IPM Model – Updates to Cost and Performance for APC Technologies

Particulate Control Cost Development Methodology

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Purpose of Cost Algorithms for the IPM Model

The primary purpose of the cost algorithms is to provide generic order-of-magnitude costs for various air quality control technologies that can be applied to the electric power generating industry on a system-wide basis, not on an individual unit basis. Cost algorithms developed for the IPM model are based primarily on a statistical evaluation of cost data available from various industry publications as well as Sargent & Lundy's proprietary database and do not take into consideration site-specific cost issues. By necessity, the cost algorithms were designed to require minimal site-specific information and were based only on a limited number of inputs such as unit size, gross heat rate, baseline emissions, removal efficiency, fuel type, and a subjective retrofit factor.

The outputs from these equations represent the "average" costs associated with the "average" project scope for the subset of data utilized in preparing the equations. The IPM cost equations do not account for site-specific factors that can significantly affect costs, such as flue gas volume and temperature, and do not address regional labor productivity, local workforce characteristics, local unemployment and labor availability, project complexity, local climate, and working conditions. In addition, the indirect capital costs included in the IPM cost equations do not account for all project-related indirect costs, such as project contingency, that a facility would incur to install a retrofit control.

Technology Description

There are two main particulate capture technologies employed in the utility industry:

- Electrostatic precipitator (ESP) and
- Fabric filter (FF).

ESPs have been widely implemented throughout the utility industry both in the U.S. and abroad since the 1960s. ESPs collect particulate matter (PM) in a three-step process: charging, collecting, and cleaning the collected ash off the electrodes. These devices, which rely on fly ash resistivity to charge and collect the particles, can reduce PM emissions to below 0.015 lb/MMBtu and opacity below 10%. However, fly ash is difficult to collect when low-sulfur coal is burned because of high fly ash resistivity. Additionally, ESPs are not well-suited for highly variable processes because the collection efficiency is sensitive to fluctuations in gas-stream conditions. Existing ESPs may be upgraded to improve PM emissions removal efficiency; however, potential ESP upgrades such as the installation of high-frequency T-R sets or adding more surface area may not be universally applicable.

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Recently, fabric filters (specifically, pulse-jet fabric filters [PJFF]) have become the preferred choice for new and retrofit particulate capture at utilities. PJFFs have been used commercially for over 25 years and are considered a mature technology. Modern PJFFs are reliable, versatile, and cost effective. In a PJFF, PM is collected on a fabric bag; then the particles are cleaned off the bag surfaces with a pulse of air. During cleaning, the collected particulate falls into hoppers and is removed via an ash handling system to a fly ash storage silo. PJFF suppliers provide PM control guarantees as low as 0.010 lb/MMBtu depending on the application.

An existing or upgraded ESP may not be capable of complying with future, more stringent $PM_{2.5}$ regulations unless a separate fabric filter is installed or the ESP is large enough to be converted to a fabric filter; however, such conversions are not universally applicable because ESPs vary in size. A full-scale or polishing PJFF can provide reduced PM emissions reliably with more operational flexibility compared with most ESP options, including a new ESP.

Air Pollution Control Equipment Co-Benefits

Because PJFFs generate filter cake on the bags, these units have additional benefits not available to ESPs:

- PJFFs enhance inherent mercury removal because the flue gas contacts the unburned carbon in the fly ash.
- Collecting injected activated carbon with a PJFF can dramatically increase mercury removal from the flue gas over that achieved using an ESP particulate collector.
- High capture of sulfur trioxide (SO_3) and hydrochloric acid (HCl) can be achieved with alkaline ashes.
- With in-duct, dry-sorbent injection, PJFFs can greatly increase sulfur dioxide (SO_2) removal over that achieved using an ESP for the sorbent capture.

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$PM_{2.5}$ Capture Technology Description

Condensable PM consists of sub-micron solid and liquid particle emissions that are generated from gas-phase constituents condensing out of the flue when they are cooled by ambient conditions. Future, more stringent PM regulations may potentially include emission limits for condensable PM in addition to those for filterable PM. SO_3, combined with available moisture in the flue gas, condenses out of the flue gas as sub-micron sized sulfuric acid (H_2SO_4) mist aerosol particles, which can contribute to condensable PM emissions and increase visible opacity. The quantity of visible sulfuric acid droplets is dependent on both the acid dew-point temperature and the concentration of H_2SO_4 in the flue gas.

Wet flue gas desulfurization (FGD) scrubbers promote the condensation of sulfuric acid mist due to rapid quenching of flue gas temperature. According to FGD suppliers, wet FGD captures between 25 and 50% of sulfuric acid aerosols. Wet FGD scrubbers are, however, less efficient at removing sulfuric acid mist compared with dry FGD systems' inherent removal (greater than 90%) with a fabric filter following the absorber vessel. It is assumed for the purposes of developing the algorithm that the removal of sulfuric acid mist achieved by a wet FGD may not meet future, more stringent $PM_{2.5}$ regulations. Due to a dry FGD system's high sulfuric acid mist removal efficiency, the outlet sulfuric acid mist in such a system can be assumed to be less than 1 ppm and, therefore, would not require further sulfuric acid mist controls.

