# IPM Model – Updates to Cost and Performance for APC Technologies

## Wet FGD Cost Development Methodology

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# Wet FGD Cost Development Methodology

## 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 impact costs, such as flue gas volume or 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 a facility would incur to install a retrofit control such as project contingency.

## Establishment of the Cost Basis

Industry data from "Current Capital Cost and Cost-effectiveness of Power Plant Emissions Control Technologies" prepared by J. E. Cichanowicz for the Utility Air Regulatory Group (UARG) in 2012 to 2014 were used by Sargent & Lundy LLC (S&L) to update the wet FGD cost algorithms from 2013. The published data were significantly augmented by the S&L in-house database of recent wet FGD and wet FGD wastewater treatment system projects. Due to recently published Effluent Limitation Guidelines (ELG), it is expected that all future wet FGDs will have to incorporate a wastewater treatment facility. The capital cost of physical/chemical treatment along with selenium control with biological treatment is included in the base scope. Other feasible technologies such as evaporation, waste fixation/stabilization, and slip stream dry scrubbing would have to be evaluated on case-by-case basis.

Cost data from the various sources showed similar trends versus generating capacity. Escalation based on the CEPI was deemed acceptable. All data sources were combined so as to provide a representative wet FGD cost basis. The cost estimation tool was benchmarked against recent wet FGD projects to confirm the applicability to the current market conditions.

## Wet FGD Cost Development Methodology

The least-squares curve fit of the data was defined as a "typical" wet FGD retrofit for removal of 98% of the inlet sulfur. It should be noted that the lowest available $SO_2$ emission guarantees, from the original equipment manufacturers of wet FGD systems, are 0.04 lb/MMBtu. The typical wet FGD retrofit was based on:

- Retrofit Difficulty = 1 (Average retrofit difficulty);
- Gross Heat Rate = 9500 Btu/kWh;
- $SO_2$ Rate = 3.0 lb/MMBtu;
- Type of Coal = Bituminous;
- Project Execution = Multiple lump-sum contracts; and
- Recommended $SO_2$ emission floor = 98% removal efficiency or 0.06 lb/MMBtu.

A wet FGD designed to treat 100% of the flue gas is capable of meeting Mercury Air Toxics Standards (MATS) limits for HCl of 0.002 lb/MBtu. Wet FGDs can remove up to 99% HCl in the flue gas.

Units below 100 MW will typically not install a wet FGD system. Sulfur reductions for small units would be accomplished by treating smaller units at a single site with one wet FGD system, switching to a lower sulfur coal, repowering or converting to natural gas firing, using dry sorbent injection, and/or reducing operating hours. Capital costs of approximately $900/kW may be used for units below 100 MW under the premise that these will be combined.

The base-case cost algorithm (without waste water treatment) remains unchanged due to the limited number of wet FGD projects installed in recent years as well as market pressure. The cost algorithm for 2016 has incorporated the cost for a wet FGD wastewater treatment system to include the capital and O&M cost associated with retrofitting the wet FGD wastewater treatment to meet the ELG regulation.

## Methodology

### Inputs

Several input variables are required in order to predict future retrofit costs. The gross unit size in MW (equivalent acfm) and sulfur content of the fuel are the major variables for the capital estimation. A retrofit factor that equates to the difficulty of constructing the system must be defined. The costs herein could increase significantly for congested sites. The gross unit heat rate will factor into the amount of flue gas generated and ultimately the size of the absorber, reagent preparation, waste handling, and balance of plant costs. The $SO_2$ rate will have the greatest influence on the reagent handling and waste handling facilities. The type of fuel (Bituminous, PRB, or Lignite) will influence the flue gas quantities as a result of the different typical heating values.

The evaluation includes a user-selected option for a wastewater treatment facility. The base capital cost includes minor physical and chemical wastewater treatment. However, in the future, more extensive wastewater handling may be required due to compliance associated with the ELG. The physical and chemical wastewater treatment system and biological treatment system costs are developed based on fixed parameters associated with the wet FGD system. It is assumed that the wastewater would be approximately 0.4 gpm/MW. For example, for 500-MWW unit, wastewater treatment will be designed for 200 gpm of wastewater. Any changes from the base assumptions should be incorporated to derive more accurate costs. Other available wastewater treatment technology systems are not considered in this cost algorithm.

