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PROBABILISTIC ANALYSIS AND OPTIMIZATION OF NEW POWER GENERATION TECHNOLOGIES: A CASE STUDY FOR THE EXTERNALLY-FIRED COMBINED CYCLE

H. CHRISTOPHER FREY, PH.D.
Assistant Professor
PANKAJ AGARWAL
Research Assistant
Department of Civil Engineering
North Carolina State University
Raleigh, NC 27695-7908

INTRODUCTION

Decisions regarding research, development, and demonstration (RD&D) of new power generation technologies are made based upon projections of the commercial scale performance, emissions, and cost of technology alternatives. However, the uncertainties inherent in these decisions often are not properly characterized. Because of the lead times and cost associated with research on new technologies, it is often necessary to make substantial commitments of resources for technology RD&D before complete information is available. Thus, uncertainties in both data and models may be significant. Often, data are scarce and models used for decision making cannot be fully validated. As a result, misleading estimates of performance and cost may be used to justify research on new technologies that might not otherwise have been pursued, or to focus research on the wrong areas of potentially promising technology. Decisions should be based upon the best use of all available technical information. Yet, current techniques for technology assessment fail to address this need. Indeed, historical studies by Rand have shown that the performance of new technologies tends to be over-estimated, while cost is often under-estimated,[1] leading to potential misallocation of scarce resources.

The National Research Council, in a 1995 report, emphasizes the importance of and need for systems analysis in energy and environmental research planning, with specific reference to coal utilization. The NRC report states that:

> *New methods to address technical and economic uncertainties are especially critical to characterize advanced processes and designs properly at early stages of development. Characterization and analysis of uncertainties are also critical to identifying robust system designs, risks, potential markets, and key problem areas that should be targeted for research to reduce technological risks* (p. 204).[2]

To address the need for integrated models of advanced power generation systems and for improved analysis techniques, the U.S. Department of Energy (DOE), through the Morgantown Energy Technology Center (METC), has supported the development of performance, emissions, and cost models of several advanced power generation systems, including integrated gasification combined cycle (IGCC), externally-fired combined cycle (EFCC), and pressurized fluidized bed combustion (PFBC) concepts.[3-5] Simultaneously, numerical methods for simulation of uncertainties and optimization of process flowsheets have been implemented in the DOE's public version of ASPEN.[3] The new process models and computational capabilities have been applied to demonstrate the benefits of quantitative approaches to dealing with uncertainty and for optimizing technologies in the face of uncertainty.

The methods demonstrated here also have applications to strategic planning, capital budgeting, and evaluation of vendor guarantees. For example, even for many commercially available technologies, such as low NO_x burners for conventional coal-fired power plants, there are significant uncertainties. The predicted environmental performance of a particular low NO_x burner installation is often uncertain due to variability in the design of boilers and burners, and in the fuels used at various power plants. There are also uncertainties in predicting unburned carbon levels and other system impacts. Thus, it may be difficult for a utility to predict what the NO_x control effectiveness and real costs will be. These difficulties are also faced by vendors, who must make guarantees that are competitive and yet balance the risks of poor performance with the costs of remediating problems.

This paper focuses on modeling and assessment of the EFCC system concept. The purpose of the paper is to demonstrate new methods for technology assessment and to provide technology-specific insights regarding the risks and potential pay-offs of the EFCC.

EXTERNALLY-FIRED COMBINED CYCLE

The EFCC is an advanced coal-fired power generation concept with a potential for higher thermal efficiency and lower cost than conventional coal-based generating systems.[6] 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.

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.[7] 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 exchange (CerHx). 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 slightly above atmospheric pressure and enters the coal combustor. Flue gas exiting the ceramic heat exchanger enters a Heat Recovery Steam Generator (HRSG), where thermal energy is transfered to a bottoming steam cycle.

