Developing and Verifying a Hydroplant Performance Calculator

by

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Abstract

The U. S. Department of Energy's (DOE's) Water Power Program is investing in a portfolio of analysis projects and R&D projects to evaluate and develop technologies with significant impacts on plant performance, including the improvement of flow measurement technologies and the development of modeling tools that can evaluate the lifecycle costs and benefits of technology advancement. Accurately characterizing, simulating, and communicating the performance of hydropower plants is essential to the success of both efforts. The development of a central tool ensures that all performance estimates and visualizations are consistent and comparable across the program.

A Hydroplant Performance Calculator (HPC) was developed and implemented as this central tool to calculate standardized metrics for hydroplant performance in the context of maximum value modeling. The Hydroplant Performance Calculator includes (1) a setup module for developing unit and plant performance characteristics and (2) a multi-unit optimization and analysis module for calculating operation efficiency analyses, generation scheduling analyses, and flow analyses as the performance metrics. This paper provides an overview of the Hydroplant Performance Calculator and discusses its verification through comparison with previous performance assessments.

1. Introduction

Under previous DOE/EPRI and DOE/ORNL projects, detailed plant performance analyses have been conducted using unit and plant performance characteristics and plant operational data for five pumped storage plants and eleven conventional hydroplants. These sixteen case studies encompass three well-established markets (MISO, NYISO, and PJM) and two non-market regions (Northwest area, Southeast area). The diverse owners for the sixteen plants include four investor-owned utilities (eight plants), two state power authorities (two plants), an industrial utility (two plants), and the three main federal hydropower producers (four plants). These previous studies provide (1) multi-year generating data under various market and non-market conditions; (2) unit performance characteristics for a range of original and upgraded units; and (3) a welldocumented methodology for analyzing optimized and suboptimized plant performance [March and Wolff, 2004; March, 2012; March et al., 2012; March et al., 2013].

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A Hydroplant Performance Calculator (HPC) was developed and implemented as this central tool to build upon previous experience and calculate standardized metrics for hydroplant performance in the context of maximum value modeling. The Hydroplant Performance Calculator includes (1) a module, HPC PlantBuilder, for developing unit and plant performance characteristics and (2) a multi-unit optimization and analysis module, HPC Analyzer, for calculating operation efficiency analyses and generation scheduling analyses as performance metrics and for computing flows from power and head values. This paper describes the performance analysis methodology, provides an overview of the Hydroplant Performance Calculator, and discusses the HPC's verification through comparison with previous performance assessments.

2. Overview of Performance Analyses

The performance assessments computed previously, and those computed by the HPC, are based on a set of analyses to quantify unit and plant performance and to enable the investigation of potential opportunities for operations-based and equipment-based performance improvements, leading to additional generation. This section briefly addresses the processes and methodologies used for the quantitative performance analyses, and additional details are available elsewhere [DOE, 2011; March, 2012; March et al., 2012; March et al., 2013].

An overview of optimization-based performance analyses is shown in Figure 2-1.

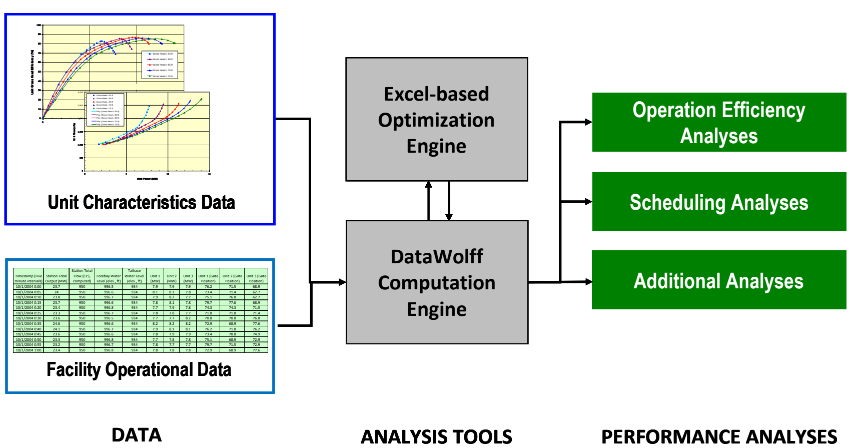

Figure 2-1: Overview of Performance Analyses

The primary data needs for performance analyses include unit characteristics data, facility operational data, and facility hydrological data. These data types are discussed in the following subsections.

Unit Characteristics Data – Hydroelectric generating facilities convert the potential energy of stored water and the kinetic energy of flowing water into a useful form, electricity. This fundamental process for a hydroelectric generating unit is described by the generating efficiency equation, defined as the ratio of the power delivered by the unit to the power of the water passing through the unit. The general expression for this efficiency (η) is

$$\eta = \frac{P}{\rho g Q H}$$

where P is the output power, ρ is the density of water, g is the acceleration of gravity, Q is the water flow rate through the turbine, and H is the head across the unit.

Efficiency curves provide guidance for the effective use of a hydropower unit or facility. The points of most efficient operation can be identified, and the efficiency penalty for operating away from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at another power level.

Facility Operational Data – Typically, facility operational data is obtained from multiple sources, including plant personnel, central engineering staff, and load control personnel. Essential operational data for operation efficiency analyses, generation scheduling analyses, flow analyses, and correlation analyses include:

- Timestamp;
- Unit Power;
- Unit Flow;
- Headwater Level;
- Tailwater Level;
- Unit Status (e.g., available, unavailable, condensing).

