Numerical Engineering Evaluation of ESP Modernization Strategies

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ABSTRACT

Electrostatic precipitator (ESP) modernization has traditionally relied on engineering judgment, vendor experience, and successive field modifications to identify effective performance-improvement strategies. As the range of available modernization technologies has expanded, selecting the optimum strategy has become an increasingly complex engineering and economic decision. Plant operators may choose among multiple technically viable alternatives involving electrical, mechanical, and process modifications, each differing in achievable particulate collection performance, implementation complexity, operating cost, and capital requirements. This paper presents an engineering methodology for evaluating these alternatives before major capital investments are committed.

The proposed **Advanced Numerical Engineering Evaluation** Methodology is founded on a calibrated **Numerical Electrostatic Precipitator (NEP)** model developed as a practical engineering decision-support tool. Actual operating data, ESP geometry, fly-ash characteristics, electrical measurements, and performance-test results are integrated to establish a calibrated digital representation of the existing precipitator. Following calibration and validation against measured plant performance, the model is used to identify the dominant performance limitations and evaluate competing modernization alternatives under a common set of operating conditions.

A representative industrial application demonstrates the methodology through the sequential evaluation of conventional operation, SO_3 Flue Gas Conditioning (FGC), Dual FGC (SO_3 + NH_3), advanced electrical energization using high-frequency power supplies (HFPS), and an integrated Dual FGC + HFPS strategy. The analysis demonstrates how the calibrated model can distinguish the incremental contribution of individual modernization measures, quantify their interaction, and determine whether a proposed upgrade addresses the actual mechanism limiting ESP performance.

The results demonstrate that Advanced Numerical Engineering Evaluation extends beyond conventional emissions performance calculation. It provides a consistent basis for investigating what-if scenarios, comparing modernization strategies, and assessing the technical consequences of each option before implementation. When combined with consideration of capital cost, operating cost, implementation complexity, reliability, and project risk, the methodology provides a practical basis for selecting the most technically effective and economically appropriate ESP modernization strategy.

Keywords: Electrostatic Precipitator (ESP); Numerical Electrostatic Precipitator (NEP); Advanced Numerical Engineering Evaluation; ESP Modernization; Decision-Support Methodology.

1 INTRODUCTION

Electrostatic precipitators remain one of the principal particulate-control technologies employed in coal-fired power generation and a wide range of industrial processes. Many operating ESPs, however, were designed decades ago for fuels, process conditions, emission limits, and electrical systems substantially different from those encountered today. As environmental requirements have become more stringent and operating conditions have evolved, plant owners are increasingly required to achieve significantly better performance from existing precipitators, often without the space, outage duration, or economic justification for complete replacement.

Historically, ESP modernization has often proceeded by identifying an apparent performance limitation and applying a corresponding hardware or process modification. Typical measures include transformer-rectifier upgrades, high-frequency power supplies, discharge-electrode replacement, collecting-area additions, gas-distribution corrections, rapping-system modifications, and chemical flue-gas conditioning. Each can be effective under appropriate conditions. In practice, however, ESP performance rarely depends on a single variable**.** Electrical operating conditions, particle resistivity, gas temperature and distribution, particle-size distribution, electrode geometry, available collecting area, and mechanical condition interact to determine overall collection performance.

As a result, a technically sound upgrade may provide only limited improvement when the principal performance constraint lies elsewhere. A comparatively modest process or electrical modification may sometimes produce a greater improvement than a major mechanical retrofit if it directly addresses the controlling limitation. The modernization problem is therefore to identify what is limiting the existing ESP and determine which individual or combined measures can provide the required emissions performance at acceptable technical risk and overall cost.

This paper presents an Advanced Numerical Engineering Evaluation Methodology developed to address this decision problem before major modernization investments are committed. The approach uses a calibrated **N**umerical **E**lectrostatic **P**recipitator (**NEP**) model to establish the performance of the existing unit, identify the mechanisms limiting that performance, and evaluate competing modernization alternatives under a common set of operating conditions. The numerical model thus becomes an engineering framework for selecting and optimizing ESP modernization strategies, rather than being limited to performance calculation.

2 THE ESP MODERNIZATION DECISION PROBLEM

ESP modernization decisions are complicated by the fact that several upgrade alternatives may appear technically reasonable when considered independently, even though they address different performance limitations. Increasing electrical power input, for example, may improve particle charging and migration velocity, but the achievable benefit can remain constrained by high-resistivity ash, back corona, excessive sparking, or deteriorated electrode condition. Chemical flue-gas conditioning may substantially improve electrical behavior by modifying particulate properties, but its effectiveness depends on gas temperature, reagent concentration and distribution, ash characteristics, and establishment of the required surface-conditioning mechanism. Similarly, mechanical modifications may restore electrode alignment, corona generation, or rapping effectiveness without correcting an underlying process or resistivity limitation.

A meaningful modernization evaluation must therefore distinguish between observed symptoms and the mechanisms responsible for them. Low secondary current, for example, is an operating observation rather than a diagnosis. It may result from high particle resistivity, back corona, excessive sparking, poor electrode alignment, inadequate voltage control, electrode deterioration, or a combination of these conditions. Similarly, elevated outlet emissions establish that collection performance is inadequate, but do not by themselves determine whether the appropriate remedy is additional collecting area, improved electrical energization, correction of gas distribution, mechanical rehabilitation, chemical conditioning, or some combination of these measures.

The central engineering question is therefore not which modernization technology performs best in isolation**,** bu**t** which mechanisms are controlling the performance of the existing ESP and which modernization measures most effectively address those mechanisms. This distinction is particularly important because improvements in one part of the precipitation process may produce limited overall benefit when another limitation remains. Modernization alternatives should consequently be evaluated as interacting elements of the complete ESP system rather than as independent equipment upgrades.

The Advanced Numerical Engineering Evaluation Methodology addresses this problem by treating the ESP as an integrated electro-mechanical-process system. The existing precipitator is first reconstructed numerically and calibrated against measured plant operation. Only after the baseline representation has demonstrated its ability to reproduce the observed performance is it used to diagnose the controlling limitations and evaluate modernization alternatives. Each alternative can then be examined against the same calibrated

baseline and common operating basis, allowing its incremental effect to be distinguished from changes caused by differing assumptions or operating conditions.

The overall Advanced Numerical Engineering Evaluation workflow is illustrated in Figure 1. The evaluation progresses from acquisition of plant design and operating data through numerical reconstruction, calibration and validation, diagnosis of the dominant performance limitations, and evaluation of individual and combined modernization strategies. This structured progression establishes a consistent engineering basis for comparing alternatives and selecting a preferred modernization strategy before significant capital expenditures are committed.

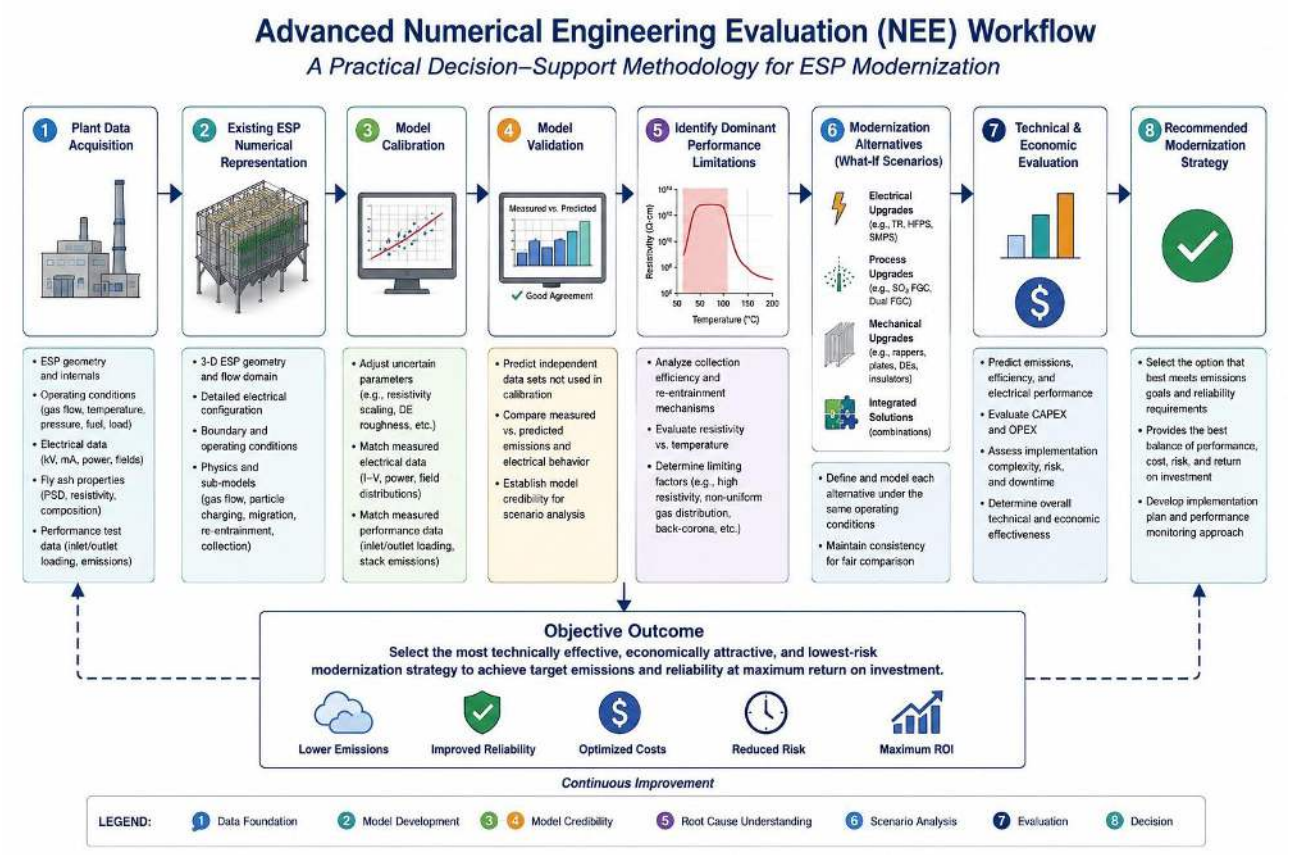


Figure 1. Advanced Numerical Engineering Evaluation Workflow

3 ADVANCED NUMERICAL ENGINEERING EVALUATION METHODOLOGY

The Advanced Numerical Engineering Evaluation methodology is structured to progress from characterization of the existing ESP to diagnosis of its controlling performance limitations and, ultimately, quantitative evaluation of potential modernization strategies. A fundamental requirement is that modernization alternatives are not evaluated against an idealized or generic ESP, but against a calibrated numerical representation of the unit under its actual operating conditions.

3.1 ESTABLISHING THE EXISTING DESIGN BASIS

The first step is to establish a defensible design and operating basis for the subject ESP. Required information typically includes precipitator geometry, number and length of electrical fields, collecting-electrode height and spacing, discharge-electrode configuration, gas-flow arrangement, transformer-rectifier ratings, electrical sectionalization, and available information concerning the mechanical condition of the precipitator.

Operating inputs include flue-gas flow and temperature, inlet particulate loading, particle-size distribution, ash composition and resistivity, moisture and sulfur-related parameters where applicable, and field-by-field voltage and current data. Performance-test information is incorporated wherever available to establish inlet loading, outlet emissions, overall collection efficiency, and the specific operating conditions represented by the test.

