

**Probabilistic Modeling and Optimization of Clean Coal Technologies:
Case Studies of the Externally-Fired Combined Cycle (EFCC) System**

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INTRODUCTION

The Externally Fired Combined Cycle (EFCC) is an advanced coal-fired power generation concept with a potential for higher thermal efficiency and lower cost than conventional coal-based systems.¹ The concept incorporates efficient gas turbine combined cycle technology for use with coal. Unlike "direct fired" combined cycles, the EFCC does not require any special fuel preparation.

The EFCC concept has yet to be demonstrated commercially. The concept is under development by Hague International and the U.S Department of Energy (DOE). The main obstacle to the development of a viable EFCC system has been the unavailability of a suitable heat exchanger which would allow for a sufficiently high gas turbine inlet temperature. Recent developments in ceramic heat exchanger (CerHx) technology for use in the EFCC process have been promising enough to warrant further development of this system.

This project involves development of engineering performance and cost models of the EFCC technology based on available performance and cost information. Since this technology is in the early stages of development, there are inherent uncertainties in the performance and cost parameter estimates. A probabilistic modeling capability has been incorporated to account for the uncertainties in the performance parameters. Details of previous work on probabilistic modeling can be found elsewhere.²⁻⁵

The results obtained from the EFCC model simulation include the possible ranges of values for the performance, environmental emissions, and cost parameters, and information about the probability of obtaining these results. These results have been used to characterize key uncertainties; optimize the flowsheet configuration and parameter values; and identify priorities for further research. The model results provide insight into the risks and potential payoffs of the EFCC technology.

DESIGN BASIS FOR THE EFCC

A conceptual process model was developed by Hague International (HI) to estimate the performance of a 300 MW EFCC system.⁶ A conceptual diagram is shown in Figure 1. Coal is combusted in an atmospheric pressure combustor. The combustor exhaust gases pass through a slag screen to remove large (> 12 micron) particles and enter a shell and tube ceramic heat exchanger. Filtered air is compressed before it enters the tube-side of the heat exchanger. In the heat exchanger, the thermal energy of the shell-side combustion flue gas is transferred to the tube-side high pressure air. The high pressure air is heated to the desired turbine inlet temperature and transported to the turbine via internally insulated piping. The hot pressurized air is expanded to provide shaft power to drive the compressor and electric generator. The turbine exhaust air exits at a pressure slightly above atmospheric and enters the coal combustor. Flue gas exiting the ceramic heat exchanger enters a Heat Recovery Steam Generator (HRSG), where thermal energy is transferred to a bottoming steam cycle. Table 1 lists typical process conditions for the stream numbers shown in Figure 1.

A bleed stream is extracted from the compressed air stream for turbine blade cooling. Leakage from the high pressure air stream in the CerHx to the low pressure flue gas stream further reduces the mass flow rate of the inlet air stream to the gas turbine. There is a slight increase in the mass flow rate of the flue gas flowing through the HRSG due to possible leakage of steam from the HRSG into the flue gas stream. An Induced Draft (ID) fan is located downstream of the fabric filter to overcome pressure drops in the slag screen, CerHx, HRSG, Flue Gas Desulfurization (FGD) unit, and the fabric filter (FF).

STATUS OF THE EFCC

In 1987, the U.S. DOE and a consortium of electric utilities and other companies initiated an EFCC Development Program. The program consists of a series of research and development activities, to be followed by the construction, installation, and operation of a prototype.

Under Phase I of the program, a low pressure CerHx was tested. The CerHx was exposed to the products of combustion of a coal/water slurry for 40 hours. The results indicated that ash buildup occurred on the

heat exchanger tubes, which in turn motivates an upstream ash collection system. Nonetheless, the ceramic tubes exhibited good durability under all test conditions.⁷ Phase I was completed in March 1989.

Phase II of the program, now underway, involves design, construction, and operation of a full scale-test facility at Kennebunk, Maine. The facility includes a 500 KW gas turbine, CerHx, slag screen, and a 7.4 MW_t (25 x 10⁶ Btu/hr) combustion system. The CerHx will function under actual gas turbine operating conditions. Therefore, the tubes will be pressurized and thermally cycled under gas turbine operating conditions. The primary objectives of this phase are to demonstrate that the ceramic heat exchanger can be reliably pressurized up to 165 psia and that it can withstand exposure to coal combustion products. Work on this phase began in December, 1991 and is nearing completion. The test results are not yet available.

Phase III will involve work on a "Prototype Externally Fired Combined Cycle", and Phase IV will involve a "Commercial EFCC Demonstration".¹ Phase III of the program was originally selected for funding under Round V of the U.S Clean Coal Technology Program in May 1993. The objective of this phase is to repower an existing coal-fired powerplant. To demonstrate the advantages of repowering an existing coal fired steam plant with an EFCC, Hague International developed a conceptual design for repowering.⁸ However, at this time the status of the project is uncertain.

UNCERTAINTY IN THE EFCC

Analyses of conceptual designs of EFCC systems have identified the potential for high thermal efficiency and low cost, with acceptable environmental emissions. However, no "fifth-of-a-kind" or commercial EFCC plant is operational as yet. Therefore, making predictions regarding the mature commercial scale performance and cost of an EFCC plant involves uncertainties. A few examples are briefly described. These include the CerHx, high temperature bottoming cycle, gas turbine modifications, and advanced sulfur controls. The uncertainties have implications for both performance and cost of the EFCC.

The CerHx for EFCC application has not yet been fully developed and tested under actual operating conditions. Most of the work done on the development of the CerHx has been related to modifying a low pressure recuperator for EFCC application. The performance of the CerHx under high pressure and in a corrosive coal combustion flue gas environment is still uncertain. The inlet temperature to the bottoming steam plant is much higher than that experienced in conventional coal-fired power plants, which may introduce uncertainty regarding long term durability of heat exchanger materials. Several modifications have to be made to a commercially available gas turbine for use in an EFCC plant. Such modifications, although conceptually possible, have yet to be proven feasible on a commercial scale. Innovative sulfur removal technology based on an amine solvent has been proposed to control sulfur emissions, but such a system has not yet been proven successful on a commercial scale. Instead a wet limestone system could be used which is in commercial use and has established performance and cost. The cost of several process equipment areas are also uncertain due to uncertainties in their performance and availability. Since the CerHx, slagging combustor, slag screen, and gas turbine modifications have not been commercially demonstrated, the process and cost parameters related to these are expected to be the most uncertain.

