IPM Model – Updates to Cost and Performance for APC Technologies

Dry Sorbent Injection for SO_2 Control Cost Development Methodology

Final

March 2013

Project 12847-002

Systems Research and Applications Corporation

Prepared by

Sargent & Lundy LLC

55 East Monroe Street • Chicago, IL 60603 USA • 312-269-2000

LEGAL NOTICE

This work was funded by the U.S. Environmental Protection Agency and reviewed by William A. Stevens, Senior Advisor – Power Technologies.

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

Technology Description

Dry sorbent injection (DSI) is a viable technology for moderate SO_2 reduction on coal fired boilers. Demonstrations and recent utility testing have shown SO_2 removals greater than 80% for systems using sodium based sorbents. The most common sodium based sorbent is Trona.

The level of removal for Trona can vary from 0 to 90% depending on the Normalized Stoichiometric Ratio (NSR) and particulate capture device. NSR is defined as:

$$\frac{\dfrac{\text{(moles of Na injected)}}{\text{(moles of SO}_2\text{ in flue gas)}}}{\text{(theoretical moles of Na required)}}$$

The target removal efficiency is a requirement from the utility and is independent of unit size. The costs for a DSI system are primarily dependent on sorbent feed rate which is a function of NSR and SO_2 mass feed rate per hour. Therefore, the cost estimation was based on sorbent feed rate and not on unit size.

The sorbent solids can be collected in either an ESP or a baghouse. Baghouses generally achieve greater SO_2 removal efficiencies than ESPs by virtue of the filter cake on the bags, which allows for longer reaction time between the sorbent solids and the flue gas. For a given removal efficiency with Trona, the NSR is reduced when a baghouse is used for particulate capture.

The dry sorbent capture ability is also a function of particle surface area. To increase the particle surface area, the sorbent must be injected into a relatively hot flue gas. Heating the solids produces micropores on the particle surface which greatly improve the sulfur capture ability. For Trona, the sorbent should be injected into flue gas above 275°F to maximize the micropore structure. However, if the flue gas is too hot (greater than 800°F), the solids may sinter and surface area is reduced thus lowering the SO_2 removal efficiency of the sorbent.

Another way to increase surface area is to mechanically reduce the particle size by grinding the sorbent. Typical Trona is delivered unmilled. The ore is ground such that the unmilled product has an average size around 30 μm. Commercial testing has shown that the reactivity of the Trona can be increased when the sorbent is ground to less than 30 μm. In the cost estimating methodology, the Trona is always delivered in the unmilled state. To mill the Trona, in-line mills are continuously used during the Trona injection process. Therefore, the delivered cost of the Trona will not change, only the reactivity and usage changes as the Trona is milled.

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

Ultimately, the NSR required for a given removal is a function of Trona particle size and particulate capture equipment. Either as delivered Trona (around 30 μm average size) or in-line milled Trona (around 15 μm average size) can be chosen for injection in the cost program. The average Trona particle size and the type of particulate removal both contribute to the predicted Trona feed rate.

Establishment of Cost Basis

For the wet or SDA FGD systems, the sulfur removal is generally specified at the maximum achievable level. With those systems, costs are primarily a function of plant size and sulfur rate. However, the DSI systems are quite different. The major cost for the DSI system is the sorbent itself. The sorbent feed rate is a function of sulfur rate, particulate collection device, and removal efficiency. To account for all of the variables, the capital cost was established based on a sorbent feed rate. The sorbent feed rate is calculated from user input variables. Cost data for several DSI systems was reviewed and a relationship was developed for the capital costs of the system on a sorbent feed rate basis.

Methodology

Inputs

Several input variables are required in order to predict future retrofit costs. The sulfur feed rate and NSR are the major variables for the cost estimate. The NSR is a function of:

- Removal efficiency;
- Trona particle size; and
- Particulate capture device.

