Economical and Practical Evaluation of the Mitsui-BF Process for Removal of SO_2 and NOx in Thermal Power Plants

Abstract

The purpose of this study is to analyze the overall aspects of sulfur dioxide (SO_2) and nitrogen oxides (NOx) removal from thermal power plants by the application of the Mitsui-BF process. For the first time, the research evaluates the efficiency and feasibility of the Mitsui-BF process in a ٣٥٠ MW fuel oil-fired thermal power plant in comparison to the traditional SO_2 and NOx removal process.

The analysis takes into account factors like process complexity, waste production, space requirements, feasibility of local production, the impact on the environment, and process efficiency.

Results show that for simultaneous removal of SO_2 and NOx, the capital cost of the Mitsui-BF process is less than that of wet lime and limestone scrubbers and SCR-KHI. The problem is that the cost of the consumable sorbent and extra utility costs required for sulfur production add up to an increased LCO for the Mitsui-BF process. However, the MITSUI-BF process is more complex, but it has a lower requirement for water, which is an important consideration in areas where water resources are scarce. The Mitsui-BF process holds promise of efficiency, with ٧٠٪ NOx removal, ٩٠-٩٨٪ SO_2 removal for simultaneous mode and >٨٥٪ NOx removal, ٩٠-٩٨٪ SO_2 removal for separate mode. The process also generates relatively lower amount of solid waste, which can be reused or sold, thus offering a sustainable solution. This process offers potential for power plant operators interested in reducing emissions and improving environmental sustainability, and additional R&D in this area could optimize the process and help overcome any implementation challenges.

Key words: Mitsui-BF process, Sulfur dioxide (SO_2) removal, Nitrogen oxides (NOx)removal, Techno-economic analysis, Comparative technology assessment, Fuel oil-fired power plant

١. Introduction

Sulfur dioxide (SO_2) and nitrogen oxides (NOx) are of major concern as pollutants in acid rain as well as photochemical smog formation. The high concentrations of such pollutants in the environment can lead to respiratory diseases such as asthma, bronchitis, and throat infection. Fossil fuel-fired thermal power plants emit approximately ٨٧٪ and ٦٧٪ of SOx and NOx, respectively, based on reported data [١, ٢].

Sulfur dioxide, as an acid gas, is typically removed from flue gas through the Wet Flue Gas Desulfurization (WFGD) process [٣-٥].

This process utilizes scrubbers and alkaline solutions to neutralize as well as capture the SO_2. Despite the widespread usage of this process and its high operational efficiency, this process is associated with challenges such as high capital cost, large space requirements, high water consumption, and the production of secondary pollutants [٦, ٧].

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The NOx separation, typically in the form of NO in flue gas, is achieved through the Selective Catalytic Reduction (SCR) process. Although NOx is significantly eliminated by the SCR process, there are also some technical issues in this process. The unreacted compounds (hydrocarbons or ammonia), if not properly managed, can lead to the significant environmental challenges. Besides to the high cost of this process, the temperature of SCR reaction is often high and it has been reported to be more than ٣٠٠ °C [٨, ٩].

On the other hand, FGD and SCR processes frequently focus on eliminating a single pollutant from flue gas, whereas simultaneous pollutant removal has recently gained attention due to its potential cost savings. Furthermore, the use of alternative processes with lower water consumption for the removal and separation of the aforementioned pollutants from flue gas appears unavoidable due to the limited water resources in power plants located in arid regions. The adsorption of tiny gas molecules onto porous and solid surfaces has the potential to be considered as an alternative process for DeSOx-DeNOx. Comparing to membrane processes or liquid absorption technology, physical adsorption of gases has been reported as an economical and efficient technology [١٠].

Adsorption is also a promising environmental remediation technique because it can remove pollutants simultaneously without leaving behind dangerous residues. Further, adsorption can also be viewed as a substitute technology for the combined NOx-SOx control, which may reduce water consumption.

Researchers have studied the physical adsorption of SO_x and NOx pollutants either separately or in combination using activated coke [١١-١٥],activated carbon [١٦-١٩], zeolites [٢٠-٢٢], calcium-based adsorbents [٢٣-٢٥], metal oxides [٢٦], solid amine adsorbents [٢٤, ٢٧], and metal-organic frameworks (MOFs) [٢٨, ٢٩].

It has been reported that carbon-based adsorbents are suitable candidates for DeSOx-DeNOx due to their high surface area, thermal stability, and reusability [٣٠].The activated coke adsorbent is found to be more effective than activated carbon adsorbent in the majority of the constituents for combined removal of NOx and SOx [٣١].

According to an analysis of the technological development levels of adsorption process, the adsorption on activated coke in the Mitsui-BF process is a mature technology that is well-developed for use in thermal power plants (TRL=٩) [٣٢].