Optimization Engine – The optimization engine for the optimization-based performance analyses is implemented using the Solver tool in Microsoft Excel. A brief summary of the implementation is included below, and a detailed explanation is provided elsewhere [DOE, 2011; March, 2012; March et al., 2012].

The optimization engine is used to determine how a given plant power level is allocated among the units to provide the highest possible plant efficiency. The information required includes the plant power, headwater, tailwater, and the unit characteristics. The optimization engine can also incorporate constraints, such as a preferred unit dispatch order. Given this information, the optimization engine computes the unit power allocation that meets the given plant power with the lowest possible water usage, providing the highest possible plant efficiency.

Computation Engine – The primary computation engine is DataWolff, a proprietary Excel-based program that enables the automating of multiple data analyses by using analysis scripts. Additional configuration of the computation engine with specific analysis scripts and calculation libraries is required for each particular type of analysis. The optimization-based performance analyses use procedures provided in detail elsewhere [DOE, 2011; March, 2012; March et al., 2012].

Operation Efficiency Analyses – Operation efficiency analyses use the unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch while meeting the actual power versus time. Computational steps for determining the operation efficiency are shown in Figure 2-2 and are discussed in detail elsewhere [DOE, 2011].

- Operation Efficiency determines how closely the actual dispatch matches the optimized dispatch
- Computational Steps:
  - Inputs are head, power, unit performance curves
  - Compares actual dispatch to optimal plant dispatch while meeting the actual load
  - Optimized dispatch requires less water
  - Water saved is converted into power at same head in the time step during which it occurs
  - Operation efficiency = 100 * (Actual Energy) / (Optimized Energy)

Figure 2-2: Operation Efficiency Analyses

At each time step of the archival data, the optimized plant efficiency is computed, apportioning the total plant load among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the actual plant load, matching the head, and operating each unit within minimum and maximum power limits). Energy gains due to water savings from optimized dispatch are computed by assuming that the water is converted into energy at the optimized plant efficiency and head for the time step in which the potential energy gain occurs. Operation efficiencies close to 100% are achievable with control systems capable of optimization-based AGC [Giles et al., 2003; March and Wolff, 2004].

Generation Scheduling Analyses – Generation Scheduling Analyses evaluate how closely the actual plant loads align with the overall peak efficiency curves for the entire plant. The steps for computing the generation scheduling analyses are shown in Figure 2-3 and are discussed in detail elsewhere [DOE, 2011]. Individual unit characteristics combine to create an overall plant efficiency that is the maximum plant efficiency achievable for any given load with optimized plant dispatch. By scheduling plant loads to align with peak operating efficiency regions when hydrologic conditions, power system needs, market conditions, and other restrictions permit, more efficient energy generation is achieved.

- Generation Scheduling Analyses determine how closely the plant load request matches the points of peak plant efficiency
- Computational Steps:
  - Compute the optimized plant efficiency curve for the range of heads
  - Create a scheduling table that defines the peak plant efficiencies, the peak efficiency loads, and the minimum efficiency loads as a function of head and the number of units on line
  - Using the plant load and head as inputs, interpolate to compute peak efficiencies and minimum efficiency loads for the given head
  - Compute the efficiency difference between the optimized plant efficiency for the given load and the maximum scheduling efficiency while maintaining the same number of units dispatched
  - Assume the water used for the given time-step is utilized to create energy at the maximum scheduling efficiency
  - Scheduling Efficiency = 100 * (Optimized Energy) / (Optimized Schedule Energy)

Figure 2-3: Generation Scheduling Analyses

Other Analyses – Flow analyses are used to compute flows from unit power and unit head data. When continuous measurements of relative or absolute flow rate are available for each unit of a plant, correlation analyses can be computed to compare the measured unit performance with the expected unit performance. Avoidable loss analyses can be used to determine how plant generation could be improved by reducing avoidable losses. Avoidable losses typically include excessive trash rack losses, excessive penstock losses, excessive tunnel losses, and excessive spill. The computational steps for the correlation analyses and the avoidable loss analyses are explained elsewhere [DOE, 2011].

3. Overview of the Hydroplant Performance Calculator (HPC)

The U. S. Department of Energy's (DOE's) Water Power Program is investing in a portfolio of analysis projects and R&D projects to evaluate and develop technologies with significant impacts on plant performance, (a) including the improvement of flow measurement technologies and (b) the development of modeling tools that can evaluate the lifecycle costs and benefits of technology advancement. Accurately characterizing, simulating, and communicating the performance of hydropower plants is essential to the success of both efforts. The development and implementation of a Hydroplant Performance Calculator (HPC) as this central tool enables standardized metrics for hydroplant performance in the context of maximum value modeling and ensures that all performance estimates and visualizations are consistent and comparable across the program.

The Hydroplant Performance Calculator includes (1) a setup module, HPC PlantBuilder (see Section 4), for developing unit and plant performance characteristics and (2) a multi-unit optimization and analysis module, HPC Analyzer (see Section 5), for calculating operation efficiencies and scheduling efficiencies and for computing flow analyses. The primary data needs for HPC PlantBuilder and HPC Analyzer include unit performance data and facility operational data.

4. Description of HPC PlantBuilder

Figure 4-1 provides a graphical overview of HPC PlantBuilder.

