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ARTICLE

Techno-economic analysis on oxy-fuel based steam turbine power system using municipal solid waste and coals with ultrasonicator sulfur removal

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Abstract

Municipal solid waste (MSW) is a carbon–neutral energy source and possesses a moderate heating value; hence, it can be used as an alternative fuel for coal. To use high ash and high sulfur Indian coals efficiently, a techno economic analysis is performed for electricity generation using supercritical and subcritical based steam turbines operating in the oxy-fuel co-combustion mode of MSW with Indian coals. The impact of the capture of direct and indirect greenhouse gasses such as CO_2, NO_x and SO_x on the net thermal efficiency of the power plants is assessed. The supercritical based steam turbine achieved a higher net thermal efficiency by 8.8% using MSW based feedstock compared to sub-critical conditions. The co-combustion mode reduced the levelized cost of electricity (LCOE) by 48–73 \$/MWh. Techno-economic analysis for sulfur removal in coal using ultrasonication technology has not yet been reported in the literature. The incorporation of an ultrasonicator (a pre-combustion sulfur remover) and a duct sorbent injector (a post-combustion SO_x absorber) increased the LCOE by 1.39–2.75 \$/MWh. In high sulfur coals, the SO_x emissions decreased from 224.79 mg/m^3 to 9.2 mg/m^3.

Keywords Municipal solid waste · Coal · Steam turbine power plant · Economic analysis · Co-combustion

Abbreviations

ACC	Annual capital cost
ASU	Air separation unit
CCU	Carbon capture and utilization
CRF	Capital recovery factor
DSI	Duct sorbent injection
FGD	Flue gas desulfurization
FW	Feedwater preheater
HAC	High ash coal
HPST	High pressure steam turbine
LAC	Low ash coal
LCOE	Levelized cost of electricit
LPST	Low pressure steam turbine
MPST	Medium pressure steam turbine
MSW	Municipal solid waste
n	Scaling factor
PCCI	Power capital cost index
PGU	Power generation unit
PPPI	Purchasing power parity index
r	Rate of capital discharge
SCR	Selective catalytic reduction
SH	Superheater
t	Lifetime of power plant
UC	Ultrasonication
WTE	Waste to energy

List of symbols

P_{HPST}, P_{MPST}, P_{LPST}	Power produced by HPST, MPST, LPST
P_{ASU}, P_{CCU}, P_{PUMP}, P_{GAS}	Power consumed by ASU, CCU, pump and gas cleaning unit
C_{INDIA}, C_{USA}	Cost in India and the USA
C_{E}	Cost of equipment with known capacity and is to be calculated
C_{B}	Cost of equipment with known capacity
Q_{E}	Capacity of equipment whose cost is to be calculated
Q_{B}	Capacity of equipment with known cost

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Introduction

MSW (Municipal solid waste) generation has been increasing substantially over the years and poses a threat to human health and the environment. The amount of MSW generated almost doubled from 2007 to 2017 in India. According to the Ministry of Statistics and Program implementation, 21.14% of the MSW generated was treated in India [1]. Landfills are the most common techniques to dispose of MSW. In India, according to the calculations made by Kulkarni annually, the area required for MSW disposal would vary between 8154 km^2 and 36695 km^2 in 2017 [1]. This would increase the burden on the current MSW treatment infrastructure. Landfill taxes were levied in countries like the UK, Australia, and Canada to discourage landfilling and improve the treatment of MSW and recycling [1]. Incineration of MSW is one of the common methods to generate energy from MSW. In 2015 and 2016, 59 WTE (waste to energy) plants were constructed in India that had a capacity of 538.3 MW, of which only 7 WTE plants were functional with the capacity of 92.4 MW [2]. During the same period, European countries had the capacity to treat 5.44×10^7 tons of MSW with 251 WTE plants [3]. In China, from 2000 to 2019, 400 WTE plants were built [4]. Hence, the number of WTE plants has to be increased in India for MSW management. Da Silva et al. [5] pointed out that MSW treatment by the incineration method is not expensive and requires a smaller area for processing than other treatment methods. The accumulation of a huge volume of MSW in landfills can be avoided by incineration. Afanasyeva and Mingaleeva [6] proposed a small-scale coal-based power plant for the production of electrical and thermal energy with the extraction of sulfur.

Depending upon the calorific value of MSW, it can be incinerated as a single fuel or with other fuels. If the calorific value of MSW is between 6.28 MJ/kg and 10.05 MJ/kg, then MSW should be co-combusted with other fuels [7]. The calorific value of MSW in many cities in India falls in the above range [8]; thus co-combusting it with Indian coals will be beneficial.

Energy and economic analysis of coal and MSW combustion have become important for the commercial utilization of MSW in thermal power plants. MSW has a comparatively lower calorific value than conventional fuels such as coal and natural gas. The net efficiency of coal-based power plants is around 32%–35% without CO_2 capture under subcritical conditions [9, 10]. When MSW is combusted under subcritical conditions, the net efficiency of WTE plants is estimated to be around 18%–22% [11–13]. This is due to the low calorific value of MSW, and it was recommended that the co-combustion of coal with MSW could enhance the efficiency of power plants [7]. The MSW power plant in Spain co-utilizes natural gas with MSW and achieves a net thermal efficiency of 31.66% [14].

MSW, as a low-quality fuel, requires pre-treatment such as drying and removal of inert components. An economic analysis of WTE plants was carried out by Zhao et al. [15]. They found that the net profit margin grew from 14.7% to 26.7% in 18 years. They concluded that the use of locally made equipment would be able to decrease investment costs by 30%–35%. By improving the efficiency of fuel utilization with simultaneous production of power and heat, pollutant gas emissions can be reduced [16]. Yassin et al. performed economic and energy analysis considering the wastes to energy under non-oxy combustion mode in the UK [12]. They found that a larger scale of operations can reduce electricity costs. As the plant scale is increased from 50 ktpa to 100 ktpa LCOE (levelized cost of electricity) decreases from 148 €/MWh to 97 €/MWh.

Combustion of coal is known to produce a high amount of greenhouse gases such as CO_2, SO_x, and NO_x. Similarly, the combustion of MSW can produce pollutants like dioxins and difurans [17]. Removal of such gases is necessary to maintain specific air quality. The existing CO_2 capture techniques can be divided into three parts post-combustion, pre-combustion, and oxyfuel combustion. In the post-combustion, technique flue gas produced is scrubbed with the help of amine solutions that react with CO_2. In pre-combustion method, fuel is gasified to form syngas. Syngas is then reacted with steam to form CO_2 and H_2 (water gas reaction). CO_2 can be separated and sequestered. In oxy-fuel combustion, fuel is combusted in a mixture of O_2 and CO_2 instead of being combusted in air. This results in the formation of flue gas with a high concentration of CO_2. Some amount of flue gas is recycled, and some are sequestered. The oxyfuel combustion technique is chemically less complex and can be easily switched from air combustion to oxy-fuel combustion mode. The amount of flue gas produced is 1/4 to 1/5 of that produced by other methods [18]. Compared to other techniques by oxyfuel combustion, SO_X and NO_x emissions are lower compared to other methods. This can help in operating high fuels with high sulfur and nitrogen contents [19]. Indian LACs contain a high amount of sulfur, and MSW contains a high amount of nitrogen. Oxyfuel combustion of such fuels becomes suitable for themselves.

Fuels having a high amount of sulfur require would require SO_x removal from flue gas to keep it within acceptable limits in air combustion and oxy-fuel combustion mode. SO_x removal becomes necessary as it can corrode boilers and decrease the concentration of CO_2 in flue gas [20]. Flue gas desulfurization (FGD) is conventionally used to remove SO_x emissions. To remove the additional amount of SO_x, duct sorbent injection (DSI) units can also be used. In the FGD unit, flue gases are scrubbed with lime or hydrated lime to form calcium sulfate or calcium sulfite, which can be separated and removed. In DSI, lime solution can be injected into ducts after the NO_x removal unit or before the scrubber unit. Similar reactions occur in this unit compared to FGD [20]. Ultrasonication (UC) of high sulfur coals using solvents like H_2O_2, HCl, and HNO_3 could aid in the removal of organic and inorganic sulfur from coals [21]. High sulfur coals and solvents are fed into an ultrasonicator, after which ultrasonic waves are created with the help of transducers. These ultrasonic waves interact with coal in the presence of solvents which results in the formation of bubbles. These bubbles break which results in coal fragmentation breaking sulfur and coal.