One of the significant advantages of the Mitsui-BF process is that both desulfurization and denitrification processes are carried out as a single unit. Additionally, the dedusting and removal of other trace contaminants such as mercury and dioxins from the flue gas are also achieved [٣٣]. Moreover, the dry contact of flue gas with the activated coke bed simplifies the process and reduces the space required for equipment pre-treatment. Furthermore, neither a wastewater treatment plant nor flue gas reheating is necessary for the Mitsui-BF process. High DeSOx-DeNOx efficiency is attained in the Mitsui-BF process at temperatures between ١٠٠ and ٢٠٠°C. A decrease in flue gas temperature within that range improves the efficiency of SO_x removal [٣٣].

However, in the relatively low temperature range of ٨٠ to ١٨٠°C, activated coke acts as a catalyst for the removal of NOx, whereas conventional transition metal catalysts (e.g., V or Ti) operate efficiently in the temperature range of ٣٠٠ to ٤٠٠°C [٣٤].

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The Mitsui-BF process can be used to treat a variety of flue gases from a range of sources, including boilers, incinerators, sintering and heating furnaces, catalyst regeneration units (i.e. FCC), and plants that produce sulfuric acid [۳۳-۳۵].

The first step in developing of Mitsui-BF process for combined SO_x and NOx removal from Iranian power plant flue gas is to conduct a technical and economic feasibility study of the process using activated coke as adsorbent. The technical perspective of the Mitsui-BF process is briefly explained at the beginning of this manuscript. Then, the economic analysis of the Mitsui-BF process has been conducted to remove SO_x and NOx simultaneously as well as separately. It is noteworthy that this analysis is being used in a ۳۵۰ MW fuel oil-fired thermal power plant for the first time.

In terms of economic, operating and environmental considerations, space requirement, consumable material costs, and performance, Mitsui-BF has been also compared with limestone- or lime-based wet scrubbing desulfurization processes, Wellman-Lord scrubbing, citrate scrubbing, and dual-alkali scrubbing for DeSOx-DeNOx, as well as DeSOx. Additionally, this comparison has been made between Mitsui-BF and Exxon thermal DeNOx process (SNCR), and KHI SCR process were used for DeNOx.

This study provides comprehensive guidelines on the process of selecting the most suitable technology for use in Iranian thermal power plants by conducting a thorough technical and economic analysis of the Mitsui-BF process and comparing it with traditional sulfur dioxide (SO_x) and nitrogen oxides (NOx) removal processes.

۲. Mitsui-BF Process Technical Specifications

The Mitsui-BF process flow diagram for simultaneous SO_x and NOx removal is presented in Fig.۱. This process is divided into an adsorption section, an activated coke (AC) regeneration section and a sulfur recovery section.

The adsorption section includes two vertical AC beds, where activated coke flow downwards from the top adsorber bed (second stage) to the bottom adsorber bed (first stage). Flue gas flows horizontally through the bottom adsorber bed (first stage) and goes into the top adsorber via a duct. The first and second stage adsorber beds are responsible for SO_x and NOx removal, respectively, and ammonia is fed into second stage.

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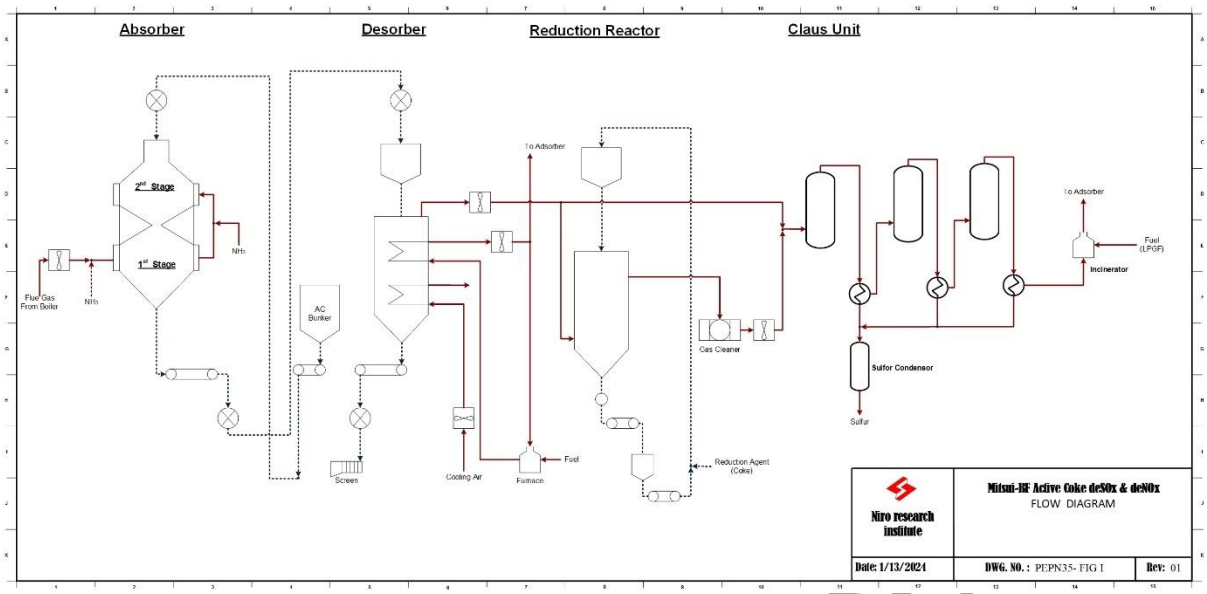