MODELING THE EFCC USING ASPEN

The DOE Morgantown Technology Energy Center (METC) has developed a performance model for a 264 MW_{net} EFCC system based on a HI conceptual design of the system. The model was developed as an ASPEN (Advanced System for Process ENgineering) input file. ASPEN is a Fortran-based deterministic steady-state chemical process simulator developed by the Massachusetts Institute of Technology (MIT) for DOE to evaluate synthetic fuel technologies.⁹ The ASPEN framework includes a number of generalized unit operation "blocks", which are models of specific process operations or equipment (e.g., chemical reactions, pumps). By specifying configurations of unit operations and the flow of material, heat, and work streams, it is possible to represent a process plant in ASPEN. In addition to a varied set of unit operation blocks, ASPEN contains an extensive physical property database and convergence algorithms for calculating results in closed loop systems, all of which make ASPEN a powerful tool for process simulation.

The METC EFCC performance model has been used to calculate mass and energy balances and to conduct sensitivity analyses of performance parameters. While the bulk of the model is comprised of generalized unit operation blocks, there are a number of Fortran blocks and design specifications which are specific to the EFCC flowsheet. There are also user models to handle coal properties, and there is a Fortran block used as a summary report writer to concisely present plant performance results. The flowsheets have been developed in a modular approach to allow sections to be "borrowed" from other flowsheets, substantially reducing development time of new EFCC simulation models.

The METC model represents a modified EFCC design. It consists of: (a) a slagging combustor fueled by Illinois No. 6 coal; (b) a ceramic heat exchanger (CerHx); (c) a 2,300°F turbine inlet temperature gas turbine; (d) a heat recovery steam generation (HRSG) system; (e) a 1,785 psia, 1,050°F superheater, and 1,050°F reheater steam cycle; and (f) a flue gas desulfurization (FGD) unit. The flue gas exiting the combustor passes through the CerHx and HRSG, and is then treated in a wet limestone FGD scrubber to remove sulfur dioxide. The CerHx indirectly heats the gas turbine expansion stream to the turbine's inlet temperature.

Several modifications have been made to the existing METC model. These modifications were identified based upon a detailed review of the METC model and design, performance, and cost information regarding the EFCC and similar technologies. Model development activities were in two main areas: (1) performance; and (2) cost. Performance model modifications focused on: (1) improving the representation of process areas already included in the original METC model (e.g., gas turbine); and (2) adding new performance models (e.g., combustor emissions, slag screen, fabric filter).

Specific performance model modifications included the following:

- Accounting for combustor heat losses.
- Incorporating water walls in the combustor.
- Specifying the carbon conversion in the coal combustor.
- Scaling the auxiliary air requirement to the flow rate of coal.
- Accounting for the air leakage in the CerHx.
- More detailed specification of gas turbine compressor and expander outlet pressures and efficiencies.
- More detailed gas turbine cooling air flow circuitry.
- New design specification to calculate gas turbine inlet air mass flow to meet a constraint for choked flow conditions at the expander inlet.
- Adding steam injection to the gas turbine.
- Adding water injection to the gas turbine.
- Estimations of NO_x, SO₂, and particulate matter emissions.
- Estimation of auxiliary power consumption based on performance parameters.
- Addition of a slag screen and fabric filter to account for the pressure drops across these units.
- Accounting for net plant efficiency penalty associated with the reheat of flue gas from the FGD unit.
- Incorporating FGD recirculation water and water in the sludge.

In the earlier METC model, the auxiliary power loads of the EFCC were estimated as a multiplier of gross plant electrical output. To estimate more realistic auxiliary power consumption requirements, new models were developed for the power consumed by each individual process area.

The METC model did not include any economics. Therefore, a new cost model was developed which includes capital, annual, and levelized total costs. The cost model was implemented as a FORTRAN subroutine which is called by the ASPEN simulation model. The cost model requires as inputs values for key performance and design variables that are specified and/or calculated in the ASPEN simulation model. Thus, the cost model is sensitive to changes in flowrates, pressures, and other performance and design variables.

Details regarding the new performance and cost model of the EFCC are reported elsewhere.^{10,11}

MODEL APPLICATIONS

The new EFCC performance model is applied here to a series of case studies. These case studies illustrate new methods for process technology evaluation and provide technology-specific insights regarding the EFCC. The methodological aspects of this work include the use of deterministic, sensitivity, and probabilistic analyses. In addition, stochastic optimization is employed to illustrate how advanced technologies may be designed in the face of uncertainties. The general features of the modeling approaches are described briefly. Results specific to the EFCC are then presented.

Modeling Methodology

Many models are developed for the purpose of providing a point-estimate which may be intended to serve as an accurate and precise prediction of some quantity. The purpose of such analyses are to provide decision makers with a best-estimate that can be used in comparison with other assessments or to develop design targets or budgetary cost estimates. However, quantitative measures of the accuracy and precision of model predictions are usually not developed, because no information on model or input uncertainty is accounted for quantitatively. Deterministic estimates for the performance and cost of new process technologies are often significantly biased toward optimistic outcomes.¹² Such biases can lead to serious misallocation of resources if decisions are made to pursue research and development on a technology whose risks were not properly quantified.

One common method for gaining insight into the risks of a new technology is to expand on deterministic analysis by evaluating the implications of alternative model input assumptions. In sensitivity analysis, the value of one or a few model input parameters are varied, usually from "low" to "high" values, and the effect on a model output parameter is observed. Meanwhile, all other model parameters are held at their "nominal" values. In practical problems with many input variables which may be uncertain, the combinatorial explosion of possible sensitivity scenarios (e.g., one variable "high", another "low," and so on) becomes unmanageable. Furthermore, sensitivity analysis provides no insight into the *likelihood* of obtaining any particular result. Thus, while they indicate that a range of possible values may be obtained, sensitivity results do not provide any explicit indication of how a decision-maker should weigh each possible outcome.