Knowledge gap

To date, researchers have not performed techno-economic analysis on oxy-fuel combustion of MSW. The literature also lacks in-depth knowledge of oxy-fuel co-combustion using MSW and coal in subcritical and supercritical conditions. Oxyfuel combustion of fuels has the potential to decrease greenhouse gas emissions. Indian coals mainly enriched in sulfur need to be investigated, as high sulfur coal combustion is expected to produce a high amount of SO_x in the flue gas. FGD, a conventional method for removing SO_x from flue gas, may not be able to remove a sufficient quantity of SO_x from flue gas. The impact of the sulfur removal technique on net thermal efficiency and economic analysis is elaborated in the present study. DSI and UC methods, which are conventional and non-conventional methods of sulfur removal, are compared economically and environmentally to analyze technique viability. Aspen plus simulations are carried out for the power plants under subcritical and supercritical conditions using the feedstocks of individual fuels and their blended conditions (HAC (high ash coal)/LAC (low ash coal):MSW) at various mass ratios for the following cases: (i) HAC, (ii) LAC, (iii) MSW, (iv) HAC:MSW (3:1), (v) HAC:MSW (1:1), (vi) HAC:MSW (1:3), (vii) LAC:MSW (3:1), (viii) LAC:MSW (3:1), and (ix) LAC:MSW (3:1).

Materials and methods

Fuel properties

In the present study, the MSW composition reported by Mboowa et al. is used for power plant simulation studies [22]. HAC and LAC are used as conventional fuels for the co-combustion with MSW. The HAC from Jharia mines, Jharkhand, and LAC from Bapung mines, Meghalaya, India are used in Aspen plus for the simulation of co-combustion based power plant studies. The proximate and ultimate analyses of the fuel are given in Table 1. MSW is a low calorific value fuel and possesses the chemical energy of 57% and 66.6% of LAC and HAC, respectively. LAC consists of a significant quantity of sulfur, whereas MSW has the lowest quantity of 0.41%.

Power plant configurations

The power plants consist of three major units: an air separation unit (ASU), a power generation unit (PGU), and a carbon capture and utilization (CCU) unit. The schematic diagram of the proposed power plant is shown in Fig. 1. In the proposed system, MSW is pre-treated to remove the moisture content. The boiler of the power plant operates at 1473 K to achieve the complete combustion of toxic materials such as polychlorinated biphenyls, polychlorinated dibenzodioxins, and dibenzofurans under subcritical conditions and 2045 K under supercritical conditions [17]. Under the co-combustion conditions, the net thermal efficiency of the steam turbine-based power plants is estimated for the various ratios of MSW and coal in the feedstock. MSW is mixed with coal varying from 0 to 100% by weight with a 25% increment in each case. A 100 MW of chemical energy of the feedstock is considered as the basis of the present study. The various operating conditions of the power plants in the present study are listed in Table 2. The reactor module used in the Aspen plus simulation is described in Table 3. HAC, LAC, and MSW are assumed to be non-conventional components, whose properties were defined by HCOALGEN and DCOALIGT models of Aspen Plus software [23]. Peng Robinson Boston Mathias model was used for the simulation of the power plants [10]. The

Table 1 Physical properties of fuel considered

Proximate analysis	Municipal solid waste (MSW, wt%) [22]	High ash coal (HAC, wt%)	Low ash coal (LAC, wt%)
Moisture content (a.r)	25.49	2	3.35
Volatile matter (d.b)	60.77	19.38	38.53
Fixed carbon (d.b)	6.08	50	59.46
Ash (d.b)	33.15	30.53	2.01
Ultimate analysis (d.b)			
Carbon	36.38	57.41	76.64
Hydrogen	4.56	5.02	4.41
Oxygen	23.62	6.06	11.22
Nitrogen	1.88	0.98	1.33
Sulfur	0.41	0	4.39
Calorific value (HHV) (MJ/kg)	14.85	22.3	26.13

a.r as received basis, *d.b* dry basis

Fig. 1 Block diagram of oxy-fuel power plant (UC and DSI units are optional). *UC* ultrasonication, *DSI* duct sorbent injection, *ASU* Air separation unit, *SCR* selective catalytic reduction, *RFG* recycleds flue gas, *FGD* flue gas desulfurization, *MSW* municipal solid waste, *CCU* carbon capture and utilization

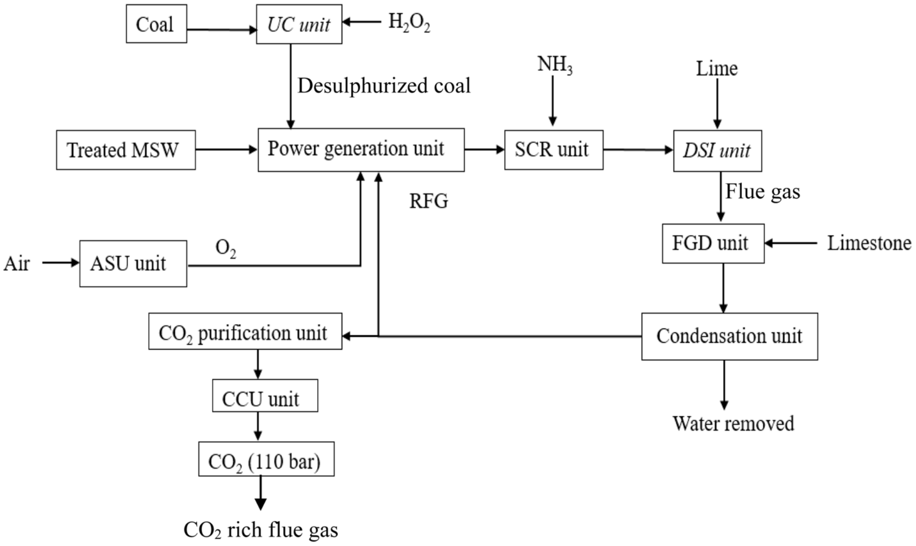


Table 2 Operating parameters of power plants used in Aspen Plus simulation

Item	Efficiency		Operating pressure		Operating temperature	
	Subcritical	Supercritical	Subcritical	Supercritical	Subcritical	Supercritical
Turbine operating conditions [38]						
HPST	89%	89.6%	19080 kPa	24220 kPa	773 K	810 K
MPST	90.3%	91.7%	3180 kPa	4200 kPa	815 K	838 K
LPST	85.1%	85.7%	518 kPa	290 kPa	569 K	488.6 K
Desulfurization techniques						
FGD unit [20]						
FGD unit inlet temperature			383–385 K			
SO_2 removal efficiency			98%			
Lime solution solids inlet			25%			
Gypsum solids			45%			
DSI unit [20]						
Inlet temperature			423 K			
SO_2 removal efficiency			50%			
SO_3 removal efficiency			80%			
Ultrasonication (UC) unit [21]						
Solvent used			H_2O_2			
Reagent concentration			0.5 mol/L			
Sulfur removal efficiency			80%			
ASU assumptions [30, 39]						
Efficiency of compressors in ASU			80%			
Output pressure of compressors			198 kPa, 346 kPa, 635 kPa			
Specific power consumption			164 kWh/t			
CCU unit [29]						
Number of compressors			5			
Operating pressure of compressors			320 kPa, 1360 kPa, 3350 kPa, 7000 kPa, 11000 kPa			

HPST High pressure steam turbine, *MPST* medium pressure steam turbine, *LPST* low pressure steam turbine, *ASU* air separation unit, *FGD* flue gas desulfurization, *DSI* duct sorbent injection, *CCU* carbon capture and utilization

Table 3 Reactor types used in Aspen plus simulations

Unit	Reactor type
Combustor	Rgibbs
Flue gas desulfurisation (FGD)	Rstoic
Selective catalytic reduction (SCR)	Rstoic
Duct sorbent injection (DSI)	Rstoic
Decomposer	Ryield

treated MSW and coal are fed to PGU. The generated flue gas is sent to flue gas cleaning and SCR (selective catalyst reduction) unit to remove SO_x and NO_x. UC and DSI units are optional for decreasing sulfur emissions. After SO_x and NO_x are removed, flue gas is sent to the condensation unit to remove water from flue gas. After water removal, part of flue gas is recycled to the combustor, and part is sent to the CO_2 purification unit.