Fig. ١. The Mitsui-BF process flow diagram for DeSOx-DeNOx

In the regeneration tower, activated coke containing $SO_٢$, NOx, and other trace pollutants such as mercury is fed to the top of the regeneration tower by a bucket conveyer. The activated coke falls downwards by gravitational flow through three indirect heat exchangers. These exchangers are designed to preheat, heat, and cool the regenerated coke. Finally, it is discharged through a hopper to the fine particle separation section, and then the regenerated adsorbent returns to the adsorption tower.

As a tail-end process, a sulfur recovery section is included. This process involves a coke reactor to convert some of $SO_٢$ to $H_٢S$, followed by a Claus unit. In Claus reactor, $SO_٢$ and $H_٢S$ are converted to elemental sulfur.

The proposed process is used for the effective removal of sulfur dioxide (DeSOx), nitrogen oxides (DeNOx), and can be also designed for the simultaneous elimination of both pollutants. The design values are based on a ٣٥٠ MW oil-fired steam power plant. The flue gas stream is described to have a flow rate of ١٢ million cubic meters per hour with an initial $SO_٢$ concentration of ٢٥٠٠ ppm. The ammonia to NOx ratio is a critical parameter for NOx removal, which is set at ١ [٣٦].

Design parameters for this process are determined by using a combination of EPRI design guidelines, relevant literature [٣٧, ٣٨], and material balance calculations. Table ١ presents the key parameters for this process.

Table ١. MITSUI-BF for DeSOx-DeNOx – basic parameters

Parameter	Value
Boiler capacity (MW (GWh/year)	٣٥٠ (٢٧٦١)
Flue gas capacity (MMSCFH[١])	٤٥.٥
Stream factor	٠.٩
Fuel type	Heavy fuel oil
Fuel oil heating value (Kj/kg (Btu/Ib))	٢٨٥١٦ (١٢٢٦٠)

[١] Million Standard Cubic Feet per Hour

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Parameter	Value
Fuel oil feed rate (tons/h)	۱۳۶
Sulfur content (wt%)	۳.۷
Sulfur as SO_2 (mg/Nm^3|ppm)	۰,۲۵ vol% (۲۵۰۰|۶۵۴۴)
Sulfur as SO_2 (mg/Nm^3|ppm)	۰.۰۰۴ vol٪ (۴۰ | ۱۳۱)
SO_2 removal efficiency	۹۰٪
Maximum SO_2 emission (Ib/MMBtu)	۰.۵۸
Activated coke (Make-up) (kg/h)	۱۳۶۵
AC flow rate (ton/h)	۶۸
Fines disposed activated coke (kg/h)	۵۶۵
Ammonia (kg/h)	۳۱۰
Coke as reducing agent (kg/h)	۷۲۵۰
Natural gas as coke substitute (kg/kWh)	۰.۰۰۷۵
Heavy oil (kg/h)	۷۵۰
Electricity (kW)	۶۵۰۰
Sulfur (kg/h)	۳۹۱۸

MITSUI-BF process is also specifically designed for DeSOx, which it uses a single adsorption bed and does not inject ammonia unlike DeSOx-DeNOx process. The model is designed on a ۳۵۰ MW oil-fired steam power plant where the rate of flue gas flow is ۱۲ million cubic meters per hour with the initial SO_2 concentration of ۲۵۰۰ ppm. Some design parameters for this process are presented in Table ۱, while different data are provided in Table ۲, calculated based on references [۳۵, ۳۷, ۳۸] and material balance.

Table ۲. MITSUI-BF for DeSOx – basic parameters

Parameter	Value
Activated coke (Make-up) (kg /hr)	۱۰۷۳
AC flow rate (ton/h)	۵۴
Fines disposed activated coke (kg/h)	۴۴۴
Heavy oil (kg/h)	۶۷۰
Electricity (kW)	۵۱۱۰

The MITSUI-BF process is also applicable for DeNOx. The flue gas used for this process, similar to the SCR process, contains low sulfur content. Therefore, this method can be effectively applied to boilers that already incorporate an SO_2 removal process, or to those firing low-sulfur fuels [۳۵, ۳۹].