The objective at this stage is to establish a complete and internally consistent operating basis for the numerical evaluation. Attention is given to whether plant measurements, performance-test data, electrical readings, and particulate characteristics represent comparable operating conditions. Where information is incomplete or uncertain, the assumptions required to complete the numerical representation are explicitly identified for subsequent calibration and sensitivity evaluation.

Figure 2 expands the calibration and validation framework through which these design and operating inputs are converted into a calibrated numerical model. The collected information is first used to construct the initial NEP representation. Selected model parameters are then adjusted, where necessary, within physically reasonable limits to reproduce measured plant behavior. Independent operating information is subsequently used, where available, to verify that the calibrated model continues to reproduce plant behavior beyond the conditions used for calibration.

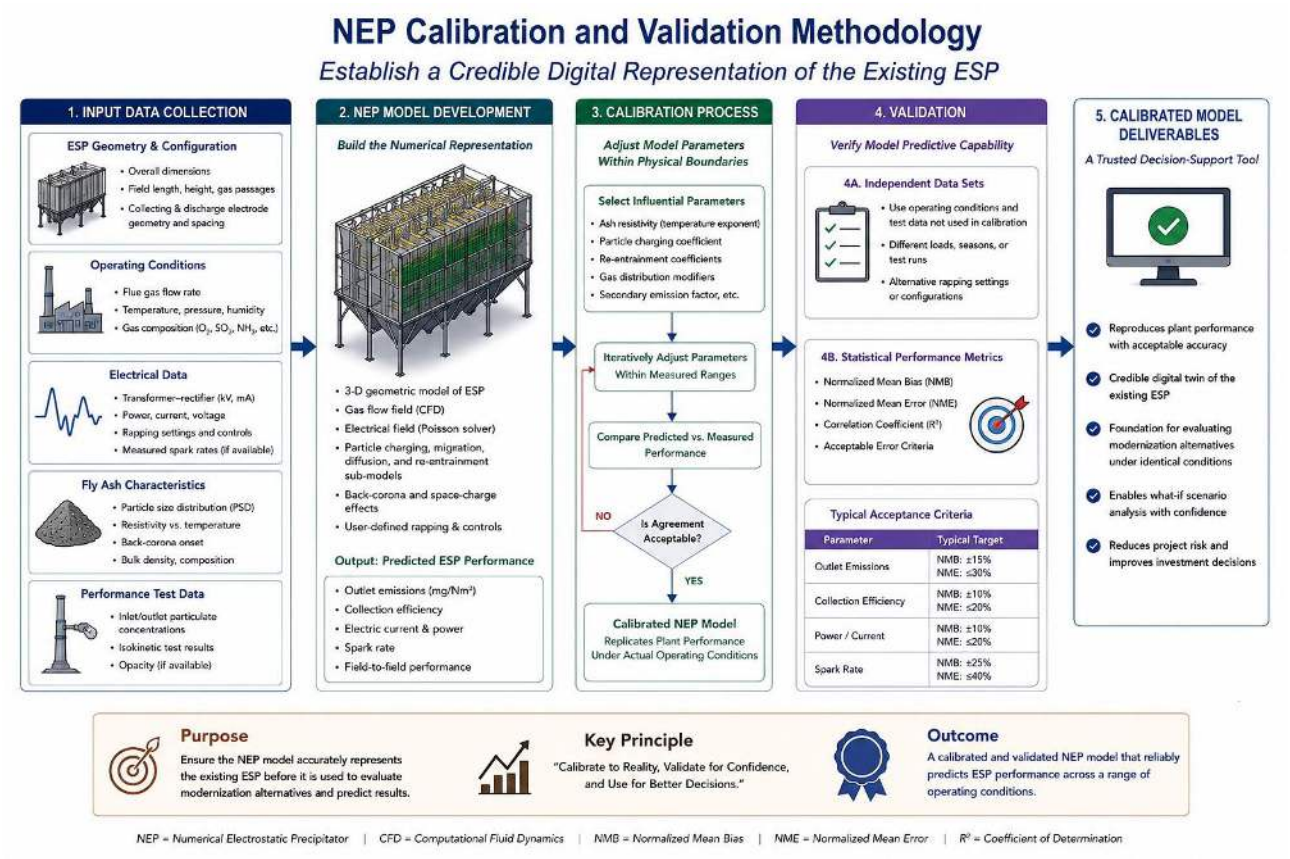


Figure 2. NEP Calibration and Validation Methodology

3.2 DEVELOPMENT OF THE NUMERICAL ESP REPRESENTATION

The NEP model converts the established physical and operating basis into a numerical representation of the precipitator. The representation accounts for the active collecting geometry, gas treatment time, particle charging and migration, electrical operating conditions, particle-size-dependent collection behavior, and the

influence of relevant process properties. The objective is not to create an idealized design calculation, but to reproduce the ESP as it actually operates.

The numerical representation therefore preserves the principal characteristics that determine precipitator performance, including collecting-field dimensions, electrode geometry and spacing, gas-flow direction, electrical sectionalization, and the arrangement of the active collecting volume. Electrical operating information is associated with the corresponding fields or sections so that the modeled charging and collection environment reflects actual operation rather than nominal equipment ratings alone.

A representative numerical ESP configuration is shown in Figure 3. The figure illustrates how the physical ESP geometry, gas-flow path, collecting fields, and electrical sectionalization are represented within the model and establishes the physical framework for the subsequent electrical and particle-transport calculations.

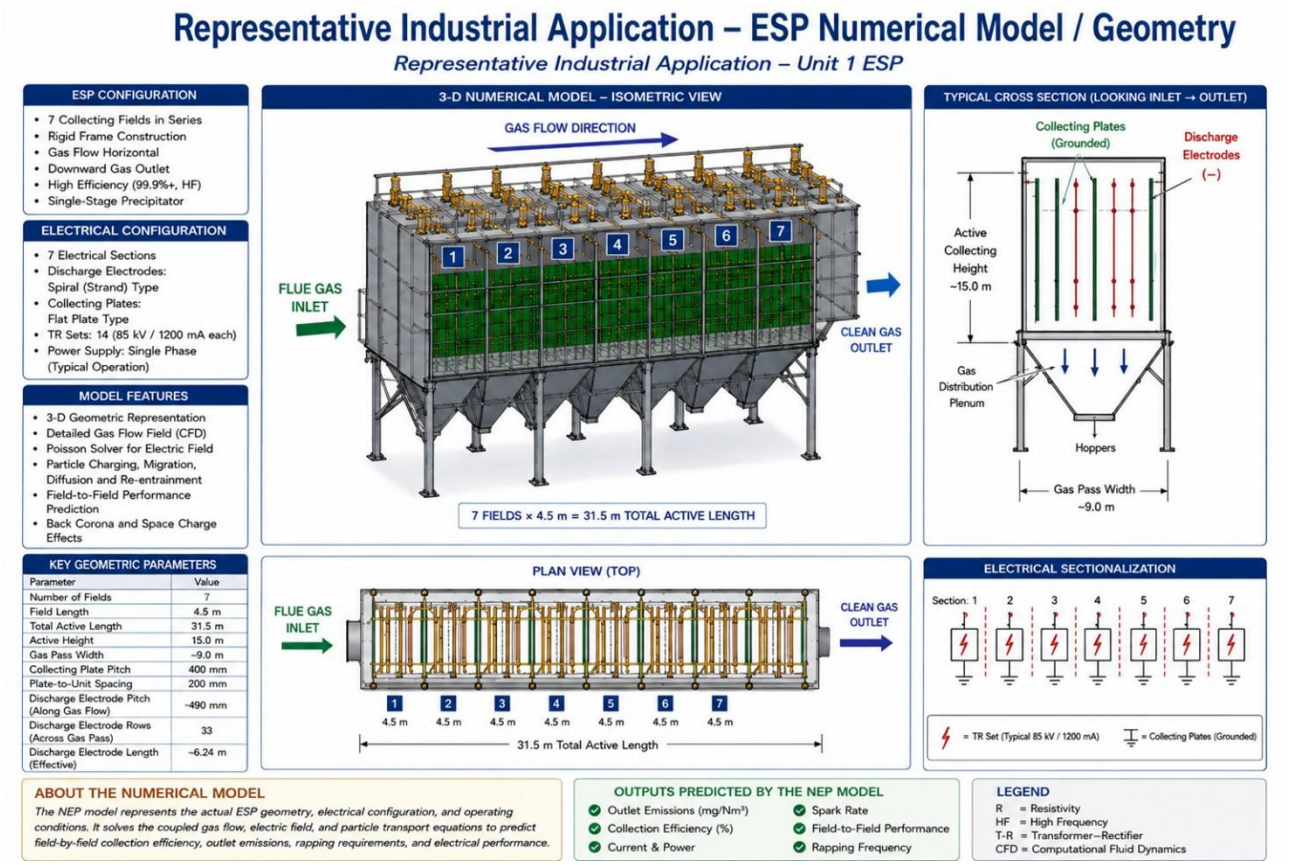


Figure 3. Representative Industrial Application – ESP Numerical Model and Geometry

3.3 NEP Model Components and Supporting Engineering Calculations

The **Numerical Electrostatic Precipitator (NEP)** model is based on the computational framework of the **ESPVI 4.0W Performance Prediction Model**, developed through a series of electrostatic-precipitator modeling efforts sponsored by the U.S. Environmental Protection Agency (EPA) [3]. ESPVI 4.0W provides a first-principles numerical framework for representing ESP geometry and operating conditions and for calculating particle charging, migration velocity, electric-field and space-charge effects, and particle-size-dependent collection performance on a section-by-section basis

For the Advanced Numerical Engineering Evaluation Methodology presented in this paper, this computational foundation is integrated with application-specific engineering calculations and procedures required to reproduce the behavior of an operating industrial ESP and to evaluate potential modernization

alternatives. These include characterization of fly-ash resistivity and its temperature dependence, particle-size-distribution analysis, simplified combustion calculations to verify flue-gas flow and combustion-product characteristics, proprietary estimation of SO_3 and ammonia conditioning requirements, reagent injection and distribution considerations, electrical operating characteristics, and calibration against measured plant performance. The resulting NEP framework therefore extends beyond a stand-alone ESP performance calculation by integrating the principal process, particulate, electrical, and operating variables that determine actual precipitator performance.

The principal NEP model components used in the present evaluation are discussed below.

3.3.1 Coal, Ash, and Combustion Analyses

Coal and fly-ash analyses form an important part of the operating basis used in the NEP evaluation. Available fuel analyses, ash chemistry, sulfur content, ash loading, and related plant operating information are reviewed to characterize the combustion products and particulate properties entering the ESP. Where multiple fuels or operating conditions are involved, the data are evaluated to establish the representative coal and ash characteristics corresponding to the modeled operating condition.

Combustion calculations are used to corroborate the principal flue-gas and particulate inputs, including flue-gas flow, moisture content, particulate loading, sulfur-related parameters, and other quantities required by the numerical evaluation [5]. These calculations provide an internally consistent link between the fuel characteristics, boiler operating conditions, and the flue-gas/particulate environment presented to the ESP. Wherever reliable plant measurements are available, measured values are retained as the primary basis and the calculated values are used principally for reconciliation and engineering verification.