FGD unit

In the present study, a wet FGD system is considered. In this system, limestone is used. A mixture of limestone, water, and oxygen is used to treat SO_2 and SO_3 in the flue gas, and as a result, the product gypsum is produced. The wet FGD system is highly efficient in removing 95%–99% of SO_x in flue gas [20]. Under oxy-fuel conditions, employing gas cleaning such as FGD, SCR for NOx removal is efficient compared to air combustion conditions due to low or zero dilution of flue gas with nitrogen [24]. In the SCR and FGD units, a pressure drop of approximately 5–10 kPa is considered. Hence, internal duct fans are used to pressurize the flue gas to avoid the ingress of air from the atmosphere. Reactions occurring in the FGD unit are given below:

$$SO_2 + H_2O \rightarrow H_2SO_3, \tag{1}$$

$$CaCO_3 + H_2SO_3 \rightarrow CaSO_3 + H_2O + CO_2, \tag{2}$$

$$CaSO_3 + 1/2O_2 + H_2O \rightarrow CaSO_4 \cdot 2H_2O. \tag{3}$$

DSI unit

DSI is a post-combustion SO_x removal technique. This process is capable of removing SO_2 and SO_3. The operating temperature of the DSI unit is found to be in the range of 393–453 K. The low operating temperature of the DSI is favorable for SO_2 removal. Various sorbents, such as lime, trona (a compound of Na_2CO_3), and ammonia, are used in this method. In the present study, lime is used as a sorbent for SO_x removal. Lime is capable of removing 50%–60% of SO_2 and > 80% of SO_3. DSI unit consumes 0.2% of the net power generated. Lime slurry is sprayed over the flue gas in the form of fine droplets, which makes it more reactive under dry conditions [20]. The chemical reactions occurring in this unit are given below [25]:

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O. \tag{4}$$

Desulfurization by UC unit

It is one of the pre-combustion sulfur removal techniques. Recent studies showed that UC technology was able to remove organic and inorganic sulfur from coals [21, 26]. In the present study, H_2O_2 solvent is used for the dissolution of sulfur from coal [21, 27]. During the UC process, the cavitation effect produces bubbles, which collapse producing high local temperature and high pressure on coal particle surfaces. These shockwaves produce shear forces, which break coal surfaces exposing sulfur sites in coal to the solvent. UC technology eliminates the mass transfer resistance and allows the solvent to diffuse easily into the sulfur site for dissolution. By employing low-cost solvents, this technology can be easily implemented for commercialization.

SCR

SCR process is used for the removal of NO_x pollutants. In this unit, ammonia or urea can be used for NO_x removal. V_2O_5 and TiO_2 are the most common types of catalysts that used in SCR units. In the current study, ammonia was used for NO_x removal [28]. Reactions occurring in NO_x unit are given below,

$$2NH_3 + 2NO + 0.5O_2 \rightarrow 2N_2 + 3H_2O, \tag{5}$$

$$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O. \tag{6}$$

CCU unit

This unit consists of five compressors operating at 320, 1360, 3350, 7000 and 11000 kPa [29]. Intercoolers and heat exchangers are used to cool the hot flue gas after compression by preheating the water required for steam generation. Additionally, the purified oxygen from the ASU unit is preheated in the CCU unit using the heat exchangers. It was found that around 78%–80% of the flue gas is recycled to maintain the combustor temperature.

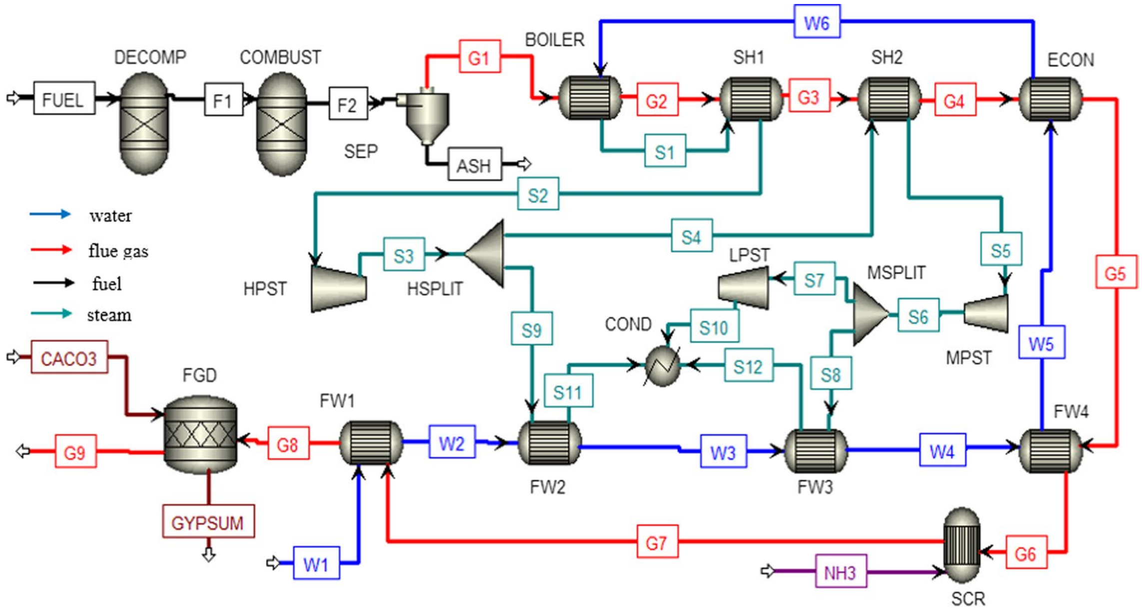


Fig. 2 Power generation unit (PGU) scheme. *FW* feedwater preheater, *S* steam, *W* water, *G* gases, *COMBUST* combustor, *COND* condenser, HSPLIT, *MPSPLIT* splitter after HPST and MPST, *ECON* economizer, *SH* superheater, *HPST* high pressure steam turbine, *MPST* medium pressure steam turbine, *LPST* Low pressure steam turbine, *SCR* Selective catalytic reduction, *Decomp* decomposer, *SEP* separator

PGU

Subcritical and supercritical power plants refer to the conditions in which operating fluid is used in steam turbines. Critical points refer to the pressure and temperature conditions above which a fluid behaves like vapor and liquid. In supercritical conditions, the working fluid is above the critical point.

The pure oxygen obtained from the ASU unit and the recycled flue gas, which is almost a pure CO_2 stream, is sent to the boiler operating at 1473 K under subcritical conditions and 2045 K under supercritical conditions. In the boiler, the oxygen levels were maintained in the range of 24%–26%, similar to the percentage of O_2 in the air [30]. The Ryield reactor in the Aspen model is used to dissociate the solid feedstock component into individual species. The pumped water is preheated from 343 K to 353 K using the heat generated during compression of air and flue gas in the ASU and CCU units, respectively (Fig. 2). Water is preheated from preheaters in the ASU and CCU units (PR8, PR3, PR7, PR6). As CCU and ASU units utilize pressurizing units, they heat gases. This heated gas is used to heat water in preheaters. Oxygen from ASU is preheated in these preheaters to increase the temperature to normal conditions. Preheaters used for oxygen are PR2, PR1, PR4 and PR5. The warm water from the ASU and the CCU unit is sent to the feedwater preheater (FW) section. The power plant consists of three steam turbines, that is high pressure steam turbine (HPST), medium pressure steam turbine (MPST), and low pressure steam turbine (LPST), which are operating under high, medium, and low pressure, respectively.

The operating conditions of steam turbines under subcritical and supercritical conditions are given in Table 2. Steam is superheated to 773 K in Superheater 1 (SH1) using hot flue gas whose temperature is reduced to 842 K under subcritical conditions (Fig. 2). In the supercritical conditions, the steam temperature reached 810 K, and the flue gas temperature was reduced to 1430 K. The superheated steam drives the HPST, which generates electric power. A fraction of the outlet steam from SH1 is sent to the FW2 and the rest of the steam is reheated using a SH2. The steam from SH2 is used to drive the MPST. Furthermore, a fraction of the outlet steam outlet from the MPST is sent to the FW3 and the rest is sent to the LPST for electricity generation. The flue gas from SH2 is sent to an economizer to heat the preheated water at 614 K, which is further sent to the boiler. The flue gas from the economizer is sent to the gas cleaning units (DSI and SCR units) to capture the SO_x and NO_x gases. The DSI is an optional process depending on the level of SO_x in the flue gas. After the gas cleaning process, a portion of flue gas is recycled to the boiler for temperature moderation. The rest of the flue gas is sent to the water condensation unit. After the removal of water, the obtained dry flue gas is sent to CO_2 purification unit (CPU) to further remove SO_x and NO_x and obtain high purity CO_2 [31]. The cleaned CO_2 is pressurized to 11000 kPa using a series of compressors in CCU (Fig. 3) [29].