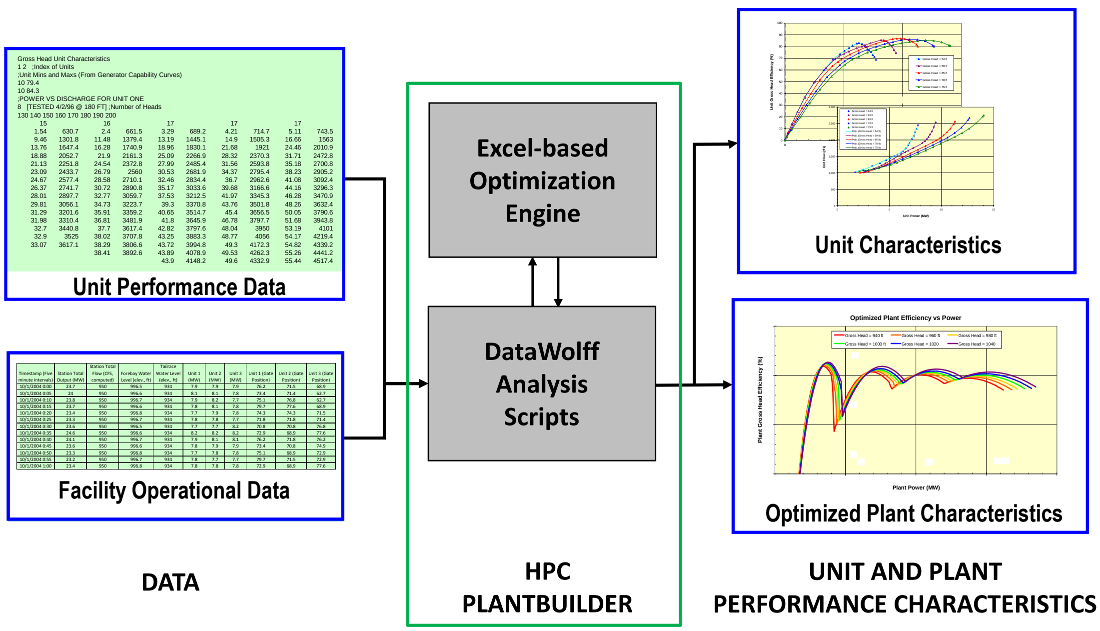

Figure 4-1: Overview of HPC PlantBuilder

Input data for the HPC PlantBuilder includes unit performance data (generator efficiency; turbine power and turbine flow versus head) and facility operational data (unit power and head versus time; unit flow versus time, if available). The input data for HPC PlantBuilder also includes plant latitude, plant elevation at the turbine centerline, and average water temperature. These values are used to compute the acceleration of gravity, g, and the water density, ρ [ASME, 2011].

Figure 4-2 shows the Excel interface for using HPC PlantBuilder.

Double Click on a cell to begin a task

Step	Description	Comments
1	***Load Plant***	Load the Plant Workbook
2	***Calculation Properties***	Enter/Review Calc Properties
3	***Plant Properties***	Enter/Review Plant Properties
4	***Unit Properties***	Enter/Review Unit Properties
5	***Configure Data Import***	Configure Data Import
6	***Import Data***	Import Data
7	***Review Unit Characteristics***	Review Unit Characteristics with Data
8	***Compute Plant Efficiency Curve***	Compute Plant Efficiency Curves
9	***View Analysis Workbooks***	Review Analysis Workbooks
10	***Exit***	Close Workbooks and Exit Excel

Figure 4-2: Excel Interface for HPC PlantBuilder

This Excel interface for HPC PlantBuilder provides an efficient, consistent, and systematic approach to creating unit and plant performance characteristics from performance data and plant operational data. The optimized plant performance characteristics are a primary input for HPC Analyzer, as discussed in Section 5.

5. Description of HPC Analyzer

Figure 5-1 provides a graphical overview of HPC Analyzer. Input data for the HPC Analyzer includes optimized plant performance data (computed by HPC PlantBuilder, as discussed in Section 4) and facility operational data (unit power and head versus time; unit flow versus time, if available).