The resulting coal, ash, and combustion data provide the input basis for subsequent evaluation of fly-ash resistivity, naturally occurring SO_3, conditioning demand, particle collection behavior, and overall ESP performance. Historical information and ALENTEC's proprietary database may also be used as engineering references; however, plant-specific measured and operating data remain the principal basis for the calibrated NEP representation.

3.3.2 Fly-Ash Resistivity Model

Fly-ash electrical resistivity is one of the principal particulate properties governing ESP performance. Resistivity determines how readily electrical charge deposited on collected particles can dissipate through the dust layer to the grounded collecting electrode. When resistivity is excessively high, charge dissipation becomes restricted and substantial electrical potential can develop across the deposited dust layer. This condition can promote back corona, limit useful voltage and current, reduce effective particle charging and migration, and ultimately increase particulate penetration through the ESP. Conversely, excessively low resistivity can reduce particle retention on the collecting plates and increase the potential for re-entrainment. Effective ESP operation therefore generally requires maintaining fly-ash resistivity within a favorable operating range [2][11][18][20].

The Bickelhaupt resistivity model is used to estimate fly-ash electrical resistivity as a function of ash composition, temperature, and flue-gas conditions. The model accounts for the transition between surface and volume conduction mechanisms and provides a practical basis for calculating fly-ash resistivity over the ESP operating temperature range [4]. The calculated resistivity is then used by the NEP model to evaluate its effect on electrical operation, back corona, and particulate collection performance.

3.3.3 Proprietary SO_3 Injection-Rate Methodology

The NEP evaluation incorporates a proprietary engineering methodology for estimating the SO_3 injection rate required to achieve the desired reduction in fly-ash resistivity. Originally developed by Coe and Krigmont [7][8] from operating data obtained from full-scale SO_3 flue-gas-conditioning installations, the methodology was intended to replace approximate or trial-and-error determination of conditioning injection rates with a quantitative engineering methodology based primarily on coal and ash properties and boiler operating conditions.

An important distinction is made between the theoretical sulfuric-acid requirement derived from resistivity calculations and the actual SO_3 injection rate required in an operating ESP. The Bickelhaupt relationships represent equilibrium conditions in which fly ash is exposed to a specified acid concentration for an extended period. In an operating boiler, however, injected SO_3 interacts with entrained fly ash over a relatively short residence time and under continuously changing temperature, concentration, and mixing conditions. The equilibrium acid concentration calculated by the resistivity model therefore cannot be directly interpreted as the required SO_3 injection rate.

The proprietary methodology bridges this gap by converting the theoretical acid requirement into a practical SO_3 injection rate. The Bickelhaupt calculation is used to determine the acid concentration required to reduce fly-ash resistivity to a selected target level. The projected injection requirement is then adjusted for factors that influence actual conditioning demand, including ash loading, coal sulfur content, naturally occurring SO_3, and ash chemistry.

Importantly, the injection-rate relationship was developed empirically from full-scale operating experience rather than laboratory resistivity data alone. The development database included a broad range of coals, ash contents, boiler configurations, and operating temperatures. The subsequently reported formulation produced a correlation coefficient of $R^2 = 0.989$ against the operating database, providing a strong empirical basis for application of the methodology within the range represented by the underlying data.

3.3.4 SO_3 FGC and Dual FGC Effects

Conventional SO_3 flue-gas conditioning is primarily used to control high fly-ash resistivity. By increasing the surface conductivity of the collected particulate, SO_3 FGC reduces effective dust-layer resistivity, suppresses back corona, and permits more stable ESP electrical operation. Its principal benefit is therefore the restoration of favorable electrical conditions when high-resistivity ash is the dominant performance limitation.

The physical conditioning mechanism provides the link between reagent demand and ESP performance. Following injection, SO_3 combines with water vapor in the flue gas to form sulfuric acid. As the conditioned gas mixes with the boiler flue gas, sulfuric acid condenses on the fly-ash particle surfaces and establishes a thin conductive surface layer. It is principally this surface-conditioning effect, rather than a change in the intrinsic bulk properties of the ash, that reduces the effective resistivity of the deposited dust layer, suppresses resistivity-related electrical limitations, and improves ESP collection performance. [1][18][20][21]

Dual FGC combines SO_3 conditioning with controlled ammonia (NH_3) injection. The SO_3 component continues to provide the primary resistivity-control mechanism, while ammonia introduces additional particulate-conditioning effects. NH_3 reacts with SO_3/H_2SO_4 to form ammonium sulfate and ammonium bisulfate species, which can increase particle cohesivity, reduce rapping-related re-entrainment, and improve particulate collection behavior. Dual FGC therefore addresses not only the electrical resistivity of the dust layer but also physical characteristics of the particulate that can limit overall ESP performance [9],[12][18].

The distinction is important in numerical evaluation. SO_3 FGC primarily improves the electrical collectability of high-resistivity ash, whereas Dual FGC combines resistivity control with additional particulate-conditioning mechanisms. Consequently, the incremental benefit of ammonia can be evaluated separately from the resistivity reduction produced by SO_3, allowing the NEP model to determine whether conventional SO_3 conditioning is sufficient or whether the additional mechanisms provided by Dual FGC are required to achieve the desired performance.

3.3.5 Particle Charging and Migration

The NEP model represents particle charging and subsequent migration toward the collecting electrodes as functions of the local electrical field, particle properties, and gas conditions. Particle charge and migration velocity determine the rate at which suspended particulate moves from the gas stream to the collecting surfaces. Because these mechanisms respond directly to electrical operating conditions and fly-ash resistivity, the model can evaluate how changes in conditioning, applied voltage and current, and electrical power input affect the effective collection capability of the ESP.

3.3.6 Particle-Size-Dependent Collection and Penetration

ESP collection performance varies significantly with particle diameter; consequently, the NEP model does not treat the particulate as a single uniform mass. The inlet particle-size distribution is divided into discrete size fractions, and charging, migration, collection, and penetration are evaluated for each fraction. This approach is particularly important for the fine and submicron particle ranges, where collection is generally more difficult and relatively small changes in electrical or conditioning performance can have a disproportionate effect on outlet emissions. The individual size-dependent results are subsequently integrated over the inlet particle-size distribution to calculate overall collection efficiency and particulate emissions.

3.3.7 Electrical Performance and Power-Input Representation

The electrical component of the NEP model represents the operating voltage, current, power input, and associated limitations of the individual ESP fields. These parameters establish the electrical conditions used in the particle-charging and migration calculations and allow the model to reproduce field-by-field ESP behavior. The same framework is used to evaluate changes in energization, including conventional transformer-rectifier (T-R) systems and high-frequency power supplies (HFPS).

An important element of this representation is the relationship between fly-ash resistivity and the useful electrical operating point of each field. The NEP methodology incorporates empirical relationships developed by Herbert Hall from extensive full-scale ESP operating data [10]. These relationships correlate useful secondary current density and average inter-electrode electric field with particulate resistivity. For a known electrode spacing, the electric field can be related to secondary operating voltage, providing an engineering basis for establishing representative voltage-current operating conditions.

Although sometimes presented graphically in a form resembling conventional voltage-current (V-I) curves, these relationships are fundamentally different. They represent empirical operating points derived from measured voltage and current data for operating ESPs collecting particulate over a broad range of resistivities. Separate relationships are applied to successive fields because particle concentration, size distribution, agglomeration, and space-charge effects evolve as the gas progresses through the precipitator, resulting in different achievable electrical conditions from field to field.

The original relationships were developed principally for ESPs with approximately 9- to 12-in. (230- to 300-mm) collecting-electrode spacing. Application to wider-spacing ESPs therefore requires engineering judgment and calibration against actual electrical data. Within the NEP methodology, these relationships provide an initial engineering basis that is reconciled with measured field-by-field voltage, current, power input, electrode geometry, particulate resistivity, and plant performance during model calibration.

This representation is particularly important when evaluating electrical modernization. Increased power-supply capability does not necessarily produce a proportional increase in useful ESP power input or collection performance. High fly-ash resistivity, back corona, sparking, and space-charge effects may restrict the voltage and current that can be effectively applied. The NEP model therefore evaluates electrical upgrades together with the prevailing particulate and process conditions, allowing the benefit of T-R or HFPS modernization to be quantified without assuming that additional available electrical power can automatically be utilized by the precipitator.

3.3.8 Reagent Distribution Considerations

Effective flue-gas conditioning requires not only the correct overall reagent injection rate but also adequate distribution across the ESP inlet gas stream. The NEP methodology therefore considers spatial variations in gas flow, temperature, and conditioning demand when evaluating reagent distribution. Where significant nonuniformities exist, the required conditioning rate can be allocated across the injection grid to provide the appropriate local treatment rather than assuming uniform reagent demand across the entire gas stream.

3.3.9 Integrated NEP Framework – Foundation of the ESP Digital Twin

ESPVI 4.0W provides the core ESP computational framework within NEP. This foundation is combined with additional resistivity, flue-gas-conditioning, particle-size, electrical-performance, reagent-distribution, and plant-specific calibration methodologies to create a calibrated numerical representation, or 'Digital Twin,' of the actual ESP.

The NEP model is therefore not simply an application of the ESPVI 4.0W performance model. Rather, ESPVI 4.0W provides the core ESP computational framework, which is combined with additional resistivity, flue-gas-conditioning, particle-size, electrical-performance, and plant-specific calibration methodologies.

The resulting integrated framework, in which the individual engineering models, plant-specific inputs, and calibration procedures are assembled into a unified numerical representation of the operating ESP, is illustrated in Figure 4.