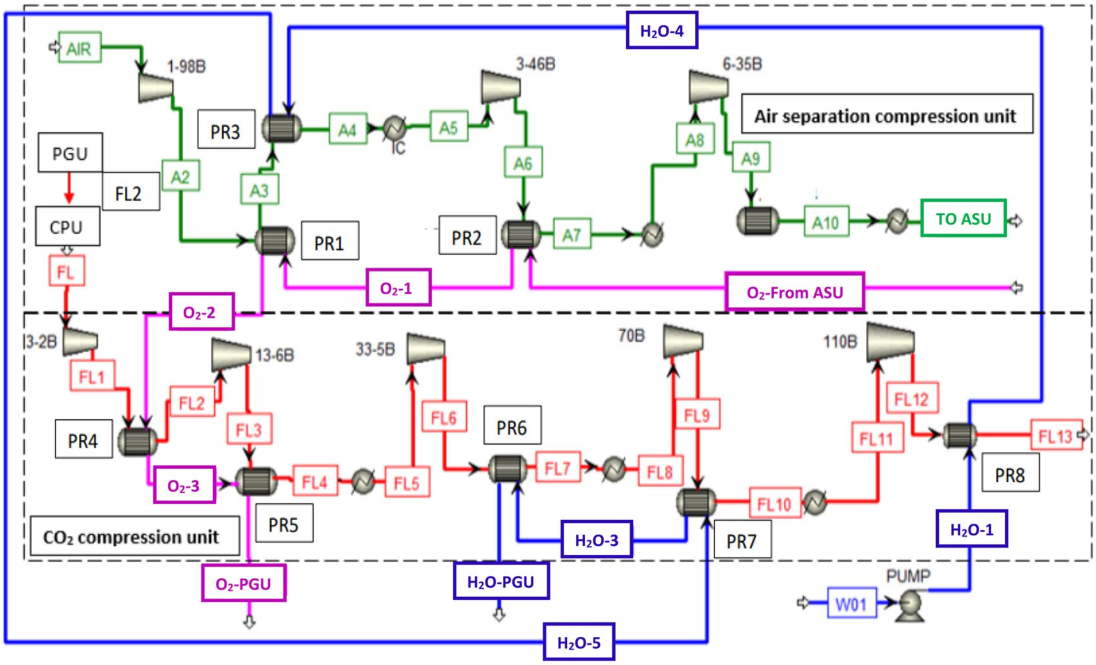


Fig. 3 Auxiliary unit CCU and ASU with PGU. *FL* flue gas, O_2 oxygen, H_2O water; *A* air, *PGU* power generation unit, *B* compressor, *CPU* CO_2 purification unit, *B* compressors, *PR* preheater, *ASU* air separation unit

MSW treatment section

MSW used in the present study contains about 1% inert materials possessing metals and glass. These inert materials should be removed before feeding the MSW into the boiler. The operational process of the MSW treatment unit in Ghazipur, New Delhi is considered in the present study [32]. The MSW from the landfills is sent to a slow conveyor where large inert materials are manually separated. The remaining MSW is sent to a magnetic separator where metals are separated. The MSW then goes to a set of two trommels where inert materials of size less than

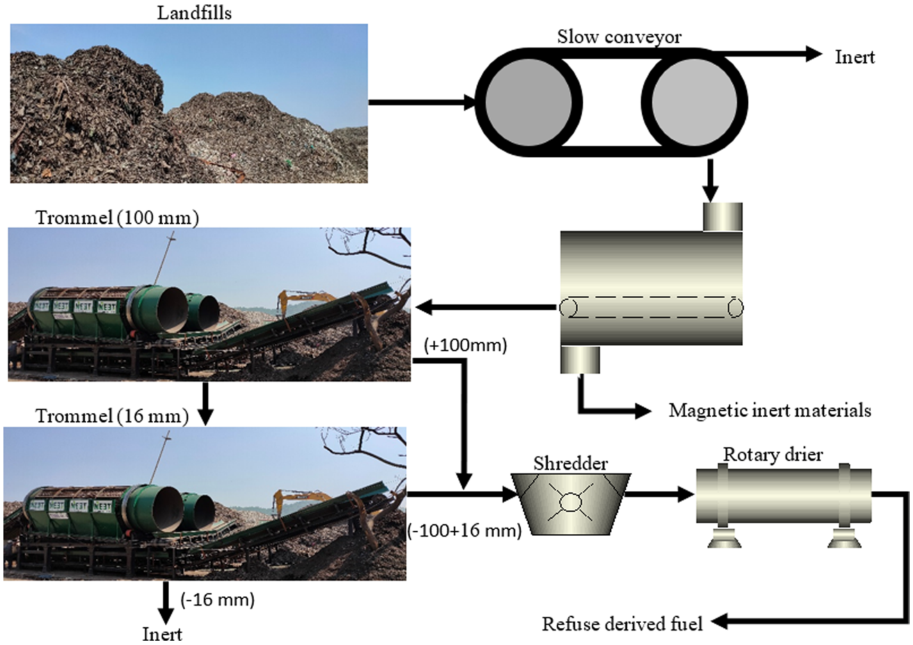


Fig. 4 MSW treatment unit

16 mm are separated. Then, the MSW with a size greater than 100 mm is sent to a shredder for size reduction. A rotary drier is used to decrease the moisture content of the MSW to 10%. Finally, the pre-treated MSW is sent to the boiler for combustion. The above-described processes are shown in Fig. 4.

Power plant efficiency calculation

The gross efficiency and net efficiency of the power plants are calculated by the following equations:

$$\text{Gross efficiency} = \frac{P_{\text{HPST}} + P_{\text{MPST}} + P_{\text{LPST}}}{\text{Input energy from feed stock}}, \tag{7}$$

$$\text{Net efficiency} = \frac{P_{\text{HPST}} + P_{\text{MPST}} + P_{\text{LPST}} - P_{\text{CCU}} - P_{\text{GAS}} - P_{\text{PUMP}} - P_{\text{ASU}}}{\text{Input energy from feed stock}}. \tag{8}$$

P_{HPST}, P_{MPST}, and P_{LPST} are the power produced by the HPST, MPST, and LPST, respectively. P_{CCU}, P_{ASU}, P_{PUMP}, and P_{GAS} are the power consumed by the CCU, ASU, water pump, and gas cleaning (SCR and FGD) units, respectively [23].

Economic analysis

The cost of the fuel feedstock is taken from the report of coal India 2020 and the recommendations given by the New Delhi Government, 2017 [32]. The cost of HAC, LAC, and MSW as per the price in India with cost parameters considered in the economic analysis are given in Table 4. The cost of MSW is estimated based on the tipping fee as per the guidelines of the New Delhi government for MSW management. The owner's cost and the land purchase cost are 15% and 5% of the total installed cost, respectively [23]. The total cost including purchase and operational costs is 3% of the total capital cost. The cost of various types of machinery and infrastructure was calculated as per the Indian scenario. Aspen software reports the cost of various machinery on an American basis. This is converted to an Indian basis by the following equation [10]:

$$C_{\text{India}} = C_{\text{USA}} \times \left(\frac{\text{PCCI for current year}}{\text{PCCI for original year}}\right) \times \text{PPPI}_{\text{India}}. \tag{9}$$

C_{India} is the cost of equipment in India, and C_{USA} is the cost of equipment in the USA. PCCI is the power capital cost index, and PPPI is the purchasing power parity index. The cost of turbines and boilers is calculated based on the report of the central electricity commission for various power plants. The cost of the infrastructure for the CCU unit is calculated using the data provided by Cau et al. [31]. The cost of equipment is calculated by Eq. 10 [23].

Table 4 Cost parameters considered for economic analysis in Aspen Plus simulation

Feed	Cost
LAC	0.043 \$/kg [32]
HAC	0.033 \$/kg [32]
MSW	0.021 \$/kg [40]
Limestone	22.4 \$/t [41]
Hydrogen peroxide	0.061 \$/L [36]
Cost parameters considered in economic analysis [23]	
Owner's cost	0.15 × total installed cost
Land purchase, surveying cost	0.05 × total installed cost
Annual discount rate	7%
Plant life	25 years

$$C_{\text{E}} = C_{\text{B}} \left(Q_{\text{E}}/Q_{\text{B}}\right)^{n}. \tag{10}$$

C_{E} is the cost of the equipment with a known capacity. Q_{E} and C_{B} are the known costs of the equipment with a given capacity Q_{B}. In Eq. 10, 'n' is the scaling factor, which is 0.7 in the present study. The cost of machinery related to MSW treatment of known capacity is taken from the detailed report of MSW management by Mohali and Medak municipality [32]. The cost of machinery related to power plants with known capacity is taken from the Central Electricity Regulatory Commission report [32] and the literature Cau et al. [31]. DSI and UC methods for sulfur removal are simulated in the present study. The capital cost of machinery for DSI and UC methods for sulfur removal was calculated based on Eq. 10, with the known cost of the equipment for a given capacity [33, 34]. The LCOE of a powerplant can be defined as the cost at which electricity should be sold so that the break-even point can be reached for the whole lifetime of the powerplant [35].