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

Based on commercial testing, removal efficiencies with DSI are limited by the particulate capture device employed. When the sorbent is captured in an ESP, a 40 to 50% SO_2 removal is typically achieved without an increase in particulate emissions. A higher efficiency (70 – 75%) is generally achieved with a baghouse. The DSI technology should not be applied to fuels with a sulfur content of greater than 2 lb SO_2/MMBtu.

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

Units with a baghouse and limited NOx control that target a high SO_2 removal efficiency with sodium sorbents may experience a brown plume resulting from the conversion of NO to NO_2. The formation of NO_2 would then have to be addressed by adding adsorbent into the flue gas. However, many coal-fired units control NOx to a sufficiently low level that a brown plume should not be an issue with sodium-based DSI. Therefore, this study does not incorporate any additional costs to control NO_2.

The equations provided in the cost methodology spreadsheet allow the user to input the required removal efficiency, within the limits of the technology. To simplify the correlation, the removal with an ESP should be set at 50% and 70% with a baghouse. The simplified sorbent NSR would then be:

For an ESP at the target 50% removal:
Unmilled Trona NSR = 2.85
Milled Trona NSR = 1.40

For a baghouse at the target 70% removal:
Unmilled Trona NSR = 2.00
Milled Trona NSR = 1.55

The correlation could be further simplified by assuming that only milled Trona is used. The current trend in the industry is to use in-line milling of the Trona to improve the utilization. For a minor increase in capital, the milling can greatly reduce the variable operating expenses. It is recommended that only milled Trona be considered in the simplified model.

Outputs

Total Project Costs (TPC)

First the base installed cost for the complete DSI system is calculated (BM). The base installed cost includes:

- All equipment;
- Installation;
- Buildings;
- Foundations;
- Electrical; and
- Average retrofit difficulty.

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

The base module cost is adjusted by the selection of in-line milling equipment. The base installed cost is then increased by:

- Engineering and construction management costs at 5% of the BM cost;
- Labor adjustment for 6 x 10 hour shift premium, per diem, etc., at 5% of the BM cost; and
- Contractor profit and fees at 5% 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:

- Owner's home office costs (owner's engineering, management, and procurement) at 5% of the CECC; and
- Allowance for Funds Used During Construction (AFUDC) at 0% of the CECC and owner's costs as these projects are expected to be completed in less than a year.

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 could be 10 to 15% higher than what is currently estimated.

Escalation is not included in the estimate. 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 DSI 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 were tabulated on a per kilowatt-year (kW-yr) basis.

- In general, 2 additional operators are required for a DSI system. The FOMO was based on the number of additional operations staff required.

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

- The fixed maintenance materials and labor is a direct function of the process capital cost (BM).

- The administrative labor is a function of the FOMO and FOMM.

Variable O&M (VOM)
Variable O&M is a function of:

- Reagent use and unit costs;
- Waste production and unit disposal costs; and
- Additional power required and unit power cost.

The following factors and assumptions underlie calculations of the VOM:

- All of the VOM costs were tabulated on a per megawatt-hour (MWh) basis.

- The reagent usage is a function of NSR and SO_2 feed rate. 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 removal efficiency required. The basis for the total reagent rate is a Trona purity of 95%.

- The waste generation rate is a function of the Trona feed rate and is adjusted for the excess sorbent fed. The waste generation rate is based on reaction products of Na_2SO_4 and unreacted dry sorbent as Na_2CO_3. Waste product adjusted for a maximum of 5% inert in the Trona sorbent.

- With the addition of a sodium sorbent that is captured in the same particulate control device as the fly ash, any fly ash produced must be landfilled. Typical ash contents for each fuel are 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.

- The user has the ability to remove fly ash from the waste disposal cost to reflect the situation where the unit has separate particulate capture devices for fly ash and dry sorbent.

- When a baghouse is installed downstream of an ESP, the sodium sorbent could be injected before the baghouse with no effect on the fly ash collection.

In that case, the disposal costs of the sodium only waste should be increased to account for the increased difficulty in handling the pure sodium waste product.

- The additional power required includes air blowers for the injection system, drying equipment for the transport air, and in-line Trona milling equipment as needed.