Probabilistic analysis can be used to propagate uncertainties in model inputs to estimate uncertainties in model outputs. Unlike sensitivity analysis, probabilistic analysis yields quantitative insight into both the possible range and the relative likelihood of values for model outputs. Probabilistic analysis helps decision makers understand both the potential pay-offs as well as the downside risks of a new technology compared to other alternatives. Probabilistic analysis also enables the identification of key sources of uncertainty, or risk, which can be targeted for further research.

Technology designs may be evaluated under uncertainty using various techniques. Two such techniques are presented here. One features probabilistic comparisons of the differences in performance for alternative designs. The other features the use of stochastic optimization techniques.¹³ In stochastic optimization, optimal values of design variables are selected based on an objective function and set of constraints that deal explicitly with uncertainty. For example, it is possible to maximize the mean estimate of plant thermal efficiency, or to minimize the probability that plant efficiency would be below a particular level, given uncertainty in process performance. The results of such analyses are designs that are robust to uncertainties. This is a substantial improvement over planning and design approaches which ignore sources of uncertainty and, hence, technological risk.

Model applications for the EFCC are presented which illustrate each of these methodological approaches. Additional details on the deterministic and sensitivity analyses of the EFCC are reported by Agarwal and Frey.¹¹

Deterministic Analysis

The new performance model of the EFCC was applied in a deterministic case study to yield a "best guess" estimate of process efficiency, electrical output, emission rates, and other performance variables. The case study was based upon a single heavy duty gas turbine such as a General Electric Frame 7F. An Illinois No. 6 coal was assumed. Selected model input assumptions are summarized in Table 2. The performance model was executed on a VAXStation 3200 using the DOE public version of ASPEN. The CPU run time for a single simulation is 70 seconds. Selected model results are shown in Table 3.

The new model yields different performance estimates than the previous METC model. For example, the net plant thermal efficiency estimated using base case assumptions is 42.4 percent (HHV basis) compared to a METC estimate of 44.1 percent. The primary differences in the estimates are due to the following features of the new model: (1) more detailed modeling of the gas turbine, including cooling air circuitry and choked flow conditions at the turbine nozzle; (2) models and assumptions regarding coal conversion, heat losses, and CerHx air leakage that are not accounted for in previous case studies; (3) consideration of FGD reheat requirements; and (4) more detailed calculation of auxiliary energy loads. The lower efficiency estimate obtained here is thus due to differences in both the performance model itself and the input assumptions. As will be demonstrated in the next section, the new model responds to changes in input assumptions, and will predict higher or lower thermal efficiencies depending on the model inputs.

The new model includes environmental aspects of the technology. Thus, best estimates of the emission rates of acid rain precursors, carbon dioxide, particulate matter, and slag from the combustor are reported. The case study developed here is intended to comply with existing environmental standards. However, it is quite likely that future permits at the federal or local levels will be more stringent than these requirements.

The thermal efficiency of the EFCC system is higher than for a conventional coal-fired power plant. Therefore, the emissions for the EFCC system tend to be lower per unit of electricity produced. For example, the estimated CO₂ emissions calculated using the new EFCC model are 1.63 lb/kWh, compared to 1.94 lb/kWh for a conventional coal fired power plant with 99.5 percent coal conversion and 608 MW net plant power output.¹⁴

Sensitivity Analysis

A total of thirteen performance and design parameters were varied as part of a series of 55 sensitivity analysis runs.¹¹ These analyses focused on four major process areas: (1) combustor; (2) ceramic heat exchanger; (3) gas turbine; and (4) environmental control. Selected results from these case studies will be described here. These include sensitivity analysis of two performance inputs, combustor heat loss and CerHx heat loss, and one design variable, steam injection rate. The range of values used for the sensitivity analyses are shown in Table 2.

The temperature of combustion in the coal combustor is approximately 2,700 °F, which is high enough to cause heat loss due to radiation. A full scale commercial combustor for the EFCC system has not yet been developed and demonstrated. Therefore, there is uncertainty regarding the exact magnitude of heat loss from the combustor. The heat loss from the combustor was varied from zero to five percent of the heat of combustion reaction in steps of one percent. Figure 2 shows the change in the net plant power output and net plant efficiency with changes in the combustor heat loss. Since the mass flow rate of air to the gas turbine and the temperature of the air at the gas turbine expander inlet is constant, the gas turbine power output is independent of the combustor parameters. However, in order to maintain thermal energy input to the gas turbine via the CerHx, an increase in the combustor heat loss is compensated for by an increase in the coal flow rate. Therefore, the flue gas flow rate from the combustor increases. Since the heat duty of the CerHx remains constant, the mass flow rate and the temperature of the flue gas entering the HRSG increases with an increase in combustor heat loss. This increases the heat input to the steam cycle and the power output from the steam cycle. As a result, the net plant power output increases by 3.3 MW as the heat loss increases from zero to five percent. As expected, the net plant efficiency decreases substantially from 42.8 percent for no combustor heat loss to 40.1 percent for five percent combustor heat loss.

The performance model responds differently to changes in the CerHx heat losses than it does for changes in combustor heat loss. Heat energy is lost through the CerHx walls due to radiation, which leads to a lower flue gas exit temperature than if the heat loss had not occurred. Thus, the heat input to the steam cycle and the steam turbine power output are both decreased. The change in net plant power output and the net plant efficiency with increasing CerHx heat loss is shown graphically in Figure 3. With an increase in CerHx heat loss, the gas turbine output remains the same, but the steam turbine power output decreases substantially. Since the coal input remains constant with a change in the CerHx heat loss, the net plant efficiency decrease by 1.6 percentage points from the lower to the upper limit of the CerHx heat loss.

