Preliminary Techno-Economic Analysis for Intensified Flue Gas Desulfurization Water Treatment for Reuse, Solidification, and Discharge

Rev 0 for DOE-NETL Review

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Executive Summary

With funding from the U.S. Department of Energy (DOE), the University of Kentucky's Center for Applied Energy Research (UKy-CAER) is developing a multi-stage process to treat flue gas desulfurization (FGD) wastewater from a coal-fired power plant. Process concepts investigated in this project included electrocoagulation, nanofiltration, zeolite filtration, capacitive deionization, and solidification. Based on laboratory results, UKy-CAER selected an electrocoagulation process for a techno-economic analysis.

A preliminary techno-economic analysis was performed using the design basis developed by DOE-NETL for its analysis of wet FGD wastewater treatment (WWT) processes for a 57 gpm FGD blowdown [DOE 2019b]. Trimeric worked with UKy-CAER to develop a process flow diagram for an electrocoagulation-based process. The total plant cost was developed from estimated purchased equipment costs using a methodology adapted from the one described in DOE-NETL's FGD WWT report and in the DOE-NETL's QGESS documents. This cost estimate was prepared based on laboratory performance data and engineering assumptions. Key process performance parameters such as required power and residence time required for the electrocoagulation reactions and the separation efficiency of the coagulated solids may change as the process is refined and it is tested at larger scale. To account for the uncertainties associated with a technology in the early stages of development, a process contingency of 20% was assumed.

The electrocoagulation process was designed by UKy-CAER to produce a wastewater that is compliant with ELG discharge limits (for Se, As, Hg, and nitrite/nitrate) and a solids stream which can be landfilled. The estimated purchased equipment costs (PEC) for the inside-the-boundary limits of the EC process was $2.67 million and the total plant cost (TPC) was $17.0 million. The primary contributors to the purchased equipment costs were the solids filter press (to dewater the solids for landfill), followed by green rust separators (to dewater the green rust between green rust reactors), and then the green rust generator and reactors. The fixed operating costs were $574,000 and the variable operating costs were $401,000.

In comparison, using the adapted methodology, Trimeric estimated that DOE's Case 1 for Biological Wastewater Treatment had a PEC of $5.26 million and a TPC of $30.0 million. The fixed and variable operating costs were higher for Case 1 than for the EC process. The electricity consumption for Case 1 was 53 kW, while it was 110 kW for the EC process; electricity consumption for both processes was very small compared to the net generating capacity of the power plant at less than 0.02%.

A more detailed engineering analysis, which was beyond the scope of this preliminary effort, would be required to better assess the optimum design for the green rust generator and reactors and the solids separation equipment needed to cycle the green rust solids through the multi-stage green rust reactors.

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List of Acronyms

Acronym	Definition
ACCE	Aspen Capital Cost Estimator
BEC	Bare erected cost
CEPCI	Chemical Engineering Plant Cost Index
CS	Carbon steel
DOE	Department of Energy
EC	Electrocoagulation
ELG	Steam Electric Power Generating Effluent Guidelines and Standards
EPC	Engineering, procure, construct
EPCC	Engineering, procurement, and construction cost
FGD	Flue gas desulfurization
FRP	Fiberglass reinforced plastic
GR	Green rust
HHV	Higher heating value
IOU	Investor-owned utility
O&M	Operating and maintenance
PEC	Purchased equipment costs
PFD	Process flow diagram
QGESS	Quality Guidelines for Energy Systems Studies
RA-PEC	Retrofit-Adjusted Purchased Equipment Cost
SCR	Selective catalytic reduction
SS	Stainless steel
TDS	Total dissolved solids
TEA	Techno-economic analysis
TPC	Total plant cost
TSS	Total suspended solids
WW	Wastewater
WWT	Wastewater treatment
ZLD	Zero liquid discharge

Section 1: Introduction

With funding from the U.S. Department of Energy (DOE), the University of Kentucky's Center for Applied Energy Research (UKy-CAER) is developing a multi-stage process to treat flue gas desulfurization (FGD) wastewater from a coal-fired power plant. The objectives of the DOE-funded project DE-FE0031555 were to evaluate the effectiveness of electrocoagulation, nanofiltration, and capacitive deionization for treating FGD wastewater to meet US Effluent Limit Guidelines for Steam Electric Generation Stations [EPA 2019]. Based on laboratory results, UKy-CAER selected an electrocoagulation (EC) process concept for a techno-economic analysis.

The primary purpose of this preliminary techno-economic analysis (TEA) was to estimate capital, operating and maintenance costs, and energy requirements for an FGD wastewater treatment process based on electrocoagulation using performance data measured in the laboratory by UKy-CAER. This preliminary analysis was conducted in part to identify potential areas for process improvements and cost savings. Section 2 provides the process description and process flow diagram, and Section 3 describes the process design methodology for the TEA, including the design basis and the process performance basis. Section 4 describes how purchased equipment sizing and costs were developed. Section 5 describes how these equipment costs were developed into an estimate of total plant cost. Quantitative economic metrics are presented in Section 6, including capital and operating costs and a comparison to a reference WWT technology (chemical precipitation + biological treatment). Section 7 provides conclusions and recommendations for further process optimization.

Section 2: Process Description

UKy-CAER is developing FGD wastewater treatment processes based on electrocoagulation.

Electrocoagulation Process Development

Electrocoagulation (EC) is an electrochemical process where iron is purposely corroded into a stream to form iron precipitates with the assistance of sulfate and/or chloride in the FGD water and without the use of added foreign chemicals that can selectively bind with various soluble specific contaminants and reduce them into a solid phase for disposal. In the case of selenate removal, particular iron-based products are needed along with a target pH region.

According to UKy-CAER, commercial EC processes suffer from competitive kinetics amongst ionic species, effluent coloration, and high energy penalties (Table 1). The UKy-CAER EC process for WFGD blowdown takes advantage of high sulfate and chloride content in the water to form an average 15-μm positive surface-charged solid sorbent – green rust (GR). GR then performs ion exchange with selenate, arsenate and nitrate in solution as well as attracting these anionic species to the surface due to the positive surface charge in neutral pH followed by electron transfer for reduction.