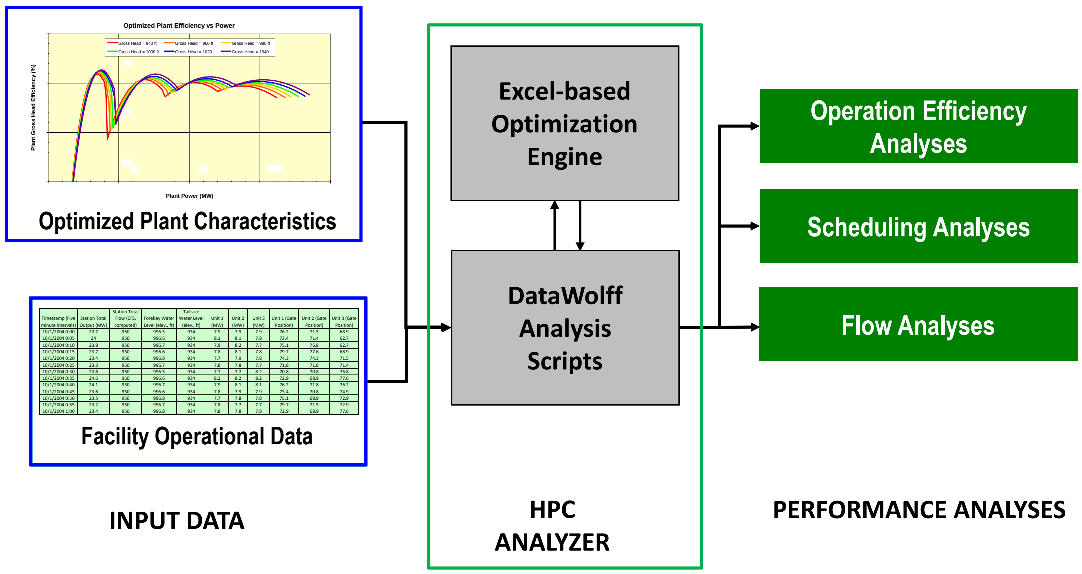

Figure 5-1: Overview of HPC Analyzer

Figure 5-2 shows the Excel interface for using HPC Analyzer. The performance assessments currently computed by HP Analyzer include operation efficiency analyses, generation scheduling analyses, and flow analyses (see Section 2).

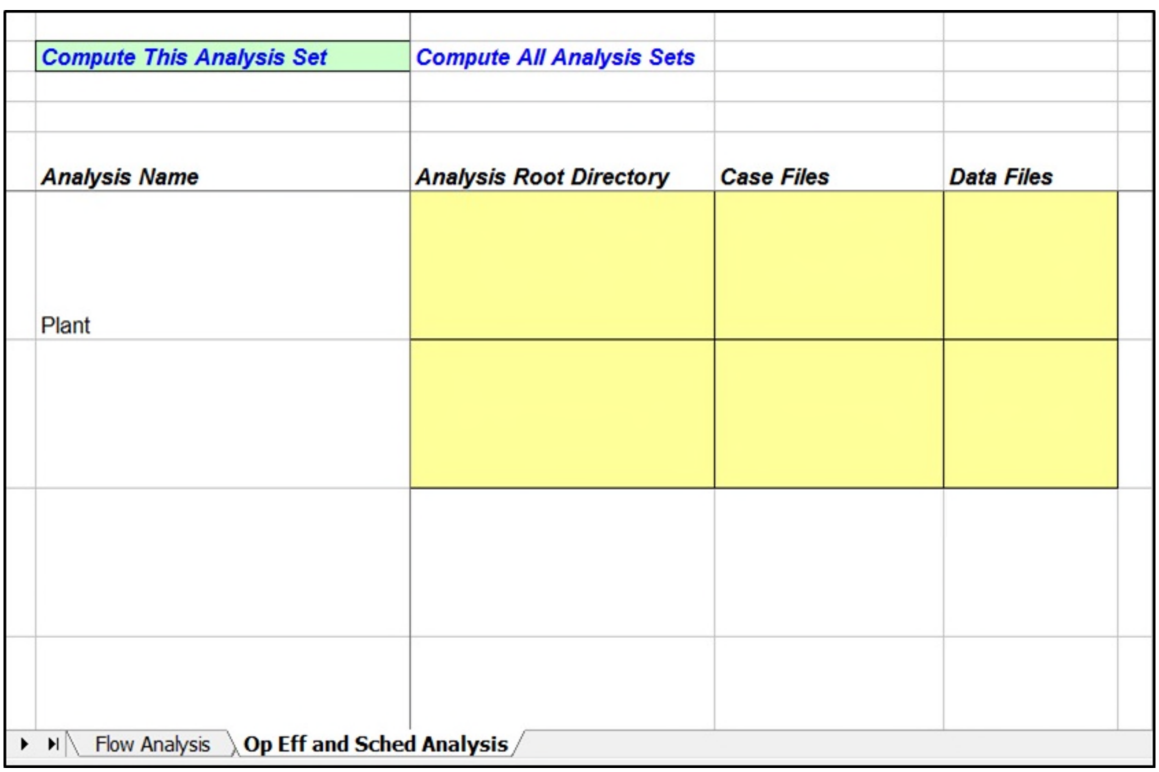

Figure 5-2: Excel Interface for HPC Analyzer

6. Verification of the Hydroplant Performance Calculator

Verification of the Hydroplant Performance Calculator was based on comparisons with previously conducted and reported performance analyses for a hydroplant with three Francis units [DOE, 2011].

Unit and Plant Performance Characteristics - Current Performance Level (CPL) unit performance curves for Unit 1 and Unit 3 were developed using the HPC PlantBuilder and 1930 turbine net head efficiency data from S. Morgan Smith Company, 1927 generator efficiency data from Westinghouse Electric & Manufacturing Company, and intake/penstock head loss information from a recent upgrade to Unit 2, with an additional assumed degradation (i.e., a net head turbine efficiency loss) of 2.5%. The CPL unit performance curves for Unit 2 were computed by the HPC PlantBuilder based on the 1927 generator curve and the net head turbine efficiency curves provided by the turbine manufacturer, American Hydro Corporation (now Weir American Hydro), at the time of the Unit 2 runner upgrade. Potential Performance Level (PPL) unit performance curves for Unit 1, Unit 2, and Unit 3 were computed by the HPC PlantBuilder based on the CPL data for the upgraded Unit 2, with an additional assumed net head turbine efficiency improvement of 1% due to improved turbine technology and a maximum assumed generator efficiency of 98% due to improved generator technology.