The primary difference between this process and simultaneous SO_2 and NOx removal configuration is that the adsorption bed is designed with a single stage for NOx control. The model is developed based on a ۳۵۰ MW oil-fired steam power station with a flue gas flow rate of ۱۲ million cubic meters containing SO_2 concentration of ۲۵۰ ppm. The basic design parameters are similar to those given in Table ۱. The EPRI institute design guidelines and

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comprehensive data from references [٣٥, ٣٧] are used to calculate the additional parameters as shown in Table ٣.

Table ٣. MITSUI-BF for DeNOx – basic parameters

Parameter	Value
Activated coke (Make-up)	٢٩٢ kg /hr
Inlet NOx (ppm)	٢٤٠
Inlet $SO_٢$ (ppm)	٢٥٠
NOx removal efficiency	٨٠٪
AC flow rate (ton/h)	١٤.٦
Fines disposed activated coke (kg/h)	١٢١
Heavy oil (kg/h)	١٢٠
Electricity (kW)	١٣٩٠

Additionally, based on literature [٣٨], the technical specifications and process design data of wet scrubbing desulfurization methods (wet scrubber) using limestone/lime, Wellman-Lord scrubbing, citrate scrubbing, double alkali scrubbing, Exxon thermal DeNOx process (SNCR), and KHI SCR process were used for economic comparison.

٣. Data Adjustment

PEP cost index and location factor were applied to update economic costs over time and location. The equations used to adjust the economic data over time are presented in reference [٤٠].

٣,١. Key economic evaluation assumptions

The present research followed the plant-gate production-cost as well as return-on-investment (ROI) methodology employed regularly in IHS Markit/PEP-type process economics reports for the purpose of economic analysis [٣٨]. In order to calculate the required product value (namely, the levelized cost of removing the pollutant), instead of employing a complete discounted-cash-flow (DCF) technique, capital and operating costs are combined with a target return on investment in this method. As a result, traditional discounted-cash-flow parameters, e.g., net present value (NPV), internal rate of return (IRR), and discount rate, are not demanded as the inputs of this approach. The same methodology, which includes the same key assumptions mentioned in the following, was consistently applied to the Mitsui-BF process and all comparator technologies analyzed in the present research to compare the results fairly and directly.

Here are the key financial assumptions considered in the economic analysis [٣٨]: the estimation of depreciation was conducted on a straight-line basis at an annual ١٠٪ of Total Fixed Capital (TFC), which is correspondent to a ١٠-year capital recovery period. The target Return on Investment (ROI) was set at an annual ١٥٪ of TFC (before applying the taxes). Insurance and taxes were assumed at an annual amount of ٢٪ of TFC. Plant overhead was assumed as ٨٠٪ of total labor costs. Finally, maintenance (labor and materials each) was assumed at an annual amount of ٠,٣٪ of Battery Limits Investment (BLI).

Table ٤ summarizes the base-year unit prices for the utilities and raw materials consumed during the analysis. Later, the same base-year prices were modified with regard to present-day

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values and Iranian conditions by considering the PEP Cost Index (for temporal escalation) and the location factors enlisted in periodic IHS reports (for the purpose of geographic adjustment), as explained above.

Table ٤. Unit prices of raw materials and utilities used in the techno-economic evaluation (base year ٢٠١٩)

Item	Price
Limestone	٠,٨٤ ¢/lb
Lime	٢,٧٧ ¢/lb
Dolomite	٣,٢١ ¢/lb
Electricity	٤,٧٢ ¢/kWh
Water	٠,١٠٥ ¢/gal
Steam (١٥٠ psia)	٠,٤٩٢ ¢/lb
Activated Coke	١٦٥ ¢/kg
Ammonia	١٣,٣ ¢/lb

٤. Economic evaluation of MITSUI-BF process for DeSOx-DeNOx

Based on the scaling exponents, an economic evaluation of the MITSUI-BF process was carried out to estimate raw materials, utility, capital, operating, and levelized costs for a ٣٥٠ MW power plant. These calculations were also performed for other processes, including wet scrubbing using limestone/lime, Wellman-Lord scrubbing, citrate scrubbing, double alkali scrubbing, Exxon's non-catalytic selective reduction (SNCR) process, and KHI's selective catalytic reduction (SCR) process [٣٧, ٣٨]. A summary of the results is presented in Table ٥.