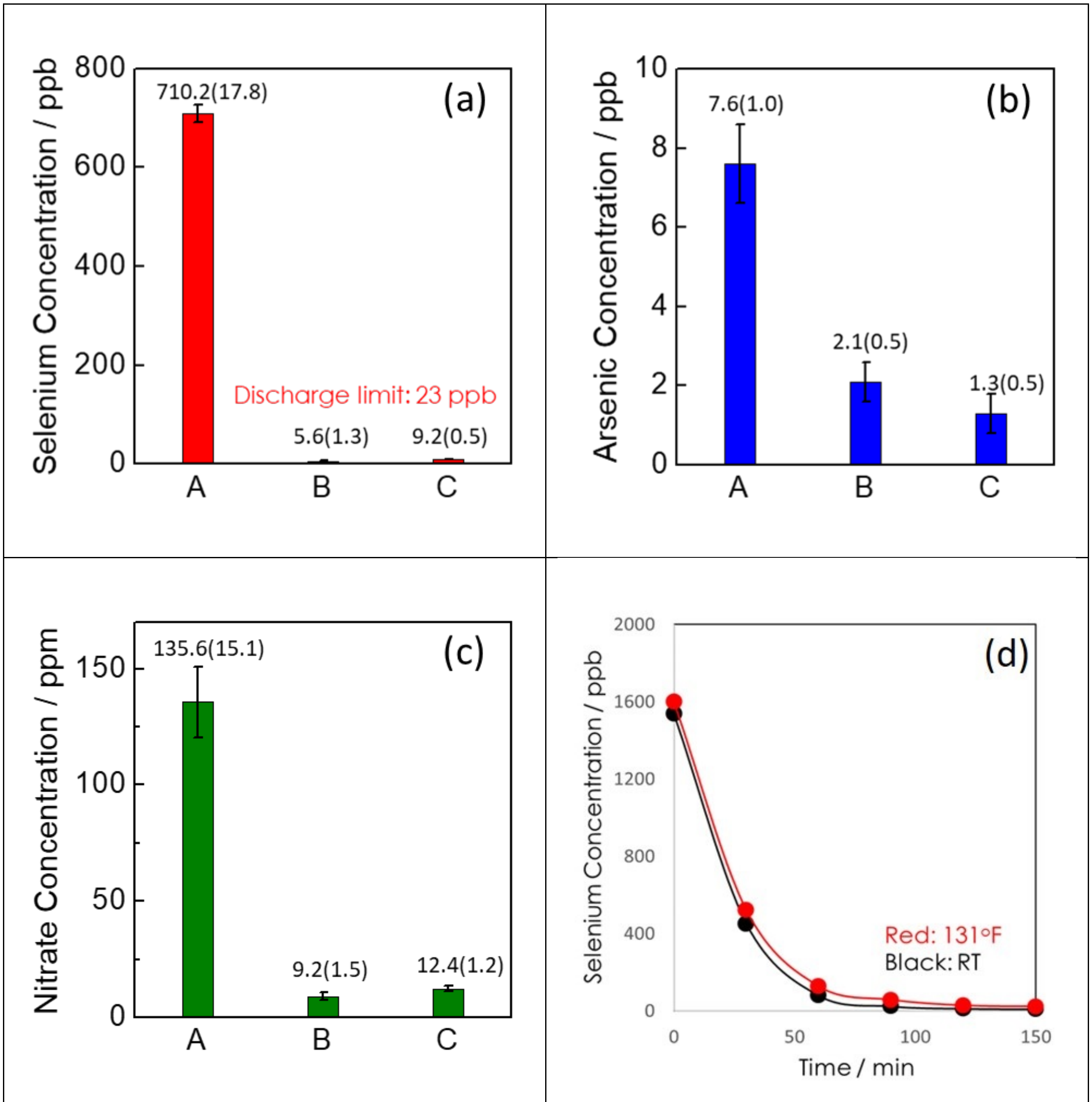
Table 1. Comparison of Conventional and UKy-CAER Electrocoagulation Processes.

Conventional Electrocoagulation	UKy-CAER Electrocoagulation
Unwanted brown/reddish rusty treated effluent	Clear treated effluent after green rust sorbent removal
High pH resulting in disposal issues	Moderate pH 6-8
High energy consumption	Low energy consumption with optimized cell design
ELG satisfied?	Satisfies ELG for selenium, arsenic, and nitrate
Dependent on low solubility of ions when combined with in-situ generated OH^- as coagulation agent	Disolved sulfate and chloride as coagulation agent and performance by ion-exchange with highly selective green rust sorbent
Se/NO_3^- selectivity > 1	Customizable Se/NO_3^- selectivity < 1 to >1

UKy-CAER has completed a series of laboratory tests to measure the wastewater treatment performance of electrocoagulation using commercial-grade iron electrodes to generate the active green rust for this treatment process. UKy-CAER's laboratory tests (Figure 1) have shown that electrocoagulation is capable of reducing the arsenic, selenium and nitrite/nitrate concentrations in FGD wastewater from a coal-fired power plant below the ELG requirements. Due to limitations in analytical capabilities in their laboratory, UKy-CAER has not measured the mercury removal performance of electrocoagulation but expects that it will exceed the selenium removal performance.

According to a vendor of commercial electrocoagulation systems, the advantage of an electrocoagulation unit is that no pre-treatment is required; electrocoagulation works better with a "dirtier" influent composition, especially higher total dissolved solids such as chloride and sulfate, which are present in an FGD wastewater. Electrocoagulation systems are marketed as an alternative to chemical-based treatment systems; the use of chemicals for treatment can be an issue when discharging into some environmentally sensitive locations.

Electrocoagulation systems typically operate without pre-treatment (other than screening of particles > 1/8" or 1/4") to remove total suspended solids from the influent stream. UKy-CAER tested FGD slurry that had been settled, such that it had very low total suspended solids. Laboratory tests are needed to show the EC performance can be maintained and fouling issues do not arise when the inlet stream contains 1-2 wt% total suspended solids, i.e., the amount that is expected in the FGD wastewater stream. For this preliminary TEA, no pre-treatment (no chemical precipitation, pH adjustment, or solids settling) of the wastewater stream was included upstream of the electrocoagulation unit. Solids removal occurs downstream of the green rust reactors.



Continuous electrocoagulation initially conditioned using 3.5 L of FGD water at 5 A for 4 hours to produce GR followed by continuously treating 8.5 L of FGD water at 3 A at 30 mL min-1. Reductions in (a) selenium, (b) arsenic, and (c) nitrate concentrations, in which sample A was collected before the conditioning step, sample B was collected after conditioning, and sample C was collected from the effluent tank when the test was completed. ELG was satisfied for selenium, arsenic and nitrate. A separate test (d) showed similar selenium reduction kinetics at room temperature and 131 °F.

Figure 1. Laboratory Results from UKy-CAER Electrocoagulation Tests.

Once the green rust reacts with the contaminants in the waste water, the green rust needs to be separated from the treated water. UKy-CAER had limited process information available for designing a system to separate the green rust from the treated water. Green rust average particle size and density were available, but no laboratory tests of separation were available. UKy-CAER's laboratory tests showed that an anti-scaling additive negatively affected the performance of the EC unit; therefore UKy-CAER specified that the green rust separator be designed without use of coagulant addition. EC vendors sell the process as an alternative to chemical treatment. As such, the proposed process does not use chemicals to aid solids coagulation and settling. For this preliminary design, hydrocyclones coupled with thickeners were used to effect the separation of the green rust solids from the treated water. Laboratory testing is needed to determine if this process arrangement will be sufficient to achieve the desired separation. If not, alternate solids dewatering equipment, such as centrifuges, may be required.