To prevent a visible plume and increases in opacity, SO_3 mitigation using alkali injection upstream of a particulate collection system would be required to achieve increased sulfuric acid mist removal. Alkali-based sorbent injection is a proven technology for the removal of SO_3 and other acid gases from coal-fired power plant flue gas that contributes to condensable PM emissions.

SO_3 mitigation is typically only required for units firing medium- to high-sulfur bituminous fuels. Units firing PRB or lignite coals, which have low SO_3 concentrations, will likely not have issues with a visible plume. Additionally, use of an SCR system will cause an increase in SO_3 emissions because the catalyst can oxidize some SO_2 to SO_3, in addition to catalyzing the reaction between NO_X and ammonia.

The required injection rate for alkali sorbents can vary depending on the required removal efficiency, Normalized Stoichiometric Ratio (NSR), and particulate capture device. The costs for an SO_3 mitigation system are primarily dependent on sorbent feed rate. This rate is a function of NSR and the required SO_3 removal (the latter is set by the utility and is not a function of unit size). Therefore, the required SO_3 removal is determined by the user-specified controlled sulfuric acid mist emission limit, and the cost estimation is based on sorbent feed rate and not on unit size.

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The most common dry sorbents used for SO_3 mitigation at power generating stations are hydrated lime and Trona. Wet sorbents such as sodium bisulfite (SBS) and soda ash have also been used for SO_3 mitigation.

Typically, sorbent is injected into the ductwork after the furnace and prior to the particulate collection device. Some sorbents (calcium- or magnesium-based sorbents) can be injected into the boiler; however, removal efficiencies can be reduced and increased slagging in the boiler can occur, which can alter the bottom ash/fly ash split and also potentially affect the heat transfer surface area and overall boiler efficiency. Therefore, the cost estimates only consider sorbent injection of either hydrated lime or unmilled Trona in the flue gas duct upstream of the fabric filter to control $PM_{2.5}$ caused by sulfuric acid mist.

High NO_X-emitting units that use a fabric filter with sodium sorbents for SO_2 control may produce a brown plume because of NO to NO_2 conversion. However, many coal-fired units control NO_X to a sufficiently low level with SCRs such that a brown plume should not result with sodium-based alkali injection for SO_3 mitigation. Also, the amount of sorbent required for sulfuric acid mist control is not large enough to cause large amounts of NO_2 to form. Therefore, this algorithm does not incorporate any additional costs to control NO_2.

Establishment of the Cost Basis

The major cost driver for a fabric filter is the required gross air-to-cloth (A/C) ratio. When a fabric filter is retrofitted following another collection device that will remain in service, such as an ESP, then a net A/C of 6.0 or lower would be appropriate. This type of polishing fabric filter would be considered if the fabric filter, with activated carbon injection for mercury removal or sorbent injection for acid gas removal, is to be installed downstream of the existing ESP. With this approach, any beneficial use of the fly ash can be maintained. In addition, a polishing fabric filter results in a smaller capital investment than that of a full-sized fabric filter.

A full-sized fabric filter, with a net A/C ratio of 4.0 or lower, should be specified when the fabric filter will be the primary particulate collection device. The lower A/C ratio will provide better bag life with the high inlet particulate loading that is expected when the filter is the sole particulate capture device used in the process.

Cost data from Sargent & Lundy's proprietary database was reviewed and a relationship was developed for the capital costs of the system on a flue gas rate basis. The capital costs include the following:

- Duct work modifications and reinforcement,

- Foundations,
- Structural steel,
- Interconnecting piping, etc., to the existing fly ash handling system,
- ID fan modifications or new booster fans, and
- Electrical modifications.

Costs for boiler reinforcement are not included. It is likely that boiler pressure control will be accounted for with instrumentation to control pressure and not with structural reinforcement.

The option to include a sorbent injection system for SO_3 mitigation is left to the user of the cost algorithm. The major cost for the dry sorbent injection (DSI) system is the sorbent itself. The sorbent feed rate is a function of SO_3 inlet rate and removal efficiency. To account for all of the variables, the capital cost of the system is established based on a sorbent feed rate. The user of the cost algorithm must pick the type of sorbent to be injected, either hydrated lime or unmilled Trona. The sorbent feed rate is then calculated using the type of sorbent and other user-specified input variables such as heat rate, type of fuel, and SO_2 rate. Cost data for several SO_3 mitigation systems were reviewed and a relationship was developed for the capital costs of the system based on sorbent feed rate.