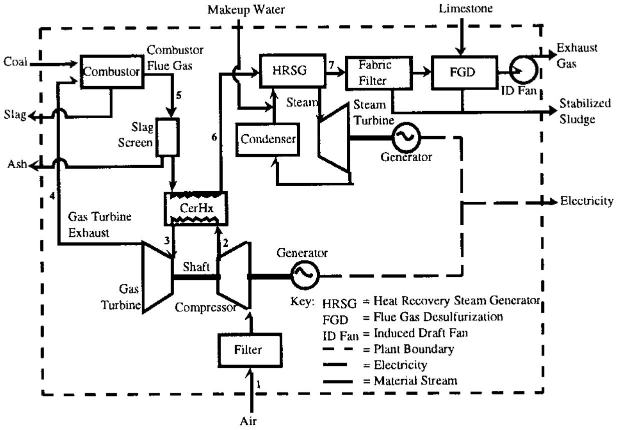

Figure 1. Conceptual Design for the EFCC.

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. 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 R&D 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. 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 10^6 Btu/hr) combustion system. Phase III will involve work on a demonstration project, and Phase IV will involve a commercial EFCC system.[6] 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. However, at this time the status of the project is uncertain.

UNCERTAINTY IN THE EFCC

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 and gas turbine modifications. The uncertainties have implications for both performance and cost of the EFCC.

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. Several modifications, such as high temperature piping to the CerHx, have to be made to a commercially available gas turbine. Such modifications have not been commercially demonstrated. Since the CerHx, slagging combustor, slag screen, and gas turbine modifications have not been commercially demonstrated, the process performance and cost parameters related to these are expected to be the most uncertain of all of the process areas.

MODELING THE EFCC USING ASPEN

DOE/METC has developed a performance model for a 264 MW$_{\mathrm{net}}$ EFCC system based on a Hague International (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.[8] 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). A process plant is represented by specifying configurations of unit operations and the flow of material, heat, and work streams. 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. 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 1,785 psia, 1,050°F superheater, and 1,050°F reheater steam cycle; and (e) 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.

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 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). Examples of specific modifications include: (a) accounting for the air leakage in the CerHx; (b) more detailed specification of gas turbine compressor and expander outlet pressures and efficiencies; (c) more detailed gas turbine cooling air flow circuitry; (d) addition of steam or water injection to the gas turbine; (e) estimation of NO_x, SO_2, and particulate matter emissions; (f) estimation of auxiliary power consumption based on performance parameters; and (g) accounting for the efficiency penalty associated with the reheat of flue gas from the FGD unit.

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.[5,9]

MODEL APPLICATIONS

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 point estimate is often 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.

One common method for gaining insight into the risks of a new technology is to expand upon 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. When there are many uncertain input variables, 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 investigation.

Technology designs may be evaluated under uncertainty using various techniques. One technique is stochastic optimization.[3] 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.[9]

Deterministic Analysis

The new performance model of the EFCC was applied 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. Illinois No. 6 coal was assumed. The model was run on a VAXStation 3200 using the DOE version of ASPEN. The run time for a single simulation is 70 seconds.

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. The model is sensitive to changes in input assumptions. For example, an EFCC system with a wet stack (no FGD reheat) would have a net plant efficiency of 44.6 percent.

The new model includes environmental aspects of the technology. Emission rates of acid rain precursors, carbon dioxide, particulate matter, and slag from the combustor are calculated. The base case design is intended to comply with current New Source Performance Standards for coal-fired power plants. Additional SO_2 control may be achieved with high efficiency (>95%) FGD, while NO_x emissions may be reduced through the use of staged combustion. However, the slagging combustor design for the EFCC has not been demonstrated at full scale.

Sensitivity Analysis

Thirteen performance and design parameters were varied in a series of 55 sensitivity analysis runs.[9] These analyses focused on four major process areas: (1) combustor; (2) CerHx; (3) gas turbine; and (4) environmental control. Selected results are described here. These include sensitivity analysis of a performance input, CerHx heat loss, and a design variable, steam injection rate.