EC Process Flow Diagram and Description

In UKy-CAER's EC WWT process, the electrocoagulation unit produces water that is of sufficient quality to meet ELG discharge regulations with respect to selenium, arsenic, mercury, and nitrite/nitrate. A solids stream containing the removed contaminants is also produced; it goes to the plant's landfill. Figure 2 shows a preliminary process flow diagram based on the EC process, with the following process areas:

- **Equalization Tank**: The as-received inlet FGD wastewater stream flows to an equalization tank which acts as a buffer holding tank to smooth out inconsistences of wastewater composition and wastewater flow.
- **Green Rust Generator**: A slipstream of the wastewater flows to the green rust generator, which is the electrocoagulation unit. Power is applied to the generator's electrodes; the iron reacts with sulfates and chlorides to form green rust. The green rust generator is operated as a continuously stirred tank reactor, with a blowdown stream of fresh green rust flowing to the green rust reactors.
- **Green Rust Reactors:** The bulk of the wastewater flows from the equalization tank to a series of three green rust reactor tanks, where the water is contacted counter-currently with green rust from the green rust generator. The raw FGD wastewater enters Reactor #1, and treated FGD wastewater exits Reactor #3. Fresh green rust from the green rust generator enters Reactor #3, and spent green rust exits Reactor #1. Each green rust reactor tank operates as a continuously stirred tank reactor, with the blowdown stream from each reactor going to the green rust separators.
- **Green Rust Separators:** The green rust separators separate green rust from the treated water so that each stream can flow counter-currently through the process. The green rust separators consist of a hydrocyclone and a thickener that separate the green rust from the treated water for each of the three green rust reactors. The bulk of the green rust particles (and associated water) report to the hydrocyclone underflow, while the smaller green rust particles (and the bulk of the water) report to the hydrocyclone overflow. The

hydrocyclone overflow is recycled back to the reactor, while the hydrocyclone underflow flows to a thickener. The thickener underflow consists of dewatered green rust solids which are cycled to the next reactor. In this way, the green rust particles are moved from Reactor #3 to Reactor #2 to Reactor #1, at which point the green rust particles are considered "spent" and are purged to a solids dewatering system. The thickener overflow consists of treated water which is cycled to the next reactor, but in this case from Reactor #1 to Reactor #2 to Reactor #3, at which point the water meets the ELG limits for selenium and other metals. This treated water flows to a polishing unit.

- **Solids Dewatering System:** The spent green rust particles and the bulk of the gypsum fines from the inlet wastewater are purged from thickener #1 and sent to a solids dewatering system which consists of a filter press and a holding tank for the green rust sludge. The dewatered solids are disposed at the plant's landfill, while the filtered water is sent to Reactor #2.
- **Polishing of Effluent Water:** The treated water is purged from thickener #3 and sent to a polishing unit that consists of a sand filter and holding tank. The green rust particles and gypsum particles settle in the clarifier and are purged from the system. The clarified water flows through a sand filter to remove solids so that the stream meets the total suspended solids criteria for discharge.

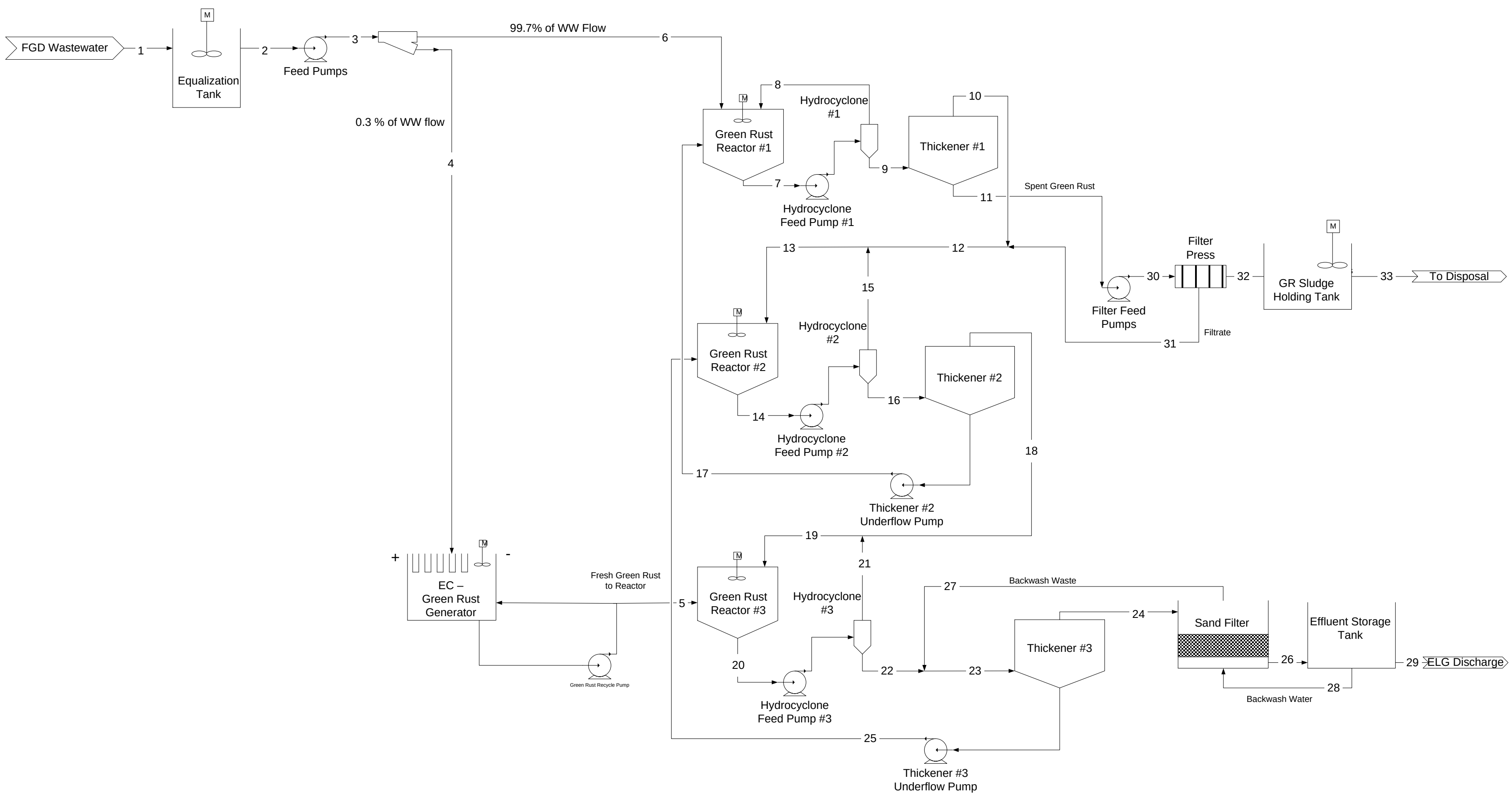


Figure 2. Process Flow Diagram (PFD) for EC Process

Section 3: Process Design Methodology

A TEA was developed for a coal-fired power plant equipped with an electrocoagulation-based wastewater treatment process to treat FGD blowdown, as represented by the block flow diagram in Figure 3. The system boundary for the TEA was the EC-Based Process box shown in Figure 3.