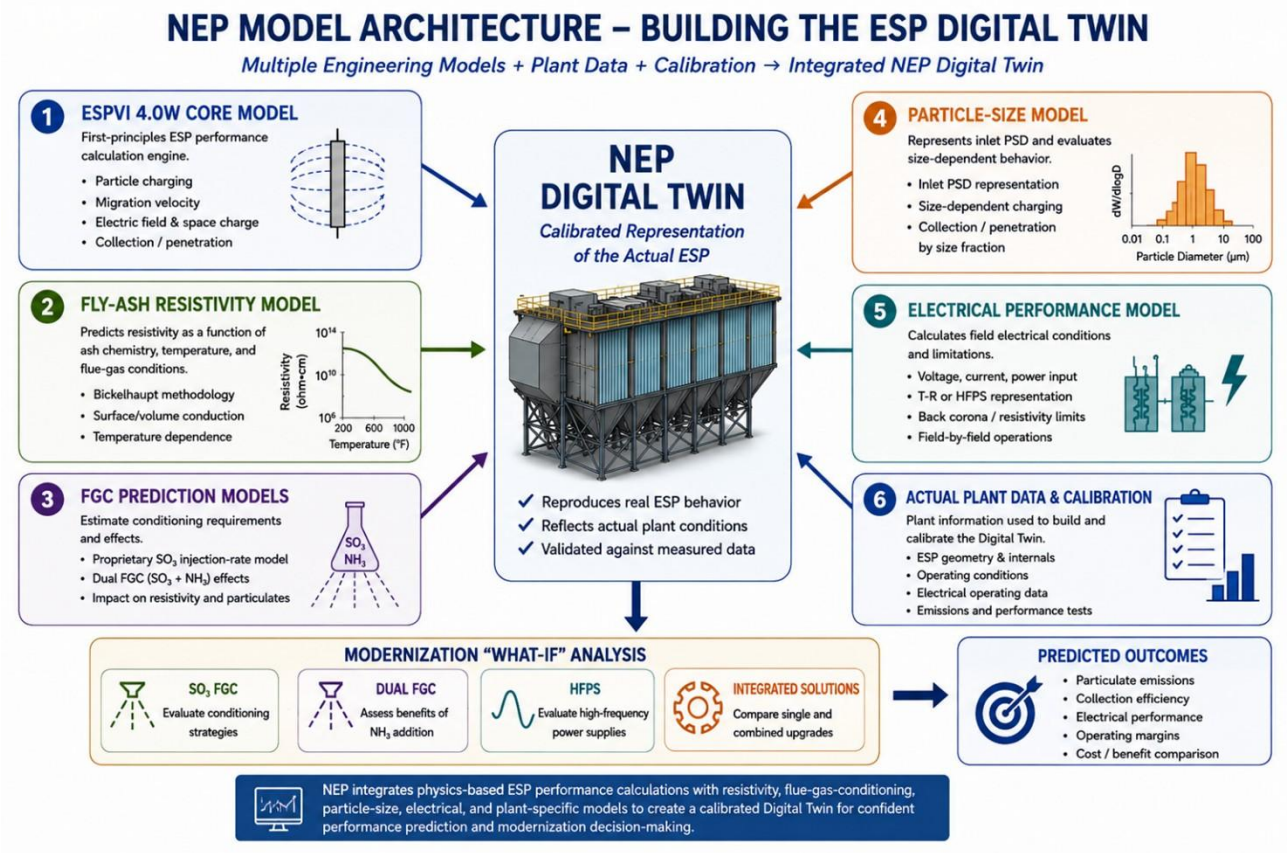


Figure 4. NEP Model Architecture – Building the ESP Digital Twin

3.4 Calibration and Validation

Calibration is the critical step that converts the numerical representation from a theoretical calculation into an engineering decision-support tool. Model parameters are adjusted only within physically reasonable bounds so that expected baseline performance reproduces measured plant behavior. Depending on the available information, calibration may include field electrical conditions, effective particle migration behavior, gas-distribution effects, particle-size-dependent penetration, and known mechanical or process limitations.

Calibration must reproduce more than the measured outlet-emission value [3]. A credible baseline representation should reproduce the principal physical and electrical characteristics responsible for that result.

Consequently, calculated particulate emissions are considered together with available field voltage and current data, power input, collection efficiency, particle-size-dependent behavior, and other relevant operating observations.

Validation is then performed against independent operating information whenever such information is available. The objective is to determine whether the calibrated model can reproduce plant behavior under conditions other than those used directly for calibration. Agreement at a single emission point without reasonable consistency with the underlying electrical and particulate behavior is not considered sufficient evidence of model validity beyond the calibration condition.

Figure 5 illustrates the baseline calibration and validation results for the representative industrial application. Calculated outlet emissions, collection efficiency, discharge current, applied power, and particle-size-dependent behavior are compared with measured plant performance. Agreement across multiple independent performance indicators provides substantially greater confidence in the calibrated baseline and establishes the basis for using the model to evaluate changes from that condition.

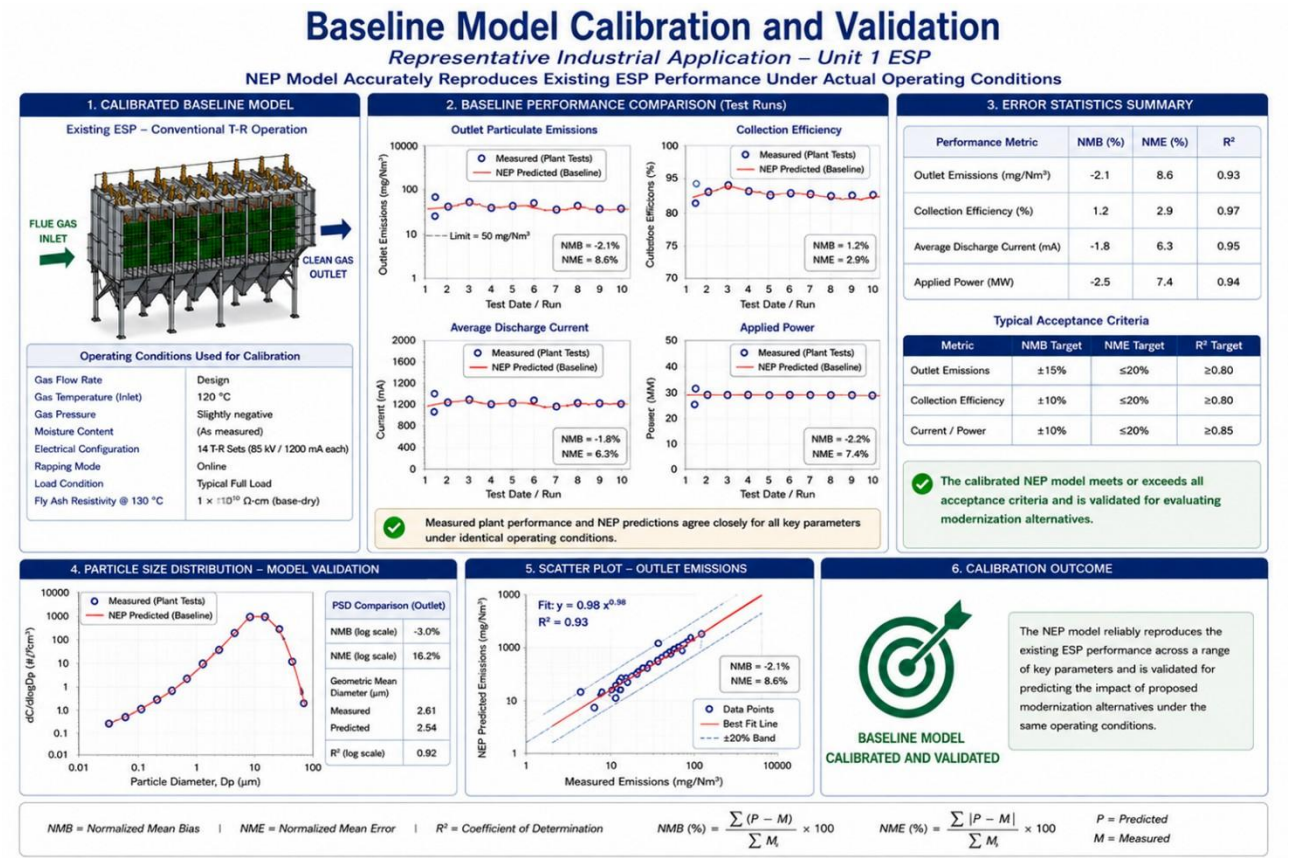


Figure 5. Baseline Model Calibration and Validation

3.5 IDENTIFICATION OF DOMINANT PERFORMANCE LIMITATIONS

Once the baseline model has been calibrated and validated, it is used diagnostically to identify the mechanisms controlling ESP performance. Sensitivity studies are performed by systematically varying relevant electrical, particulate, process, and geometric parameters and observing their effect on projected outlet emissions and collection behavior.

This step is particularly important because it separates **diagnosis from technology selection**. Rather than beginning with a preferred modernization technology and attempting to demonstrate its benefit, the analysis

first determines which variables exert the greatest influence on performance. Potential modernization measures are considered only after the controlling mechanisms have been identified.

The resulting diagnosis may indicate a single dominant limitation or, more commonly, an interaction among several constraints. High particulate resistivity, for example, may restrict useful electrical energization, while nonuniform gas or reagent distribution may prevent the available collecting area from being fully utilized. Identifying these interactions establishes the technical basis for determining whether an individual modification or an integrated modernization strategy is required.

3.6 Evaluation of Modernization Alternatives

Once the controlling performance limitations have been identified, modernization alternatives are selected specifically to address those limitations. The alternatives may involve electrical, mechanical, process, or integrated modifications, as summarized below.

Table 1. Evaluated Alternatives

Alternative Category	Representative Modernization Measures
Electrical	Advanced automatic voltage control; upgraded transformer-rectifier (T-R) systems; high-frequency power supplies (HFPS/SMPS); revised electrical sectionalization; and field-by-field energization optimization.
Mechanical	Discharge-electrode replacement or upgrading; collecting-electrode repair and alignment; correction of electrode spacing and geometry; rapping-system optimization; insulator and high-voltage component improvements; and other internal modifications affecting corona generation, particulate collection, or re-entrainment.
Process	SO_3 flue-gas conditioning; ammonia-assisted or Dual FGC; optimization of reagent injection rate and distribution; gas-temperature management; gas-flow and distribution improvements; and other process modifications affecting fly-ash resistivity and collectability.
Integrated	Coordinated combinations of electrical, mechanical, and process modifications selected to address multiple interacting performance limitations and achieve the required emissions, reliability, and operating objectives.

Each alternative is evaluated against the same calibrated baseline and under the same gas flow, inlet particulate loading, temperature, particle characteristics, and other common operating assumptions unless the alternative itself intentionally changes one of those conditions. This controlled comparison isolates the incremental effect of the modernization measure and permits individual technologies and combinations of technologies to be evaluated on a consistent engineering basis.

The resulting model evaluations provide more than a ranking of alternative outlet-emission levels. They indicate why performance changes, which limitation has been relieved, whether another limitation becomes controlling, and what incremental benefit is obtained by adding one modernization measure to another. This cause-and-effect evaluation forms the technical basis for the engineering and economic decision-support framework discussed in the following section.

4 ENGINEERING DECISION-SUPPORT FRAMEWORK

Calculated emissions alone should not determine the preferred ESP modernization strategy. An alternative that produces the lowest modeled emissions may not represent the most appropriate engineering solution if the additional performance margin requires an extended outage, major structural modifications, excessive reagent consumption, increased maintenance, or equipment with limited lifecycle support. An alternative with somewhat higher expected emissions may still provide adequate compliance margin at

substantially lower cost, complexity, and implementation risk. The numerical performance evaluation is therefore combined with an engineering and commercial screening process.

The principal comparison criteria include anticipated particulate emissions and collection efficiency, electrical stability, expected reliability, retrofit complexity, outage requirements, operating and maintenance implications, capital investment, recurring operating cost, and implementation risk. Where appropriate, consideration may also be given to future operating flexibility and the ability of the modernization strategy to accommodate changes in fuel, process conditions, or emission requirements. The purpose of the comparison is to make the principal technical and economic tradeoffs visible and, where possible, quantifiable.

A useful outcome of this evaluation is a modernization decision matrix in which technically viable alternatives are compared against the same performance objective and common engineering criteria. Such a matrix can identify alternatives that fail to achieve the required emission level, alternatives that satisfy the requirement with limited operating margin, and alternatives that provide progressively greater performance margin at correspondingly different levels of cost, complexity, and risk. Importantly, an alternative may also be eliminated because it does not adequately address the dominant performance limitation identified during the diagnostic phase of the evaluation.

The decision process can therefore distinguish between the maximum-performance alternative and the optimum modernization strategy. These are not necessarily the same. The preferred strategy should provide the required particulate-emission performance and an appropriate operating margin while maintaining acceptable reliability, implementation complexity, lifecycle cost, and technical risk. In some applications this may justify an integrated modernization approach; in others, the numerical evaluation may demonstrate that a less extensive modification is sufficient.

Advanced Numerical Engineering Evaluation provides a direct connection between numerical performance evaluation and capital planning. Rather than asking which technology produces the lowest calculated emissions, the decision-support framework addresses the more practical engineering question: what level of modernization is actually required to achieve the owner's performance objective with an appropriate margin and at a justified level of investment and risk? The representative industrial case study presented in the following section illustrates this approach.