Steam injection from the steam cycle to the gas turbine increases the power output from the gas turbine by adding to the mass flow of the air at the turbine expander inlet. Steam diverted from the steam cycle leads to a reduction in steam cycle power output. The change in the net plant power output and the net plant efficiency with increasing rates of steam injection is shown graphically in Figure 4. The net plant power output increases by 2.25 MW for a steam injection rate of 400,000 lb/hr. For higher steam injection rates, there is a slight decrease in net plant output. Compared to the base case, the net plant efficiency increases by 0.12 percent points for 200,000 lb/hr steam injection. However, for higher steam injection levels, it decreases. At 500,000 lb/hr, the net plant efficiency decreases below the base case value by 0.15 percentage points. While steam injection offers only a modest increase in plant output and a small effect on plant efficiency, its most attractive feature may be with regard to system costs. By offsetting increases in gas turbine output with corresponding reductions in steam turbine output, it would be possible to reduce the size and, hence, the cost of the steam turbine. The gas turbine capital cost would remain approximately constant, except for costs to install steam injection. Thus, an overall decrease in plant cost may be achieved.

Probabilistic Analysis

A probabilistic modeling capability for ASPEN is available for evaluating process technologies in the face of uncertainty.¹³ The probabilistic modeling capability can be used to evaluate uncertainties in the performance or cost of any chemical process plant which can be modeled using the ASPEN simulator. This capability is utilized here for the evaluation of uncertainties in the EFCC system.

Uncertainty Assumptions. The development of ranges and probability distributions for EFCC performance model input parameters may be based on information available in published studies, statistical data analysis, and/or the judgments of process engineers with relevant expertise. Due to the unavailability of sufficient experimental and full scale process performance data, it was not possible to conduct statistical data analysis. Selection of uncertain EFCC performance parameters, and their ranges and probability distributions were based on published data⁶⁻⁸ and conversations with experts.

Table 4 lists some of the performance variables selected for stochastic analysis, along with the deterministic value, range, and distributions for each of these variables. A total of 35 variables were treated probabilistically. Four of these are shown as examples in the table. Uniform, triangular, and normal distributions were used to quantify judgments regarding uncertainties. For example, a triangular distribution was chosen for variables for which the mode or the most probable value was known, and for which an expert also specified upper and lower bounds. The development of input assumptions for an uncertainty analysis is illustrated with one example. The value of carbon conversion in the coal combustor has been reported to be 99 percent,⁸ but an expert suggested that the carbon conversion could be 100 percent.

Probabilistic Results. For the probabilistic simulation, the deterministic model is executed a number of times, with a different set of values (samples) assigned to uncertain input parameters each time. For the analysis of the EFCC system with 35 uncertain input variables, a sample size of 100 was chosen. Results for all the uncertain output variables are collected at the end of each deterministic run, which can then be analyzed statistically to gain an insight into the key uncertainties of the system. Such an analysis enables the identification of key model uncertainties that are the most important determinants of uncertainty in model outputs.

The frequency distributions for output variables in the performance model can be estimated from the probabilistic simulation. The results of the simulation can be summarized using statistics, such as the mean and the standard deviation, or using graphs of the cumulative distribution function (cdf). As an example, the result for plant thermal efficiency is graphed as a cdf in Figure 5. The mean value of plant efficiency is 41.5 percent and the median is 41.6 percent, both of which are significantly lower than the deterministic value of 42.4 percent. From previous sensitivity analysis studies, the net plant efficiency was found to strongly depend on the combustor heat loss, CerHx heat loss, and carbon conversion.¹¹ An increase in the heat losses leads to a decrease in the plant efficiency. The heat losses were assigned positively skewed triangular distributions. Since the modal values of the heat losses are much lower than the upper limit, the assigned distributions lead to high probability of lower than the deterministic efficiency. There is a 95 percent probability that the plant efficiency will be lower than the deterministic value. Thus, the deterministic analysis appears to overestimate the plant efficiency.

Identification of Key Sources of Uncertainty. The key variables contributing to the uncertainties in EFCC process performance were identified using three general approaches. Statistical analysis using regression techniques was used to help identify input variables which are most highly correlated with output variables. Probabilistic sensitivity analysis was also used for identifying key uncertainties. In this approach, the interaction between different subsets of uncertain input variables as they affect uncertainty in output variables can be studied by isolating the uncertainties in different process sections. Probabilistic simulations are then performed using only the uncertainties in those process areas. The third approach, uncertainty screening, which is similar to the probabilistic sensitivity analysis, can be used to confirm the results of a regression or probabilistic sensitivity analysis by deleting uncertainties which are not believed to be important from the model. The results of the screening study can be compared to the results obtained from the original probabilistic analysis. If the results are similar, then the deleted uncertainties need not be considered probabilistically in further studies. Efforts to develop improved estimates of model input uncertainties can then be focused on the key uncertainties remaining after the screening study.

Uncertainties in the combustor process area result in the greatest variance in the net plant efficiency, leading to results very similar to those obtained when all areas of uncertainty are considered. Uncertainty in net plant efficiency is also influenced by the CerHx process area uncertainties. The HRSG uncertainties lead to only a small range of uncertainty in plant efficiency, although they do tend to shift the central tendency of the results toward slightly higher values. Because of the simplified manner in which NO_x emissions are represented in the current model, the environmental parameters do not effect plant efficiency. The results of a regression analysis confirmed that the combustor and CerHx process areas contribute most to the variance in plant efficiency. Uncertainties in combustor heat loss, CerHx heat loss, carbon conversion, and CerHx air leakage are the primary contributors to uncertainty in net plant thermal efficiency.

Uncertainties which were found to be statistically insignificant in the regression analysis were removed from the probabilistic model. The uncertain parameters which were removed from the screening case study were assigned their respective deterministic "best guess" values. The model was then run only with the significant uncertainties and the results compared to simulation results where all uncertainties were considered. Probabilistic simulations were performed with the four and seven most significant input parameter uncertainties included in the probabilistic model. The results of these analyses are shown graphically in Figure 6 for net plant efficiency. The probability distributions based upon 7 and 35 uncertain inputs are almost indistinguishable. The results for the case where only the four most significant uncertainties were considered deviated from the base case more significantly. The shift in the probability distributions of the output variables for the case when only the four most significant uncertain variables are considered is due to skewed distributions of three uncertain parameters which are left out from the simulation, i.e., uncertainties in flue gas pressure drop across the CerHx, heat loss from the superheater, and heat loss from the evaporator.