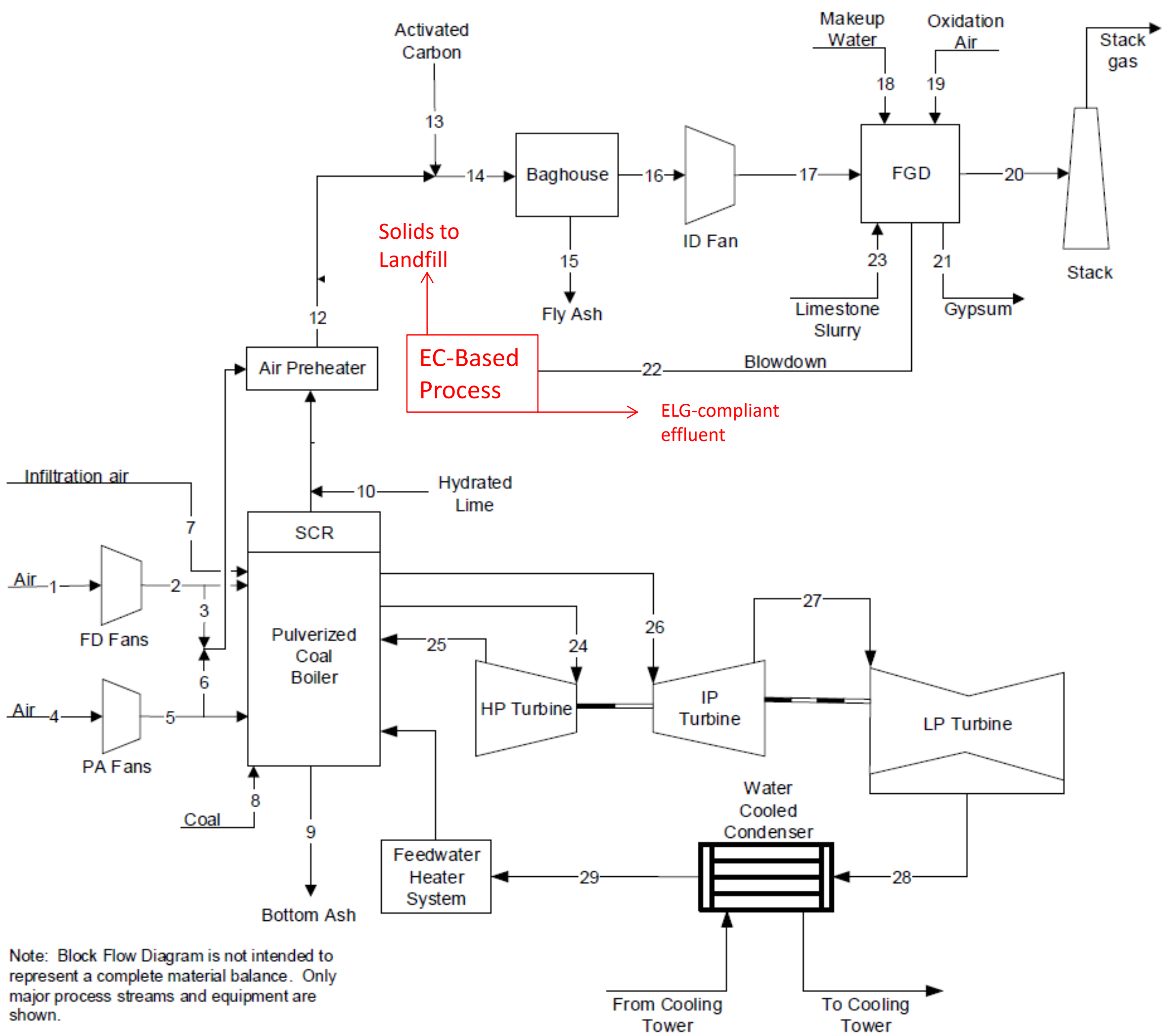


Figure 3. Plant Block Flow Diagram with Integration of an EC-Based Process.

Design Basis

The power plant used as the basis for this TEA was the hypothetical plant described in Case B11A from the DOE-NETL's "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 4" [DOE 2019a]. DOE-NETL removed the spray dryer evaporator from the unit configuration to more accurately represent a typical, non-ELG compliant subcritical coal unit. FGD wastewater characteristics are described in DOE-NETL's "Techno-economic Analysis and Evaluation of Wet FGD Wastewater Treatment Processes at Existing Plants" [DOE 2019b]. Some design parameters were based on

DOE-NETL's Quality Guidelines for Energy Systems Studies (QGESS) [DOE 2011, DOE 2013b, DOE 2013c, DOE 2015]. Table 2 shows the resulting parameters used for the technical design basis for the TEA.

Process Performance Basis

For the design basis for this TEA, Trimeric used a flow rate of 57 gpm as the maximum possible flow rate for sizing the WWT system. DOE did not specify whether the 57 gpm value used in [DOE 2019b] was an average or maximum flow rate. Where possible, process performance parameters measured in the laboratory by UKy-CAER were used as the inputs for sizing equipment, as summarized in Table 3.

A preliminary water balance was calculated for the process to account for the internal recycle loops associated with the overflow and underflow steams of the hydrocyclones and thickeners. These flows were used for sizing equipment. Green rust/water separation data were not available. To facilitate a very preliminary water balance, the following water split was assumed across each hydrocylone and thickener: 30% of water to underflow and 70% of water to overflow. In future refinements of the EC process, laboratory data should be provided to equipment vendors to obtain a more accurate estimation of water and green rust separation efficiency.

Table 2. Technical Design Basis for the TEA

Parameter	Value	Source of Value
Location	Midwestern U.S.	[DOE 2019b]
Gross Generating Capacity (MW)	686	[DOE 2019b]
Net Generating Capacity (MW)	650	[DOE 2019b]
Net Plant Heat Rate	8,773 Btu/kWh	[DOE 2019b]
Capacity Factor	0.85	[DOE 2019b]
Boiler Type	Pulverized Coal	[DOE 2019b]
Coal Type	Illinois No. 6 Bituminous	[DOE 2019b]
Air pollution control devices (APCDs)	Low-NO_X Burners with Over-fired Air and SCR for NO_X Control (76% efficiency), Hydrated Lime Injection for SO_3 Control, Activated Carbon Injection, for Mercury Control Bag House for Particulate Matter Control (99.8% efficiency), wet FGD for SO_2 control (98% efficiency)	[DOE 2019b]
FGD Wastewater Characteristics		
FGD wastewater flow rate (gpm)	57	[DOE 2019b]
Temperature of FGD wastewater (°F)	133	[DOE 2019b]
pH	7.2	[DOE 2019b]
Cl concentration (ppm)	20,000	[DOE 2019b]
Sulfate concentration (ppm)	7,600	[DOE 2019b]
As concentration (ppb)	1,400	[DOE 2019b]
Hg concentration (ppb)	700	[DOE 2019b]
Se concentration (ppb)	5,000	[DOE 2019b]
Nitrate/Nitrite concentration (ppb)	30,000	[DOE 2019b]
Total Dissolved Solids (TDS) concentration (ppm)	43,494	[DOE 2019b]
Total Suspended Solids (TSS) concentration (ppm)	15,000	[DOE 2019b]
Product Water Specifications		
If water discharged	Meet ELG specifications for Steam Electric Generating Stations	UKy-CAER