5 REPRESENTATIVE INDUSTRIAL CASE STUDY

The application of the Advanced Numerical Engineering Evaluation Methodology is illustrated through a representative ESP modernization study. The case demonstrates how a calibrated baseline can be used first to identify the dominant performance limitation and then to quantify the incremental benefit of process and electrical modernization measures, individually and in combination.

5.1 EXISTING ESP AND PERFORMANCE CHALLENGE

The representative application involved a large coal-fired ESP experiencing particulate emissions materially above the desired modernization target. The precipitator possessed substantial collecting area and conventional high-voltage equipment, but the fly ash exhibited very high electrical resistivity under the prevailing operating conditions. Plant experience and the calibrated numerical baseline indicated that insufficient collecting area was not the principal performance limitation. The more significant constraint was the ability of the existing ESP to utilize the available collecting area effectively under the prevailing particulate and electrical conditions.

The calibrated baseline reproduced an outlet particulate concentration of approximately **121 mg/Nm³**. This condition was established as the common reference against which the modernization alternatives were evaluated, allowing the projected performance improvement associated with each modification to be quantified while maintaining the same underlying ESP geometry and operating basis.

Particle-size distribution is an important input to this evaluation because ESP collection performance, and therefore outlet penetration, varies strongly with particle diameter. Figure 6 presents the representative fly-ash particle-size distribution used in the NEP analysis. The continuous distribution is divided into discrete

particle-size classes so that charging, migration, collection, and penetration can be evaluated throughout the particle-size spectrum rather than represented by a single bulk collection-efficiency value.

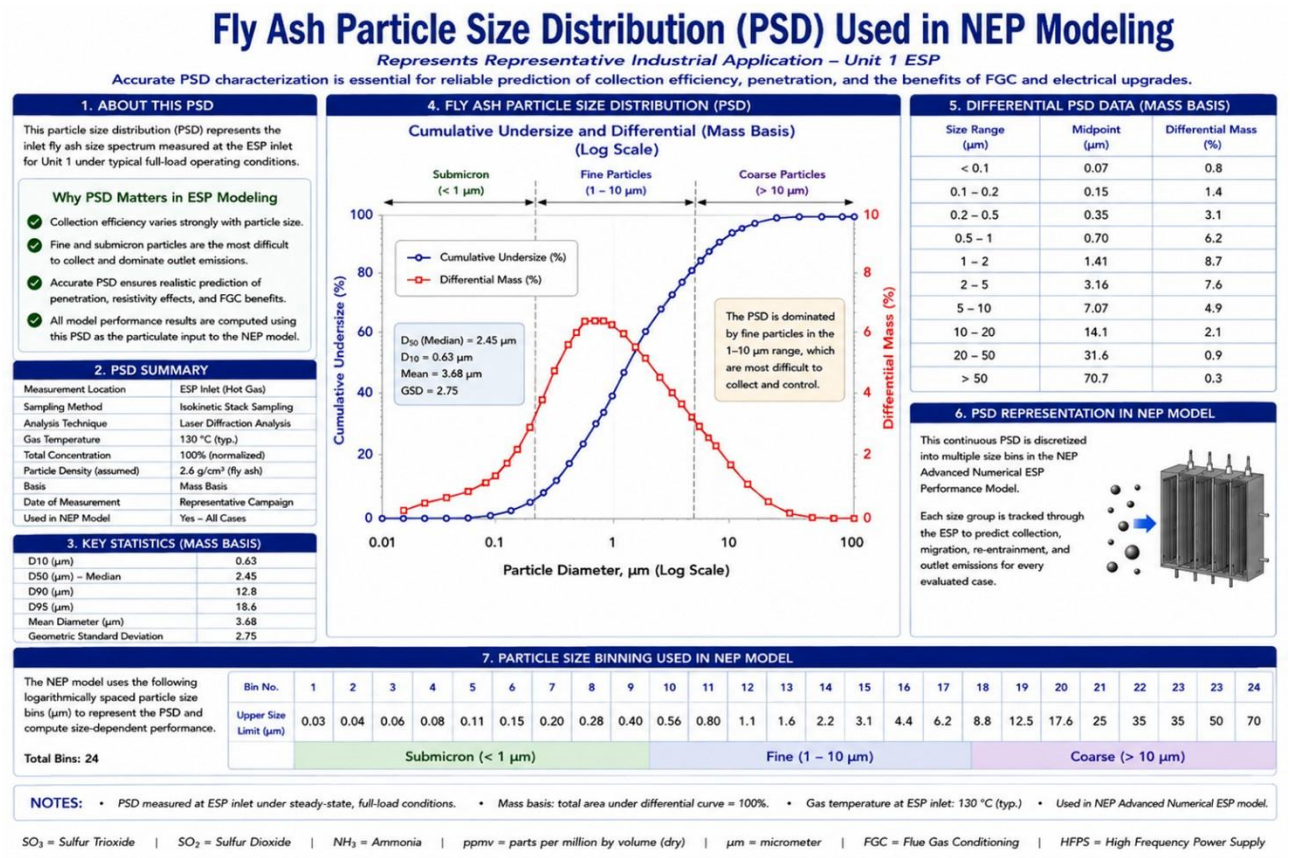


Figure 6. Particle Size Distribution Used in NEP Modeling

5.2 CASES EVALUATED

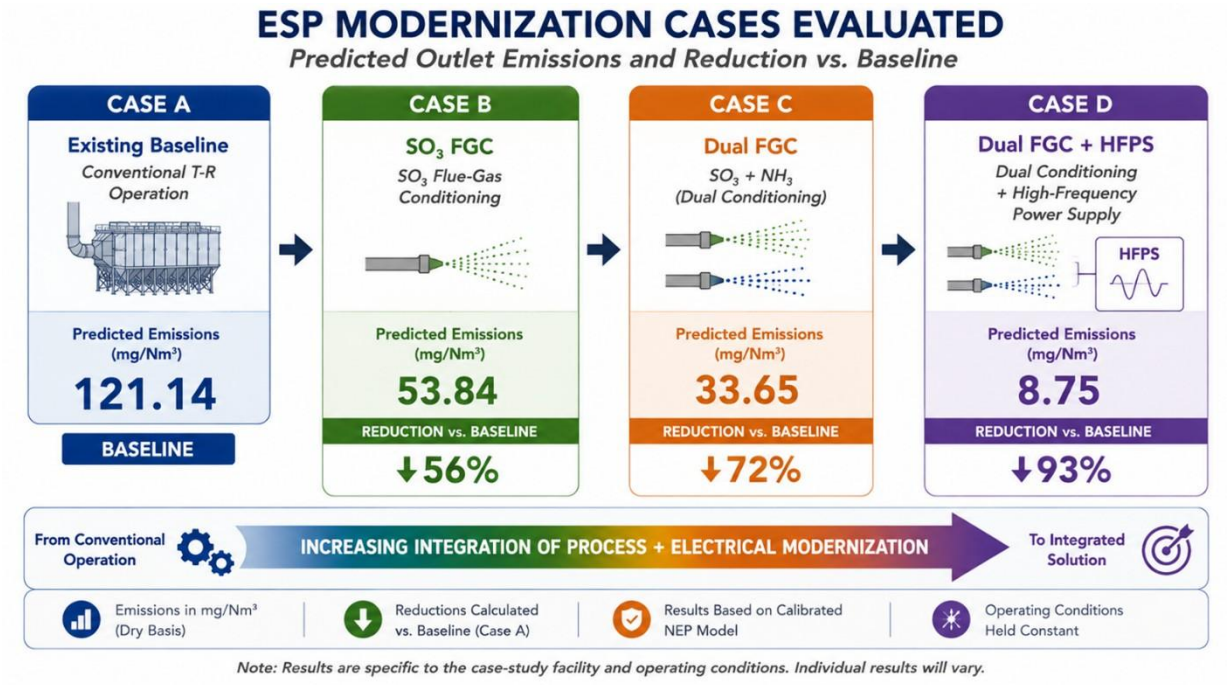
Four operating and modernization cases were evaluated against the same calibrated baseline. The sequence was intentionally structured to distinguish the incremental effects of process conditioning and advanced electrical energization.

The selected cases (Table 2) represent a progressive response to the performance limitations identified during the baseline evaluation. The sequence begins with conventional SO_3 conditioning, progresses to Dual FGC, and then considers the contribution of advanced electrical energization before evaluating the combined Dual FGC + HFPS configuration. This progression allows the incremental contribution of each modernization measure to be distinguished while maintaining the same calibrated ESP and operating basis.

5.3 INTERPRETATION OF RESULTS

The case study illustrates why modernization alternatives should be evaluated as components of an integrated ESP system. Electrical modernization can improve voltage control, spark response, and useful power input, but it does not by itself change the intrinsic electrical resistivity of the collected particulate. Where high resistivity is the controlling limitation, the benefit obtainable from improved power electronics may therefore remain constrained until the underlying particulate condition is addressed.

Table 2. Cases Evaluated



5.3.1 Conventional SO_3 Flue-Gas Conditioning

SO_3 conditioning materially improved calculated collection performance by reducing the effective resistivity of the collected dust layer and permitting more favorable electrical operation. Projected emissions decreased from approximately 121 mg/Nm³ to 54 mg/Nm³**,** corresponding to a reduction of approximately 56% relative to the calibrated baseline. This represented a substantial improvement, although the modeled result did not provide the same performance margin as the more integrated alternatives.

The modeled response to conventional SO_3 flue-gas conditioning is summarized in Figure 7. The analysis demonstrates the relationship between SO_3 concentration, reduced effective fly-ash resistivity, improved electrical operation, and the resulting decrease in anticipated outlet emissions. The results also illustrate why reagent distribution across the ESP inlet gas cross section is an important element of the conditioning strategy.

5.3.2 Dual Flue-Gas Conditioning

Dual FGC further improved the projected result to approximately 34 mg/Nm³**,** representing a reduction of approximately 72% relative to the baseline. Under the modeled conditions, the combined use of SO_3 and NH_3 provided an additional improvement in particulate and electrical behavior beyond that obtained with conventional SO_3 conditioning alone.

The corresponding Dual FGC case is presented in Figure 8. Because the same ESP geometry and operating basis are retained, the incremental improvement associated with adding NH_3 to the SO_3 conditioning strategy can be evaluated directly.