Methodology

Inputs

Several input variables are required in order to predict the total future retrofit costs:

- Type of coal,
- Unit size,
- Unit heat rate, and
- PJFF A/C ratio.

A retrofit factor that equates to difficulty of system construction must be defined. The gross unit size and gross heat rate will factor into the amount of SO_3 generated.

The cost methodology is based on a unit located within 500 feet of sea level. The actual elevation of the site should be considered separately and factored into the flue gas rate because the rate is directly affected by the site elevation. The flue gas rate should be increased based on the ratio of the atmospheric pressure at sea level and at the unit location. As an example, a unit located 1 mile above sea level would have an approximate atmospheric pressure of 12.2 psia. Therefore, the flue gas rate should be increased by the following multiplier:

14.7 psia/12.2 psia = 1.2 multiplier to the flue gas rate

For an SO_3 mitigation system, SO_3 feed rate and NSR are the major variables for the cost estimate. The NSR is a function of the following:

- Removal efficiency and
- Reagent type.

The equations provided in the cost methodology estimate the required sulfuric acid mist removal efficiency to achieve the user-specified controlled condensable H_2SO_4 emission (lb/MMBtu) for potential future regulations.

Outputs

Total Project Costs (TPC)

First, an installed cost for the fabric filter base module is calculated (BMB). Then an installed cost for the sorbent injection system (as applicable) is calculated (BMC). The base module installed cost includes the following:

- All equipment,
- Duct work modifications,
- Duct work reinforcement,
- New ID or booster fans,
- Modifications to the fly ash handling system,
- Installation,
- Buildings,
- Foundations,
- Electrical, and
- Retrofit difficulty.

The total base module cost (BM) is then increased by the following:

- Engineering and construction management costs at 10% of the BM cost;
- Labor adjustment for 6 x 10-hour shift premium, per diem, etc., at 10% of the BM cost; and
- Contractor profit and fees at 10% of the BM cost.

A capital, engineering, and construction cost subtotal (CECC) is established as the sum of the BM and the additional engineering and construction fees.

Additional costs and financing expenditures for the project are computed based on the CECC. Financing and additional project costs include the following:

- Owner's home office costs (owner's engineering, management, and procurement) are added at 5% of the CECC.
- Allowance for Funds Used During Construction (AFUDC) is added at 6% of the CECC to account for AFUDC, based on a complete project duration of 2 years.

The total project cost is based on a multiple lump-sum contract approach. Should a turnkey engineering procurement construction (EPC) contract be executed, the total project cost would be 10 to 15% higher than what is currently estimated.

Escalation is not included in the cost equations, but could be applied by the end user as applicable. The total project cost (TPC) is the sum of the CECC and the additional costs and financing expenditures.

Fixed O&M (FOM)

The fixed operating and maintenance (O&M) cost is a function of the additional operations staff (FOMO), maintenance labor and materials (FOMM), and administrative labor (FOMA) associated with the fabric filter installation. The FOM is the sum of the FOMO, FOMM, and FOMA.

The following factors and assumptions underlie calculations of the FOM:

- All of the FOM costs are tabulated on a per-kilowatt-year (kW-yr) basis.
- In general, no additional operators are required for a PJFF, and if a sorbent injection system is required, 0.5 additional operators are generally required for equipment maintenance and sorbent unloading.
- The fixed maintenance materials and labor are a direct function of the process capital cost at 0.5% of the BM.
- The administrative labor is a function of the FOMO and FOMM at 3% of the sum of (FOMO + 0.4FOMM).

Variable O&M (VOM)

Variable O&M is a function of the following:

- Bag and cage replacement and unit costs,
- Additional power required and unit power cost,
- Sorbent use and unit costs, as applicable, and
- Waste production and unit disposal costs, as applicable.

The following factors and assumptions underlie calculations of the VOM:

- All of the VOM costs are tabulated on a per-megawatt-hour (MWh) basis.
- Bag and cage replacement every 3 and 9 years, respectively, is assumed for unit operations with 6.0 A/C.
- Bag and cage replacement every 5 and 10 years, respectively, is assumed for unit operations with 4.0 A/C.
- The additional power required includes increased fan power to account for the added fabric filter pressure drop and, as applicable, air blowers and transport-air drying equipment for the SO_3 mitigation system.
- The additional power is reported as a percentage of the total unit gross production. In addition, a cost associated with the additional power requirements can be included in the total variable costs.
- The reagent usage is a function of NSR and required SO_3 removal to meet the user-specified controlled sulfuric acid mist emission. The gross unit size and gross heat-rate factor multiplied by the SO_2 rate determine the SO_2 feed rate. The estimated NSR is a function of the removal efficiency required. The basis for total reagent rate purity is 95% for hydrated lime and 98% for Trona.
- The waste-generation rate, which is based on the reaction of Trona or hydrated lime with SO_3, is a function of the sorbent feed rate. The waste-generation rate is also adjusted for excess sorbent fed. The waste-generation rate is based on the reaction products of $CaSO_4$ and Na_2SO_4 and unreacted dry sorbent such as $Ca(OH)_2$ and Na_2CO_3.
- The user can remove fly ash disposal volume from the waste disposal cost to reflect the situation where the unit has separate particulate capture devices for fly ash and dry sorbent.
- If Trona is the selected sorbent, the fly ash captured with this sodium sorbent in the same particulate control device must be landfilled. Typical ash content for each fuel is used to calculate a total fly ash production rate. The fly ash production is added to the sorbent waste to account for a total waste stream in the O&M analysis.
- When a fabric filter is installed downstream of an ESP, the sorbent could be injected before the fabric filter with no effect on the fly ash collection. The disposal costs of Trona-only waste, however, should be increased because disposing of the pure sodium waste product is more difficult.