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 cost due to the effects on the flue gas volume. The base absorber island and balance of plant costs are directly impacted by the site elevation. These two base cost modules should be increased based on the ratio of the atmospheric pressure at sea level and that 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 base absorber island and balance of plant costs should be increased by:

14.7 psia/12.2 psia = 1.2 multiplier to the base absorber island and balance of plant costs

## Outputs

### *Total Project Costs (TPC)*

First, the installed costs are calculated for each required base module. The base module installed costs include:

- All equipment;
- Installation;
- Buildings;
- Foundations;
- Electrical;
- Minor physical and chemical wastewater treatment (WWT); and
- Retrofit difficulty.

## Wet FGD Cost Development Methodology

The base modules are:

| | |
|---|---|
| BMR = | Base absorber island cost |
| BMF = | Base reagent preparation cost |
| BMW = | Base waste handling cost |
| BMB = | Base balance of plant costs including: ID or booster fans, new wet chimney, piping, ductwork and reinforcement, minor WWT, etc. |
| BMWW = | Base wastewater treatment facility to comply with the ELG |
| BM = | BMR + BMF + BMW + BMB + BMWW |

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

- 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:

- 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 10% of the CECC and owner's costs. The AFUDC is based on a three-year engineering and construction cycle.

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.

# Wet FGD Cost Development Methodology

***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 wet FGD installation. The fixed O&M cost category to account for a wastewater treatment facility that meets ELG regulations is included in the fixed cost for maintenance labor and materials (FOMM). 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, 12 additional shift operators are required for a 500-MW or smaller installation. Units larger than 500 MW require a total of 16 additional shift operators. The FOMO was based on the number of additional operations staff required as a function of generating capacity.
- The fixed maintenance materials and labor are a direct function of the process capital cost at 1.5% of the BM.
- The administrative labor is a function of the FOMO and FOMM at 3% of the sum of (FOMO + 0.4 FOMM).

***Variable O&M (VOM)***

Variable O&M is a function of:

- Reagent use and unit costs;
- Waste production and unit disposal costs;
- Additional power required and unit power cost;
- Makeup water required and unit water cost; and
- Operation of a wastewater treatment facility to meet ELG regulations.

**Wet FGD Cost Development Methodology**

The following factors and assumptions underlie calculations of the VOM:

- All of the VOM costs are tabulated on a per-megawatt-hour (MWh) basis.
- The reagent usage is a function of gross unit size, $SO_2$ feed rate, and removal efficiency. While the capital costs are based on a 98% sulfur removal design, the operating sulfur removal percentage can be adjusted to reflect actual variable operating costs.
- A calcium-to-sulfur stoichiometric ratio of 1.03 was used as the basis for the reagent use rate. In addition, a limestone purity of 90% $CaCO_3$ with the balance being inert material was defined to establish the total reagent feed rate.
- The waste generation rate is directly proportional to the reagent usage and is estimated based on 10% moisture in the by-product.
- The additional power required includes increased fan power to account for the added wet FGD pressure drop. This requirement is a function of gross unit size (actual gas flow rate) and sulfur rate.
- 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 makeup water rate is a function of gross unit size (actual gas flow rate) and sulfur feed rate.

Due to wide range of variability of FGD wastewater chemistry and power and chemicals consumption of the wastewater treatment system associated with a wet FGD, the variable O&M cost is developed as a fixed amount based upon the S&L in-house project data and design assumptions identified in the capital cost section of this report.

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:

- Limestone cost in $/ton. No escalation is observed in pebble lime cost. However, the cost could significantly vary with the location.
- Waste disposal costs in $/ton. The site-specific cost could be significantly different.
- Auxiliary power cost in $/kWh. No noticeable escalation has been observed for auxiliary power cost since 2013.
- Makeup water costs in $/1000 gallon.
- Operating labor rate (including all benefits) in $/hr.