- The additional power is reported as a percent of the total unit gross production. In addition, a cost associated with the additional power requirements can be included in the total variable costs.

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

- Trona cost in $/ton;
- Waste disposal costs in $/ton that should vary with the type of waste being disposed;
- Auxiliary power cost in $/kWh;
- Operating labor rate (including all benefits) in $/hr.

The variables that contribute to the overall VOM are:

VOMR =	Variable O&M costs for trona reagent
VOMW =	Variable O&M costs for waste disposal
VOMP =	Variable O&M costs for additional auxiliary power

The total VOM is the sum of VOMR, VOMW, and VOMP. The additional auxiliary power requirement is also reported as a percentage of the total gross power of the unit. Table 1 contains an example of the complete capital and O&M cost estimate worksheet.

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

Table 1. Example Complete Cost Estimate for a DSI 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
SO2 Rate	D	(lb/MMBtu)	2	<--- User Input
Type of Coal	E		Bituminous	<--- User Input
Particulate Capture	F		ESP	<--- User Input
Milled Trona	G		☑ TRUE	Based on in-line milling equipment
Removal Target	H	(%)	50	Maximum Removal Targets: Unmilled Trona with an ESP = 65% Milled Trona with an ESP = 80% Unmilled Trona with an BGH = 80% Milled Trona with an BGH = 90%
Heat Input	J	(Btu/hr)	4.75E+09	A*C*1000
NSR	K		1.43	Unmilled Trona with an ESP = if (H<40,0.0350*H,0.352e^(0.0345*H)) Milled Trona with an ESP = if (H<40,0.0270*H,0.353e^(0.0280*H)) Unmilled Trona with an BGH = if (H<40,0.0215*H,0.295e^(0.0267*H)) Milled Trona with an BGH = if (H<40,0.0160*H,0.208e^(0.0281*H))
Trona Feed Rate	M	(ton/hr)	16.33	(1.2011x10^-06)*K*A*C*D
Sorbent Waste Rate	N	(ton/hr)	11.65	(0.7387-0.00073696*H/K)*M Based on a final reaction product of Na2SO4 and unreacted dry sorbent as Na2CO3. Waste product adjusted for a maximum of 5% inert in the Trona sorbent.
Fly Ash Waste Rate Include in VOM? ☑	P	(ton/hr)	20.73	(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 = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Aux Power **Include in VOM?** ☑	**Q**	**(%)**	**0.65**	=if Milled Trona M*20/A else M*18/A
Trona Cost	R	($/ton)	170	<--- User Input
Waste Disposal Cost	S	($/ton)	50	<--- User Input (Disposal cost with fly ash = $50. Without fly ash, the sorbent waste alone will be more dificult to dispose = $100)
Aux Power Cost	T	($/kWh)	0.06	<--- User Input
Operating Labor Rate	U	($/hr)	60	<--- User Input (Labor cost including all benefits)

Costs are all based on 2012 dollars

Capital Cost Calculation	**Example**	**Comments**
Includes - Equipment, installation, buildings, foundations, electrical, and retrofit difficulty		
BM ($) = Unmilled Trona if (M>25 then (745,000*B*M) else 7,500,000*B*(M^0.284) Milled Trona if (M>25 then (820,000*B*M) else 8,300,000*B*(M^0.284)	$ 18,348,000	Base DSI module includes all equipment from unloading to injection
BM ($/KW) =	37	Base module cost per kW
Total Project Cost		
A1 = 5% of BM	$ 917,000	Engineering and Construction Management costs
A2 = 5% of BM	$ 917,000	Labor adjustment for 6 x 10 hour shift premium, per diem, etc…
A3 = 5% of BM	$ 917,000	Contractor profit and fees
CECC ($) - Excludes Owner's Costs = BM+A1+A2+A3	**$ 21,099,000**	Capital, engineering and construction cost subtotal
CECC ($/kW) - Excludes Owner's Costs =	**42**	Capital, engineering and construction cost subtotal per kW
B1 = 5% of CECC	$ 1,055,000	Owners costs including all "home office" costs (owners engineering, management, and procurement activities)
TPC' ($) - Includes Owner's Costs = CECC + B1	**$ 22,154,000**	Total project cost without AFUDC
TPC' ($/kW) - Includes Owner's Costs =	**44**	Total project cost per kW without AFUDC
B2 = 0% of (CECC + B1)	$ -	AFUDC (Zero for less than 1 year engineering and construction cycle)
TPC ($) = CECC + B1 + B2	**$ 22,154,000**	Total project cost
TPC ($/kW) =	**44**	Total project cost per kW