Table ٥. Economic evaluation of processes for DeSOx, DeNOx and DeSOx-DeNOx

Process	Boiler Capacity (MW)	Capital Cost ($ Million)	Raw Materials and Utility Costs (¢/ kWh)	Levelized Cost* (¢/ kWh)
Limestone Forced Oxidization (LSFO) Limestone Scrubbing	٣٥٠	١٤٤.٩	٠.٢٨	١.٩٨
Magnesium Enhanced-Lime Process (MEL) Wet Scrubbing	٣٥٠	١٢٧.٩٥	٠.٢٣	١.٧٤
Double Alkali Scrubbing	٣٥٠	١٢٨.٣٣	٠.٧١	٢.٢٣
MITSUI-BF (DeSOx)	٣٥٠	١٣٥.٥	٠.٨٧	٢.٥٩
Citrate Scrubbing	٣٥٠	٢١٣.٢٢	٠.٥	٢.٩٧
Wellman-Lord scrubbing	٣٥٠	٢٣٨.٦٩	١.٤	٤.١٦
MITSUI-BF (DeNOx)	٣٥٠	٥٥.٣٧	٠.٢٢٦	٠.٩٦
Exxon (SNCR)	٣٥٠	٩.٣	٠.٠٣	٠.١٤
KHI (SCR)	٣٥٠	٣٣.٨	٠.٠٦	٠.٤٥
MITSUI-BF (DeSOx-DeNOx)	٣٥٠	١٥٣.٦	١.٠٤٨	٢.٩٧
KHI + MEL	٣٥٠	١٦١.٧٥	٠.٢٩	٢.١٩
KHI + LSFO	٣٥٠	١٧٨.٧	٠.٣٤	٢.٤٣

* Cost of pollution removal per power generation

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As results show in Table ٥, among processes designed exclusively to SO_x removal, the MITSUI-BF process exhibits a higher levelized cost compared to technologies that do not produce sulfur as by-products, such as LSFO and MEL. The capital cost of MITSUI-BF process is comparable to that of alternative technologies; however, its higher levelized cost is primarily attributed to the additional utility cost incurred during sulfur production and higher cost of activated coke as raw material.

In addition, according to the results in Table ٥, when the processes are solely focused on NOx removal, SCR-KHI and SNCR-Exxon processes offer lower capital and levelized cost comparing to the MITSUI-BF process. This is due to the cost of additional equipment required for adsorbent recovery and higher consumed adsorbent in MITSUI-BF process.

In processes where SO_x and NOx are simultaneously removed; the capital cost of the MITSUI-BF process is lower than LSFO and SCR-KHI processes. However, the high cost of the consumed adsorbent and additional utility cost during sulfur production contribute the higher levelized cost for the MITSUI-BF process comparing to the aforementioned processes.

٥. Operational Feasibility

In this section, the operational feasibility of the MITSUI-BF process is assessed by comparing it with the least cost desulfurization process, limestone/lime wet scrubbers, and the most commonly used NOx removal process, SCR-KHI.

٥,١. Process complexity

In terms of process complexity, the MITSUI-BF method is the most complex since it is an integrated dry process which eliminates SOx and NOx simultaneously. It includes continuous circulation of solids and high-temperature regeneration of the coke, as well as challenging operation such as bed clogging, equipment erosion, and handling of the spent adsorbent, which increase both technical and cost complexity.

In comparison, the limestone/lime wet scrubber system has a moderate level of complexity, mainly due to liquid handling and chemical reactions. The primary problems are pH control, scaling, plugging and corrosion, along with the generation of significant amounts of wastewater and wet sludge which need to be treated and disposed of.

The SCR process also exhibit moderate complexity, focusing on catalyst management and precise ammonia injection. Some of the key problems are keeping the temperature in the optimum range, preventing ammonia slip, minimizing catalyst deactivation, and the high cost of catalyst materials.

Therefore, the wet scrubber and SCR systems are moderately complex with different operational considerations, while MITSUI-BF is considered the most complex.

٥,٢. Consumable Materials and Waste Production

The consumable materials, especially absorbents used in desulfurization processes, are the critical factors. The type, quantity, and availability of absorbents affect the choice of an appropriate desulfurization process. Furthermore, water demand, especially in the wet process, is also an important factor to consider in the selection of the desulfurization method, particularly in areas where water supplies are limited. The specifications of these two components, as well as other consumable materials needed for each of the selected processes, are provided in Table ٦.