Based on the CPL and PPL unit performance curves, HPC PlantBuilder computed the optimized plant gross head efficiency versus power curves and the optimized plant flow versus plant power curves. Figure 6-1 presents the HPC's CPL results for optimized plant gross head efficiency versus plant power, and Figure 6-2 presents HPC's CPL results for optimized plant flow versus plant power. HPC PlantBuilder also computed CPL results for optimized unit power versus plant power, as shown in Figure 6-3. Similarly, HPC's PPL results for optimized plant gross head efficiency versus plant power, optimized plant flow versus plant power, and optimized unit power versus plant power are provided in Figure 6-4, Figure 6-5, and Figure 6-6, respectively.

The CPL and PPL unit performance curves and optimized plant performance curves developed with HPC PlantBuilder are virtually identical to the corresponding performance curves previously computed and reported [DOE, 2011].

Operation Efficiency Analyses - Operation efficiency analyses were computed with the HPC Analyzer for the verification plant using a year of operational data for 2010. Typical results from the original operation efficiency analyses [DOE, 2011] are provided in Figure 6-7. Typical results from the HPC operation efficiency analyses are provided in Figure 6-8. In these figures, the red, gold, and green lines refer to the secondary axis on the right and represent the unit power values. The red lines represent the actual Unit 1 generation, the gold lines represent the actual Unit 2 generation, and the blue lines represent the actual Unit 3 generation. The dotted red lines represent the optimized Unit 1 generation, the dotted gold lines represent the optimized Unit 2 generation, and the dotted blue lines represent the optimized Unit 3 generation. In addition, the green lines show the actual plant gross head efficiency (primary axis on the left), and the dotted green lines show the optimized plant gross head efficiency.