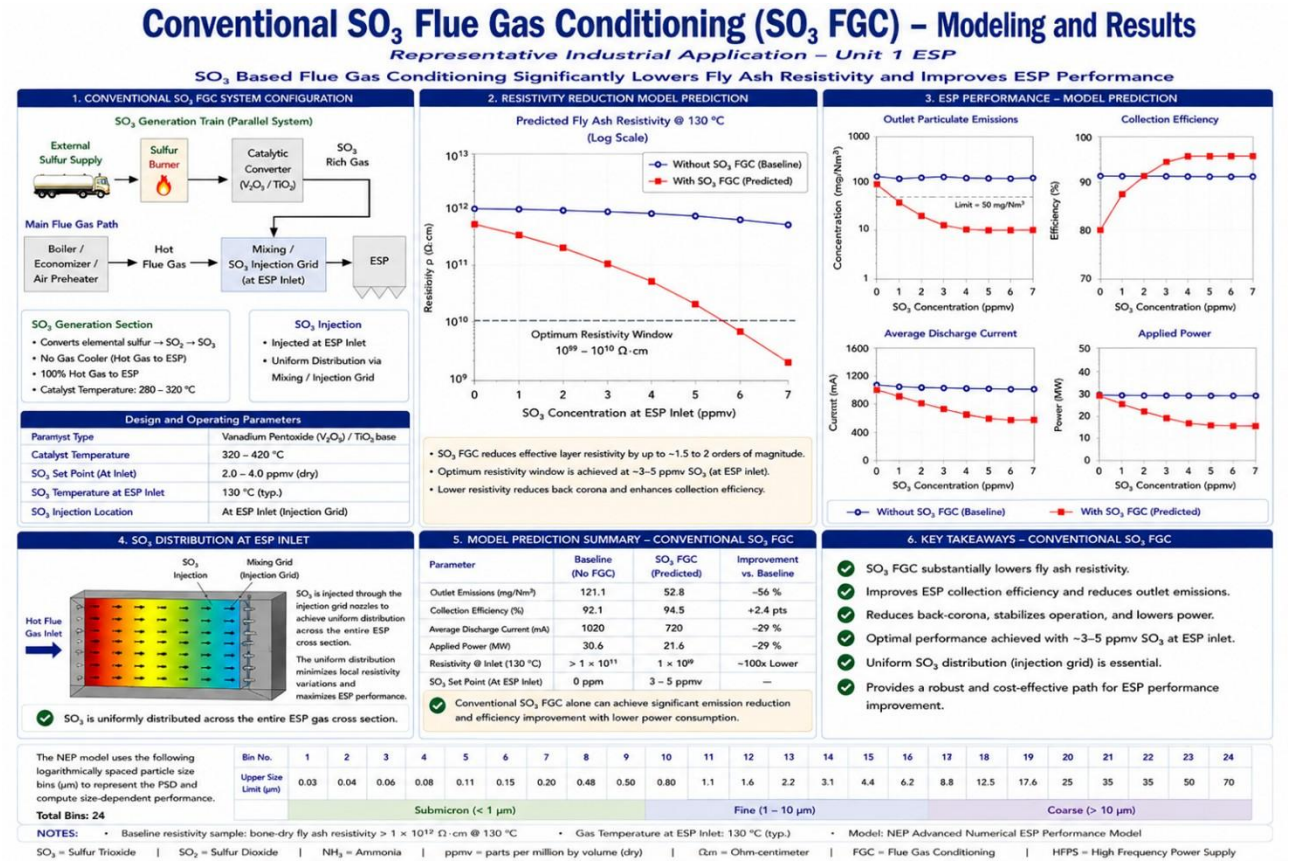


Figure 7. Conventional SO_3 Flue-Gas Conditioning (SO_3 FGC)

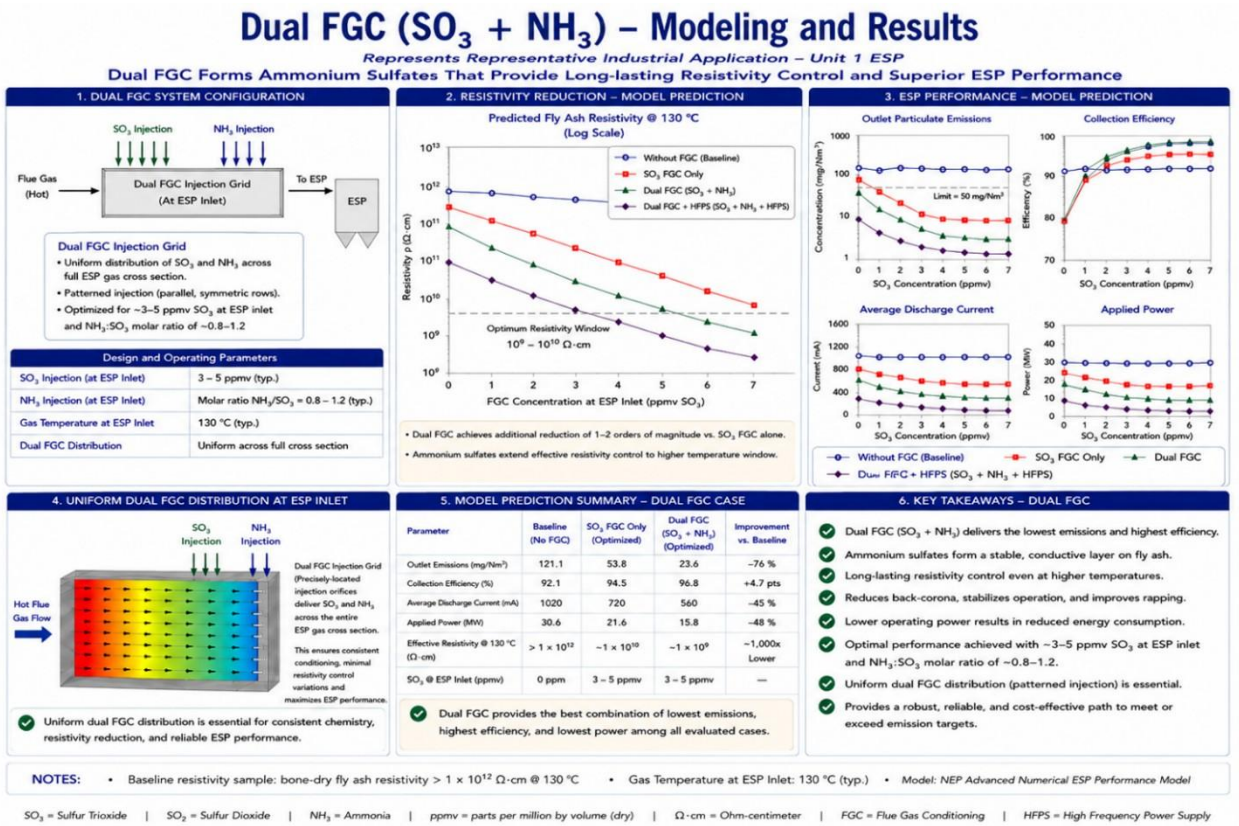


Figure 8. Dual Flue-Gas Conditioning (SO_3 + NH_3)

5.3.3 High-Frequency Electrical Energization

Before evaluating the final integrated modernization case, the contribution of advanced electrical energization should be considered separately. Conventional transformer-rectifier (T-R) systems and high-frequency power supplies (HFPS) differ significantly in their voltage-control characteristics, response to sparking and re-strikes, and ability to maintain effective ESP energization under changing electrical conditions.

Figure 9 compares the principal electrical-performance characteristics of conventional T-R and HFPS operation. HFPS provides faster and more responsive voltage control, allowing the ESP to operate closer to its optimum electrical condition while reducing the severity of sparks and re-strikes. This can increase effective particle charging, improve corona stability, and enhance overall collection performance. Importantly, however, advanced energization does not eliminate the underlying high-resistivity characteristics of the fly ash. Its greatest benefit is therefore realized when resistivity-related limitations have first been sufficiently controlled, allowing the ESP to take full advantage of the increased electrical capability.

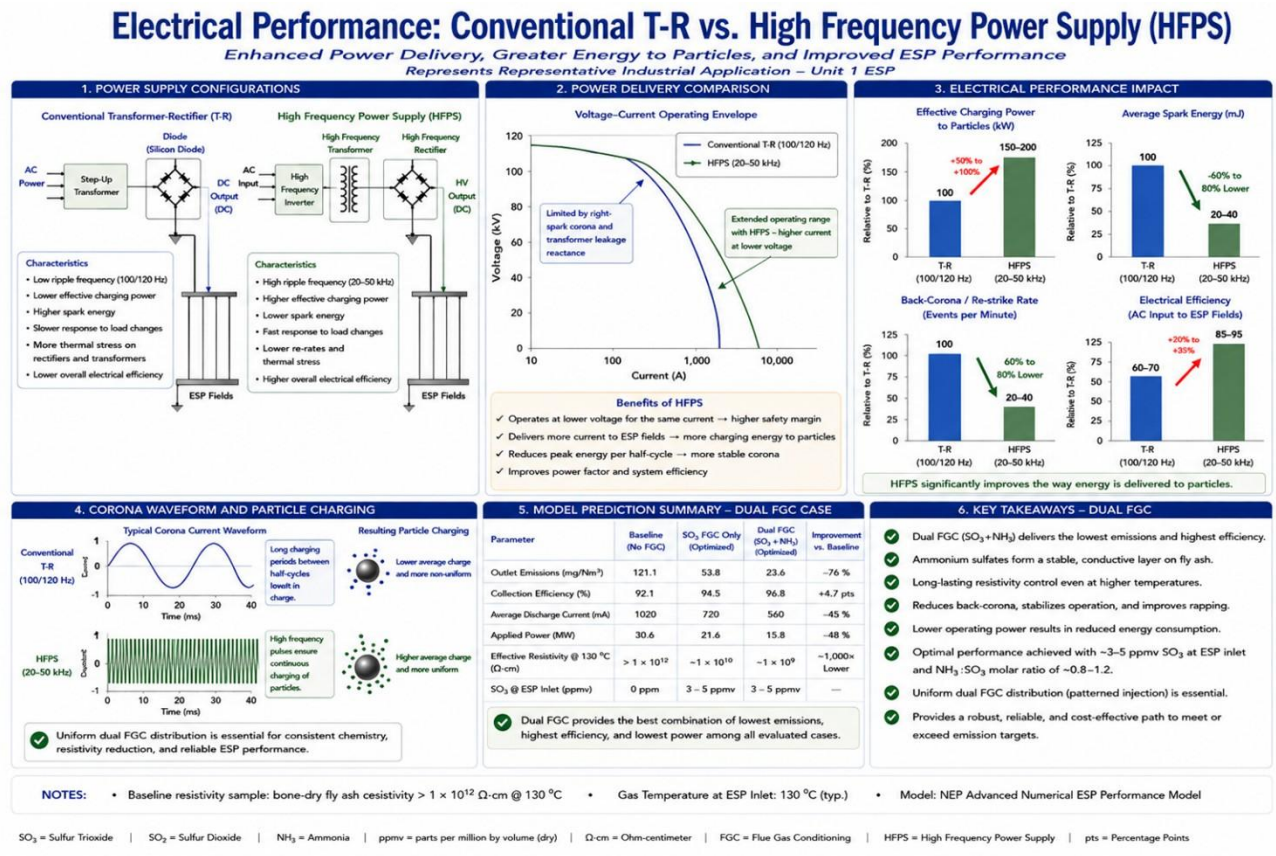


Figure 9. Electrical Performance: Conventional T-R vs. High-Frequency Power Supply (HFPS)

5.3.4 Integrated Dual FGC + HFPS

The strongest modeled result was obtained when Dual FGC was combined with high-frequency power supplies. Calculated emissions decreased to approximately 8.8 mg/Nm³, a reduction of about 93 percent relative to the calibrated baseline. This result does not imply that the most equipment-intensive alternative should always be selected. Its significance is that the calibrated model quantifies the incremental value of each modernization step and provides a basis for determining whether the additional complexity is justified by the required performance margin.

Figure 10 presents the resulting integrated Dual FGC + HFPS case. By combining chemical control of the high-resistivity limitation with improved electrical energization, the model calculates the lowest outlet emissions and highest collection efficiency among the alternatives evaluated. The comparison demonstrates the principal advantage of evaluating modernization measures as interacting components of a single ESP system rather than as independent upgrade technologies.

