Performance Assessment Manual

Revision 1.1, 12/5/2012

Prepared by
Hydro Performance Processes, Inc.
Doylestown, PA 18901

and

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
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CONTENTS

1.0 Introduction

The Hydropower Advancement Project (HAP) was initiated by the Wind and Water Power Program within the Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) as a systematic approach to best practices implementation for improving the efficiency, capability, and water utilization of existing U.S. hydropower plants.

The HAP considers three performance levels for hydropower facilities: (1) the Installed Performance Level (IPL); (2) the Current Performance Level (CPL); and (3) the Potential Performance Level (PPL). The Installed Performance Level is that achievable by the facility under design conditions immediately after commissioning (typically, the installed name-plate capacity performance). The Current Performance Level is often lower than the IPL due to wear and tear and/or due to changes in the constraints placed on a facility that prevent it from operating as originally designed. However, the CPL can be higher than the IPL if the facility has undergone some degree of modernization or has utilized advanced maintenance practices such as cavitation welding to best-blade contours [Spicher, 2004]. The Potential Performance Level is that which could be achieved under current operating constraints through installation of best available technology and implementation of best practices for operations and maintenance.

2.0 Overview of Performance Assessments and Analyses

The Hydropower Advancement Project is designed for both condition assessment and performance assessment of existing hydropower plants. The quantitative condition assessment aims to characterize and trend the asset conditions across the U.S. existing hydro fleet for identifying and evaluating the upgrading opportunities, as previously discussed. The performance assessments aim to quantify unit and plant performance and to investigate the opportunities for operations-based, equipment-based, and maintenance-based performance improvements leading to additional generation. This document, as the Performance Assessments section of the HAP Assessment Manual, addresses the processes and methodologies used for the performance assessments and the quantitative performance analyses.

In the context of the HAP, three types of performance assessments or analyses are conducted: (1) a performance process assessment; (2) hydrology-based performance analyses; and (3) optimization-based performance analyses. An overview of the hydrology-based performance analyses and the optimization-based performance analyses is shown in Figure 1.