The LCOE was calculated by the following equations,

$$\text{LCOE} = \frac{\text{ACC} \times \text{Total operating and maintenance cost}}{\text{Net elelctricity produced}}, \tag{11}$$

$$\text{ACC} = \text{Total capital cost}\,(TC) \times \text{Capital recovery factor (CRF)}, \tag{12}$$

$$\text{CRF} = \frac{r(1+r)^{t}}{(1+r)^{t} - 1}, \tag{13}$$

ACC means annual capital cost, r is the rate of capital discharge, and t is the lifetime of the power plant [23].

Results and discussion

Net thermal efficiency of sub/supercritical power plants

The energy analysis of the power plants is performed in terms of their gross and net efficiency. Tables 5 and 6 show the estimation of the net thermal efficiency of the proposed steam turbine power plants under subcritical and supercritical conditions, respectively. The electric power produced by the steam turbines and the energy penalty associated with the auxiliary units, such as ASU, CCU, FGD, and SCR, are assessed. LAC, having the highest calorific value, results in the highest net thermal efficiency of the power plants. As LAC contains a high quantity of fixed carbon among other fuels, a larger quantity of oxygen is required for combustion, leading to a higher ASU penalty (about 7.9 MW). With the increase in the MSW content in the feedstock under co-combustion conditions, the oxygen requirement decreased, leading to a low energy penalty of the ASU (about 5.3 MW). MSW alone as the feedstock produces the least net electric power of 20 MW, whereas LAC achieved 30 MW production of electricity. However, the addition of 25% LAC with MSW had increased their electric power production (about 25 MW) with a net thermal efficiency of 25%. The ash effect in HAC leads to a 2% reduction in the net thermal efficiency compared to the LAC feedstock.

Desulfurization of HAC fuel is not needed, as it contains a negligible amount of sulfur. The NOx supercritical reduction unit consumes 0.6–1 MW under subcritical conditions whereas it cosumes 0.3–0.4 MW under supercritical conditions. The total energy penalty associated with the gas cleaning section is around 0.4–0.8 MW under supercritical conditions and 1–1.5 MW under subcritical conditions. The energy penalty of the NO$_x$ and SO$_x$ reduction units constitutes 3%–10% of the overall energy penalty of the power plants.

The net efficiency of the power plants operating with LAC and MSW at a 3:1 mass ratio is found to be almost similar (about 28.8%) to that of HAC-based power plants under both subcritical and supercritical conditions. Under

Table 5 Energy analysis in subcritical conditions

Item	HAC	MSW	LAC	HAC:MSW(3:1)	HAC:MSW(1:1)	HAC:MSW(1:3)	LAC:MSW(3:1)	LAC:MSW(1:1)	LAC:MSW(1:3)
HPST (MW)	14.42	10.45	15.35	13.57	12.95	12.33	15.03	13.93	12.81
MPST (MW)	12.78	9.26	13.6	12.17	11.47	10.93	13.16	12.34	11.35
LPST (MW)	15.7	11.34	16.66	15.11	14.09	13.43	15.88	15.18	13.94
Power produced (MW)	42.9	31.05	45.63	40.85	38.51	36.69	44.07	41.45	38.1
Pump penalty (MW)	0.68	0.46	0.7	0.66	0.58	0.54	0.66	0.62	0.57
ASU penalty (MW)	7.58	5.31	7.87	7.44	6.77	6.47	7.84	7.45	6.71
CCU penalty (MW)	4.94	3.66	5.36	4.94	4.63	4.44	5.36	5.10	4.63
SCR penalty (MW)	0.81	0.66	0.94	0.85	0.81	0.75	0.95	0.89	0.8
FGD penalty (MW)	0	0.34	0.55	0.43	0.41	0.41	0.49	0.49	0.41
Total energy penalty (MW)	14.00	10.43	15.43	14.32	13.2	12.61	15.3	14.55	13.12
Net efficiency (%)	28.89	20.62	30.18	26.53	25.31	24.08	28.77	26.90	24.99

Table 6 Energy analysis in supercritical conditions

Item	HAC	MSW	LAC	HAC:MSW(3:1)	HAC:MSW(1:1)	HAC:MSW(1:3)	LAC:MSW(3:1)	LAC:MSW(1:1)	LAC:MSW(1:3)
HPST (MW)	14.19	12.15	14.77	13.89	13.69	13.49	14.43	14.13	13.34
MPST (MW)	17.31	14.83	18.02	16.46	16.22	15.99	17.6	17.25	16.29
LPST (MW)	12.58	11.03	13.23	12.16	11.99	11.81	12.85	12.59	11.89
Power produced (MW)	44.08	38.01	46.02	42.51	41.9	41.29	44.88	43.97	41.52
Pump penalty (MW)	0.77	0.7	0.816	0.76	0.75	0.74	0.8	0.78	0.74
ASU penalty (MW)	4.67	4.08	4.96	4.55	4.46	4.35	4.93	4.87	4.52
CCU penalty (MW)	3.29	3.08	3.55	3.29	3	3.19	3.55	3.51	3.13
SCR penalty (MW)	0.38	0.36	0.4	0.38	0.38	0.38	0.45	0.43	0.43
FGD penalty (MW)	0	0.37	0.38	0.36	0.36	0.35	0.37	0.38	0.37
Total energy penalty (MW)	9.1	8.6	10.1	9.34	8.96	9.01	10.1	9.97	9.19
Net efficiency (%)	34.98	29.41	35.92	33.17	32.94	32.28	34.78	34	32.33

supercritical conditions, the net efficiency of the power plants increased by 5% to 10%. One of the main reasons is the production of higher electrical power under supercritical conditions due to the higher values of the operating temperature and pressure. In MSW-based fuel, there is a significant rise in the net thermal efficiency under supercritical conditions by 8.79% due to the low energy penalty associated with these conditions. Energy penalty under subcritical conditions is estimated as 10.43% whereas it is reduced to 8.6% under supercritical conditions. Furthermore, under supercritical conditions, the quantity of temperature moderator used is low by 34%–76%, and thus the energy penalty for flue gas treatment is reduced by 0.8–2.2 MW. The amount of flue gas generated under subcritical and supercritical conditions is given in Fig. 5. The ratio of the flue gas produced under subcritical conditions to supercritical conditions is found to be between 1.3 and 1.64, and this ratio is lowest for MSW and highest for LAC. This could be due to the low oxygen requirement for MSW and higher oxygen requirement for LAC.

Economic analysis

The economic analysis of the oxy-fuel combustion-based power plants under subcritical and supercritical conditions are reported in Tables 7 and 8, respectively. The CRF of the power plants is calculated as 0.086 using Eq. 13. The total installed cost under supercritical conditions is found to be higher (about 8% to 16%) than that under subcritical conditions, which could be due to the increased costs associated with boilers and turbines. MSW-based power plants showed the highest total installed cost in both subcritical (194 million $) and supercritical (230 million $) power plants. Although the installed costs are higher under supercritical conditions, the estimated LCOE is found to be low by 9–11.5 $/MWh for the coal feedstocks compared to the subcritical conditions. In the case of MSW, the LCOE is low by 59 $/MWh under supercritical conditions. LAC has shown the lowest LCOE among other fuels and their blends.

The operating cost of the power plants depends on the fuel cost and maintenance cost. The fuel cost of LAC is 1.3–2 times higher than that of HAC and MSW. With the increase in the MSW content in the fuel blend, the operating cost of the power plant increases because a higher quantity of MSW would be required to maintain the energy input level to the boiler. MSW has the least amount of carbon and thus requires a lower amount of oxygen gas for complete combustion. This directly affects the capital costs associated with the ASU. This is reflected in the installed cost of the ASU unit under the blended feedstock conditions. When MSW proportion in the feedstock increases from 0 to 75%, the installed cost of the ASU unit decreases by 10.47% and 4.88% for HAC-MSW fuel blends under subcritical and supercritical conditions, respectively. Correspondingly, in the case of LAC-MSW fuel blends, it increases by 10.58% and 6.26% under subcritical and supercritical conditions, respectively.

Overall, the increase in the proportion of MSW in the fuel blend increased the LCOE of the power plants. In HAC-MSW fuel blends, the LCOE increases by 37.7 $/MWh and 28.15 $/MWh for subcritical and supercritical conditions, respectively when MSW content in fuel blend is increased from 0 to 75%. Similarly, in LAC-MSW fuel blends, the LCOE increases by 37.21 $/MWh and 25.38 $/MWh when MSW content increases from 0 to 75%.