Table 3. Process Performance Parameter Values for the TEA

Parameter	Value	Technical Basis
Electrocoagulation Parameters		
Equilibrium adsorption capacity of green rust	Equilibrium Capacity (mol Se / mol GR) = $\frac{0.257x}{1 + 0.257x}$ where x = ppm Se in the treated water	Langmuir fit developed from UKy-CAER laboratory data
Excess green rust reagent	2x equilibrium adsorption capacity	Preliminary engineering assumption
Time required to generate targeted excess green rust concentration	13 minutes	UKy-CAER laboratory data
Residence time in green rust generator	3x time required to generate targeted excess green rust concentration	Preliminary engineering assumption for sufficient mixing in continuously stirred tank reactor
Flowrate required for green rust generator	Flowrate corresponding to 20 wt% green rust solids in the generator effluent	UKy-CAER laboratory data
Time required for green rust to react with Se to meet ELG effluent concentration	1 hour total across all reactors	UKy-CAER laboratory data
Electricity required for electrocoagulation process	28.5 kW	UKy-CAER calculation for the process design basis, based on laboratory results
Residence time in green rust reactors	3x time required to react green rust with water	Preliminary engineering assumption for sufficient mixing in continuously stirred tank reactor
Amount and time required for green rust to react with As, Hg to meet ELG requirements	Same as selenium or lower	Preliminary engineering assumption; UKy-CAER does not have laboratory data for Hg; Se is expected to be most difficult species to treat
Amount and time required for green rust to react with nitrite/nitrate to meet ELG requirements	Same as selenium or lower	UKy-CAER laboratory data
Density of green rust	3.58 g/cm^3	UKy-CAER laboratory data
Average particle size of green rust particles	15 micron	UKy-CAER laboratory data

Section 4: Purchased Equipment Design and Costs

To estimate the purchased equipment costs (PEC) for the EC process configuration, the sizes and costs of the major equipment were estimated using the water balance. Throughout this report, the term "equipment" refers to major process equipment (e.g., filtration units, vessels, pumps, tanks). Equipment sizes were estimated using a combination of spreadsheet calculations and vendor supplied data.

Equipment selection and sizing for the wastewater treatment system were based on the FGD wastewater blowdown stream from the 650-MWe net plant heat and material balance [DOE 2019b]. The full equipment list is shown in Appendix A. The equipment lists include additional sizing criteria, materials of construction, the type of equipment, the resulting sizes, and the number of units, including spares. Spare pump capacity of 100% was included in the equipment cost estimate for all major pumps within the process.

Materials of construction were selected according to compatibility tables to provide either an estimated good (i.e., less than 20 mil/year penetration) or an estimated excellent lifetime (i.e., less than 2 mil/year penetration), or to be resistant as shown in Table 4. For the FGD wastewater, compatibility tables for salt water and dilute calcium chloride were consulted [Schweitzer 1991].

The sizing and costing methodology for each of the major equipment items is described below.

Table 4. Expected Compatibility of Materials of Construction with FGD Wastewater.

Fluid	Carbon Steel (CS)	Coated Carbon Steel	Bronze	Stainless Steel (SS)	Monel	Nickel	Hastelloy	Fiberglass Reinforced Plastic (FRP)
FGD Wastewater	U	R	U	G	G	E	E	E

Source: [Schweitzer 1991] for compatibility tables for dilute CaCl2 and salt water.
E = Excellent (penetration < 2 mills/year; or recommended by vendor)
G= Good (penetration < 20 mills/year)
U = Unsatisfactory
R = Resistant (for coatings)

Equipment costs were estimated using a combination of in-house data, vendor quotes for similar equipment, literature values, and cost estimating software (Aspen Capital Cost Estimator or ACCE). Vendor quotes for similar pieces of equipment were scaled for size and also for the date of the quote using the Chemical Engineering Plant Cost Index (CEPCI), as reported by Chemical Engineering magazine [Chemical Engineering]. To be consistent with the most recent DOE-NETL Cost and Performance Baseline for Fossil Energy Plants, all costs are presented in **2018 dollars**, which has a Chemical Engineering Plant Cost Index CEPCI value of 576.4 [DOE 2019a].

Equalization Tank

The equalization tank was sized for 57 gpm flow rate, with a 12-hour hydraulic residence time, and assuming operation at 80% full. Cost for the equalization tank was obtained from [EPRI 2013].

Green Rust Generator

The green rust generator consists of an electrocoagulation unit and associated silicon controlled rectifier to control current to the generator.

UKy-CAER laboratory data were used to size the electrocoagulation unit for the green rust generator. The amount of green rust needed to treat the FGD wastewater was based on the spent green rust leaving Reactor #1 being in equilibrium with the water leaving Reactor #1. The time required to generate this green rust was based on kinetic data obtained by UKy-CAER. The electrocoagulation unit was sized for a 0.25 gpm flow rate so that the effluent stream contained 20 weight percent green rust solids, as specified by UKy-CAER. The cost for an electrocoagulation unit with sufficient residence time to generate the green rust was obtained from an electrocoagulation vendor.

Costs for a silicon controlled rectifier were obtained from a vendor based on a DC output of 0 to 48 volts and current generation of 0 to 800 amps. The SCR sizing was based on information provided by the electrocoagulation unit vendor.

Green Rust Reactors

Each of the three green rust reactors was sized for 1 hour of residence time, operating at 80% full. The reactors were costed as closed FRP tanks using Aspen Capital Cost Estimator.

Green Rust Separators

The green rust separator associated with each green rust reactor consisted of a hydrocyclone feed pump, hydrocyclone, thickener, and thickener underflow pump.

The electrocoagulation vendor consulted for this project typically uses a lamella clarifier to clarify water before discharge, with the vendor noting that it is challenging to settle the solids. For the UKy-CAER process, the purpose of the green rust separators is to isolate the green rust from the treated water so that the green rust can travel counter-currently to the treated FGD wastewater. Because the green rust then enters a reactor with a dirtier water stream than from whence it originated, the green rust needs to be thickened sufficiently such that the volume of clean, treated water associated with the green rust and returned to a reactor with less clean water is reduced.

Because solids thickening, and not just wastewater clarification, is required for the UKy-CAER process, Trimeric selected a hydrocyclone to preliminarily thicken the green rust stream, followed by a thickener. Laboratory testing is needed to determine if this process arrangement will be sufficient to achieve the desired separation. If not, alternate solids dewatering equipment, such as centrifuges, may be required.

Pricing for the hydrocyclone and thickener were obtained from Aspen Capital Cost Estimator.

Filter Press

A filter press was sized based on the solids recovery rate, which included both the green rust solids and the FGD fines. Costs for the filter press, including centrifugal feed pumps and a sludge holding tank with mixer, were obtained from [EPRI 2013].