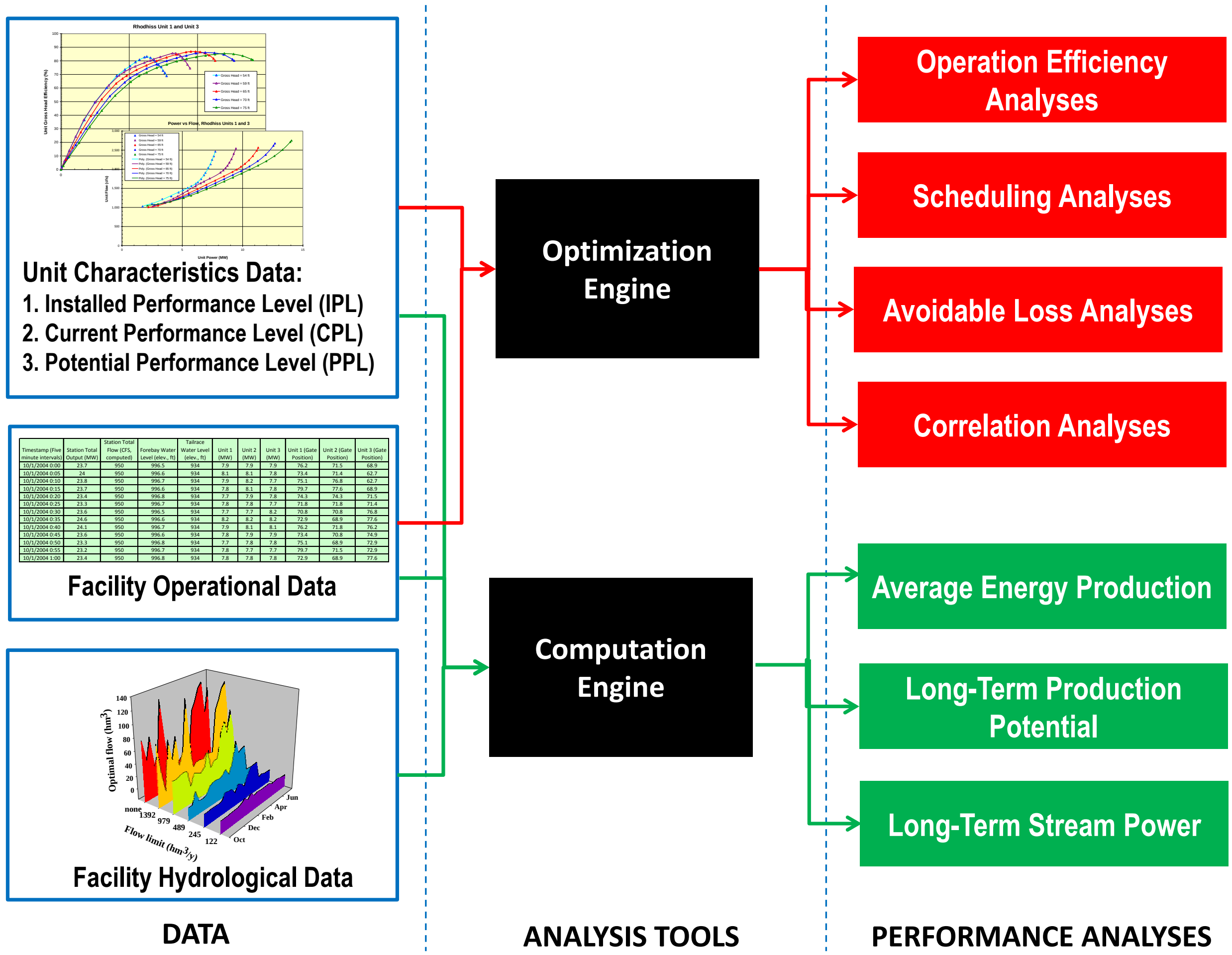

Figure 1: Overview of Performance Analyses

The performance process assessment, which is described in Appendix 2.01 and Appendix 2.02, is based on information from the condition assessment, discussed in another part of the HAP Assessment Manual. Unit characteristics, facility operational data, and facility hydrological data are discussed in Section 3, Data for Performance Analyses. Performance analysis tools are discussed in Section 4, Tools for Performance Analyses. Hydrology-based performance analyses are discussed in Section 5, and optimization-based performance analyses are discussed in Section 6.

3.0 Data for 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 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 to the turbine, and H is the head across the unit.

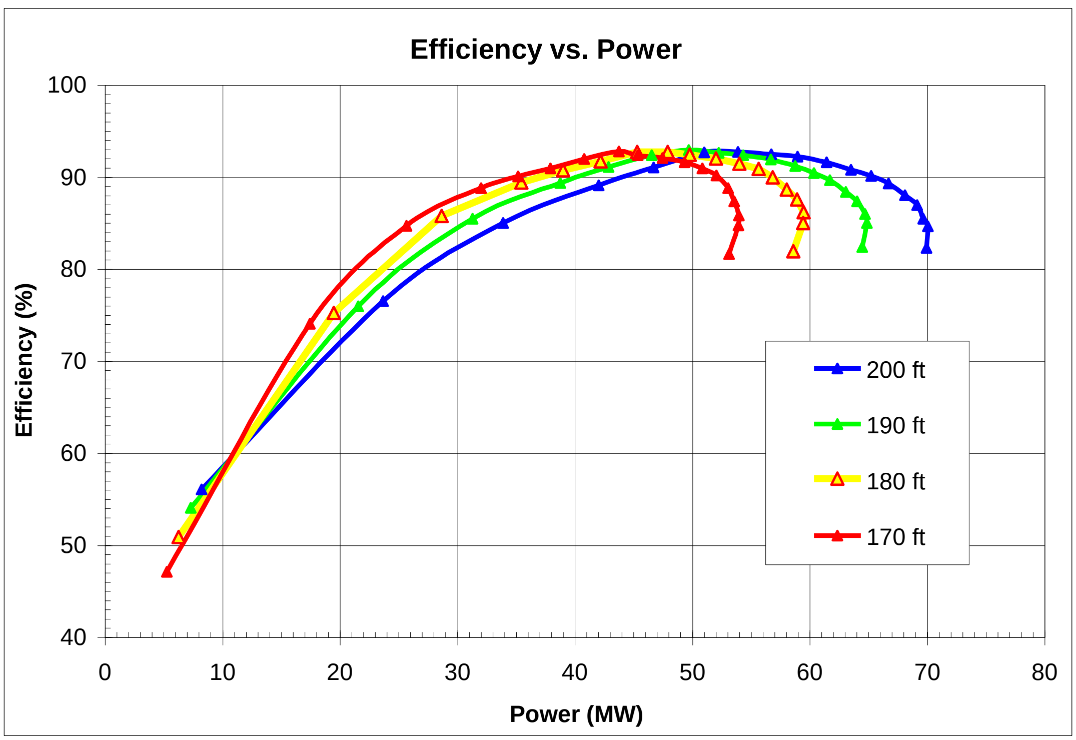

Figure 2: Example of Single Unit Efficiency Characteristics versus Head

As an example, Figure 2 shows the unit characteristics at multiple heads for a single, conventional Francis unit at an intermediate-head, two-unit, 120 MW hydroelectric plant. Efficiency curves such as these provide guidance for effective use of a hydro unit. In this case, the points of most efficient operation can be identified and the efficiency penalty for straying from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at another power level. When maximum power output is required, these curves show that there is a point at which very small gains in power result in drastic reductions in efficiency. Operation in this high-load, lower-efficiency region is also associated with increased cavitation damage to the turbine and accelerated bearing wear.

However, information from the single-unit efficiency characteristics alone is not sufficient for achieving effective operations in a multi-unit plant. This is illustrated in Figure 2, which shows overall plant efficiency characteristics, assuming all units are available, at multiple heads for generating mode operation of reversible Francis units at a high-head, six-unit, 3,000 MW plant with one new unit and five original units. The overall plant efficiency is dramatically affected by the plant load and head. For example, when operating at 1140 feet of head, a 500 MW load is quite inefficient for this plant, with an efficiency penalty of about 5%.