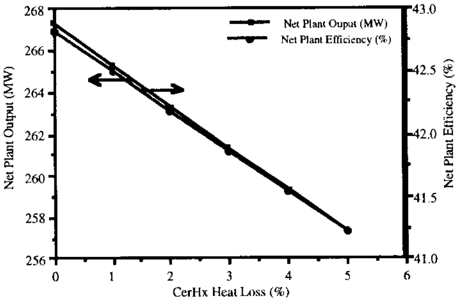

Figure 2. Net Plant Output and Efficiency Versus Ceramic Heat Exchanger Heat Losses.

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 2. 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 decreases by 1.6 percentage points from the lower to the upper limit of the CerHx heat loss.

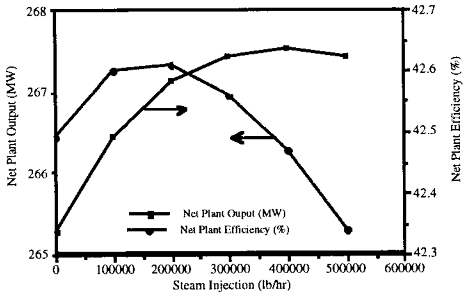

Figure 3. Net Plant Output and Efficiency Versus Steam Injection Mass Flow Rate.

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, with a simultaneous reduction in steam cycle output. The change in the net plant power output and efficiency with steam injection rates is shown in Figure 3. The net plant output increases by 2.25 MW for an injection rate of 400,000 lb/hr. 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. 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 costs. By offsetting increased gas turbine output with reductions in steam turbine output, it would be possible to reduce the size and, hence, 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 the DOE version of ASPEN is available for evaluating process technologies in the face of uncertainty.[3] This capability is utilized here for the evaluation of uncertainties in the EFCC system.

Uncertainty Assumptions. The development of ranges and probability distributions for 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 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 data and expert judgments.

Table 1. 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 parantheses.

Table 1 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, but an expert suggested that the carbon conversion could be close to 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 result for plant thermal efficiency is graphed as a cumulative distribution function in Figure 4. The mean value of plant efficiency is 41.5 and the median is 41.6, both of which are significantly lower than the deterministic value of 42.4. 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.[9] An increase in the heat losses leads to a decrease in the plant efficiency. The heat losses were assigned positively skewed triangular distributions. This leads to a negatively skewed distribution for plant efficiency. Based on these input assumptions, 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.

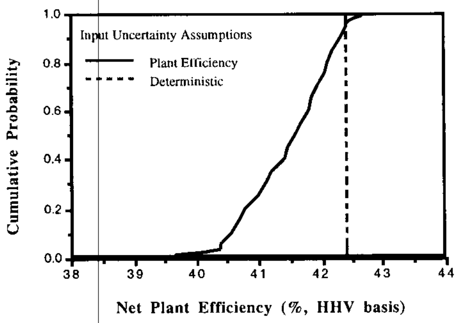

Figure 4. Comparison of Deterministic and Probabilistic Results for Net Plant Thermal Efficiency

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 identify input variables which are most highly correlated with output variables. The interaction between different subsets of uncertain input variables, as they affect uncertainty in output variables, was studied by isolating the uncertainties in different process sections. Probabilistic simulations were then performed using only the uncertainties in those process areas. The third approach, uncertainty screening, can be used to confirm the results of a regression or probabilistic sensitivity analysis by deleting uncertainties from the model which are believed to be unimportant. If the results with and without suspected unimportant uncertainties are similar, then the deleted uncertainties need not be considered probabilistically in further studies

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. 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 and were assigned their respective deterministic "best guess" values. When only the seven most significant input uncertainties were treated probabilistically, the probabilistic model results for plant efficiency and output were almost indistinguishable from the base case analysis of 35 input uncertainties. Thus, it is possible to substantially narrow the focus of further research and design activities to a handful of key performance parameters.

Stochastic Optimization

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:

$$\text{Max } E[MW_{net}]$$

s.t.

$$13.5 \le P_r \le 15.0$$

$$0 \le m_{steam} \le 600{,}000$$

where $E[MW_{net}]$ 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, or the range and likelihood of results due to uncertainties in model inputs..

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.

Stochastic optimization combines features of both sensitivity and uncertainty analysis to the systematic search for the best plant design. 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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