
	CEP	164.08	kW
	CWP	223.94	kW
	CWCP	3338.77	kW
	FD Fan	350.98	kW
	ID Fan	895.69	kW
Net power	From steam cycle	218051.1	kW
	From GT cycle	50000	kW
Total net output	From repowered plant	268051.1	kW
Efficiency	Net	43.27	%

Table 6 performance comparison between the existing and repowered plant

Name of Parameters	Units	Existing plant	After repowering
Net power of Steam turbine	MW	210	218.05
Net power of Gas turbine	MW	NA	50
Net Heat rate	kJ/kWh	10632.014	8319.85
Net Efficiency of the plant	%	33.86	43.27
Specific CO_2 emission	t/MW-h	0.9292	0.663
Total capacity of the plant	MW	210	268

A comparison among the individual heat load of existing FWHs, heating arrangements and the requirement of bleed steam for feed water heating of the existing and the repowered plant is given in Table 4. The configuration of the plant after repowering is shown in the Fig. 2. The major performance and operating parameters of the repowered plant, simulated in cycle tempo software, are given in the Table 5. Table 5 indicates that the net output of the steam cycle is increased by about 3.8%. This increment in net output happens because of decrease in bleed steam due to conventional feed water heating. At the same time 50 MW capacity is added from the gas turbine. Finally the total net output of the plant increased by 58 MW collectively.

Table 7 Comparison of economic performance existing, repowered and new power plant

Parameters	Existing plant	Repowered plant	New green field plant
P_{st} (MW)	210	218	268
P_{GT} (MW)	-	50	-
P_{Total} (MW)	210	268	268
η_{st} (%)	33.86	46.88	43.2
η_{GT} (%)	-	32.37	-
$\eta_{Overall}$ (%)	33.86	43.27	43.2
$UCOE_{CAP}$ (\$/MW-h)	17.35	17.09	24.07
$UCOE_{O\&M}$ (\$/MW-h)	5.59	5.50	7.77
$UCOE_{FUEL}$ (\$/MW-h)	34.02	29.95	26.67
$UCOE$ (\$/MW-h)	56.96	52.54	58.51

A comparison between the performances of the existing and repowered plants is given in the Table 6. It can be clearly seen from Table 6 that, the present repowering scheme helps to increase in capacity and overall efficiency by about 27% and 28%, respectively and decrease the specific CO_2 emission by about 29%. The different cost components of the UCOE of the existing and repowered plant are given in the Table 7. A comparison among the different components of the existing plant, repowered plant and a green field USCPP is given in the Table 7. From the Table 7 it is clearly seen that the UCOE of the repowered plant has been lowered than the existing one. It can be also interpreted from the Table 7 that, if a new a green field power plant is established which would have similar capacity and efficiency of the repowered plant, then also the UCOE goes higher than the repowered plant. The initial capital investment is also high for the new establishment than the GT integrated repowering scheme. The partial repowering scheme results in reduction of the UCOE by 8.4%. So it can be said that the partial repowering is profitable and cost effective for capacity and efficiency improvement.

9. Conclusions

In the present study, partial repowering of an old 210MW coal based power plant by replacing one operating coal mill with a natural gas fired GT unit and waste heated feed water heating, has been analyzed techno-economically. The net output of the plant increases by about 28% as well as the net efficiency of the plant also increases by 28%. The specific CO_2 emission of the plant decreases by about 29% after repowering. The economic analysis reveals that the unit cost of electricity (UCOE) generation decreases by 8.4% due to repowering. The economic analysis further shows that a partially repowered plant, as proposed herein, is favorable compared to a new plant of similar capacity both in terms of capital investment and unit cost of electricity. So it can be concluded that without much more capital investment, an existing power plant can be transformed into such plant which have more capacity, improved efficiency and emission characteristics. The study therefore establishes that partial repowering is a techno-economically viable option, wherein land space and equipment of existing plants could be utilized and at the same time improvement in capacity, overall efficiency and emission can be achieved at reasonable cost.

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CC

List of symbols

A	Area [m^2]
a	Auxiliary consumption [%]
c	Specific [kJ/kg-K]
d	Discount rate [%]
E	Annualized net generated electricity [kWh]
$\dot{m}$	Mass flow rate [kg/s]
n	Plant life [years]
$\dot{Q}$	Rate of heat input [kW]
$\dot{W}$	Power [kW]
η	Efficiency [%]
ξ	Specific emission rate [kg/MWh]
χ	Emission rate [kg/s]

Abbreviation

CC	Capital cost per MW [$]
CUF	Capacity utilization factor
LHV	Lower heating value [kJ/kg]

Subscript

CAP	Capital
dfg	Dry flue gas
EP	Existing Plant
fg	Flue gas
GT	Gas turbine
in	Input
O&M	Operation and Maintenance
p	Pressure
RP	Repowered plant
st	Steam turbine