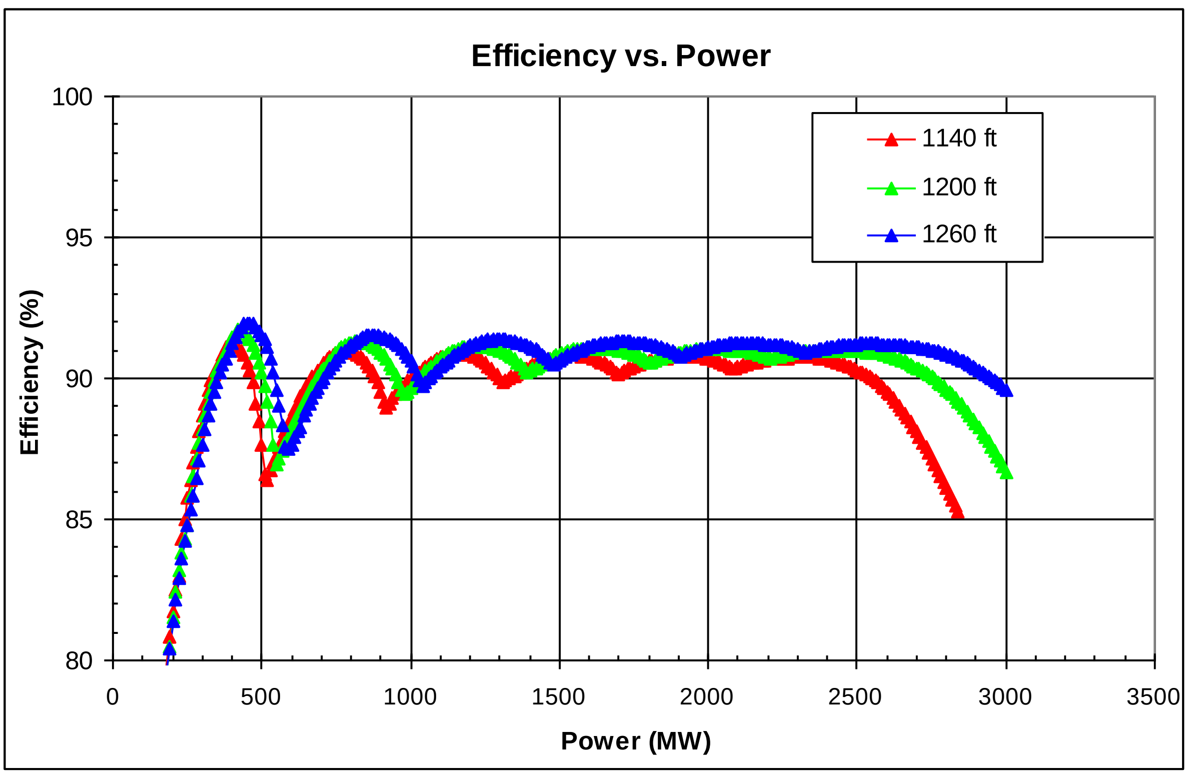

Figure 3: Example of Overall Plant Efficiency Characteristics versus Head

As discussed in Section 1, the HAP considers three performance levels for hydropower facilities: (1) the Installed Performance Level (IPL); (2) the Current Performance Level (CPL); and (3) the Potential Performance Level (PPL). The unit performance characteristics corresponding to the three performance levels are described below:

> ***Installed performance characteristics*** (η_I) are used in performance analyses that indicate the production potential of a facility under an assumption that the plant condition and capability are those existing immediately after the units were installed and commissioned. For a non-trivial number of facilities across the U.S., the installed performance characteristics are the only formal documentation available to describe unit and plant performance. In many cases, the installed performance characteristics may be based entirely on model tests of unit performance.
>
> ***Actual performance characteristics (***η_A) can be used in performance analyses if recent performance tests results for the units are available. The actual performance characteristics provide reduced uncertainty to performance analyses examining the overall plant performance under conditions of optimal commitment and dispatch.
>
> ***State-of-the-art performance characteristics*** (η_0) are used in performance analyses that indicate the production potential of the facility under an assumption that the units and balance of plant equipment are upgraded to best available technology. The state-of-the-art changes over time, so performance results based on the state-of-the-art represent a "moving target."

Facility Operational Data – Facility operational data is typically obtained from multiple sources, including plant personnel, central engineering staff, and load control personnel (if applicable). A preliminary data survey is desirable to determine "what, how, where, and who:"

- What performance-related parameters are measured?
- How well are the parameters measured?
- Where is the archival data stored?
- Who is the proper contact for obtaining the archival data?

Essential operational data for operation efficiency analyses and schedule analyses include:

1. Timestamp;
2. Unit Power;
3. Headwater Level (by unit if appropriate);
4. Tailwater Level (by unit if appropriate);
5. Unit Status (e.g., available, unavailable, condensing).

Additional operational data may also be required, depending on the facility. The additional data could include:

- Unit Wicket Gate Opening;
- Unit Winter-Kennedy Differential, Acoustic Flow Meter Output, or Other Unit Flow Rate;
- Spill Flow (if any);
- Unit Trash Rack Differential;
- Unit Blade Angle (for Kaplan Units);
- Unit Valve(s) Position (for Pelton Units);
- Unit Air Status (on/off) and Unit Air Flow Rate (for aerating units);
- Facility Environmental Flows (e.g., minimum flows, fish attraction flows, fish spill flows);
- Facility Leakage Flows.

In general, “snapshot” data are preferable to hourly averages. For most facilities, a few years’ data is sufficient to capture operational patterns. However, for some facilities more years may be appropriate to capture longer term events (e.g., market effects on dispatch, excessive outages due to reliability problems, hydrology-related patterns, etc.). Additional information should be solicited to determine how the facility’s units are dispatched (e.g., generation, ancillary services, both), to establish the unit operational constraints (e.g., cavitation and vibration constraints, generator constraints, transmission constraints), and to understand the environmental constraints (e.g., minimum flows, DO and TDG constraints, fish attraction flows, etc.).