Probabilistic Design Analysis. Alternate EFCC design cases were analyzed probabilistically to study the effect of uncertainty in input parameters on process performance and to compare the results to the base case EFCC design. One of these included evaluation of the effect of steam injection on plant performance. The same input assumptions were used as for the base case probabilistic analysis, with the exception that a

steam injection rate of 400,000 lb/hr was assumed. Steam injection from the steam cycle into the gas turbine can be employed to obtain a higher net plant power output, but at the cost of penalizing the overall net plant efficiency. Figure 7 shows the uncertainty in the change in net plant power output for steam injection due to uncertainty in input performance parameters. Also shown is the deterministic value of the change in plant output. The results show that steam injection at the specified rate will increase plant output by approximately 1.3 to 2.3 MW. Based on deterministic analyses, one would estimate that the increase in power output would be 2.2 MW. The deterministic estimate in this case is at the high end of the distribution. There is over a 95 percent probability that the increase in power output would be less than the deterministic estimate, based upon the assumptions used here. These results indicate that failure to consider the interactions among multiple uncertainties, some of which are skewed, can lead to potentially misleading predictions of plant performance.

Stochastic Optimization

Stochastic optimization combines optimization and probabilistic analysis. As an example, we consider one case study. In this case study, the objective is to maximize the net plant output by selecting the design of the gas turbine and by specifying a steam injection rate. Rather than optimize based upon point-estimates, the objective function is based on the mean, or expected value, for plant output. The problem may be summarized as:

$$\begin{aligned} & \text{Max } E[\text{MW}_{\text{net}}] \\ & \text{s.t.} \\ & 13.5 \leq P_r \leq 15.0 \\ & 0 \leq m_{\text{steam}} \leq 600,000 \end{aligned}$$

where $E[\text{MW}_{\text{net}}]$ is the expected value (mean) of the net plant power output, P_r is the gas turbine pressure ratio, and m_{steam} is the gas turbine steam injection rate in lb/hr. The ASPEN simulation model for the EFCC represents the constraints for the joint values of the decision variables and the average net plant thermal input. The simulation of uncertainties in this optimization case study is based upon the seven most important uncertain variables, as identified by probabilistic sensitivity analysis. A sample size of 25 was used. The optimization requires that the uncertainty analysis be performed for alternative values of the decision variables until there is convergence on the optimal solution.

The optimal solution was found to be for a pressure ratio of 15 and a steam injection rate of 480,000 lb/hr, which yields an average net plant output of 301 MW. The uncertainty in the net plant output for the selected values of the decision variables ranges from 295 to 305 MW. These values are considerably higher than the net plant output of the base case, which has an average of 264 MW. Thus, optimization of the plant offers the potential for substantial improvements in performance. The explicit consideration of uncertainties in this case study provides confidence in the robustness of the model results to uncertainty and risk.

CONCLUSIONS

A new performance and cost model for the EFCC has been developed. This model has been applied in a series of case studies to illustrate a variety of methods for technology assessment. The model applications also provide insight into the risks and potential pay-offs of the EFCC.

Deterministic analysis provides point-estimates for key measures of plant performance. However, the degree of confidence that should be placed in such values is typically unreported and unknown. Deterministic sensitivity analysis was employed to demonstrate how the new simulation model of the EFCC responds to changes in key inputs. Such an analysis can only provide an insight into the system behavior with respect to variation in one input parameter at a time, and cannot take into account the skewness in input parameter uncertainties, the effect of simultaneous variation in multiple inputs, or the range and likelihood of results due to uncertainties in model inputs. The skewness of uncertainties that may exist in key performance parameters can be taken into account by probabilistic modeling. The effect

of simultaneous variation in several input parameters on system performance can also be readily evaluated using a probabilistic modeling approach.

Comparisons of probabilistic results to deterministic estimates indicate that the deterministic estimates are biased toward optimistic outcomes. Because probabilistic analysis enables consideration of the simultaneous effect of multiple uncertainties, it provides more realistic estimates of technology performance than does deterministic analysis. Furthermore, probabilistic analysis enables identification of the input uncertainties which significantly affect output parameters. The case study here demonstrated that of 35 uncertainties, only a handful significantly affect uncertainty in plant efficiency. These key uncertainties are in the slagging combustor and CerHx process areas. Thus, efforts to reduce the technological risk of the EFCC should be focused on these process areas.

The performance of alternate EFCC designs was evaluated probabilistically in comparison with the base case EFCC design. These comparisons enabled an insight into the risks and payoffs involved with possible alternate system designs. Results of the probabilistic simulation of an EFCC design with steam injection indicated that modest increase in plant output would be obtained at the cost of a slight efficiency penalty. Such a design would be useful for generating addition power without making any changes to the base case system design.

Stochastic optimization combines features of both sensitivity and uncertainty analysis to the systematic search for the best plant design. Optimization involves searching a decision space for a combination of decision variable values that optimize an objective function. Stochastic optimization accounts for the effect of uncertainties in model inputs on the value of the objective function. In the example case study here, the expected value of plant output was optimized in the face of uncertainties in factors affecting plant performance.

The analysis and evaluation methods demonstrated here represent improved approaches for technology assessment. Future work will involve the refinement of the methods used here and their application to further case studies.