Input options are provided for the user to adjust the per-unit variable O&M costs. Average default values are included in the base estimate. The variable O&M costs per unit options are as follows:

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- Auxiliary power cost in $/kWh; no noticeable escalation has been observed for auxiliary power cost since 2012.
- Bag and cage costs in $/item; escalation has been observed for bag costs since 2012 due to the advancements in material used.
- Sorbent cost in $/ton, as applicable.
- Waste disposal costs in $/ton that should vary with the type of waste being disposed, as applicable.
- Operating labor rate (including all benefits) in $/hr (as applicable).

The variables that contribute to the overall VOM are as follows:

VOMB = Variable O&M costs for bags and cage replacement

VOMP = Variable O&M costs for additional auxiliary power

VOMR = Variable O&M costs for sorbent

VOMW = Variable O&M costs for waste disposal

The total VOM is the sum of the VOMB, VOMP, VOMR and VOMW. Table 1 contains an example of the complete capital and O&M cost estimate worksheet for a fabric filter installation at an air-to-cloth ratio of 4.0 with Trona injection. Table 2 contains an example of the complete capital and O&M cost estimate worksheet for a fabric filter installation at an air-to-cloth ratio of 6.0 with Trona injection. Table 3 contains an example of the complete capital and O&M cost estimate worksheet for a fabric filter installation at an air-to-cloth ratio of 4.0 with hydrated lime injection. Table 4 contains an example of the complete capital and O&M cost estimate worksheet for a fabric filter installation at an air-to-cloth ratio of 6.0 with hydrated lime injection.

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Table 1. Example of a Complete Cost Estimate for a 4.0 A/C PJFF Installation with a Trona Injection System

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous	<--- User Input
SO2 Rate	E	(lb/MMBtu)	2	<--- User Input
Existing FGD System	F		Wet FGD	<--- User Input (Removal by Wet FGD may not meet future PM2.5 limits)
Existing SCR	G		☑ TRUE	<--- User Input
Existing PM Control	H		ESP	<--- User Input
Baghouse Air-to-Cloth Ratio	J		4.0 Air-to-Cloth	<--- User Input for retrofit of new baghouse for PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	1,719,500	Downstream of an air preheater For Bituminous Coal = A*C*0.362 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.435
SO2 Feed Rate	M	(lb/hr)	9,500	= E*K/1,000,000
SO2 to SO3 Oxidation	N		0.02	If SCR and PRB then 3% If no SCR and PRB then 0.5% If SCR and Not PRB then 2% If no SCR and Not PRB then 1%
SO3 Mitigation Sorbent Type	P		Trona	<--- User Input
Sorbent Injection Location	Q		Upstream of New	<--- User Input
SO3 Removal Target	S	(%)	80	<--- User Target
NSR	T		1.06	Hydrated Lime: If injected upstream of New Baghouse = 0.0006*(S^1.8506), if injected upstream of Existing ESP = 0.4663*(S^0.4861) Trona: If injected upstream of New Baghouse = (4.00E-10)*(S^4.9518), if injected upstream of Existing ESP = (8.00E-10)*(S^4.9518)
Sorbent Feed Rate	U	(lb/hr)	388	Hydrated Lime = 0.974*(M*N*T) Trona = 1.922*(M*N*T)
Sorbent Waste Rate	V	(lb/hr)	349	Based on a final reaction product of CaSO4 or Na2SO4 and unreacted dry sorbent as Ca(OH)2 or Na2CO3. Hydrated Lime = 1.05*U + 0.775*(M*N)*(S/100) Trona = 0.7235*U + 0.45*(M*N)*(S/100)
Fly Ash Waste Rate	W	(ton/hr)	20.7	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11,000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8,400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7,200
Total Waste Rate	X	(ton/hr)	20.9	Baghouse only = W Baghouse + SO3 Mitigation = W + V/2000 Polishing Baghouse + SO3 Mitigation = V/2000
Aux Power Include in VOM? ☑	Y	(%)	0.61	Baghouse only = 0.6 Baghouse + SO3 Mitigation = 0.6 + U*0.009/A
Sorbent (Trona) Cost	Z	($/ton)	170	<--- User Input (Trona = $170, Hydrated Lime = $150)
Waste Disposal Cost	AA	($/ton)	50	<--- User Input (Disposal cost with fly ash = $50. Without fly ash, the sorbent waste alone will be more dificult to dispose = $100)
Aux Power Cost	AB	($/kWh)	0.06	<--- User Input
Bag Cost	AC	($/bag)	100	<--- User Input
Cage Cost	AD	($/cage)	30	<--- User Input
Operating Labor Rate	AE	($/hr)	60	<--- User Input (Labor cost including all benefits)