Facility Hydrological Data – Facility hydrological data is required for the hydrology-based performance analyses, for example to quantify the total plant inflows and outflows. For many facilities, the total outflow is not measured but rather computed from unit power data and the unit characteristics (typically in the form of flow tables) that relate the unit flow to unit power and head. Flows bypassing the turbines, which include spill flows, environmental flows, and leakage flows, are also required for determining the total plant outflow. In some cases, it may also be beneficial to compute total plant outflow by performing a flow balance on the reservoir. This requires measured inflows, the measured reservoir elevations, reservoir bathymetric data, and evaporation from the reservoir.

4.0 Tools for Performance Analyses

As shown previously in Figure 1, the primary tools for performance analyses include an optimization engine and a computation engine, as described in the following subsections.

Optimization Engine – The optimization engine used for the optimization-based performance analyses is implemented using the Solver tool in Microsoft Excel. A brief summary of the implementation is described below, and a detailed explanation is included in Appendix 2.03.

The optimization engine is used to determine how a given plant load 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 load allocation that meets the given plant load with the lowest possible water usage, providing the highest possible plant efficiency.

Computation Engine – The computation engine is an Excel-based program that enables the automating of multiple data analyses. Additional configuration of the computation engine with an analysis script and calculation libraries is required for each particular type of analysis. The specific analyses can be configured to compute both the hydrology-based performance analyses (see Section 5) and the optimization-based performance analyses (see Section 6), using the equations and procedures described in the relevant sections.

5.0 Hydrology-Based Performance Analyses

The hydrology-based performance analyses produce a set of statistics and indices that characterize the historical extent to which a facility has converted the potential energy at a site to electrical energy for the electric power system. These statistics and indices are similar and, in some cases, identical to those used in design, decision-support, and scheduling for hydropower plants and units. As defined below, the performance metrics enable benchmarking and trending of performance across many facilities in a variety of river system, power system, and water availability contexts. The typical hydrology-based performance analyses include the Average Energy Production, the Long-Term Production Potential, and the Long-Term Stream Power.

Appendix 2.04 provides examples of results from the hydrology-based performance analyses for a three-unit facility.

Average Power Production – Produced power is a measure of the energy actually delivered to the power system by the facility. It is computed using historical generation data ($P\Delta t$ in kWh):

$$P_A \equiv \sum_{i=1}^{M} [P\Delta t] \Bigg/ \sum_{i=1}^{M} \Delta t$$

Long-Term Stream Power – The baseline measure of energy at a plant site is the Long-Term Stream Power (LTSP), P_S:

$$P_S \equiv \sum_{i=1}^{M} [(\rho g h_i Q_i)\Delta t] \Bigg/ \sum_{i=1}^{M} \Delta t$$

The LTSP is computed over a sufficient number of time steps M to characterize the variances of the total releases (powerhouse, spillway, leakage and other flows) from the plant (Q) and the gross head (h) at the plant. The LTSP includes a weak functional dependence on the dam and reservoir geometry via the gross head history, but it is primarily a function of the site hydrology and physical relief and not related to the technology installed at the site. Because the LTSP is defined in terms of the plant releases rather than unregulated inflows, it is also influenced by the water management strategy implemented in regulated river systems. The practical import of this dependence on water management strategy is that performance metrics defined in terms of the LTSP are "local" to the plant. In other words, metrics using the LTSP as a baseline indicate how well the plant is able to convert energy from the flows and storage (gross head) dictated by the river system and water management strategy.

The LTSP will most often be computed using hourly data (Δt = 1 hour), although for some run-of-river plants with persistent flows a daily time step (Δt = 24 hours) may be appropriate. In cases where flow, gross head, and load vary significantly or often within the hour, the appropriate time step of the computation (and that of the required data) could be less than one hour. The most common LTSP parameter will be the multi-year LTSP (M>>8760 hours). When the duration is M = 8760 hours and corresponds to a water year or calendar year time frame, the resulting LTSP parameter is termed an annual stream power (ASP) for a specific year. A related statistic is the monthly or seasonal LTSP computed over N years of data:

$$P_{S,j} \equiv \sum_{i=1}^{N}\sum_{k=1}^{M_j}\left[\left(\rho g h_{k,i,j} Q_{k,i,j}\right)\Delta t\right] \Big/ \sum_{i=1}^{N}\sum_{k=1}^{M_j}\Delta t$$

j ϵ [Jan, Feb, …, Dec; Winter, Spring, Summer, Fall; Irrigation, Non-Irrigation]

in which M_j is the number of time steps in month or season j.

Long-Term Production Potential – Not all of the water moving past the plant site is available for power generation. Only the water passing through the powerhouse (Q_{PH}) is available as potential energy for conversion to electrical energy. As with any power production, conversion of potential and mechanical energy to electrical energy by hydroelectric technology is less than complete. The hydroelectric units in the powerhouse are assumed to be optimally committed and dispatched to produce the maximum amount of energy from the powerhouse flow in each time step, thereby defining a set of plant performance characteristics $\eta = f(h, Q_{PH})$ that quantify the ability of a plant with its set of units to convert energy over a range of gross head and powerhouse flow conditions. It is then possible to define the Long-Term Production Potential (LTPP) for a plant:

$$P_P \equiv \sum_{i=1}^{M}\left[\rho g\left(\eta h_i Q_{PH,i}\right)\Delta t\right] \Big/ \sum_{i=1}^{M}\Delta t$$

The appearance of the plant performance characteristics η in the LTPP formula means that the LTPP is a function of the technology installed at the site. One can select different plant performance characteristics corresponding to assumptions about the condition of the technology present over the duration M of the computation:

These performance assumptions can also be used in a monthly or seasonal LTPP computation:

$$P_{P,j} \equiv \sum_{i=1}^{N}\sum_{k=1}^{M_j}\left[\rho g\left(\eta h_{k,i,j} Q_{k,i,j}\right)\Delta t\right] \Big/ \sum_{i=1}^{N}\sum_{k=1}^{M_j}\Delta t$$

j ϵ [Jan, Feb, …, Dec; Winter, Spring, Summer, Fall; Irrigation, Non-Irrigation]

The use of performance characteristics in the monthly or seasonal computation highlights the possibility that installed, state-of-the-art, or actual performance characteristics are not necessarily constant throughout annual cycles as different operational modes are activated. Examples include performance characteristics that depend upon seasonally-deployed turbine aeration systems or fish exclusion screens in unit intakes.