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Table 1. Typical Stream Process Conditions for an EFCC System.^{a,6}

Stream #	1	2	3	4	5	6	7
Stream Description	Inlet Air to Compressor	Compressed Air	Turbine Inlet Air	Turbine Exhaust	Combustor Exhaust	CerHx Exhaust	HRSG Exhaust
Flow Rate (lb/sec)	918	918	872	872	1,066	1,074	1,089
Temperature (°F)	59	685	2,183	1,087	2,701	1,564	122
Pressure (psia)	14.7	197	193	15.1	14.9	13.9	13.6

^aSteam Cycle: 2600 psia/1050 °F/1050 °F reheat. CerHX = Ceramic Heat Exchanger; HRSG = Heat Recovery Steam Generator

Table 2. Selected Model Input Assumptions for Base Case and Sensitivity Analyses of the EFCC

Description of Sensitive Parameter	Units	Base Case Assumption	Sensitivity Range	
			Low	High
Combustor Radiative Heat Loss	% of heat released	0.5	0.0	5.0
Combustor Carbon Conversion	% of inlet carbon	99.0	99.0	100.0
Air Leakage in CerHx	% of mass flow	0.5	0.0	3.0
CerHx Radiative Heat Loss	% of heat duty	1.0	0.0	5.0
Turbine Inlet Temperature	°F	2,300	2,300	2,400
Gas Turbine Pressure Ratio ^a	Ratio	13.5	13.5	17
Steam Injection	lb/hr	0	0	500,000
Ambient Temperature	°F	59	20	95
Stack Gas Temperature	°F	181	150	200

^a The sensitivity analysis for pressure ratio is related to the sensitivity analysis for gas turbine inlet temperature. For a 2,300 °F turbine inlet temperature, a pressure ratio of 13.5 was used. For a 2,350 °F turbine inlet temperature, a pressure ratio of 15 was used. For a turbine inlet temperature of 2,400 °F, the pressure ratio was varied from 15 to 17.

Table 3. Selected Simulation Results for Deterministic Analysis of the EFCC

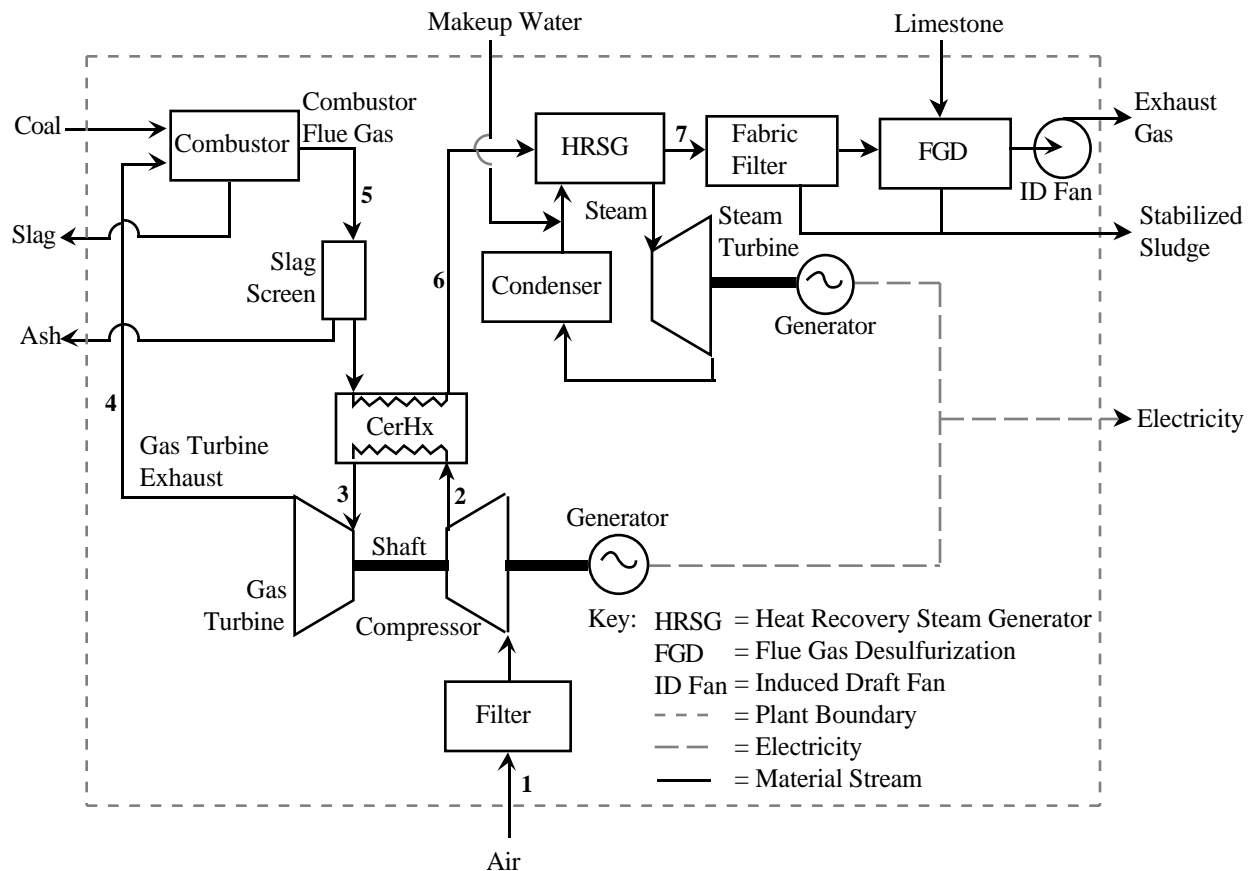
Parameter	Unit	Model Result
Performance		
Coal Consumption	lb/hr	189,500
Gas Turbine Output	MW	138.2
Steam Turbine Output	MW	142.6
Total Auxiliaries	MW	16.1
Net Plant Output	MW	264.7
Thermal Efficiency	(%, HHV basis)	42.4
Environmental		
Flyash	lb/10 ⁶ BTU	0.008
SO ₂ Emissions	lb/10 ⁶ BTU	0.60
NO _x Emissions	lb/10 ⁶ BTU	0.5
CO ₂ Emissions	lb/kWh	1.63
Stack Gas Temperature	°F	181.0
Slag	lb/hr	11,960

Table 4. Selected (4 of 35) Input Assumptions for Probabilistic Analysis

Variable	Unit	Deterministic Value	Distribution ^a	Range ^b
Carbon conversion	%	99.0	T	99.0-100.0 (99.0)
Combustor heat loss	%	0.5	T	0.25-5.0 (0.5)
CerHx air leakage	%	0.5	T	0.25-3.0 (0.5)
CerHx heat loss	%	1.0	T	0.25-4.0 (1.0)

^a T = triangular distribution.