Costs are all based on 2016 dollars

Capital Cost Calculation		Example	Comments
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMB ($) =	if(J = 6.0 Air-to-Cloth then 530, J = 4.0 Air-to-Cloth then 600)*B*L^0.81	$ 67,426,000	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMC ($) =	9,000,000*B*((U/2000)^0.284)	$ 5,647,000	Base module for unmilled sorbent includes all equipment from unloading to injection, including dehumidification system, as applicable
BM ($) =	BMB + BMC	$ 73,073,000	Total Base module cost including retrofit factor
BM ($/KW) =		146	Base module cost per kW
Total Project Cost			
A1 = 10% of BM		$ 7,307,000	Engineering and Construction Management costs
A2 = 10% of BM		$ 7,307,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 10% of BM		$ 7,307,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3		**$ 94,994,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =		**190**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC		$ 4,750,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = 6% of CECC + B1		$ 5,985,000	AFUDC for baghouse: 6% for a 2 year engineering and construction cycle
TPC ($) = CECC + B1 + B2		**$ 105,729,000**	Total project cost
TPC ($/kW) =		**211**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW yr) =	if(baghouse only = 0 additional operators, baghouse and SO3 mitigation = 0.5 additional operators)*2080*AE/(A*1000)	$ 0.13	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.005/(B*A*1000)		$ 0.73	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)		$ 0.01	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA		**$ 0.87**	Total Fixed O&M costs
Variable O&M Cost			
VOMB ($/MWh) = L/(J*A*341640)*if(J = 6.0 Air-to-Cloth then ((AC)/3+(AD)/9) else J = 4.0 Air-to-Cloth then ((AC)/5+(AD)/10))		$ 0.06	Variable O&M costs for bags and cages.
VOMP ($/MWh) =Y*(AB)*10		$ 0.36	Variable O&M costs for additional auxiliary power required.
VOMR ($/MWh) = U*Z/(2000*A)		$ 0.07	Variable O&M costs for sorbent, as applicable
VOMW ($/MWh) = X*(AA)/A		$ 2.09	Variable O&M costs for waste disposal that includes fly ash and sorbent waste, as applicable
VOM ($/MWh) = VOMP + VOMB + VOMR + VOMW		**$ 2.58**	

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Table 2. Example of a Complete Cost Estimate for a 6.0 A/C PJFF Installation with a Trona Injection System

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous	<--- User Input
SO2 Rate	E	(lb/MMBtu)	2	<--- User Input
Existing FGD System	F		Wet FGD	<--- User Input (Removal by Wet FGD may not meet future PM2.5 limits)
Existing SCR	G		☑ TRUE	<--- User Input
Existing PM Control	H		ESP	<--- User Input
Baghouse Air-to-Cloth Ratio	J		6.0 Air-to-Cloth	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	1,719,500	Downstream of an air preheater For Bituminous Coal = A*C*0.362 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.435
SO2 Feed Rate	M	(lb/hr)	9,500	= E*K/1,000,000
SO2 to SO3 Oxidation	N		0.02	If SCR and PRB then 3% If no SCR and PRB then 0.5% If SCR and Not PRB then 2% If no SCR and Not PRB then 1%
SO3 Mitigation Sorbent Type	P		Trona	<--- User Input
Sorbent Injection Location	Q		Upstream of New	<--- User Input
SO3 Removal Target	S	(%)	80	<--- User Input
NSR	T		1.06	Hydrated Lime: If injected upstream of New Baghouse = 0.0006*(S^1.8506), if injected upstream of Existing ESP = 0.4663*(S^0.4861) Trona: If injected upstream of New Baghouse = (4.00E-10)*(S^4.9518), if injected upstream of Existing ESP = (8.00E-10)*(S^4.9518)
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Total Waste Rate	X	(ton/hr)	20.9	Baghouse only = W Baghouse + SO3 Mitigation = W + V/2000 Polishing Baghouse + SO3 Mitigation = V/2000
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Sorbent (Trona) Cost	Z	($/ton)	170	<--- User Input (Trona = $170, Hydrated Lime = $150)
Waste Disposal Cost	AA	($/ton)	50	<--- User Input (Disposal cost with fly ash = $50. Without fly ash, the sorbent waste alone will be more dificult to dispose = $100)
Aux Power Cost	AB	($/kWh)	0.06	<--- User Input
Bag Cost	AC	($/bag)	100	<--- User Input
Cage Cost	AD	($/cage)	30	<--- User Input
Operating Labor Rate	AE	($/hr)	60	<--- User Input (Labor cost including all benefits)