6.0 Optimization-Based Performance Analyses

Optimization technologies and recent advances in automated data analyses provide the opportunity to conduct detailed, optimization-based performance analyses [March and Wolff, 2003; March, 2004; March and Wolff, 2004; March et al., 2005; Wolff et al., 2005; Jones and Wolff, 2007; March, 2008]. Typical optimization-based performance analyses include Operation Efficiency Analyses, Scheduling Analyses, Avoidable Loss Analyses, and Correlation Analyses. Results from these analyses can be presented in easily understood units, including lost energy opportunity (LEO, in MWh) and lost revenue opportunity (LRO, in $). A diagram of the overall process for optimization-based performance analyses is shown in Figure 3, and the specific analyses are described in the following subsections.

Appendix 2.05 provides examples of results from optimization-based performance analyses for a three-unit facility.

Operation Efficiency Analyses – Operation Efficiency Analyses use unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch. Computational steps for determining the operation efficiency are shown in Figure 4.

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).

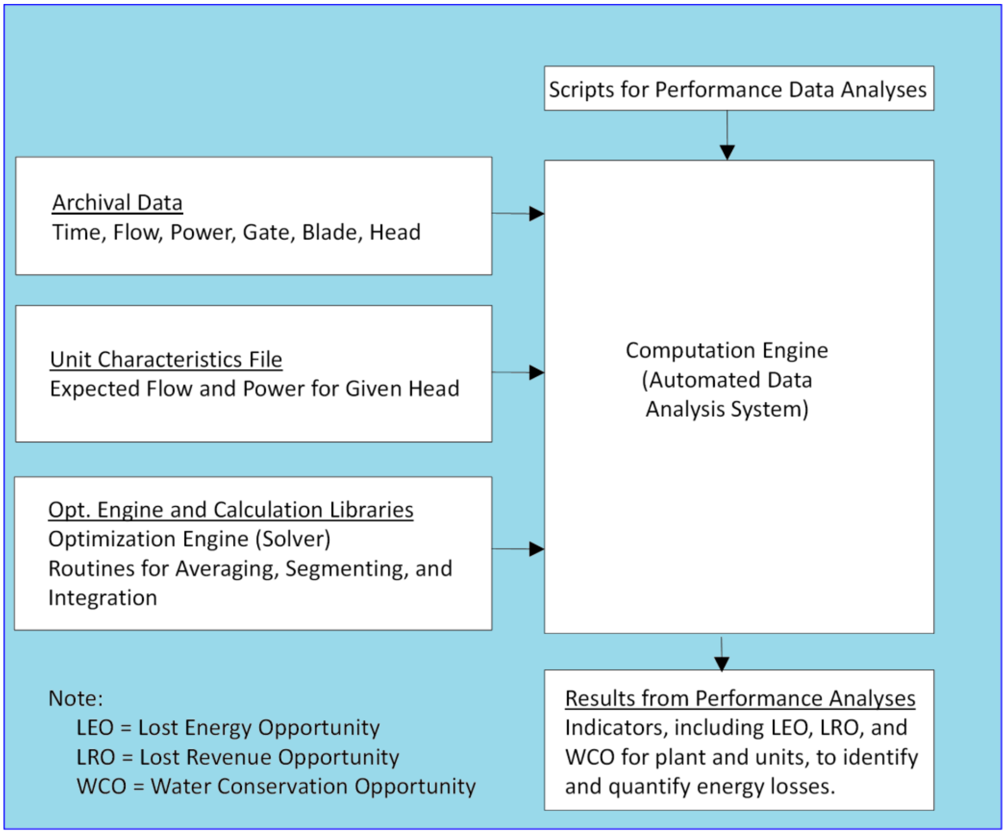

Figure 3: Process Diagram for Optimization-Based Performance Analyses

- 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 4: Operation Efficiency Analyses

The optimized plant efficiency is compared to the actual plant efficiency, as operated, to evaluate the potential gain that could be achieved for that time step. Note that the deficit in operation efficiency (i.e., 100% minus the operation efficiency) represents the efficiency gain theoretically achievable by continuously optimizing the plant load. 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].

Scheduling Analyses – 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 scheduling efficiency are shown in Figure 5. 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, market conditions, and other restrictions permit, more efficient energy generation is achieved.

- 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
  - Determine the number of units to dispatch by comparing the plant load to the minimum efficiency load; find the lowest plant efficiency load that is greater than the plant load (the number of units at which this occurs is the reference number of units)
  - Compute the efficiency difference between the optimized plant efficiency for the given load and the maximum scheduling efficiency
  - Assume the water used for the given timestep is utilized to create energy at the maximum scheduling efficiency
  - Scheduling Efficiency = 100 * (Optimized Energy) / (Optimized Schedule Energy)

Figure 5: Scheduling Analyses

Avoidable Loss Analyses – The Avoidable Loss Analyses determine how the optimized dispatch could be improved by reducing avoidable losses. Avoidable losses typically include excessive trash rack losses, excessive penstock losses, and excessive tunnel losses. The computational steps for the Avoidable Loss Analyses are shown in Figure 6.