Sand Filter

The sand filter was sized based on the effluent flow rate. Pricing for a sand filter and its associated effluent storage tank was obtained from [EPRI 2013].

Feed Pumps

The wastewater feed pumps were sized based on the required head and flow rate. The required head was calculated from the assumed elevation changes, frictional drop across process lines, and pressure drop across major unit operations and piping.

All pumps were assumed to be centrifugal pumps. Pricing was obtained from Aspen Capital Cost Estimator.

Section 5: Total Plant Costs

As described in Section 4, estimates for the total plant costs for EC process were developed from purchased equipment costs for the major equipment shown in the process flow diagram (Figure 2). To estimate total plant costs for the EC process, Trimeric adapted the DOE's methodology for scaling the purchased equipment costs to total plant costs [DOE 2019b]. First, an explanation of how the DOE developed total plant costs is provided, using Case 1 (Chemical Precipitation plus Biological Treatment) as an example. Next, an explanation of how Trimeric modified the DOE's methodology to develop the total plant costs for the EC process is provided.

TPC Methodology for Case 1 Biological Treatment

Purchased equipment costs for the reference case (chemical precipitation plus biological treatment for selenium removal) were obtained from Exhibit C-2 from the reference DOE techno-economic analysis for wet FGD wastewater treatment [DOE 2019b]. A snapshot of the purchased equipment cost data is shown below:

Exhibit C-2. Wet FGD wastewater treatment configurations equipment costs

Option	Description	Equipment Costs, $/1,000					
		Pretreatment	Treatment	Brine Disposal	Buildings	Construction[A]	Total
1	Chemical Precipitation + Biological Treatment	$2,940	$2,320	$0	$320	$5,640	$16,800

Exhibit C-2 shows equipment costs included pretreatment, treatment, brine disposal (not applicable for Case 1), buildings, and construction. The "Total" equipment costs listed in Exhibit C-2 is the summation of the purchased equipment costs for these five categories, <u>multiplied by a factor of 1.5</u>. Although the origin of this 1.5 factor is never explicitly stated within this DOE reference document, Section 2.7 "Cost Estimating Methodology" states the following:

"For the wet FGD wastewater treatment configurations reviewed in this study, order-of-magnitude (±50 percent) capital and operation and maintenance (O&M) cost estimates were prepared based on in-house information (provided by Black & Veatch), supplemented with budgetary vendor quotes."

Based on the data in Exhibit C-2 Trimeric surmised that 1.5 factor reflects DOE's use of the +50% cost estimate as the base total equipment cost estimate when scaling total equipment costs to total plant costs.

Table 5 shows the assumptions and calculations that were used by DOE-NETL to transform the purchased equipment costs (PEC) into the Total Plant Cost (TPC) associated with a wastewater treatment process being retrofitted into an existing plant. The scale-up of purchased equipment costs to total plant costs for Case 1 (chemical precipitation plus biological treatment) is summarized in the snapshot and details below:

Exhibit A-19. Case 1 total plant cost details

	Case:	1	-Subcritical PC, No Capture, Chemical Precipitation + Biological Treatment				Estimate Type:			Conceptual	
	Plant Size (MW, net):	650					Cost Base:			Dec 2018	
Item No.	Description	Equipment Cost	Material Cost	Labor		Bare Erected Cost	Eng'g CM H.O.& Fee	Contingencies		Total Plant Cost	
				Direct	Indirect			Process	Project	$/1,000	$/kW
3				Feedwater & Miscellaneous BOP Systems							
3.8	Spray Dryer Evaporator	$17,657	$0	$11,197	$0	$28,854	$4,328	$1,443	$10,388	$45,013	$69
	Subtotal	$17,657	$0	$11,197	$0	$28,854	$4,328	$1,443	$10,388	$45,013	$69

- In the above exhibit, DOE-NETL's reported "Equipment Cost" (termed Retrofit-Adjusted Purchased Equipment Cost, or RA-PEC, for this Trimeric report) consisted of the "Total" equipment costs from Exhibit C-2 (termed Purchased Equipment Cost, or PEC, for this Trimeric report), multiplied by a retrofit difficulty factor. The retrofit difficulty factor is a multiplier applied to greenfield equivalent costs to represent cost premiums, addressing minor differences in equipment specifications, layout, duct routing, and items where additional complexity is likely to be encountered [DOE 2013c]. According to Exhibit 2-14 of the DOE reference document for wet FGD wastewater treatment, a 5% retrofit difficulty factor is applied to equipment [DOE 2019b].

- The Bare Erected Cost (BEC) was estimated as 1.55 times the RA-PEC, or 1.63 times the PEC. The BEC includes the cost of the process equipment as well as the on-site facilities that support the process, and the direct and indirect labor required for construction and/or installation, as well as taxes, freight, and insurance associated with the equipment. The BEC includes a 15% retrofit factor applied to the direct labor that contributed to the BEC [DOE 2013c].

- The Engineering, Procurement, and Construction Cost (EPCC) comprises the BEC and the cost of services provided by the EPC contractor. EPC services include detailed design, contractor permitting, project management, and construction costs. The EPCC is 15% of the BEC per the cost information in Exhibit A-19 [DOE 2019b].

- The Total Plant Cost (TPC) comprises the EPCC plus process and project contingencies. Per the cost information in Exhibit A-19, process contingency is 5% of the BEC for the base case of chemical precipitation plus biological treatment. The project contingency is

30% of the sum of the BEC, EPCC, and process contingency. Per the cost information in Exhibit A-19, TPC was estimated as 2.55 times the PEC.

Table 5. Components of Total Capture Plant Cost for Reference Case

Capital Cost Component	Value Used by DOE-NETL for Case 1	Calculation based on PEC	Technical Basis
Purchased Equipment Cost (PEC)	PEC	Sum of individual equipment line items for WWT	
Retrofit Adjusted Purchased Equipment Cost (RA-PEC)	1.05*PEC	1.05 * PEC	Vendor Quotes and Equipment Cost Databases; Includes retrofit difficulty factor of 1.05 for equipment
Bare Erected Cost (BEC)	1.55 x RA-PEC	1.63 * PEC	Multiplier includes cost of taxes, insurance, freight for equipment; Includes retrofit difficulty factor of 1.15 for direct labor
Engineering, Procurement, Construction Costs (EPCC)	0.15 x BEC	0.245 * PEC	
Process Contingency	0.05 x BEC	0.08 * PEC	
Project Contingency	30% of Sum of BEC, EPCC, and Process Contingency	0.59 * PEC	
Total Plant Cost	Sum of BEC, EPCC, Process Contingency, and Project Contingency	2.55 * PEC	

To the wastewater treatment total plant costs, DOE-NETL added costs associated with sub-accounts impacted by the installation of a wet FGD wastewater treatment system (i.e., items outside the boundary limits of the treatment system itself, also known as balance of plant costs): Account 11 (Accessory Electric Plant), Account 12 (Instrumentation and Control), and Account 13 (Improvements to Site). For the purpose of this report, Trimeric focused on the wastewater treatment total plant costs (i.e., without the addition of these balance of plant account costs) for Case 1 and neglected the balance of plant cost changes.