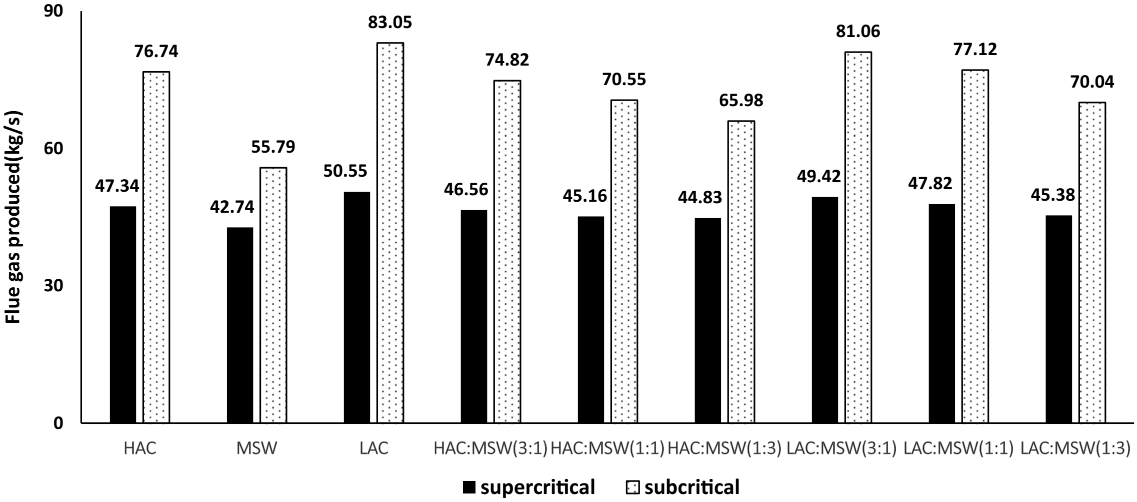


Fig. 5 Amount of flue gas generated during subcritical and supercritical conditions of steam turbine power plants. *HAC* High ash coal, *LAC* low ash coal

Table 7 Economic analysis of power plants under subcritical conditions

Cost in (million $)	HAC	MSW	LAC	HAC:MSW(3:1)	HAC:MSW(1:1)	HAC:MSW(1:3)	LAC:MSW(3:1)	LAC:MSW(1:1)	LAC:MSW(1:3)
MSW treatment cost	0	0.57	0	0.17	0.3	0.43	0.16	0.28	0.41
Coal handling system	1.02	0	0.92	0.89	0.71	0.47	0.81	0.67	0.46
ASU	20.43	11.5	20.97	19.98	18.86	18.29	20.92	20.17	18.75
Gas cleaning	0.42	8.27	5.79	6.77	7.19	7.7	6.24	6.77	7.43
CO_2 compressor	1.33	1.05	1.38	1.3	1.24	1.21	1.37	1.27	1.19
CO_2 removal and injection infrastructure	11.37	9.05	11.83	11.17	10.67	10.36	11.81	10.91	10.19
Water system	2.29	3.05	2.05	2.44	2.6	2.81	2.22	2.43	2.7
Heat exchangers	0.25	0.18	0.33	0.29	0.48	0.31	0.24	0.26	0.32
Turbine	38.23	50.83	34.25	40.68	43.48	46.82	37.09	40.59	45.02
Boiler	57.68	76.7	51.69	61.38	65.6	70.64	55.96	61.24	67.94
Total installed cost	133.02	161.2	129.21	145.1	151.17	159.05	136.84	144.61	154.44
Land surveyor cost	6.65	8.06	6.46	7.25	7.56	7.95	6.84	7.23	7.72
Owner's cost	19.95	24.2	19.4	21.8	22.7	23.9	20.5	21.7	23.2
Utilities	2.71	1.48	2.19	1.99	1.94	1.69	2.14	2.06	1.85
Total capital cost	162.35	194.93	157.25	176.1	183.3	192.25	166.36	175.59	187.15
Labour and maintenance cost	5.15	9.31	5.03	5.6	5.82	6.1	5.31	5.59	5.93
Plant overhead	0.2	0.23	0.23	0.22	0.22	0.21	0.2	0.22	0.22
Fuel cost	3.94	4.45	5.21	4	4.11	4.24	5.08	4.91	4.7
Slag disposal cost	0.69	0.92	0.026	0.52	0.57	0.63	0.67	0.74	0.82
CO_2 transport	0.57	0.56	0.74	0.7	0.66	0.64	0.74	0.68	0.63
Limestone cost	0	0.045	0.34	0.01	0.02	0.03	0.32	0.25	0.16
Operating and financial cost	10.6	15.5	11.59	11.05	11.4	11.8	12.32	12.4	12.47
Annual capital cost (ACC)	13.93	16.73	13.49	15.1	15.7	16.52	14.28	15.07	16.06
LCOE	96.77	178.62	94.85	112.59	122.35	134.47	105.53	116.53	130.33

NO_x and SO_x pollutant emissions

Figure 6a, b show the NO_x and SO_x emission levels in the flue gas after treatment in the respective units. The permissible concentrations of NO_x and SO_x allowed in the flue gas after flue gas condensation are 640 mg/m^3 and 120 mg/m^3, respectively [30]. These limits are achieved in the treatment units (Fig. 6a). Under subcritical conditions, the NO_x emissions remain fairly constant at about 7 mg/m^3 irrespective of the fuel blend used. However, under supercritical conditions, NO_x emissions are significantly higher. This could be due to the higher operating temperatures of the boiler and lower flue gas emissions. MSW has the highest NO_x emissions due to the high nitrogen content in MSW compared to HAC and LAC. Hence, with the increase in the MSW content in the fuel blend, the NO_x level in the flue gas also increases. NO_x emissions for the HAC-MSW fuel blend increase from 30.65 mg/m^3 to 49.67 mg/m^3, and for the LAC-MSW fuel blend, the NO_x emissions increase from 35.54 mg/m^3 to 55.46 mg/m^3.

It can be observed from Fig. 6b that the SO_x emissions under subcritical conditions are well below the permissible limit in the flue gas (120 mg/m^3). LAC produces the highest SO_x level as it contains 4% sulfur. With the addition of MSW as a fuel blend with LAC (0–75%), the SO_x emission decreases to the permissible level of 119.46 mg/m^3 (1:3 ratio of LAC:MSW). In the HAC-MSW fuel blending conditions, the SOx emission increases from the highest levels of 12.83 mg/m^3 and 27.63 mg/m^3 under subcritical and supercritical conditions, respectively. SO_x emissions can increase by 2–12 times under supercritical conditions compared to subcritical conditions.

Under supercritical conditions, it can be found that for LAC, LAC:MSW (3:1), LAC:MSW (1:1), and the SO_x emissions are higher than the permissible limit of 120 mg/m^3. Hence, additional SO_x removal techniques, such as DSI and UC of coals, are employed for the treatment of LAC. The SO_x emissions after treating the LAC-based flue gas in the DSI/UC units are given in Fig. 7. The addition of the DSI unit and UC effectively decreased the LAC-based SO_x emissions by 116.4 mg/m^3 and 215.09 mg/m^3, respectively. With the LAC-MSW blend at a 3:1 mass ratio, the SO_x emission decreases by 106.91 mg/m^3 and 159.35 mg/m^3. The UC method is a pre-combustion sulfur removal technique. The energy penalty for this UC treatment is considered based on the solvent utilization and the electric power consumption for ultrasound generation per kg of coal treated. A UC