- Avoidable Loss Analyses determine how the optimized dispatch could be improved by reducing avoidable losses (e.g., excessive trash losses, excessive penstock losses, and excessive tunnel losses)
- Computational Steps:
    - Inputs are head, power, unit performance curves, and piezometric heads corresponding to trash losses, penstock losses, tunnel losses
    - Energy losses for each component are based on piezometric heads and computed flow rates
    - Avoidable Loss Efficiency = 100 * (Actual Energy) / (Actual Energy + Avoidable Energy Loss)

Figure 6: Avoidable Loss Analyses

Correlation Analyses – When continuous measurements of relative or absolute flow rate are available for each unit, Correlation Analyses can be computed to compare the measured efficiencies with the expected unit performance characteristics [March and Wolff, 2004; Jones and Wolff, 2007]. Computational steps for the correlation analyses are shown in Figure 7. The measured efficiency for each unit, based on archival data, is compared at each time step of data to the expected unit characteristics. The energy loss at each time step is computed by assuming that a 1% efficiency difference produces a corresponding 1% energy loss. Linking the efficiency difference to energy is important because it enables the prioritization of attention for units within a system. Analyses, trouble-shooting efforts, and testing can then be focused on the units with the largest potential for improvement. In reality, the specific effects of errors in unit characteristics on optimized plant dispatch will depend on the unit characteristics, the plant configuration, the specific schedule request, and the distribution of the correlation efficiency deficit among the units.

- Correlation Analyses evaluate the accuracy of the unit characteristics and unit instrumentation
- Computational Steps:
  - Inputs are flow, head, power, and unit characteristics (wicket gate and blade data provide additional information for troubleshooting)
  - Measured efficiencies are compared to expected efficiencies
  - Deviations are assumed to be an efficiency loss
  - Efficiency losses are converted to energy losses based on unit power production
  - Correlation Efficiency = 100 * (Actual Power – Power Loss) / (Actual Power)

Figure 7: Correlation Analyses

7.0 Outcome from Performance Assessments and Analyses

The performance assessment results are used as input to two of the three Impact Indices, namely the Efficiency Impact Index, representing the potential of generating performance improvement, and the Cost Impact Index, representing the level of dollar cost for upgrading/replacing an asset in terms of \$/kW or \$/kWh. These two Impact Indices, in conjunction with the Reliability Impact Index, can collectively provide a base for decision-making on further assessment or studies and for prioritizing the investment opportunities at a facility.

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Appendix 2.01 - Discussion of Best Practices for Unit and Plant Performance Processes

Revision 1.0, 12/12/2011

Discussion of Best Practices for Unit and Plant Performance Processes

Data, Utilization, and Integration - For single unit and multi-unit efficiency characteristics to provide maximum benefit, the data-driven performance information, such as the unit and plant characteristics summarized previously in Figures 2 and 3, must be effectively incorporated into the load planning, dispatching, and other processes to optimize generation for the plant or power system.

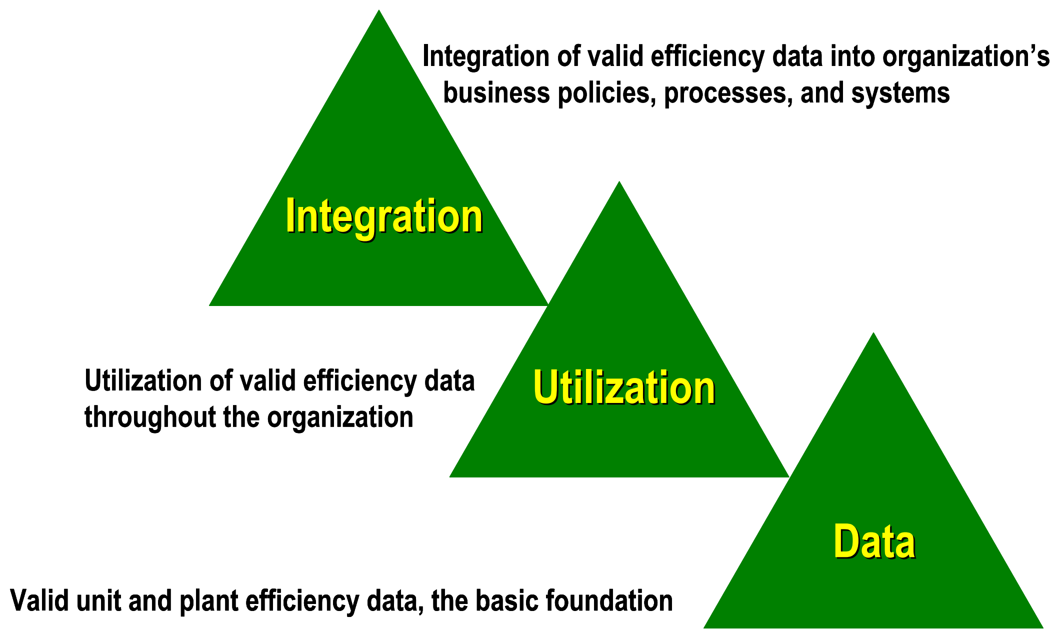


Figure 2.01-1: Conceptual Diagram of Best Practices for Unit and Plant Performance Processes

Figure 2.01-1 is presented as a useful way to consider efficiency-related processes in the context of the Best Practices for Unit and Plant Performance Processes, which is described in this appendix and provided in detail in Appendix 2.02. Figure 2.01-1 shows that valid unit and plant performance data form the basic foundation for effective performance processes, but the performance data must be widely available in useful form, such as unit and plant efficiency characteristics. The efficiency data must be incorporated into operator-based or automation-based optimization systems at the unit, plant, and system levels and at a variety of time scales ranging from real-time to a year or longer and utilized appropriately throughout the organization.