^b For triangular distribution, the lower and upper bounds are given, and the mode is given in parentheses.

**Figure 1. Process Flow Diagram of an EFCC Conceptual Model**

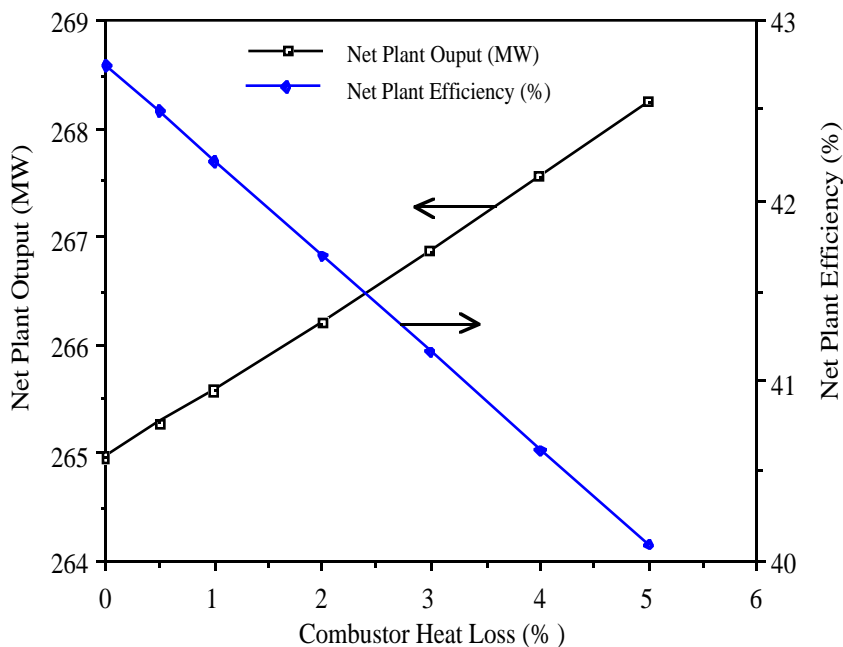


Figure 2. Net Plant Power Output and Net Plant Efficiency versus Combustor Heat Loss.

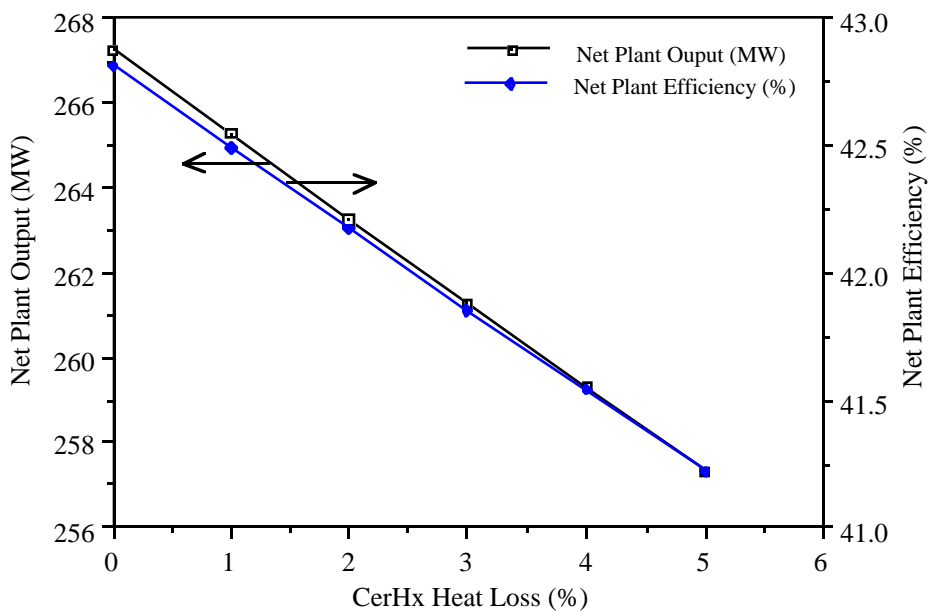


Figure 3. Net Plant Power Output and Net Plant Efficiency versus Ceramic Heat Exchanger Heat Loss.

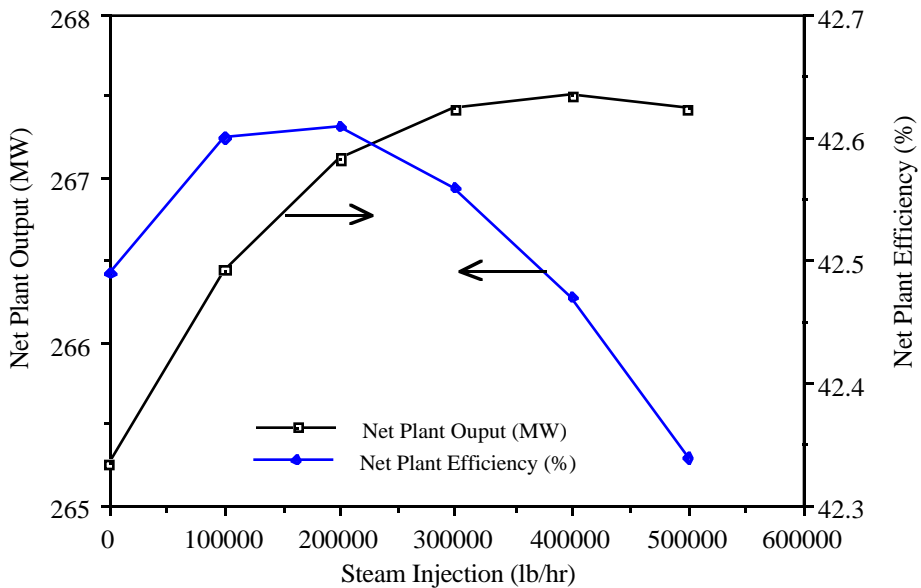


Figure 4. Net Plant Power Output and Net Plant Efficiency versus Steam Injection Rate.