## Wet FGD Cost Development Methodology

The variables that contribute to the overall VOM are:

| | |
|---|---|
| VOMR = | Variable O&M costs for limestone reagent |
| VOMW = | Variable O&M costs for waste disposal |
| VOMP = | Variable O&M costs for additional auxiliary power |
| VOMM = | Variable O&M costs for makeup water |
| VOMWW = | Variable O&M costs for wastewater treatment |

The total VOM is the sum of VOMR, VOMW, VOMP, VOMM, and VOMWW. Table 1 shows a complete capital and O&M cost estimate worksheet.

# Wet FGD Cost Development Methodology

## Table 1. Example of a Complete Cost Estimate for a Wet FGD

| Variable | Designation | Units | Value | Calculation |
|---|---|---|---|---|
| Wastewater Treatment | | Phys Chem-Biological | | |
| Unit Size (Gross) | A | (MW) | 500 | <--- User Input (Greater than 100 MW) |
| 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) | 3 | <--- User Input |
| Type of Coal | E | | Bituminous | <--- User Input |
| Coal Factor | F | | 1 | Bit=1, PRB=1.05, Lig=1.07 |
| Heat Rate Factor | G | | 0.95 | C/10000 |
| Heat Input | H | (Btu/hr) | 4.75E+09 | A*C*1000 |
| Operating $SO_2$ Removal | J | (%) | 95 | <--- User Input (Used to adjust actual operating costs) |
| Design Limestone Rate | K | (ton/hr) | 12 | 17.52*A*D*G/2000 (Based on 98% Removal) |
| Design Waste Rate | L | (ton/hr) | 23 | 1.811*K (Based on 98% Removal) |
| **Aux Power**<br>**Include in VOM?** ☑ | **M** | **(%)** | **1.69** | (1.12e^(0.155*D))*F*G |
| Makeup Water Rate | N | (1000 gph) | 38 | (1.674*D+74.68)*A*F*G/1000 |
| Limestone Cost | P | ($/ton) | 30 | <--- User Input |
| Waste Disposal Cost | Q | ($/ton) | 30 | <--- User Input |
| Aux Power Cost | R | ($/kWh) | 0.06 | <--- User Input |
| Makeup Water Cost | S | ($/kgal) | 1 | <--- User Input |
| Operating Labor Rate | T | ($/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, minor physical/chemical wastewater treatment and retrofit difficulty | | | |
| BMR ($) = | 584000*(B)*((F*G)^0.6)*((D/2)^0.02)*(A^0.716) | $ 48,869,000 | Base absorber island cost |
| BMF ($) = | 202000*(B)*((D*G)^0.3)*(A^0.716) | $ 23,674,000 | Base reagent preparation cost |
| BMW ($) = | 106000*(B)*((D*G)^0.45)*(A^0.716) | $ 14,536,000 | Base waste handling cost |
| BMB ($) = | 1070000*(B)*((F*G)^0.4)*(A^0.716) | $ 89,730,000 | Base balance of plant costs including: ID or booster fans, new wet chimney, piping, ductwork modifications and strengthening, etc… |
| BMWW ($) = | 10600000*(B)*(A/500)^0.6 | $ 10,600,000 | Base wastewater treatment facility to comply with ELG. Based on ~ 0.4 gpm/MW waste water treatment facility |
| BM ($) = | BMR + BMF + BMW + BMB + BMWW | $ 187,409,000 | Total base cost including retrofit factor |
| BM ($/KW) = | | 375 | Base cost per kW |
| **Total Project Cost** | | | |
| A1 = 10% of BM | | $ 18,741,000 | Engineering and Construction Management costs |
| A2 = 10% of BM | | $ 18,741,000 | Labor adjustment for 6 x 10 hour shift premium, per diem, etc… |
| A3 = 10% of BM | | $ 18,741,000 | Contractor profit and fees |
| **CECC ($) - Excludes Owner's Costs = BM+A1+A2+A3** | | **$ 243,632,000** | Capital, engineering and construction cost subtotal |
| **CECC ($/kW) - Excludes Owner's Costs =** | | **487** | Capital, engineering and construction cost subtotal per kW |
| B1 = 5% of CECC | | $ 12,182,000 | Owners costs including all "home office" costs (owners engineering, management, and procurement activities) |
| **TPC' ($) - Includes Owner's Costs = CECC + B1** | | **$ 255,814,000** | Total project cost without AFUDC |
| **TPC' ($/kW) - Includes Owner's Costs =** | | **512** | Total project cost per kW without AFUDC |
| B2 = 10% of (CECC + B1) | | $ 25,581,000 | AFUDC (Based on a 3 year engineering and construction cycle) |
| C1 = 15% of (CECC + B1) | | $ - | EPC fees of 15% |
| **TPC ($) - Includes Owner's Costs and AFUDC = CECC + B1 + B2** | | **$ 281,395,000** | Total project cost |
| **TPC ($/kW) - Includes Owner's Costs and AFUDC =** | | **563** | Total project cost per kW |