Costs are all based on 2016 dollars

Capital Cost Calculation	Example	Comments
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty		
BMB ($) = if(J = 6.0 Air-to-Cloth then 530, J = 4.0 Air-to-Cloth then 600)*B*L^0.81	$ 59,560,000	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMC ($) = 9,000,000*B*((U/2000)^0.284)	$ 5,647,000	Base module for unmilled sorbent includes all equipment from unloading to injection, including dehumidification system, as applicable
BM ($) = BMB + BMC	$ 65,207,000	Total Base module cost including retrofit factor
BM ($/KW) =	130	Base module cost per kW
Total Project Cost		
A1 = 10% of BM	$ 6,521,000	Engineering and Construction Management costs
A2 = 10% of BM	$ 6,521,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 10% of BM	$ 6,521,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3	**$ 84,770,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =	**170**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$ 4,239,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = 6% of CECC + B1	$ 5,341,000	AFUDC for baghouse: 6% for a 2 year engineering and construction cycle
TPC ($) = CECC + B1 + B2	**$ 94,350,000**	Total project cost
TPC ($/kW) =	**189**	Total project cost per kW
Fixed O&M Cost		
FOMO ($/kW yr) = if(baghouse only = 0 additional operators, baghouse and SO3 mitigation = 0.5 additional operators)*2080*AE/(A*1000)	$ 0.13	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.005/(B*A*1000)	$ 0.65	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)	$ 0.01	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA	**$ 0.79**	Total Fixed O&M costs
Variable O&M Cost		
VOMB ($/MWh) = L/(J*A*341640)*if(J = 6.0 Air-to-Cloth then ((AC)/3+(AD)/9) else J = 4.0 Air-to-Cloth then ((AC)/5+(AD)/10))	$ 0.06	Variable O&M costs for bags and cages.
VOMP ($/MWh) =Y*(AB)*10	$ 0.36	Variable O&M costs for additional auxiliary power required.
VOMR ($/MWh) = U*Z/(2000*A)	$ 0.07	Variable O&M costs for sorbent, as applicable
VOMW ($/MWh) = X*(AA)/A	$ 2.09	Variable O&M costs for waste disposal that includes fly ash and sorbent waste, as applicable
VOM ($/MWh) = VOMP + VOMB + VOMR + VOMW	**$ 2.58**	

Particulate Control Cost Development Methodology

Table 3. Example of a Complete Cost Estimate for a 4.0 A/C PJFF Installation with a Hydrated Lime Injection System

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous	<--- User Input
SO2 Rate	E	(lb/MMBtu)	2	<--- User Input
Existing FGD System	F		Wet FGD	<--- User Input (Removal by Wet FGD may not meet future PM2.5 limits)
Existing SCR	G		☑ TRUE	<--- User Input
Existing PM Control	H		ESP	<--- User Input
Baghouse Air-to-Cloth Ratio	J		4.0 Air-to-Cloth	<--- User Input for retrofit of new baghouse for PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	1,719,500	Downstream of an air preheater For Bituminous Coal = A*C*0.362 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.435
SO2 Feed Rate	M	(lb/hr)	9,500	= E*K/1,000,000
SO2 to SO3 Oxidation	N		0.02	If SCR and PRB then 3% If no SCR and PRB then 0.5% If SCR and Not PRB then 2% If no SCR and Not PRB then 1%
SO3 Mitigation Sorbent Type	P		Hydrated Lime	<--- User Input
Sorbent Injection Location	Q		Upstream of New	<--- User Input
SO3 Removal Target	S	(%)	80	<--- User Input
NSR	T		2.00	Hydrated Lime: If injected upstream of New Baghouse = 0.0006*(S^1.8506), if injected upstream of Existing ESP = 0.4663*(S^0.4861) Trona: If injected upstream of New Baghouse = (4.00E-10)*(S^4.9518), if injected upstream of Existing ESP = (8.00E-10)*(S^4.9518)
Sorbent Feed Rate	U	(lb/hr)	369	Hydrated Lime = 0.974*(M*N*T) Trona = 1.922*(M*N*T)
Sorbent Waste Rate	V	(lb/hr)	506	Based on a final reaction product of CaSO4 or Na2SO4 and unreacted dry sorbent as Ca(OH)2 or Na2CO3. Hydrated Lime = 1.05*U + 0.775*(M*N)*(S/100) Trona = 0.7235*U + 0.45*(M*N)*(S/100)
Fly Ash Waste Rate	W	(ton/hr)	20.7	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11,000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8,400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7,200
Total Waste Rate	X	(ton/hr)	21.0	Baghouse only = W Baghouse + SO3 Mitigation = W + V/2000 Polishing Baghouse + SO3 Mitigation = V/2000
Aux Power Include in VOM? ☑	Y	(%)	0.61	Baghouse only = 0.6 Baghouse + SO3 Mitigation = 0.6 + U*0.009/A
Sorbent (Hydrated Lime) Cost	Z	($/ton)	150	<--- User Input (Trona = $170, Hydrated Lime = $150)
Waste Disposal Cost	AA	($/ton)	50	<--- User Input (Disposal cost with fly ash = $50. Without fly ash, the sorbent waste alone will be more dificult to dispose = $100)
Aux Power Cost	AB	($/kWh)	0.06	<--- User Input
Bag Cost	AC	($/bag)	100	<--- User Input
Cage Cost	AD	($/cage)	30	<--- User Input
Operating Labor Rate	AE	($/hr)	60	<--- User Input (Labor cost including all benefits)