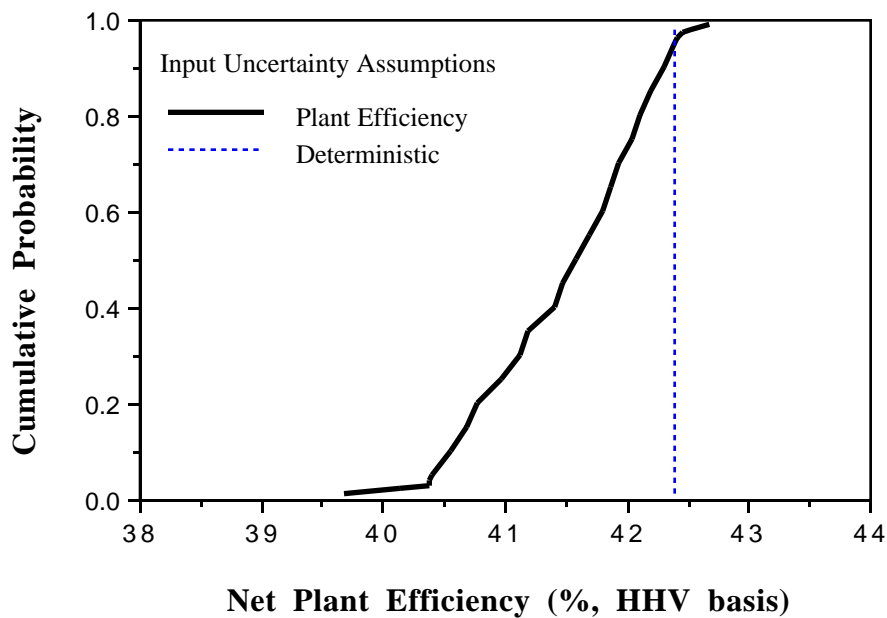


Figure 5. Comparison of Deterministic and Probabilistic Results for the Net Plant Efficiency

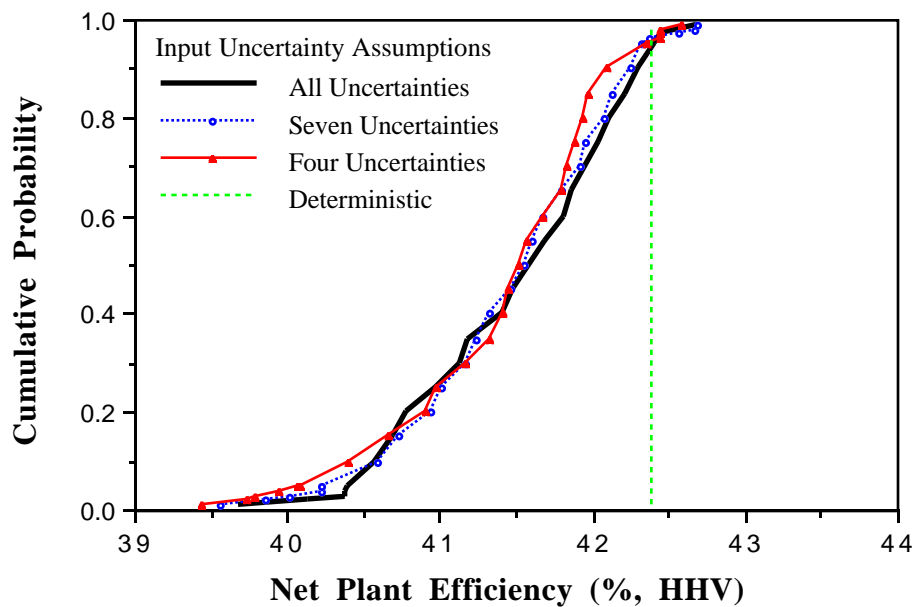


Figure 6. Comparison of Uncertainty in Plant Efficiency for Original and Screened Sets of Uncertainties

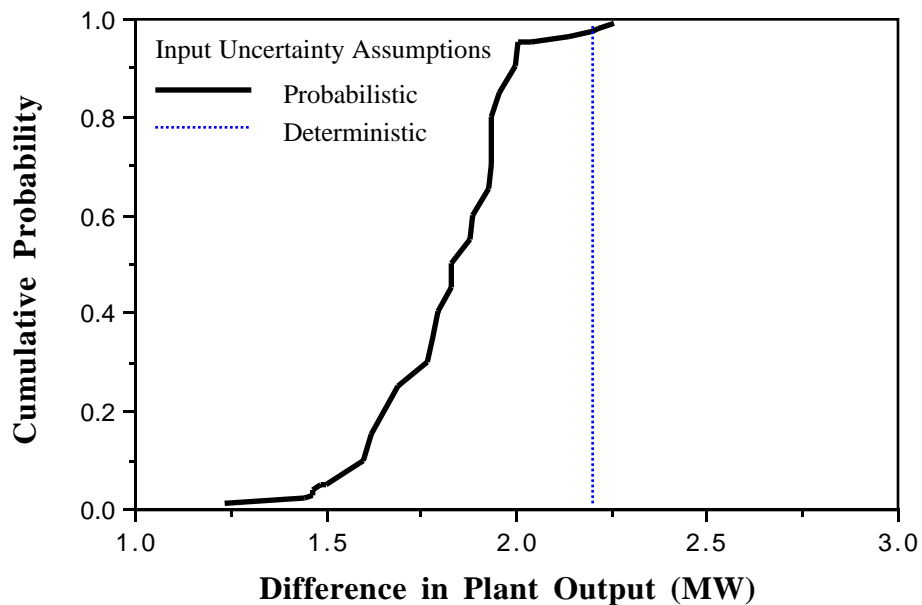


Figure 7. Difference in Probabilistic Results for the Net Plant Output for Steam Injection Case Versus Base Case