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Table ٦. Specifications of materials used in desulfurization processes in a ٣٥٠ MW power plant (٢٧٦١ GWh per year) with stream factor: ٠,٩

Specifications of Adsorbent						
Process	Adsorbent	Adsorbent Required				Absorbent Supply Feasibility in Iran
LSFO	Limestone	lb/ kWh	٠,٠٨٦	kg/h	١١٠٢٧	Available
	Lime	lb/ kWh	٠,٠٠٧	kg/h	٩٠١	
	Dolomite	lb/ kWh	٠,٠٠٢٤	kg/h	٣٠٩	
MEL	Lime	lb/ kWh	٠,٠٠٩٤	kg/h	١٢٠٩	
	Dolomite	lb/ kWh	٠,٠١٤٢٩	kg/h	١٨٣٩	
Mitsui	Activated Coke (DeSOx- DeNOx)	kg/ kWh	٠,٠٠٣٩	kg/h	١١٠٦	The number of companies supplying this absorbent is limited. However, there is a potential to produce it in Iran through efforts of researchers and catalyst manufacturers.
	Activated Coke (DeSOx)	kg/ kWh	٠,٠٠٣٢	kg/h	٩٠٨	
	Activated Coke (DeNOx)	kg/ kWh	٠,٠٠٠٨٣٤	kg/h	٢٣٧	
	Ammonia (DeSOx-DeNOx) or (DeNOx)	kg/ kWh	٠,٠٠٠٨٩	kg/h	٢٥٢	Limited Availability
SCR-KHI	Ammonia	lb/ MMBtu	٠,٠٠٠٦٥٩	kg/h	١٨٧	Limited Availability
	Catalyst	٧٦ Ton/ year				Imported, Limited accessibility in Iran

Water Demand					
Process	Water Demand for DeSOx				Water Quality
LSFO	gal/kWh	٠,٠٨-٠,٠٩٨	m^3/h	٨٦-١٠٥	Well Water
MEL	gal/kWh	٠,٠٨-٠,٠٩٨	m^3/h	٨٦-١٠٥	Well Water
Mitsui	Negligible				-
SCR-KHI	Negligible				-

Another important parameter for choosing and applying desulphurization processes is the quantity of solid/semi-solid wastes. The approximate quantities of waste produced by the selected processes are given in Table ٧.

Table ٧. Waste and by-products from desulfurization processes in a ٣٥٠ MW power plant (٢٧٦١ GWh per year) with stream factor: ٠,٩

Specifications of Solid Waste							Ref.
Process	Waste Type	Quantity of Waste				Marketability	
LSFO	Gypsum	kg/h	٢٢٢٤٣	Ton/year	١٧٥٣٣٦	Negligible due to low quality	
MEL	Gypsum	kg/h	٦٦٣٢	Ton/year	٥٢٢٥٨	Negligible	
Mitsui	Fine A.C. (DeSOx-DeNOx)	kg/h	٥٦٥	Ton/year	٤٤٥٤	None	
	Fine A.C. (DeSOx)	kg/h	٤٤٤	Ton/year	٣٥٠٠		
	Fine A.C. (DeNOx)	kg/h	١٢١	Ton/year	٩٥٤	Usable as Fuel in Coal Boilers or Reductant in Claus Process	
SCR-KHI	Catalyst Disposal	Periodic				Recovery of Valuable Metals from Spent Catalyst	
Specifications of Wastewater							
Process	Quantity of Wastewater					Type of Wastewater	
LSFO	m^3/h	٢٠-٢٥				Saline Wastewater Containing Sulfate and Sulfite	[٣٨]
MEL	m^3/h	٢٠-٢٥				Move to Treatment Plant for Neutralization and Disposal	
Mitsui	Negligible					-	
SCR-KHI	Negligible					-	

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٥,٣. Space Requirement

There are two main categories for space requirements for installing the LSFO process in a power plant:

١) Provide spacing between the boiler and the chimney flue gas transfer area. The estimated space requirement for this area in a ٣٥٠ MW LSFO FGD system is approximately ٧٠٠ m^2. The total area is distributed as follows: an absorber tower with an area of approximately ١٢٠ m^2, flue gas path and booster fans which estimated to require between ٣٠٠ and ٥٠٠ m^2, and an additional ٢٠٠ to ٣٥٠ m^2 is allocated for maintenance access, platforms, piping networks, and safety clearance [٤١-٤٤]

٢) The space needed within the power plant itself extends out to:

٢,١. Absorbent preparation and distribution system. This accounts for the space required for slurry preparation, crushing plant, loading plant, and storage areas, which is roughly ٨٠٠ m^2. This footprint is divided several critical components: a covered storage yard designed for a ١٥-day limestone supply (occupying roughly ٤٠٠ m^2), unloading hoppers equipped with vibrating feeders and conveyors (١٥٠–٢٥٠ m^2), and the crushing facility (١٥٠–٢٠٠ m^2). Additionally, space allocated for crushed limestone silos with a ٢٤-hour storage capacity is ١٠٠–١٥٠ m^2.