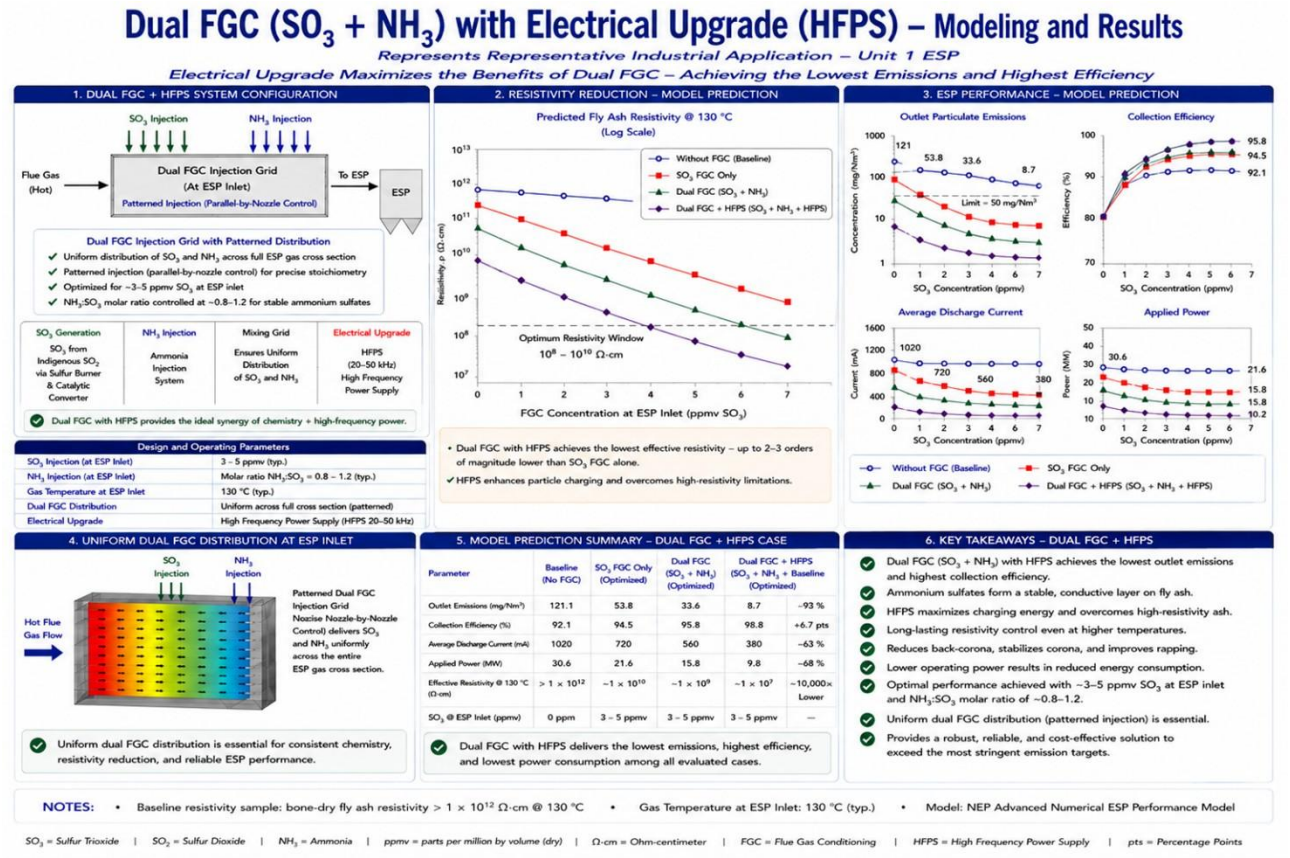


Figure 10. Dual FGC with Electrical Upgrade (HFPS)

5.4 What the Case Study Demonstrates

An electrical upgrade alone would not have directly addressed the underlying high-resistivity limitation. Chemical conditioning alone, while substantially improving performance, would not have captured the additional benefit available from improved electrical energization. The numerical evaluation allowed both effects to be examined individually and in combination before implementation.

The progression of projected emissions is particularly instructive: from 121.14 mg/Nm³ for the calibrated baseline, to 53.84 mg/Nm³ with SO_3 conditioning, to 33.65 mg/Nm³ with Dual FGC, and finally to 8.75 mg/Nm³ with the integrated Dual FGC + HFPS configuration. Because these alternatives were evaluated against the same calibrated baseline, the incremental contribution of each modernization step can be directly assessed.

The case study demonstrates the value of identifying the controlling performance mechanisms before selecting the modernization technology. By evaluating each measure separately and then in combination, the calibrated model establishes the contribution of each modification and provides an engineering basis for determining how much modernization is required. The remaining question is whether the additional performance provided by each successive alternative justifies its associated cost, complexity, and implementation risk.

6 FROM PERFORMANCE EVALUATION TO ECONOMIC DECISION

One of the principal economic benefits of numerical evaluation is the ability to reduce the risk of both under-design and over-design. An under-designed modernization may fail to achieve the emission objective and require additional capital expenditure after implementation. An over-designed project may achieve excellent performance but require additional investment that provides little practical operating benefit.

For each technically viable alternative, the expected performance can be considered together with budgetary capital cost, recurring operating cost, outage duration, implementation complexity, and expected lifecycle requirements. The preferred alternative can then be selected based on the required performance margin and the cost and risk associated with achieving the target emissions.

This approach is particularly useful where several alternatives cross the required emissions threshold. In such cases, the model can identify the least complex alternative that provides an adequate compliance margin, as well as the incremental cost and benefit associated with moving to a more aggressive modernization strategy.

The representative case study illustrates this point. SO_3 conditioning, Dual FGC, and the integrated Dual FGC + HFPS configuration produced progressively lower projected emissions. The lowest calculated emission level, however, does not automatically identify the optimum economic choice. That decision depends on the required emissions objective, desired operating margin, expected future operating conditions, and the incremental cost and risk associated with achieving additional performance.

The numerical analysis therefore provides the technical foundation for a risk-informed economic decision. The practical question becomes: what level of investment is justified to achieve the required performance with an appropriate operating margin, reliability, and acceptable implementation risk?

7 PRACTICAL APPLICATION AND LIMITATIONS

The reliability of any numerical engineering evaluation depends on the quality and representativeness of the information used to construct and calibrate the model. Missing or uncertain geometry, incomplete or unreliable electrical data, non-representative performance tests, and poorly characterized particulate or ash properties can introduce uncertainty into the expected results. Significant assumptions and data limitations should therefore be explicitly identified and, where appropriate, evaluated through sensitivity analysis over a credible range of input conditions.

Particular attention should be given to ensuring that the data used for calibration represent a reasonably consistent operating condition. Gas flow, temperature, particulate loading, ash characteristics, electrical operation, and measured emissions can vary with unit load, fuel characteristics, and process conditions. Combining information obtained under substantially different operating conditions without appropriate consideration can create an apparently well-defined numerical baseline that does not accurately represent any actual plant condition.

The numerical model complements, rather than replaces, engineering judgment, field inspection, vendor design responsibility, and performance testing. It provides a structured quantitative framework for integrating these inputs and evaluating their implications. Mechanical condition, constructability, materials selection, outage planning, equipment reliability, and vendor-specific design limitations remain essential elements of a complete modernization study and must be considered together with the numerical performance evaluation.

Similarly, model calculations should be interpreted as engineering estimates rather than guarantees of future plant performance. Their value lies in establishing a consistent basis for comparing alternatives, identifying performance sensitivities, and quantifying the expected direction and magnitude of improvement under defined operating assumptions. Where uncertainty in a particular input materially affects the anticipated outcome, that uncertainty should become part of the modernization decision rather than being obscured by a single calculated result.

The methodology is most valuable when applied early in the modernization process, before a preferred technology or equipment configuration has been selected. Used at this stage, the calibrated model can objectively compare competing approaches, identify combinations that warrant further development, and eliminate alternatives that do not adequately address the controlling performance limitations. If numerical

modeling is performed only after a modernization concept has already been selected, its role can be reduced from objective decision support to confirmation of a predetermined approach.

Ultimately, the numerical model does not make the modernization decision. It provides a technically consistent framework within which measured plant performance, engineering judgment, equipment capabilities, project constraints, and uncertainty can be considered together.

8 DISCUSSION

ESP modernization projects increasingly require decisions among technologies that influence different mechanisms within the precipitation process. Advanced high-voltage power supplies can improve electrical energization and control; mechanical upgrades can restore or improve electrode geometry and particulate removal; process conditioning can modify particle resistivity and cohesivity; and gas-distribution modifications can improve utilization of the available collecting area. Each measure can provide substantial benefit when applied to the appropriate limitation, but none is universally superior.

The central value of Advanced Numerical Engineering Evaluation is that it places these alternatives on a **common analytical basis**. The calibrated baseline represents the existing ESP under defined operating conditions and serves as the reference for subsequent comparisons. Modernization cases can then be treated as controlled engineering evaluations in which selected variables are changed while the remainder of the operating basis is held constant. This allows the anticipated improvement to be associated with a specific modification and, equally important, helps identify when the benefit of that modification remains constrained by another limiting mechanism.

The representative case study demonstrates this interaction clearly. High particulate resistivity limited the ability of the ESP to utilize improved electrical energization effectively. Process conditioning progressively reduced this limitation, while advanced electrical energization provided additional benefit once the particulate conditions permitted the available electrical capability to be more effectively utilized. The resulting performance improvement reflected the interaction between particulate properties, electrical operation, and particle collection rather than a simple additive effect of the individual technologies.

The benefit of this integrated evaluation becomes particularly apparent when performance is examined on a particle-size-dependent basis. Overall outlet concentration provides an essential measure of ESP performance, but it does not show how individual modernization measures affect different portions of the particle-size distribution. Figure 11 compares calculated penetration across the particle-size spectrum for the evaluated modernization cases using the same representative PSD introduced in Figure 6. The results show progressive reductions in penetration from conventional operation through SO_3 conditioning and Dual FGC to the integrated Dual FGC + HFPS configuration, with particularly important improvements in the fine and submicron particle ranges where ESP collection is generally most challenging.

The particle-size-dependent comparison also illustrates why a single overall collection-efficiency value may not fully characterize the benefit of a modernization measure. Two alternatives producing similar bulk collection efficiencies may perform differently within the particle-size ranges that contribute most strongly to residual outlet emissions. Incorporating particle-size-dependent behavior into the numerical evaluation therefore provides an additional basis for distinguishing among modernization strategies and understanding the mechanisms responsible for the anticipated improvement.

The same framework supports staged modernization. A plant owner can evaluate a minimum-compliance alternative, an intermediate performance and reliability alternative, and a maximum-performance configuration before deciding how much modernization is justified. Because each successive case is evaluated against the same calibrated baseline, the expected performance increment associated with each additional measure can be quantified before implementation. This allows modernization to be considered as a progression of technically defined options rather than as an all-or-nothing equipment decision.

The methodology also creates a technical record of why a particular modernization strategy was selected. The calibrated baseline, identified performance limitations, evaluated alternatives, and projected incremental benefits collectively document the engineering basis for the decision. Such documentation can be valuable during internal technical review and capital authorization and can provide a reference if future changes in fuel,

process conditions, equipment condition, or emissions requirements require the modernization strategy to be reconsidered.