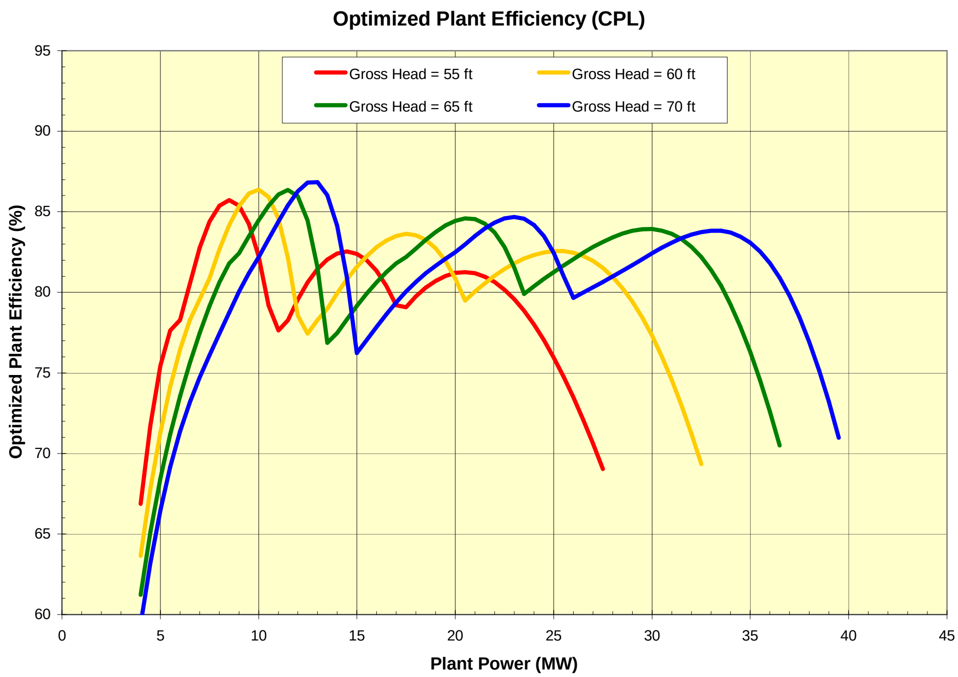

Figure 6-1: CPL Optimized Plant Efficiency versus Plant Power

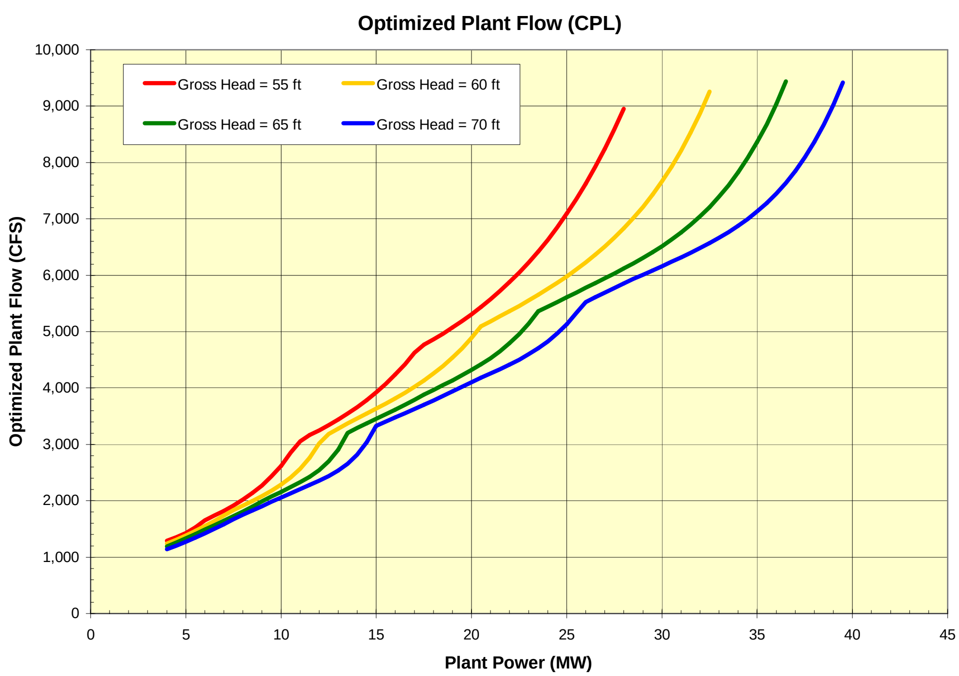

Figure 6-2: CPL Optimized Plant Flow versus Plant Power

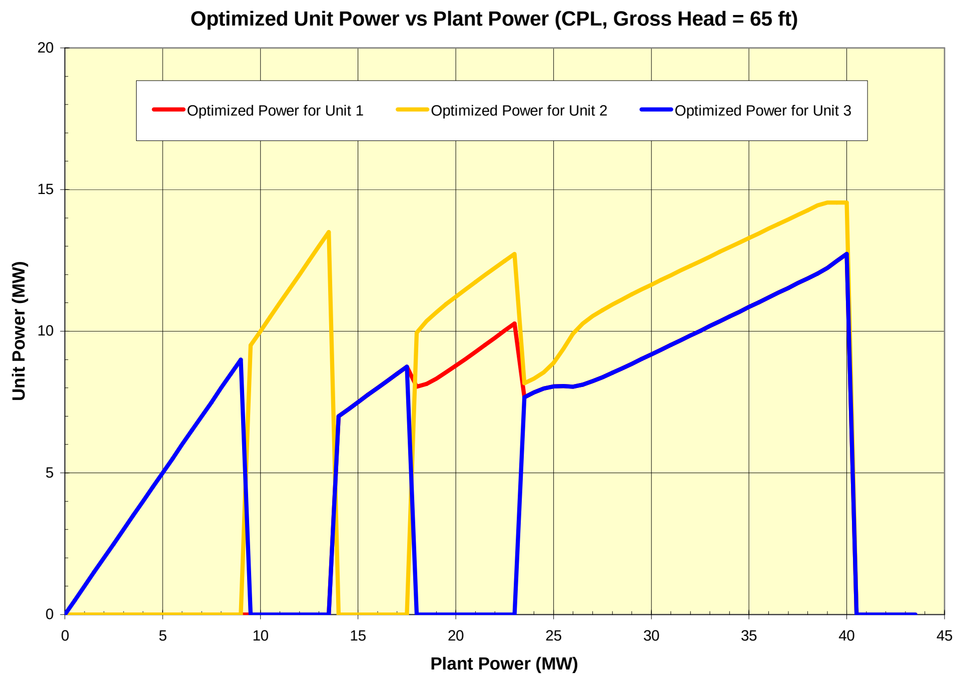

Figure 6-3: CPL Optimized Unit Power versus Plant Power

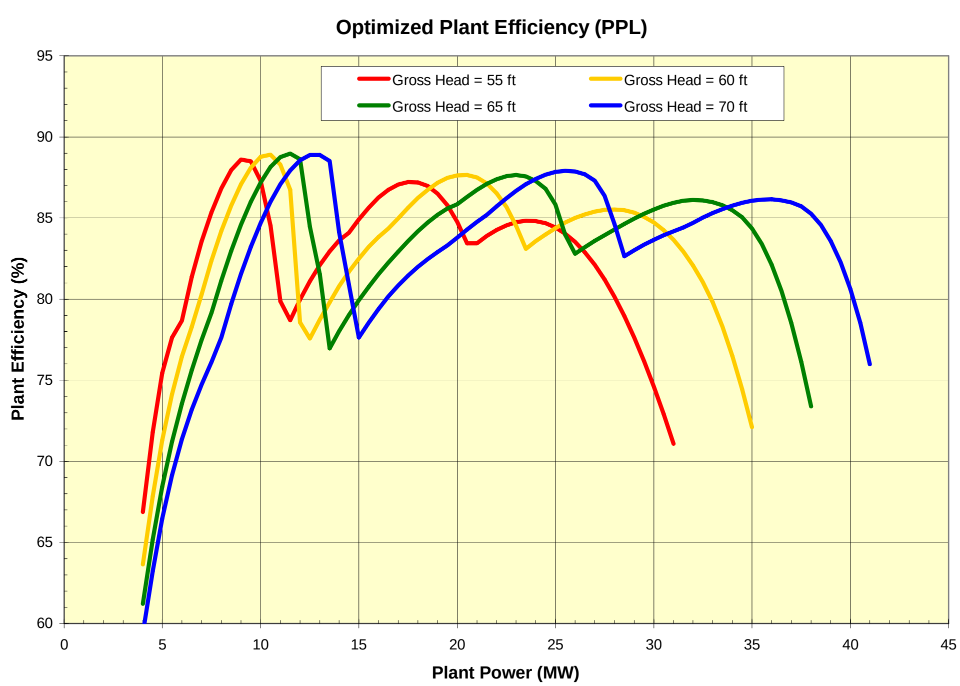

Figure 6-4: PPL Optimized Plant Efficiency versus Plant Power

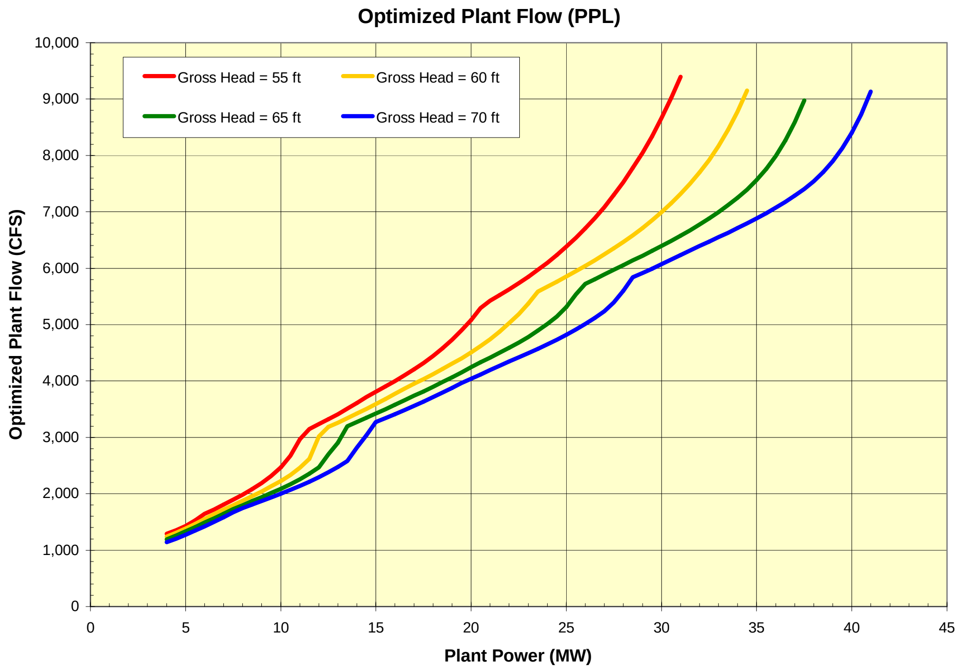

Figure 6-5: PPL Optimized Plant Flow versus Plant Power

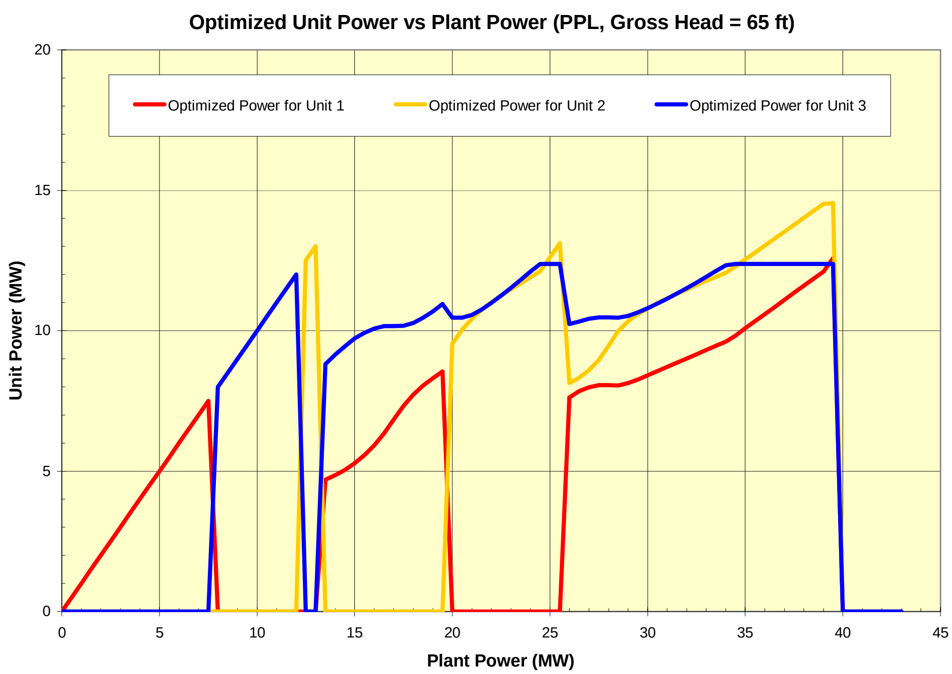

Figure 6-6: PPL Optimized Unit Power versus Plant Power

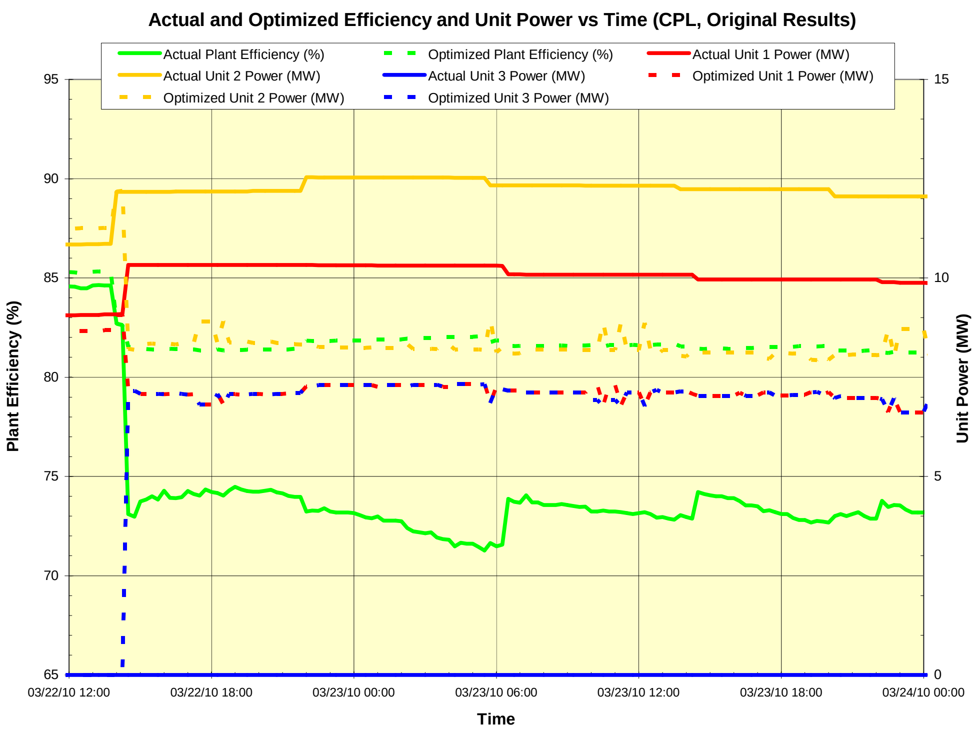

Figure 6-7: Original Operation Efficiency Results, CPL (March 23, 2010)

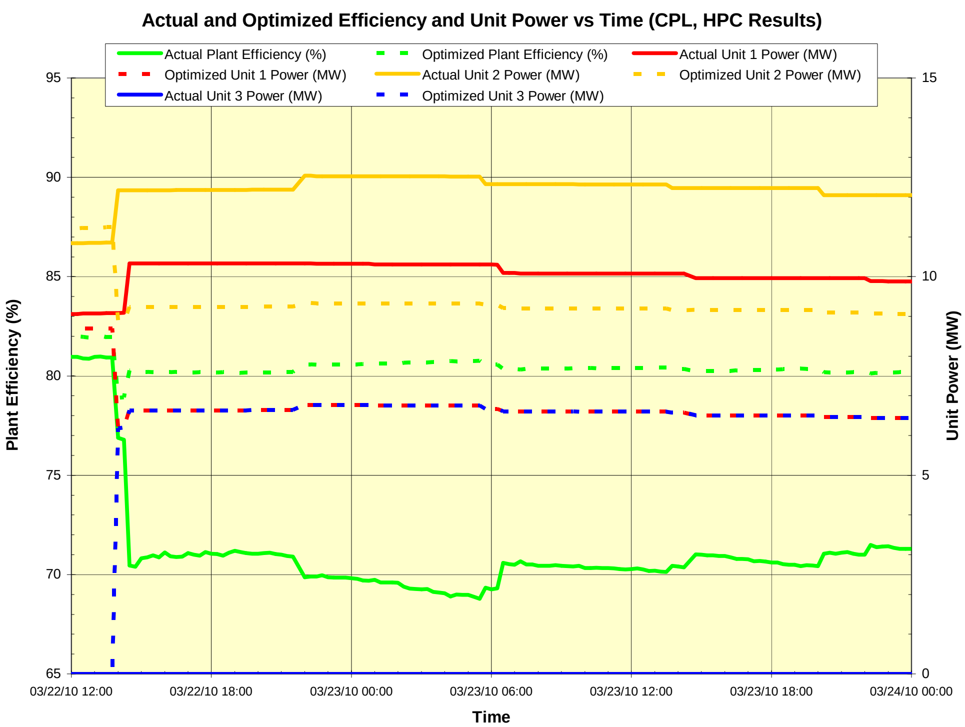

Figure 6-8: HPC Operation Efficiency Results, CPL (March 23, 2010)

The operation efficiency results developed with the HPC are comparable to the corresponding operation efficiency results previously computed and reported [DOE, 2011]. However, the Hydroplant Performance Calculator's curve-fitting and error-trapping improvements and its stability improvements to the optimization engine result in slight differences from the previously reported results (see Figures 6-7 and 6-8).