٢,٢. Grinding, slurry preparation, and storage section, which is estimated to require ٩٠٠ m^2 in a ٣٥٠ MW LSFO FGD system. This plant needs two streams of wet ball mills equipped with gravimetric feeders requiring ٢٠٠-٣٠٠ m^2, hydro-cyclones and slurry tanks with ١٢–٢٤ hours storage capacity occupying ٣٠٠–٥٠٠ m^2, and auxiliary equipment (interconnected pumps, agitators, piping networks, and access platforms), which account for ٢٥٠–٤٠٠ m^2. An additional space for layout optimization and maintenance clearance is also estimated at ١٥٠–٢٠٠ m^2.

٢,٣. Other supporting systems. These include gypsum dewatering equipment, communication paths, solid transfer equipment, pumps, and piping. These take up approximately ١٢٠٠ m^2.

Similar space classifications are used for the MEL process:

١) The transfer path space for the flue gas is reduced, and the transfer path area is about ٧٠٠ m^2 considering space around the tower for access and auxiliary equipment.

٢) Space needed inside the power plant area is similar to that for the LSFO process:

٢,١. Absorbent preparation and distribution require approximately ٨٠٠ m^2, assuming the same conditions as in the LSFO process.

٢,٢. Grinding, slurry preparation and storage section. This area required for this section is estimated at approximately ٧٠٠ m^2 which is lower than LSFO process. The quicklime is used in MEL process which requires less grinding comparing to limestone in LSFO system. Therefore, the MEL process uses simpler hydrators instead of wet ball mills leading to a significant reduction in the area required for grinding, slurry preparation and storage section.

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۲,۳. Other equipment space is estimated at ٦۰۰ m^2. The MEL process can operate with a simpler filtration and stabilization setup. Therefore, the estimated area for dewatering and gypsum handling in MEL system is less than that for LSFO process since the large vacuum filters have been eliminated in MEL process.
The total area requirement for MEL process is significantly lower than LSFO system due to the elimination of complex dewatering systems and simpler reagent preparation. For a ۳٥۰ MW unit, the MEL process footprint is estimated at a total of approximately ۲,۸۰۰ m^2 compared to ۳,٦۰۰ m^2 required for the LSFO process.

The space needed for introducing the Mitsui process in a power plant can be divided into two main categories: the first is the space that needs to be allocated along the flue gas transfer route from the boiler to the chimney, and the second is the space near the chimney that will be used to install the stripping tower and Claus unit. The lower bound total installation area for a ۳٥۰ MW Mitsui-BF FGD unit, commercially also known as ReACT, is estimated at ۲۳۰۰ m^2, based on the ٦۰۰ MW reference plant area (~٤,۰۰۰ m^2) considering an economy of scale factor of ۰,۷ [٤٥, ٤٦]. The main equipment along the flue gas transfer path is an adsorption tower, which its space requirement is estimated at ٦۰۰ m^2. The other components include the regenerator and auxiliary equipment (about ٦۰۰ m^2), the by-product recovery section (about ۳۰۰ m^2), and additional maintenance clearances which requires approximately ۸۰۰ m^2.
The minimum installation area for the SCR system on a ۳٥۰ MW steam power plant is estimated to be about ۳۰۰ m^2. This area consists of three main sections: ۱) the SCR reactor zone, which takes up nearly ۱۰۰ m^2, including the reactor vessel with dimensions of about ۸,۳ m by ۸,۳ m and a height of approximately ۱۲ m, ۲) the reductant storage and supply area occupying about ٥۰ m^2, ۳) and the auxiliary equipment and ducting area, requiring roughly ۱٥۰ m^2 [٤۷-٤۹].
Generally, for a ۳٥۰ MW steam plant, the Mitsui process needs to occupy noticeably less plant floor storage and auxiliary space compared to LSFO and MEL processes with the same level of SO_2/NOx reduction, resulting in a more compact on-site layout.

٥,٤. Feasibility of implementing processes in terms of domestic manufacturing

Many components used in wet scrubber systems, such as heat exchangers, tanks, scrubbers, and pipes, can be manufactured locally. However, there are some parts of the equipment, like atomizers, nozzles, fans, some pumps, and some parts of control systems that cannot be produced in Iran.
All equipment related to the Mitsui process is licensed from global manufacturer. These companies are only authorized to perform local production of any parts.
Similarly, the equipment used in the SCR process, mainly the catalyst, is also sourced from international manufacturing companies.

٥,٥. Feasibility of process implementation regarding environmental impact

The selected desulfurization processes produce large quantities of wastewater and solid wastes.
The wastewater generated also contains sulfite and sulfate ions and some fatty acids, which are directed to the treatment plant for chemical and biological treatment. These processes generate

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considerable wastewater, and it is necessary to extend the current treatment plant or construct a new one.