TPC Methodology for EC Process

To develop the wastewater treatment total plant costs for the EC case, Trimeric used the following approach, with the noted adjustments to maintain consistency with the Case 1 wastewater treatment total plant costs. Table 6 provides a summary of the key differences between the reference case and EC case.

- Pretreatment and treatment purchased equipment costs for the EC-based process were developed as described in Section 4.
- DOE-NETL's +50% adder to equipment costs was ignored, for both the EC-based process and Case 1, because the origins of the factor were unclear, as discussed previously.
- A process contingency of 20% was used for the EC-based process to reflect its earlier stage of development as compared to the Case 1 biological treatment technology (for which DOE-NETL used a 5% process contingency).
- The resulting Lang factor for the EC-based process was 5.8, as compared to 5.7 for Case 1 with its lower process contingency. These Lang factors were applied to the pretreatment and treatment equipment costs for the EC-based process and Case 1, respectively. Building and construction were not treated as equipment costs but instead rolled into the Lang factor where they are treated as indirect construction costs.
- The Lang factor of 5.7 for Case 1 included retrofit difficulty factors applied to individual equipment costs. For the EC-based process, the Lang factor of 5.8 did not include a retrofit factor. Instead, a 10% retrofit difficult factor was applied to the wastewater treatment total plant costs for the EC-based process, per DOE QGESS reference document for retrofit difficult factors [DOE 2013c]. That is, the 10% retrofit factor was applied after the 5.8 Lang factor was applied.

The total of pretreatment and treatment equipment costs for Case 1 was $5.26 MM USD, without the 1.5 factor DOE used for a +50% cost estimate. The wastewater treatment total plant costs associated with this equipment cost was $30.0 MM, for a Lang factor of 5.70. In DOE-NETL's WWT TEA report [DOE 2019b], the wastewater treatment total plant costs were reported as $44.97 MM; the difference between this value and the $30.0 MM Trimeric used as the baseline technology costs for Case 1 is the 1.5 factor referenced above.

Table 6. Comparison of Lang Factor and Retrofit Difficulty Factors used for Case 1 and EC-Based Process.

Description	**DOE Case 1 Reference Case**	**EC Case**
Lang Factor to Scale Pretreatment and Treatment PEC to TPC, which included these factors which were different between the cases:	5.70	5.80
Equipment Retrofit Difficulty Factor	*1.05*	*1.00*
Direct Labor Retrofit Difficulty Factor	*1.15*	*1.00*
Process Contingency (% of BEC)	*5%*	*20%*
Overall TPC Retrofit Difficulty Factor	1.00	1.10

Section 6: Economic Analysis Results

This section presents the results from the preliminary economic analysis for the EC process.

Purchased Equipment Costs for the EC Process

Table 7 summarizes the purchased equipment costs, grouped by equipment category, estimated for the EC process. The filter press was the largest cost center, followed by the green rust separators, then the green rust generator, and then the green rust reactors.

Table 7. Purchased Equipment Costs

Equipment Category	**EC Purchased Equipment Cost (2018$)**
Filter Press	$1,319,000
Green Rust Separators	$690,000
Green Rust Generator	$279,000
Green Rust Reactors	$153,000
Sand Filter	$112,000
Equalization Tank	$101,000
Feed pumps	$18,000
TOTAL	$2,672,000

Total Plant Cost

Table 8 shows the development of the total wastewater treatment plant cost from the purchased equipment costs.

Table 8. Total Plant Cost for EC-Based WWT Process

Item	**EC Calculated Value (2018$)**
PEC	$2,672,000
TPC (based on 5.8 Lang Factor)	$15,498,000
TPC with 1.1 Retrofit Factor	$17,047,000

O&M Cost Estimation

Operating and maintenance (O&M) costs have a fixed and a variable component. The fixed O&M costs are shown in Table 9; they include incremental operating labor for the wastewater treatment process; maintenance labor; the associated administrative and support labor; and property taxes and insurance. These fixed O&M costs are incremental costs (i.e., they are on top of the existing fixed O&M operating costs to operate the power generation facility) to retrofit the power generation facility with the EC process technology.

Table 9. Fixed O&M Costs for EC-Based WWT Process

	Incremental Fixed Operating Costs for EC-Based Process	Basis for Annual Cost	Comments
Operator	$87,688	0.25 operator/shift; 2 shifts/day; 12 hours/shift; 365 operational days/year; $38.50/hr labor rate (base); operating labor burden of 30% of base	DOE assumes 0.25 operator/shift increase in labor for operators from the existing FGD physical/chemical WWT to chemical pretreatment plus biological treatment [2019b]
Maintenance Labor	$106,237	0.62% of TPC	Calculated from information in Exhibits A-19 and A-21 [DOE 2019b]
Administrative and Support Labor	$48,481	25% of Operating and Maintenance Labor	Calculated from information in Exhibit A-21 [DOE 2019b]
Property Taxes/Insurance	$331,990	1.95% of TPC	Calculated from information in Exhibits A-19 and A-21 [DOE 2019b]
TOTAL FIXED OPERATING COSTS	**$574,396**		

Variable O&M costs are shown in Table 10 for the EC process. Variable O&M costs were calculated with an 85% capacity factor. These costs include reagent costs (iron electrodes); annual maintenance materials; and disposal costs for the EC reject solids stream (including gypsum fines).

The unit pricing for the iron electrodes was based on the vendor quote for the electrocoagulation unit, assuming annual replacement of the unit internals.

Total maintenance material costs were calculated as 0.93% of TPC from information in Exhibits A-19 and A-21 [DOE 2019b].

There are approximately five tons per day of gypsum solids that will be dewatered to 50 wt% solids, which results in 10 tons per day of solids disposal. The daily rate of green rust solids disposal is a small fraction of gypsum solids disposal, and Trimeric assumes that overall daily solids disposal rate remains unchanged. Trimeric used the waste disposal cost of $38/ton listed in Exhibit A-21 [DOE 2019b].

Electricity requirements for the pumps and agitators were calculated assuming efficiencies of 75%.

The DOE WWT TEA cases included electricity consumption as part of the power plant auxiliary load; it was not included in the variable O&M costs. Table 11 summarizes the parasitic energy demands of the EC-based process as applied to treat 57 gpm FGD wastewater from 660-MW gross coal-fired power plant. The electricity consumption for the EC process was 110 kW.

Table 10. Variable O&M Costs for EC Case.