Table 8 Economic analysis of power plants under supercritical conditions

Cost in (million $)	HAC	MSW	LAC	HAC:MSW(3:1)	HAC:MSW(1:1)	HAC:MSW(1:3)	LAC:MSW(3:1)	LAC:MSW(1:1)	LAC:MSW(1:3)
MSW treatment cost	0	0.57	0	0.17	0.3	0.43	0.16	0.28	0.41
Coal handling system	1.15	0	1.03	1.02	0.8	0.53	0.91	0.75	0.51
ASU	14.54	13.24	15.17	14.29	14.09	13.83	15.11	14.98	14.22
Gas cleaning	0.69	8.74	6.17	7.06	7.72	8.1	6.69	7.23	8.05
CO_2 compressor	0.97	0.94	1.03	0.98	0.92	0.96	1.03	1.08	0.95
CO_2 removal and injection infrastructure	11.03	10.56	11.63	8.83	10.37	10.82	11.66	12.15	10.67
Water system	2.67	3.55	2.39	2.84	3.03	3.27	2.58	2.83	3.14
Heat exchangers	1.11	0.96	1.48	1.38	1.53	1.4	1.36	1.31	1.28
Turbine	40.87	54.33	36.62	43.49	46.48	50.05	39.64	43.39	48.13
Boiler	71.78	95.44	64.32	76.38	81.64	87.9	69.63	76.2	84.54
Total installed cost	144.83	188.35	139.85	157.41	168.11	177.3	150.22	160.22	171.92
Land surveyor cost	7.24	9.42	6.99	7.87	8.4	8.87	7.51	8.01	8.6
Owner's cost	21.72	28.3	20.98	23.6	25.21	26.6	22.5	24.03	25.8
Utilities	4.41	3.84	4.65	4.37	4.27	4.13	4.68	4.49	4.26
Total capital cost	178.2	229.85	172.47	193.27	206	216.89	184.94	196.76	210.57
Labour and maintenance cost	5.56	7.18	5.42	6.08	6.46	7.87	5.83	6.19	6.6
Plant overhead	0.15	0.18	0.17	0.18	0.18	0.18	0.18	0.18	0.18
Fuel cost	3.92	4.46	5.21	4	4.11	4.24	5.08	4.91	4.7
Slag disposal cost	0.69	0.92	0.026	0.52	0.57	0.63	0.67	0.73	0.82
CO_2 transport	0.52	0.5	0.55	0.52	0.49	0.51	0.55	0.57	0..5
Limestone cost	0	0.053	0.34	0.01	0.02	0.03	0.3	0.24	0.16
Operating and financial cost	10.84	13.29	11.7	11.33	11.84	13.46	12.62	12.83	12.97
ACC	15.29	19.72	14.8	16.58	17.68	18.61	15.87	16.88	18.07
LCOE	85.27	128.15	84.2	96.05	102.27	113.42	93.5	99.37	109.58

reactor consumes 500 W of power and has a working capacity of 8 L [36].

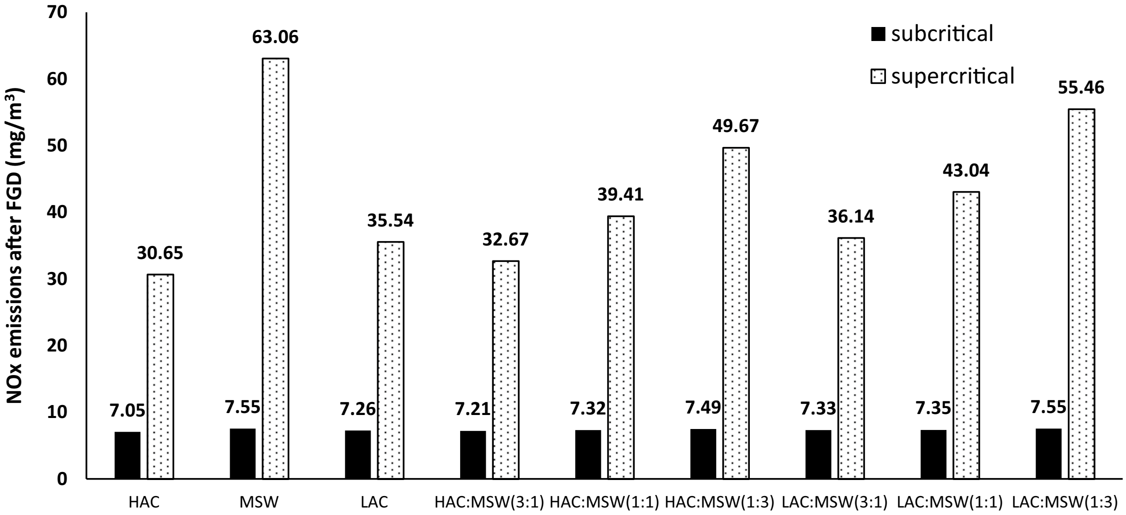
In Fig. 7, it can be observed that the addition of MSW with LAC decreases the SO_x emissions when FGD and DSI, the post-combustion treatment units, are used for SO_x capture. However, in the UC, the pre-combustion deSOx method, the SO_x in the flue gas at a LAC-MSW ratio of 1:1 is slightly higher than the flue gas obtained from the feedstock at a 3:1 ratio. This is due to the removal of sulfur only from LAC by the UC method at the pre-combustion stage. Hence, the SO_x emissions gradually increased with the addition of MSW in the LAC-MSW fuel blend.

Energy and economic analysis after the addition of UC and DSI units

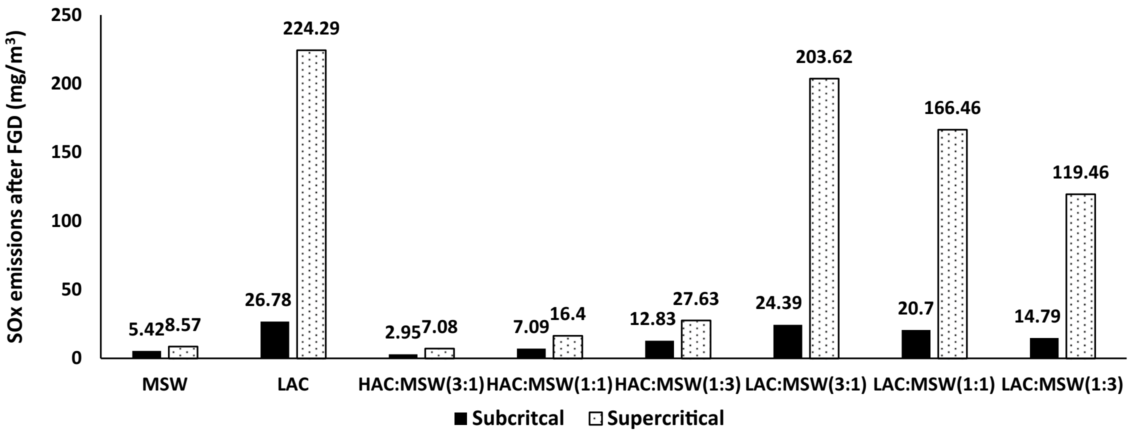
Table 9 provides the energy analysis of the power plants after the addition of DSI or UC units under supercritical conditions. LAC-based supercritical power plants cause high SO_x emissions beyond the permissible level. Hence, the techno-economic analysis of the power plants incorporating the UC or DSI unit is performed only for the supercritical condition of the turbines. The energy penalty associated with DSI is comparatively lower than that of the UC method. The DSI addition decreases the net energy efficiency by 0.09%, and by adding the UC, the net efficiency of the power plants decreases even further by 0.34%–1.06%.

The energy penalty of the UC is directly proportional to the amount of LAC in the LAC-MSW fuel blend. The energy penalty associated with UC addition decreases from 0.34 MW to 0.22 MW as the quantity of LAC decreases from 100% to 50%. In the UC method, as sulfur is also a combustible substance, the removal of sulfur before combustion affects the adiabatic flame temperature of the boiler. On average, the oxygen content for coal combustion has decreased by 0.5 kg/s, compared to the power plant without the addition of the UC unit.

The ASU energy penalty for UC is lower by 0.06–0.12 MW when the DSI unit is used for sulfur removal. The amount of flue gas recycled to maintain the combustor temperature declines when UC is used for sulfur removal. This in turn decreases the quantity of flue gas supply to the CCU unit. The CCU energy penalty of the UC-based power plants is slightly higher (0.1–0.4 MW) than that of the DSI-based energy power plants. The energy penalty for gas cleaning is highly dependent on the quantity of flue gas generated sent to the SCR and FGD units. As the volume of the flue gas decreases slightly in the UC-based power plants, the energy penalty decreases by 0.03–0.05 MW.



(a) Estimated NO$_x$ emissions after the treatment of flue gas in the SCR unit



(b) Estimated SO$_x$ emissions after the treatment of flue gas in the FGD unit

Fig. 6 NO$_x$ and SO$_x$ emissions after treatment (**a**) Estimated NO$_x$ emissions after the treatment of flue gas in the SCR unit. (**b**) Estimated SO$_x$ emissions after the treatment of flue gas in the FGD unit

Economic analysis of the supercritical power plants after the addition of the DSI and UC unit is given in Table 10. The addition of sulfur removal units such as DSI/UC increases the LCOE by 1–2 \$/MWh (compared to the LCOE without DSI/UC units from Table 8). The equipment cost (MSW treatment, coal handling, CO_2 compressor, heat exchanger) and operating costs are common to power plants with and without DSI/UC units. As discussed earlier, the oxygen required for the UC unit is comparatively low, and hence, the cost of ASU unit becomes low. However, the cost of a UC unit is higher than that of a DSI unit, which affects the capital cost. UC and DSI units employ H_2O_2 and lime for sulfur removal, respectively. As lime is comparatively costlier than H_2O_2, the operating cost of the DSI unit is higher than that of the UC unit. Overall,