Costs are all based on 2016 dollars

Capital Cost Calculation		Example	Comments
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMB ($) =	if(J = 6.0 Air-to-Cloth then 530, J = 4.0 Air-to-Cloth then 600)*B*L^0.81	$ 67,426,000	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMC ($) =	9,000,000*B*((U/2000)^0.284)	$ 5,570,000	Base module for unmilled sorbent includes all equipment from unloading to injection, including dehumification system, as applicable
BM ($) =	BMB + BMC	$ 72,996,000	Total Base module cost including retrofit factor
BM ($/KW) =		146	Base module cost per kW
Total Project Cost			
A1 = 10% of BM		$ 7,300,000	Engineering and Construction Management costs
A2 = 10% of BM		$ 7,300,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 10% of BM		$ 7,300,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3		**$ 94,896,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =		**190**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC		$ 4,745,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = 6% of CECC + B1		$ 5,978,000	AFUDC for baghouse: 6% for a 2 year engineering and construction cycle
TPC ($) = CECC + B1 + B2		**$ 105,619,000**	Total project cost
TPC ($/kW) =		**211**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW yr) =	if(baghouse only = 0 additional operators, baghouse and SO3 mitigation = 0.5 additional operators)*2080*AE/(A*1000)	$ 0.13	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.005/(B*A*1000)		$ 0.73	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)		$ 0.01	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA		**$ 0.87**	Total Fixed O&M costs
Variable O&M Cost			
VOMB ($/MWh) = L/(J*A*341640)*if(J = 6.0 Air-to-Cloth then ((AC)/3+(AD)/9) else J = 4.0 Air-to-Cloth then ((AC)/5+(AD)/10))		$ 0.06	Variable O&M costs for bags and cages.
VOMP ($/MWh) =Y*(AB)*10		$ 0.36	Variable O&M costs for additional auxiliary power required.
VOMR ($/MWh) = U*Z/(2000*A)		$ 0.06	Variable O&M costs for sorbent, as applicable
VOMW ($/MWh) = X*(AA)/A		$ 2.10	Variable O&M costs for waste disposal that includes fly ash and sorbent waste, as applicable
VOM ($/MWh) = VOMP + VOMB + VOMR + VOMW		**$ 2.58**	

Particulate Control Cost Development Methodology

Table 4. Example of a Complete Cost Estimate for a 6.0 A/C PJFF Installation with a Hydrated Lime Injection System