8. Summary, Conclusions, and Recommendations

This paper describes the Hydroplant Performance Calculator (HPC), which was developed and is being implemented as a central tool to calculate standardized metrics for hydroplant performance in the context of maximum value modeling. The Hydroplant Performance Calculator includes (1) a setup module, HPC PlantBuilder, for developing unit and plant performance characteristics and (2) a multi-unit optimization and analysis module, HPC Analyzer, for calculating operation efficiency analyses, generation scheduling analyses, and flow analyses as the performance metrics. This paper provides an overview of the Hydroplant Performance Calculator and discusses its verification through comparison with previous performance assessments.

Conclusions and recommendations are listed below:

1. HPC PlantBuilder streamlines the compilation of unit characteristics and operational data to ensure that the unit characteristics extend to cover the appropriate power range for each unit and head.

2. HPC PlantBuilder simplifies the calculation of optimized plant performance characteristics, providing useful operational guidance and required input to HPC Analyzer.

3. HPC Analyzer automates the analysis of large data sets, including data sets for multiple years of operation.

4. HPC Analyzer streamlines the comparison of various unit configurations. For example, the current performance level of a plant can be compared to the potential performance level with upgraded units to assess the value of upgrading units.

5. The flexible framework for HPC Analyzer can be readily adapted to incorporate additional calculations, analyses, and plots.

6. The Hydroplant Performance Calculator provides consistent, standardized hydroplant performance metrics which can help to increase generation and/or water conservation opportunities.

7. The Hydroplant Performance Calculator can be used to perform fleetwide performance analyses and to easily compare the results using pivot tables.

8. Utilization of the Hydroplant Performance Calculator for standardized USA-wide performance and flow analyses is recommended.

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