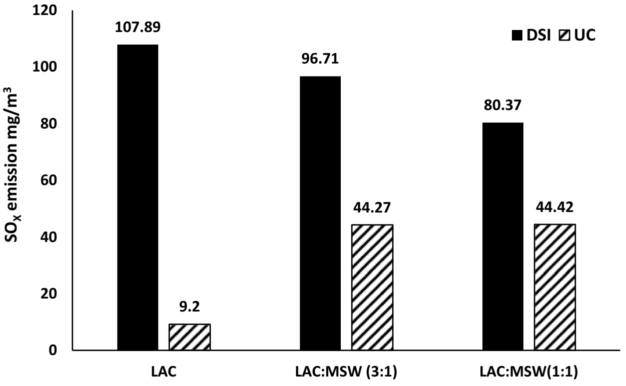


Fig. 7 SO$_x$ emissions after flue gas desulfurization (FGD) with DSI and UC

Table 9 Energy analysis of the power plant after the addition of DSI/UC unit in supercritical systems

Item	LAC (DSI)	LAC:MSW (3:1) (DSI)	LAC:MSW (1:1) (DSI)	LAC (UC)	LAC:MSW (3:1) (UC)	LAC:MSW (1:1) (UC)
HPST (MW)	14.77	14.43	14.13	14.52	14.28	14.08
MPST (MW)	18.02	17.6	17.25	17.72	17.43	17.19
LPST (MW)	13.23	12.85	12.59	12.94	12.72	12.54
Power produced (MW)	46.02	44.88	43.97	45.18	44.43	43.81
Pump power (MW)	0.81	0.8	0.78	0.8	0.79	0.78
ASU penalty (MW)	4.96	4.93	4.87	4.84	4.82	4.81
CCU penalty (MW)	3.55	3.55	3.51	3.58	3.56	3.55
SCR penalty (MW)	0.4	0.45	0.43	0.39	0.43	0.41
FGD penalty (MW)	0.38	0.37	0.38	0.37	0.36	0.37
DSI/UC penalty (MW)	0.092	0.09	0.088	0.43	0.36	0.27
Total energy penalty	10.18	10.19	10.06	10.4	10.33	10.2
Net efficiency (%)	35.84	34.69	33.91	34.77	34.1	33.6
Decrease in net efficiency (%)	0.09	0.09	0.09	1.15	0.68	0.4

Table 10 Economic analysis after the addition of DSI and UC units

Costs (million $)	LAC (DSI)	LAC (UC)	LAC:MSW (3:1) (DSI)	LAC:MSW (3:1) (UC)	LAC:MSW (1:1) (DSI)	LAC:MSW (1:1) (UC)
ASU	15.17	14.92	15.11	14.88	14.98	14.86
CO_2 removal and injection infrastructure	11.63	11.71	11.66	11.68	11.56	11.66
DSI/UC capital cost	0.41	1.22	0.37	1.08	0.32	0.89
Dryer cost (with UC unit)	–	0.14	–	0.12	–	0.1
Common installed cost	113.04	113.04	122	122	133.02	133.02
Total installed cost	140.81	141.58	150.61	151.21	159.9	160.56
Land surveyor cost	7.04	7.08	7.53	7.56	7.99	8.03
Owner's cost	21.1	21.2	22.6	22.7	23.98	24.08
Utilities	4.65	4.65	4.68	4.68	4.49	4.49
Total capital cost	173.62	174.55	185.41	186.13	196.37	197.15
Labour and maintenance cost	5.46	5.48	5.85	5.87	6.17	6.2
Common operating cost	5.786	5.786	6.3	6.3	6.19	6.19
Plant overhead	0.17	0.17	0.18	0.18	0.18	0.18
Limestone and lime cost	0.18	0.07	0.16	0.07	0.12	0.063
H_2O_2 cost	–	0.02	–	0.017	–	0.012
DSI operating cost	0.59	–	0.52	–	0.42	–
Total operating cost	12.16	11.51	13.07	12.44	13.08	12.66
ACC	14.9	14.98	15.91	15.97	16.85	16.92
LCOE	86.21	86.95	95.19	95.12	100.76	100.45

the UC based system has shown a higher LCOE than DSI based system due to the additional costs incurred for UC and drying units. As the MSW quantity in the LAC-MSW fuel blend increases from 0 to 50%, the costs of the UC unit decline from 1.22 million $ to 0.89 million $ due to the reduction in the amount of LAC treated in the UC unit.

Comparison with literature

The net efficiency and economic analysis of the power plants are compared with the literature results, and are shown in Table 11. It can be noted that the LCOE estimated in the present study for LAC and HAC is almost comparable with the

Table 11 Comparison of net efficiency and LCOE values with literature for oxy-fuel based coal combustion power plants

References	Net efficiency (%)	LCOE ($/MWh)
Cormos [42]	34.64	94.56**
Adams et al. [37] and Cormos [43]	34.31	82.3*
Cormos [43]	32.2	99.16*
Lockwood [30]	33.4	79
Maddahi et al. [44]	26.32	75.07**
Guandalini et al. [45]	33.6	106.6
Xiong et al. [46]	36.24	55.04
Present values (LAC)	35.92	84.2
Present values (HAC)	34.98	85.27
MSW (compared with post CCU method)		
Present values (MSW)	29.41	128.15
Yassin et al. [12]	22.4	108.64**
Sahu et al. [32]	26.49	133.95
Mondal [47] (combined cycle)	44.24	123.5
Chaiyat [48] (organic rankine cycle)	37.43	153

**Values calculated from Euro/MWh to Dollar/MWh (1 Euro = 1.12 Dollar)

*Converted to 2017-year basis by Adams (2017) [37]

literature values for oxy-fuel combustion based technology. Adams et al. [37] recalculated the net efficiency and LCOE of the power plants reported in the literature based on 2017 (Table 11). Using MSW as the feedstock, Yassin et al. [12] reported an LCOE value of 108.64 $/MWh with the integration of post CCU method; whereas the present study under the oxy-combustion method showed a lower LCOE value with a difference of 10.97 $/MWh.

Conclusions

In the present study, a techno-economic analysis of oxy-fuel co-combustion-based power plants using high ash and low ash Indian coals with MSW was performed. It can be concluded that MSW, as a low-quality fuel, cannot be incinerated alone for electricity generation, as the calculated LCOE values are not economically favorable. The following conclusions can be drawn from the present study.

- The co-combustion of MSW with coals exhibits certain advantages. The addition of 25% HAC and LAC with MSW increased the net thermal efficiency of the steam turbine by 5.91% and 8.15% for HAC and LAC, respectively, under subcritical conditions. The co-combustion of coal with MSW reduced the LCOE by 48–73 $/MWh compared to MSW alone as the feedstock for the power plants.
- The net thermal efficiency of MSW-based power plants under supercritical conditions is significantly increased by 8.79%, compared to that under subcritical conditions. Furthermore, the LCOE of MSW-based power plants is reduced by 50 $/MWh under supercritical conditions.
- The addition of MSW from 0 to 75% in the fuel blend increased the NO_x emissions by 0.44 mg/m^3 and 0.29 mg/m^3 for HAC and LAC fuel blends, respectively, under subcritical conditions. Similarly, in supercritical conditions, the emissions increased by about 19 mg/m^3 for HAC and LAC fuel blends. The addition of an SCR unit for NO_x reduced the thermal efficiency of the power plant by 0.4%–0.45% under supercritical conditions and 0.75%–0.95% under subcritical conditions.
- High sulfur coal treatment by DSI and UC method leads to the energy penalty of 0.09 MW and 0.4–1.15 MW in the power plants. These units increased the LCOE by 1.2–2.4 $/MWh. On average, DSI-operated power plants have 0.25% to 0.98% higher efficiency, compared to UC-based power plants.
- With an increase in the MSW in the LAC blended feedstock (25% and 50%), the operating cost of the UC unit is lower than that of the DSI unit, which decreases the LCOE of UC-based power plants even though the capital costs associated with the UC unit are higher. Power plants based on pure LAC have a higher LCOE in the UC sulfur treatment method than the DSI sulfur treatment method (86.95 $/MWh versus 86.21 $/MWh).

To utilize MSW in power plants significant subsidies must be provided so electricity generation from MSW becomes attractive, as the difference between the LCOE of coals and MSW is 30–75 $/MWh. To control SO_x emissions from Indian LAC, utilizing only FGD units is not enough to decrease SO_x emissions below the acceptable limit. UC method was found to be economically and environmentally more viable than the DSI technique. Treatment and separation of MSW can appreciably decrease the burden on power plant authorities.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical rules Authors have followed ethical rules given on the journal website. The author has not submitted the article to any other journal for consideration. The article has not been published in any other language. Statements and procedures followed are properly cited and acknowledged.

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