The amount of waste generated in the LSFO process is quite large, approximately ١٧٥,٠٠٠ tons per year, which is equivalent to approximately ٥,٢٥٠,٠٠٠ tons of waste over ٣٠ years. The density of gypsum is ١٤٠٠ kg/m^{٣}, and assuming it is landfilled over a ٣٠-year period, it occupies some ٣,٧٥٠,٠٠٠ m^{٣} of space. The area of land required to be able to store this volume of waste at a height of ٢٠ m is about ١٩٠,٠٠٠ m^{٢}, close to the power plant.

The MEL process produces around ٥٢,٠٠٠ tons of waste each year or ١,٥٦٠,٠٠٠ tons over ٣٠ years. With the same gypsum density, this waste would take up about ١,١١٤,٠٠٠m^{٣}. It would require approximately ٥٦٠٠٠ m^{٢} around the power plant if it were to be stored at ٢٠ m high.

The Mitsui process generates solid waste but in much smaller quantities. The main components of these wastes are coke powder and ash precipitated in the adsorption bed. The produced coke powder can be burned in industrial boilers. In addition, this powder can be used as a reducing agent for $SO_٢$ gas to $H_٢S$ during the process. The ash is rich in metals, which can be sold, such as vanadium and nickel. If the unit is operated incorrectly, ammonia used in processes for simultaneous removal of $SO_٢$ and NOx or NOx alone is released into the environment as residual ammonia in the flue gas. Anhydrous ammonia is toxic and can be hazardous to the health of power plant employees. Hence, it is important to control the concentration of the residual ammonia in the exhaust gas. Residual ammonia in the flue gas is a pollutant generated by the SCR process, when too much ammonia is injected in the SCR process.

Mitsui process as a whole shows much lower environmental impacts than LSFO and MEL, mainly because of its much smaller solid waste generation and the higher potential for resource recovery.

٥,٦. Feasibility of implementing processes in terms of process efficiency and performance

The separation efficiency according to the values reported in literature is presented in Table ٨. As shown in Table ٧, the Mitsui process is superior to other processes in terms of overall performance in the simultaneous removal of NOx and $SO_٢$. It shows high efficiency of ٩٠-٩٨٪ $SO^{٢}$ removal and approximately ٧٠٪ NOx removal in simultaneous mode, thus maintaining a good balance for the removal of both pollutants simultaneously. Mitsui also has a high removal efficiency for both NOx and $SO_٢$, at over ٨٥٪ and ٩٠-٩٨٪ respectively, and is effective even if separate removal is required [٣٣].

Table ٨. Removal efficiency for $SO_٢$ and NOx

Process	% $SO_٢$ removal	% NOx removal
LSFO	٩٠	-
MEL	٩٠-٩٥	-
Mitsui for DeSOx	٩٠-٩٨	-
Mitsui for DeNOx	-	>٨٥
Mitsui for DeSOx- DeNOx	٩٠-٩٨	٧٠
SCR-KHI	-	٨٥-٩٠ depending on temperature and catalyst

٦. Limitations and Future Studies

The present research used the economic figures derived from established third-party techno-economic reports (EPRI guidelines and PEP reports), instead of using site-specific vendor

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quotations. Moreover, a fully parametric sensitivity analysis of all cost components was beyond the scope of the available data. Additionally, although domestic production of activated coke in Iran may enhance the economic competitiveness of the Mitsui-BF process, its potential is still a future possibility rather than a validated current condition. Future research should be focused on field- or pilot-scale validation of the Mitsui-BF process by utilizing real flue gas from Iranian fuel-oil-fired power plants, techno-economic feasibility of activated coke production within the country, vendor-specific cost estimation for the governing conditions in Iran, and sensitivity analysis upon the access to more granular, project-specific cost data.

۷. Conclusion

This study has made it possible to analyze the Mitsui-BF process in the removal of sulfur dioxide (SO_2) and nitrogen oxides (NOx) in Iranian thermal power plants in a comprehensive way. By comparing the technical and economic aspects of the Mitsui-BF process with traditional SO_x and NOx removal processes, the results reveal that the operating costs are higher for a Mitsui-BF process than for other processes, with a possible lower capital cost.
Compared to the limestone/lime wet scrubbers and SCR-KHI, respectively, the operational feasibility of the MITSUI-BF process was assessed.
The overall process of the MITSUI-BF is probably more complicated and expensive, but the high efficiency and performance of the process make it competitive. The less water demand of the MITSUI-BF process makes it as a viable solution in regions with limited water sources. The process can be done in a sustainable way if waste management and control measures are put in place, and the process is not that impactful on the environment. Moreover, the feasibility of domestic manufacturing and the possibility of international collaboration in implementing the process in Iran support its feasibility. In the future, the Mitsui-BF process could require additional research and development to overcome the process challenges and enhance the economic viability of the process for use in Iranian thermal power plants.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Hyperwriter to improve the language of parts of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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