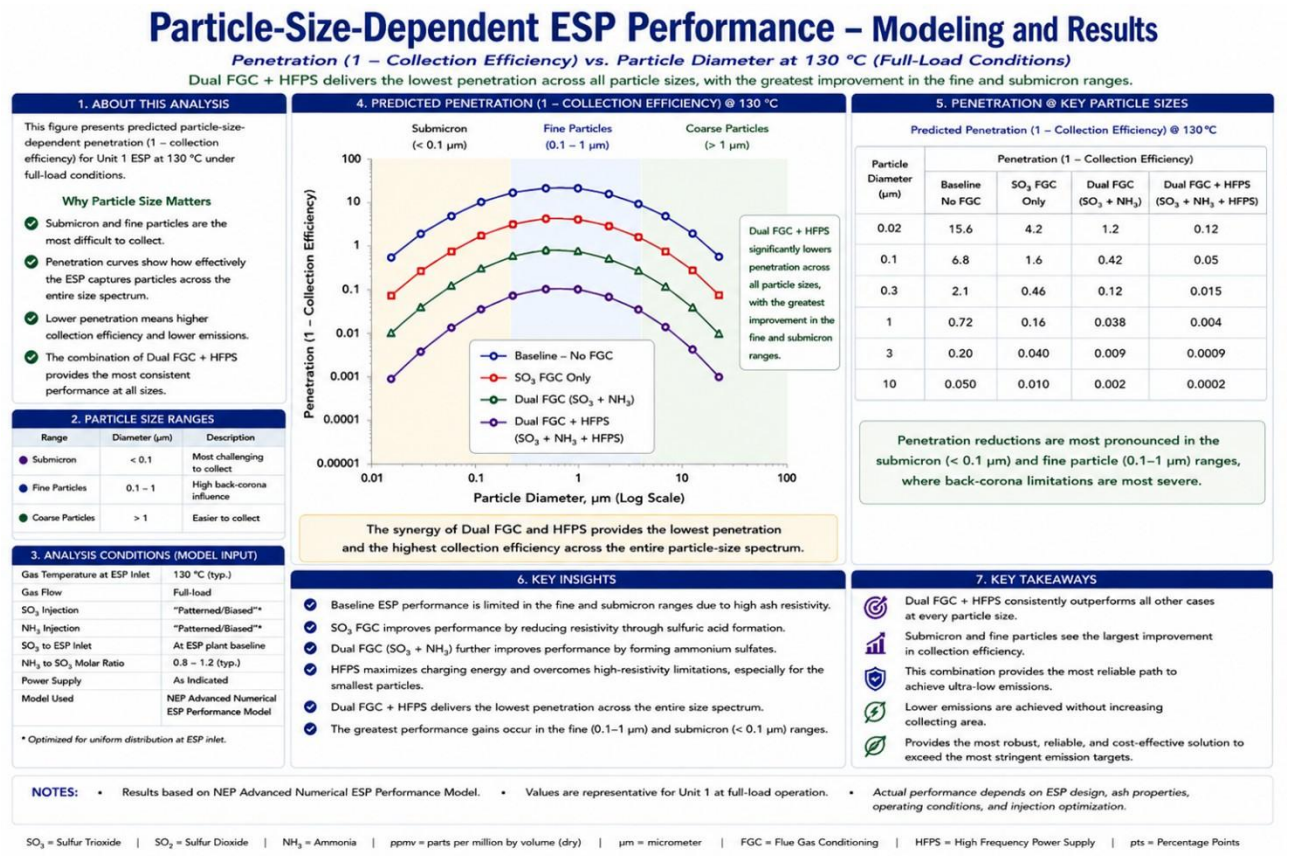


Figure 11. Particle-Size-Dependent ESP Performance – Modeling and Results

More broadly, the principal value of calibrated numerical evaluation extends beyond the calculation of a single future emissions value. Its greater value lies in establishing a cause-and-effect framework within which competing modernization alternatives can be investigated before physical modifications are made. By identifying the controlling mechanisms first and then evaluating measures specifically intended to address them, modernization decisions can be based on demonstrated engineering need rather than technology preference.

9 CONCLUSIONS

The following conclusions are drawn from the development and representative application of the Advanced Numerical Engineering Evaluation Methodology:

- ESP modernization should be treated as an integrated engineering decision rather than as the selection of an individual upgrade technology. Electrical, mechanical, particulate, process, and operating characteristics interact, and improvement of one component may provide limited benefit if another mechanism remains controlling.
- **A calibrated numerical representation of the existing ESP provides a defensible common basis for modernization evaluation.** Competing alternatives can be examined under consistent operating conditions, allowing their incremental effects to be distinguished and compared before physical modifications are implemented.
- **Calibration and validation against measured plant performance are essential to the methodology.** Agreement with a single outlet-emission value is insufficient; confidence in the baseline

is strengthened when the model also reproduces available electrical, collection-efficiency, and particle-size-dependent performance characteristics.

- **Identification of the dominant performance limitation should precede selection of the modernization technology.** This reduces the risk of selecting a technically effective technology that does not address the actual cause of the performance limitation.
- **Electrical, mechanical, process, and integrated modernization strategies can be evaluated individually and in combination.** This allows the incremental contribution of each measure to be quantified and identifies interactions among technologies that may not be apparent when they are considered independently.
- **The representative industrial case demonstrates the importance of such interactions.** For the high-resistivity application evaluated, projected emissions decreased from **121.14 mg/Nm³** for the calibrated baseline to **53.84 mg/Nm³** with SO_3 conditioning, **33.65 mg/Nm³** with Dual FGC, and **8.75 mg/Nm³** when Dual FGC was combined with HFPS. The results demonstrate that addressing the particulate-resistivity limitation enabled substantially greater benefit to be obtained from advanced electrical energization.
- The modernization alternative producing the lowest anticipated emissions is not necessarily the optimum engineering or economic solution. Anticipated performance should be considered together with the required operating margin, capital and recurring costs, outage requirements, reliability, implementation complexity, and technical risk to determine the appropriate level of modernization.
- **The principal value of Advanced Numerical Engineering Evaluation extends beyond performance calculation.** The methodology provides a structured basis for investigating what-if scenarios, identifying cause-and-effect relationships, and quantifying the incremental benefit of competing modernization measures before implementation. This can reduce technical uncertainty and the risk of either under-design or unnecessary capital expenditure.
- Applied early in the modernization process, the methodology provides a practical decision-support framework for optimizing ESP performance before capital is committed. It enables plant owners and engineers to select a modernization strategy based on demonstrated performance limitations, quantified improvement potential, required operating margin, and project-specific economic and implementation considerations.

9.1 FUTURE DEVELOPMENT

The next phase of this work is the development of an ESP Digital Twin that extends the calibrated NEP engineering model from a project-specific evaluation tool to a dynamic representation of the operating electrostatic precipitator. The proposed system will integrate real-time and historical plant operating data with the numerical model and incorporate artificial intelligence (AI) to identify performance trends and developing operating limitations and to predict the effects of changing process and electrical conditions.

By combining physics-based numerical modeling, plant operating data, and AI-assisted analysis, the Digital Twin is intended to refine its representation of actual ESP behavior as operating information becomes available [23]. The system would support predictive evaluation and optimization of electrical operation, flue-gas conditioning, rapping, and other controllable parameters. The objective is to extend the present methodology from periodic engineering evaluation to continuous performance monitoring, prediction, and operating decision support. This ESP Digital Twin is being developed as a proprietary technology and is the subject of a patent-pending application.

The proposed operating architecture is illustrated in Figure 12. The closed-loop framework integrates the physics-based NEP model, plant operating data, and AI-assisted analysis to support monitoring, prediction, what-if evaluation, and optimized operating recommendations.

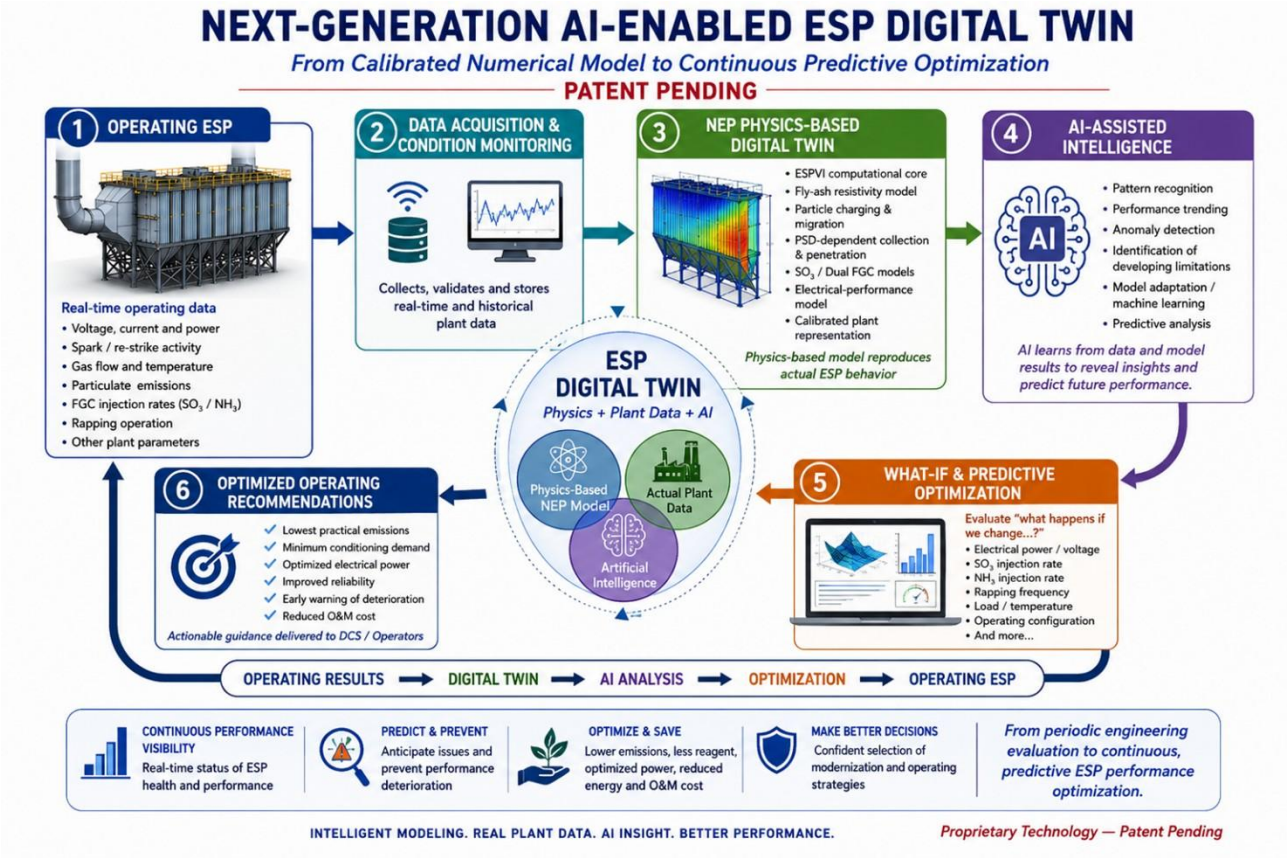


Figure 12. Next-Generation AI-Enabled ESP Digital Twin – Proposed Operating Architecture (Patent Pending)

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