Item	**Operating Costs for EC Process**
Iron Electrodes	$119,000
Maintenance Materials	$159,355
Solids Disposal	$122,611
Total Variable O&M Costs	**$400,966**

Table 11. Parasitic Energy Requirements of the EC Process

Equipment Name	**Equipment Type**	**Size**	**Number of Units**	**Total kW**
EQ Tank Agitator	Mech Seal Agitator	5.13 hp	1	3.83
Feed Pumps	Centrifugal pump	5 hp	2	7.46
Green Rust Generator	Electro-coagulation unit	28.5 kW	1	28.50
GR Reactor Agitator	Fixed propeller gear motor	20.85 hp	3	46.64
Hydrocyclone Feed Pumps	Centrifugal pump	5 hp	3	11.19
Thickener Underflow Pumps	Centrifugal pump	5 hp	2	7.46
Thickener	Thickener with rake	0.75 hp	3	1.68
Filter Press Feed Pump	Centrifugal pump	5 hp	1	3.73
Total				***110.47***

Lifetime Cost Analysis

The cost of treating 57 gpm FGD wastewater was calculated based on an assumed 10-year remaining lifetime for the plant, which was in accordance with [DOE 2019b]. To determine the cost, the TASC was added to 10 years of O&M costs, and then divided by the amount of water treated (i.e., at 85% capacity factor for the power plant). The result was a cost of $33.12/m^3 of treated water, as shown in Table 12.

Table 12. Lifetime Cost of Treating FGD Wastewater with EC Process.

Parameter	$	$/m^3 water treated
Plant Lifetime (years)	10	
Water produced over lifetime (m^3)	963,975	
TASC	$22,172,091	$23.00
Fixed O&M, annual	$574,396	$5.96
Variable O&M, annual	$400,966	$4.16
Total Cost over lifetime	$31,925,712	$33.12

Comparison to Case 1 Chemical Precipitation + Biological Treatment

Table 13 compares key economic metrics between the EC process and DOE-NETL's Case 1. The equipment costs for the EC process are 50% less than equipment costs for Case 1. The Total Plant Costs are 46% less for the EC process than Case 1. Fixed operating costs, which are mostly a function of total plant cost, are likewise lower for the EC process. Variable operating costs for the EC process included replacement of iron electrodes and solids disposal costs; these costs were $109,000 less than for Case 1, which had operating costs that included chemical usage and solids disposal costs. The electricity consumption for EC process was 110 kW, while was 53 kW for Case 1; both values are very small compared to the overall net generating capacity of the power plant.

Table 13. Comparison of EC Process to DOE-NETL Case 1.

	EC Process	Case 1: Chemical Precipitation + Biological Treatment
Equipment Costs	$2,672,000	$5,260,000
Total Plant Costs, including Retrofit Factors	$17,047,000	$29,982,000
Fixed Operating Costs	$574,000	$927,000
Variable Operating Costs	$401,000	$510,000
Electricity Consumption	110 kW	53 kW

Section 7: Conclusions and Recommendations

A preliminary techno-economic analysis was performed using the design basis developed by DOE-NETL for its analysis of wet FGD wastewater treatment (WWT) processes for a 57 gpm FGD blowdown [DOE 2019b]. Trimeric worked with UKy-CAER to develop a process flow diagram and an energy and material balance for an electrocoagulation-based process. The total plant cost was developed from estimated purchased equipment costs using a methodology adapted from the one described in DOE-NETL's FGD WWT report and in the DOE-NETL's QGESS documents. This cost estimate was prepared based on laboratory performance data and engineering assumptions. Key process performance parameters such as required power and residence time required for the electrocoagulation reactions and the separation efficiency of the coagulated solids may change as the process is refined and it is tested at larger scale. To account for the uncertainties associated with a technology in the early stages of development, a process contingency of 20% was assumed.

The electrocoagulation process was designed by UKy-CAER to produce a wastewater that is compliant with ELG discharge limits (for Se, As, Hg, and nitrite/nitrate) and a solids stream which can be landfilled. The estimated purchased equipment costs (PEC) for the inside-the-boundary limits of the EC process was $2.67 million and the total plant cost (TPC) was $17.0 million. The primary contributors to the purchased equipment costs were the solids filter press (to dewater the solids for landfill), followed by green rust separators (to dewater the green rust between green rust reactors), and then the green rust generator and reactors. The fixed operating costs were $574,000 and the variable operating costs were $401,000.

In comparison, using the adapted methodology, Trimeric estimated that DOE's Case 1 for Biological Wastewater Treatment had a PEC of $5.26 million and a TPC of $30.0 million. The fixed and variable operating costs were higher for Case 1 than for the EC process. The electricity consumption for Case 1 was 53 kW, while it was 110 kW for the EC process; electricity consumption for both processes was very small compared to the net generating capacity of the power plant.

A more detailed engineering analysis, which was beyond the scope of this preliminary effort, would be required to better assess the optimum design for the green rust generator and reactors and the solids separation equipment needed to cycle the green rust solids through the multi-stage green rust reactors.

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APPENDIX A: EQUIPMENT TABLE FOR EC PROCESS

Equipment Name	Equipment Type	MOC	Sizing Basis	Size	Unit Cost, Original Basis Year	Year Basis for Cost Estimate	Number of Units	Total PEC Cost, 2018	Source of Cost
Equalization Tank	FRP tank mixers	FRP	57 gpm 12 hr residence time 80% full	51,300 gallons					
EQ Tank Agitator	Fixed propeller gear motor	chloride-resistant metallurgy	0.1 hp / 1000 gallons	5.13 hp	$100,000	2013	1	$101,000	EPRI Cost Curve, 2013
Feed Pumps	Centrifugal pump	chloride-resistant metallurgy	57 gpm, 2 @ 100%	5 hp	$8,400	2016	2	$18,000	ACCE, 2016
Silicon Controlled Rectifier	Air-cooled silicon controlled rectifier with PLC		AC input: 480 Volts, 3 phase, 60 Hz	DC output: 1 to 48 volts, 0 to 800 amps	$35,633	2019	1	$34,000	Vendor quote, 2019
EC - Green Rust Generator	High flow reactor	FRP	0.2 gpm water flow		$125,000	2019	1	$119,000	Vendor quote, 2019
Green Rust Reactor	FRP tank (closed)	FRP	278 gpm 1 hr residence time 80% full	20,850 gallons					ACCE, 2016
GR Reactor Agitator	Fixed propeller gear motor	chloride-resistant metallurgy	1 hp / 1000 gallons	20.85 hp	$86,717	2016	3	$279,000	ACCE, 2016
Hydrocyclone Feed Pumps	Centrifugal pump	Ni	278 gpm, 10 psi head	5 hp	$14,500	2016	3	$47,000	ACCE, 2016
Hydrocyclone	Water cyclone	heavy ceramic lined CS	10 psi presure drop	6" diameter	$8,300	2016	15	$134,000	ACCE, 2016
Thickener Underflow Pumps	Centrifugal pump	Ni	25 gpm	5 hp	$8,200	2016	2	$18,000	ACCE, 2016
Thickener	Thickener with rake	rubber covered CS	19' ID x 10' H 83 gpm	0.75 hp	$152,600	2016	3	$491,000	ACCE, 2016
Sand Filter and Effluent Storage Tank	FRP tank Continuous backwash sand filter	FRP	57 gpm		$110,000	2013	1	$112,000	EPRI Cost Curve, 2013
Filter Press and Sludge Holding Tank	Filter press Centrifugal feed pumps Sludge holding tank with mixer	chloride-resistant metallurgy	15,000 lb/day		$1,300,000	2013	1	$1,319,000	EPRI Cost Curve, 2013
TOTAL								***$2,672,000***	