# Wet FGD Cost Development Methodology

## Table 1 Continued

| Variable | Designation | Units | Value | Calculation |
|---|---|---|---|---|
| Wastewater Treatment | | Phys Chem-Biological | | |
| Unit Size (Gross) | A | (MW) | 500 | <--- User Input (Greater than 100 MW) |
| 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) | 3 | <--- User Input |
| Type of Coal | E | | Bituminous | <--- User Input |
| Coal Factor | F | | 1 | Bit=1, PRB=1.05, Lig=1.07 |
| Heat Rate Factor | G | | 0.95 | C/10000 |
| Heat Input | H | (Btu/hr) | 4.75E+09 | A*C*1000 |
| Operating $SO_2$ Removal | J | (%) | 95 | <--- User Input (Used to adjust actual operating costs) |
| Design Limestone Rate | K | (ton/hr) | 12 | 17.52*A*D*G/2000 (Based on 98% Removal) |
| Design Waste Rate | L | (ton/hr) | 23 | 1.811*K (Based on 98% Removal) |
| **Aux Power**<br>**Include in VOM?** ☑ | **M** | **(%)** | **1.69** | (1.12e^(0.155*D))*F*G |
| Makeup Water Rate | N | (1000 gph) | 38 | (1.674*D+74.68)*A*F*G/1000 |
| Limestone Cost | P | ($/ton) | 30 | <--- User Input |
| Waste Disposal Cost | Q | ($/ton) | 30 | <--- User Input |
| Aux Power Cost | R | ($/kWh) | 0.06 | <--- User Input |
| Makeup Water Cost | S | ($/kgal) | 1 | <--- User Input |
| Operating Labor Rate | T | ($/hr) | 60 | <--- User Input (Labor cost including all benefits) |

## Costs are all based on 2016 dollars

**Fixed O&M Cost**

| | | | |
|---|---|---|---|
| FOMO ($/kW yr) = (if MW>500 then 16 additional operators else 12 operators)*2080*T/(A*1000) | $ | 3.00 | Fixed O&M additional operating labor costs |
| FOMM ($/kW yr) = BM*0.015/(B*A*1000) | $ | 5.62 | Fixed O&M additional maintenance material and labor costs |
| FOMA ($/kW yr) = 0.03*(FOMO+0.4*FOMM) | $ | 0.16 | Fixed O&M additional administrative labor costs |
| FOMWW ($/kW yr) = | $ | - | Fixed O&M costs for wastewater treatment facility |
| **FOM ($/kW yr) = FOMO + FOMM + FOMA + FOMWW** | **$** | **8.77** | Total Fixed O&M costs |

**Variable O&M Cost**

| | | | |
|---|---|---|---|
| VOMR ($/MWh) = K*P/A*J/98 | $ | 0.73 | Variable O&M costs for limestone reagent |
| VOMW ($/MWh) = L*Q/A*J/98 | $ | 1.32 | Variable O&M costs for waste disposal |
| VOMP ($/MWh) =M*R*10 | $ | 1.02 | Variable O&M costs for additional auxiliary power required including additional fan power (Refer to Aux Power % above) |
| VOMM ($/MWh) = N*S/A | $ | 0.08 | Variable O&M costs for makeup water |
| VOMWW ($/MWh) = 0.17 (Approximate for Phys-Chem biological system) | $ | 0.17 | Variable O&M costs for wastewater treatment facility |
| **VOM ($/MWh) = VOMR + VOMW + VOMP + VOMM + VOMWW** | **$** | **3.30** | |