Variable	Designation	Units	Value	Calculation
Unit Size (Gross)	A	(MW)	500	<--- User Input
Retrofit Factor	B		1	<--- User Input (An "average" retrofit has a factor = 1.0)
Gross Heat Rate	C	(Btu/kWh)	9500	<--- User Input
Type of Coal	D		Bituminous	<--- User Input
SO2 Rate	E	(lb/MMBtu)	2	<--- User Input
Existing FGD System	F		Wet FGD	<--- User Input (Removal by Wet FGD may not meet future PM2.5 limits)
Existing SCR	G		☑ TRUE	<--- User Input
Existing PM Control	H		ESP	<--- User Input
Baghouse Air-to-Cloth Ratio	J		6.0 Air-to-Cloth	<--- User Input for retrofit of an additional baghouse after the existing PM control.
Heat Input	K	(Btu/hr)	4.75E+09	= A*C*1000
Flue Gas Rate	L	(acfm)	1,719,500	Downstream of an air preheater For Bituminous Coal = A*C*0.362 For PRB Coal = A*C*0.400 For Lignite Coal = A*C*0.435
SO2 Feed Rate	M	(lb/hr)	9,500	= E*K/1,000,000
SO2 to SO3 Oxidation	N		0.02	If SCR and PRB then 3% If no SCR and PRB then 0.5% If SCR and Not PRB then 2% If no SCR and Not PRB then 1%
SO3 Mitigation Sorbent Type	P		Hydrated Lime	<--- User Input
Sorbent Injection Location	Q		Upstream of New	<--- User Input
SO3 Removal Target	S	(%)	80	<--- User Input
NSR	T		2.00	Hydrated Lime: If injected upstream of New Baghouse = 0.0006*(S^1.8506), if injected upstream of Existing ESP = 0.4663*(S^0.4861) Trona: If injected upstream of New Baghouse = (4.00E-10)*(S^4.9518), if injected upstream of Existing ESP = (8.00E-10)*(S^4.9518)
Sorbent Feed Rate	U	(lb/hr)	369	Hydrated Lime = 0.974*(M*N*T) Trona = 1.922*(M*N*T)
Sorbent Waste Rate	V	(lb/hr)	506	Based on a final reaction product of CaSO4 or Na2SO4 and unreacted dry sorbent as Ca(OH)2 or Na2CO3. Hydrated Lime = 1.05*U + 0.775*(M*N)*(S/100) Trona = 0.7235*U + 0.45*(M*N)*(S/100)
Fly Ash Waste Rate	W	(ton/hr)	20.7	(A*C)* Ash in Coal*(1-Boiler Ash Removal)/(2*HHV) For Bituminous Coal: Ash in Coal = 0.12; Boiler Ash Removal = 0.2; HHV = 11,000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8,400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7,200
Total Waste Rate	X	(ton/hr)	21.0	Baghouse only = W Baghouse + SO3 Mitigation = W + V/2000 Polishing Baghouse + SO3 Mitigation = V/2000
Aux Power Include in VOM? ☑	Y	(%)	0.61	Baghouse only = 0.6 Baghouse + SO3 Mitigation = 0.6 + U*0.009/A
Sorbent (Hydrated Lime) Cost	Z	($/ton)	150	<--- User Input (Trona = $170, Hydrated Lime = $150)
Waste Disposal Cost	AA	($/ton)	50	<--- User Input (Disposal cost with fly ash = $50. Without fly ash, the sorbent waste alone will be more dificult to dispose = $100)
Aux Power Cost	AB	($/kWh)	0.06	<--- User Input
Bag Cost	AC	($/bag)	100	<--- User Input
Cage Cost	AD	($/cage)	30	<--- User Input
Operating Labor Rate	AE	($/hr)	60	<--- User Input (Labor cost including all benefits)

Costs are all based on 2016 dollars

Capital Cost Calculation		Example	Comments
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty			
BMB ($) =	if(J = 6.0 Air-to-Cloth then 530, J = 4.0 Air-to-Cloth then 600)*B*L^0.81	$ 59,560,000	Base module for an additional baghouse including: ID or booster fans, piping, ductwork, etc…
BMC ($) =	9,000,000*B*((U/2000)^0.284)	$ 5,570,000	Base module for unmilled sorbent includes all equipment from unloading to injection, including dehumidification system, as applicable
BM ($) =	BMB + BMC	$ 65,130,000	Total Base module cost including retrofit factor
BM ($/KW) =		130	Base module cost per kW
Total Project Cost			
A1 = 10% of BM		$ 6,513,000	Engineering and Construction Management costs
A2 = 10% of BM		$ 6,513,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 10% of BM		$ 6,513,000	Contractor profit and fees
CECC ($) = BM+A1+A2+A3		**$ 84,669,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) =		**169**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC		$ 4,233,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
B2 = 6% of CECC + B1		$ 5,334,000	AFUDC for baghouse: 6% for a 2 year engineering and construction cycle
TPC ($) = CECC + B1 + B2		**$ 94,236,000**	Total project cost
TPC ($/kW) =		**188**	Total project cost per kW
Fixed O&M Cost			
FOMO ($/kW yr) =	if(baghouse only = 0 additional operators, baghouse and SO3 mitigation = 0.5 additional operators)*2080*AE/(A*1000)	$ 0.13	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.005/(B*A*1000)		$ 0.65	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)		$ 0.01	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA		**$ 0.79**	Total Fixed O&M costs
Variable O&M Cost			
VOMB ($/MWh) = L/(J*A*341640)*if(J = 6.0 Air-to-Cloth then ((AC)/3+(AD)/9) else J = 4.0 Air-to-Cloth then ((AC)/5+(AD)/10))		$ 0.06	Variable O&M costs for bags and cages.
VOMP ($/MWh) =Y*(AB)*10		$ 0.36	Variable O&M costs for additional auxiliary power required.
VOMR ($/MWh) = U*Z/(2000*A)		$ 0.06	Variable O&M costs for sorbent, as applicable
VOMW ($/MWh) = X*(AA)/A		$ 2.10	Variable O&M costs for waste disposal that includes fly ash and sorbent waste, as applicable
VOM ($/MWh) = VOMP + VOMB + VOMR + VOMW		**$ 2.58**	