And, for effective performance processes, all of the relevant performance-related data, information, and analyses must be fully integrated into the organization's business policies, processes, and systems.

These three process components, data, utilization, and integration, are discussed in more detail in the following sections.

Valid Unit Efficiency Data, the Basic Foundation - The hydroturbine and generator together constitute a hydro unit. Unit efficiency characteristics consistent with current international and/or national standards should be available for each generating unit over the entire range of operating heads. Efficiency-related data consistent with relevant international and/or national standards [ASME, 2011], including power, headwater elevation, tailwater elevation, flow rate, water temperature, gate opening, trash rack differential, and blade angle (where appropriate) should be continually measured and readily available for each generating unit.

In addition, adequate personnel, budgets, systems, processes, and procedures should be in place for the following activities:

- Properly manage and maintain efficiency-related instrumentation, including obsolescence management for hardware and software and succession planning for personnel;
- Periodically compare expected performance characteristics for each unit with measured performance characteristics;
- Periodically evaluate and train relevant personnel; and
- Take timely and appropriate action when necessary.

Organizational Utilization of Appropriate Performance Results - Unit efficiency characteristics and past efficiency test results should be readily available to appropriate personnel (e.g., operations, maintenance, engineering, power management, water management, environmental management) and systems (e.g., monitoring system, automation system, optimization system, maintenance management system, environmental management system) within the organization. The efficiency information should be used in the long-term, medium-term, short-term, and real-time optimization of unit/plant and system operations for relevant operational modes (e.g., specific power, specific flow, most efficient power, most efficient power within a range, conventional AGC, optimization-based AGC).

Real-time and archival efficiency-related data, as well as supplementary efficiency-related information (e.g., unit operational data; electrical, mechanical, and hydraulic operational limits; power/energy and ancillary services rates versus time; operational scheduling information such as unit status and schedule request;) should be securely stored, appropriately backed-up, and readily available to appropriate personnel and systems within the organization. Systems, processes, and procedures should be in place to periodically compare expected efficiency data for each unit with real-time and archival efficiency-related data and supplementary efficiency-related information to ensure that improvements and corrections to unit characteristics are incorporated in a timely fashion into all appropriate optimization systems and related procedures, such as operator guidelines.

Adequate personnel, budgets, systems, processes, and procedures should be in place to properly manage and maintain performance-related communications infrastructure, archival software with appropriate data compression settings, operator-based and/or automation-based optimization infrastructure and software, including training, obsolescence management for hardware and software, and succession planning for relevant personnel.

Integration of Efficiency Results with Business Policies, Processes, and Systems - Unit performance characteristics should be used in the evaluation and quantification of economic losses associated with optimization systems, instrumentation, avoidable losses, unit/plant scheduling, environmental operations, and operational impacts on maintenance (e.g., AGC operation, exceeding cavitation limits, rough zone operation). Systems, processes, and procedures should be in place to compute quantitative performance metrics which ensure that relevant economic results are available for establishing maintenance priorities, developing capital equipment priorities, and evaluating operational policies, such as:

- Timely comparison of actual operations to optimized operations under the same conditions;
- Timely comparison of expected (i.e., historical) performance data for each unit with real-time and/or archival performance-related data to ensure that improvements and corrections to performance characteristics and instrumentation are incorporated in a timely fashion;
- Timely evaluation of avoidable energy losses (e.g., trash rack fouling, penstock/tunnel fouling, penstock/tunnel degradation); and
- Timely evaluation of unit/plant scheduling.

Adequate personnel, budgets, systems, processes, and procedures should also be in place to properly manage and maintain the infrastructure and software for integrating performance-related data and related information into the organization's business policies, processes, and systems; to periodically evaluate and train relevant personnel; and to take timely and appropriate action when necessary.

Best Practices Protocol for Unit and Plant Performance Processes - The Best Practices Protocol for Unit and Plant Performance Processes addresses three aspects related to the operational performance of hydropower units and plants, namely data, utilization, and integration. The protocol and the three appraisal aspects are inspired by, and, in part, derived from, the International Hydropower Association's Sustainability Guidelines [IHA, 2004] and Sustainability Assessment Protocol [IHA, 2006]. The protocol was developed from decades of experience with the Tennessee Valley Authority's integrated, multi-purpose power and water system and experience with additional hydropower systems in the United States, Canada, New Zealand, and Brazil. The protocol was initially presented in draft form at the World Renewable Energy Conference in 2004 [March, 2004]. The current protocol is derived from a similar protocol presented at Waterpower XIII in 2005, published in the conference proceedings [March et al., 2005], and submitted as an "Annex on Best Practice for Hydropower Performance" to the International Energy Agency.

The protocol is useful for assessing the overall operational performance of hydropower units, plants, and systems; comparing the relative performance of units and plants within a system; and providing guidance for allocating capital and maintenance resources and for prioritizing upgrades and improvements. Implementation of comprehensive unit and plant performance processes is important for the successful implementation of more efficient turbines and generators, improved automation and control systems, and advanced optimization systems. Improved performance can provide increased generation, increased revenue, additional water supply, and reduced maintenance costs.