Dry Sorbent Injection for SO_2 Control
Cost Development Methodology

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
SO2 Rate	D	(lb/MMBtu)	2	<--- User Input
Type of Coal	E		Bituminous	<--- User Input
Particulate Capture	F		ESP	<--- User Input
Milled Trona	G		☑ TRUE	Based on in-line milling equipment
Removal Target	H	(%)	50	Maximum Removal Targets: Unmilled Trona with an ESP = 65% Milled Trona with an ESP = 80% Unmilled Trona with an BGH = 80% Milled Trona with an BGH = 90%
Heat Input	J	(Btu/hr)	4.75E+09	A*C*1000
NSR	K		1.43	Unmilled Trona with an ESP = if (H<40,0.0350*H,0.352e^(0.0345*H)) Milled Trona with an ESP = if (H<40,0.0270*H,0.353e^(0.0280*H)) Unmilled Trona with an BGH = if (H<40,0.0215*H,0.295e^(0.0267*H)) Milled Trona with an BGH = if (H<40,0.0160*H,0.208e^(0.0281*H))
Trona Feed Rate	M	(ton/hr)	16.33	(1.2011x10^-06)*K*A*C*D
Sorbent Waste Rate	N	(ton/hr)	11.65	(0.7387-0.00073696*H/K)*M Based on a final reaction product of Na2SO4 and unreacted dry sorbent as Na2CO3. Waste product adjusted for a maximum of 5% inert in the Trona sorbent.
Fly Ash Waste Rate Include in VOM? ☑	P	(ton/hr)	20.73	(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 = 11000 For PRB Coal: Ash in Coal = 0.06; Boiler Ash Removal = 0.2; HHV = 8400 For Lignite Coal: Ash in Coal = 0.08; Boiler Ash Removal = 0.2; HHV = 7200
Aux Power **Include in VOM?** ☑	**Q**	**(%)**	**0.65**	=if Milled Trona M*20/A else M*18/A
Trona Cost	R	($/ton)	170	<--- User Input
Waste Disposal Cost	S	($/ton)	50	<--- User Input (Disposal cost with fly ash = $50. Without fly ash, the sorbent waste alone will be more dificult to dispose = $100)
Aux Power Cost	T	($/kWh)	0.06	<--- User Input
Operating Labor Rate	U	($/hr)	60	<--- User Input (Labor cost including all benefits)

Costs are all based on 2012 dollars

Fixed O&M Cost			
FOMO ($/kW yr) = (2 additional operators)*2080*U/(A*1000)	$	0.50	Fixed O&M additional operating labor costs
FOMM ($/kW yr) = BM*0.01/(B*A*1000)	$	0.37	Fixed O&M additional maintenance material and labor costs
FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM)	$	0.02	Fixed O&M additional administrative labor costs
FOM ($/kW yr) = FOMO + FOMM + FOMA	**$**	**0.89**	Total Fixed O&M costs
Variable O&M Cost			
VOMR ($/MWh) = M*R/A	$	5.55	Variable O&M costs for Trona reagent
VOMW ($/MWh) = (N+P)*S/A	$	3.24	Variable O&M costs for waste disposal that includes both the sorbent and the fly ash waste not removed prior to the sorbent injection
VOMP ($/MWh) =Q*T*10	$	0.39	Variable O&M costs for additional auxiliary power required (Refer to Aux Power % above)
VOM ($/MWh) = VOMR + VOMW + VOMP	**$**	**9.18**	