Scoring for the Best Practices Protocol for Unit and Plant Performance Processes is based on the following system:

5 for each aspect where the hydro plant meets all of the relevant criteria;
3 where most of the criteria are met;
1 where only some of the criteria are met;
0 where none of the criteria is met.

In the protocol, Aspect P1 relates to unit efficiency data; Aspect P2 relates to organizational utilization of efficiency data for multiple purposes, including optimization; and Aspect P3 relates to integration of efficiency data and related information with business policies, processes, and systems.

Appendix 2.02 provides the complete protocol, including specific guidance on scoring for each aspect.

Appendix 2.02 - Assessment of Best Practices for Unit and Plant Performance Processes

HAP
HYDROPOWER ADVANCEMENT PROJECT

Revision 1.0, 12/12/2011

ASSESSMENT OF BEST PRACTICES FOR UNIT AND PLANT PERFORMANCE PROCESSES

Best Practices for Unit and Plant Performance Processes - This draft protocol describing best practices for unit and plant performance processes of hydroelectric facilities addresses three aspects related to operational performance. This protocol and these aspects are inspired by, and, in part, derived from, the International Hydropower Association's *Sustainability Guidelines* [IHA, 2004] and *Sustainability Assessment Protocol* [IHA, 2006].

Implementation of comprehensive best practices for unit and plant performance is critical for justifying and verifying increased generation through more efficient turbines and generators, improved automation and control systems, and advanced optimization systems. Improved efficiency can provide increased generation, increased revenue, additional water supply, and reduced maintenance costs, contributing directly to the goals of the IHA's *Sustainability Assessment Protocol* and to the goals and objectives of the Hydropower Advancement Project.

The rating scores from the protocol are useful for: (1) assessing hydropower unit and plant efficiency; (2) comparing the relative performance of units and plants within a system; (3) providing guidance for allocating capital and maintenance resources; (4) prioritizing and justifying upgrades and improvements; and (5) verifying and documenting efficiency and generation improvements [March et al., 2005; Schofield and March, 2008; March, 2008].

Scoring for this best practices protocol is based on the following system:

- 5 points for each aspect where the hydro facility meets all of the relevant criteria;
- 3 points where most of the criteria are met;
- 1 points where only some of the criteria are met; and
- 0 points where none of the criteria is met.

Overview details for the hydroelectric facility under appraisal are shown in Tables 2.02-1 and 2.02-2. Three best practices aspects for unit and plant efficiency are listed in Tables 2.02-3 through 2.02-5. Aspects P1 to P3 relate to the economic aspects of unit and plant efficiency.

Guidance on scoring is provided for each aspect. Scores can be totaled and divided by the number of aspects to obtain an average or converted to a percentage score. Unit scores are typically generation-weighted to provide a facility score. The resulting scores can be displayed in a variety of ways, depending on individual preferences.

Table 2.02-1: Facility Overview Details for Appraisal of Best Practices for Unit and Plant Performance Processes

PLANT NAME	
LOCATION DETAILS	
DATE OF ASSESSMENT	
NAME AND POSITION OF PERSON CARRYING OUT ASSESSMENT	
DETAILS OF OTHERS CONSULTED DURING ASSESSMENT	
SIGNATURE OF AUTHORIZING OFFICER	

Table 2.02-2: Summary of Aspects and Scores for Appraisal of Best Practices for Unit and Plant Performance Processes

No.	Aspect	Score	No.	Aspect	Score
P1	Unit performance data for economic operations		**P3**	Integration with economic business policies, processes, and systems	
P2	Organizational utilization of performance data for economic operations				

	Total	Average	Percentage	Range
Score				
Comments				

Table 2.02-3: Aspect P1, Unit Performance Data for Economic Operations

<table>
<tr><th colspan="2">P1 - Data</th></tr>
<tr><td colspan="2">Valid unit performance data provides the basic foundation for effective hydro performance processes.</td></tr>
<tr><th colspan="2">Performance Processes Scoring</th></tr>
<tr><td>5 = Highest</td><td>• Turbine and generator (i.e., unit) performance characteristics consistent with relevant international and/or national standards (e.g., IEC 60041-1991-11, ASME PTC18-2002) are available for each generating unit over the entire range of operating heads.
• Performance-related data consistent with relevant international and/or national standards, including power, headwater elevation, tailwater elevation, flow rate, water temperature, gate opening, trash rack differential, and blade angle (where appropriate) are continually measured and readily available for each generating unit.
• Adequate personnel, budgets, systems, processes, and procedures are in place to properly manage and maintain performance-related instrumentation, including obsolescence management for hardware and software and succession planning for personnel; to periodically compare expected performance characteristics for each unit with measured performance characteristics; to periodically evaluate and train relevant personnel; and to take timely and appropriate action when necessary.</td></tr>
<tr><td>3 = Medium</td><td>• Unit performance characteristics consistent with relevant international and/or national standards are available for most units (i.e., 50% or more of total generation) over most of the range of operating heads, and relative unit performance characteristics based on index testing are available for the remaining units.
• Performance-related data consistent with relevant international and/or national standards, including power, headwater elevation, tailwater elevation, flow rate, water temperature, gate opening, trash rack differential, and blade angle (where appropriate) are continually measured and readily available for most units, but some flow rates are relative rather than absolute.
• Significant personnel, budgets, systems, processes, and procedures are in place to properly manage and maintain performance-related instrumentation. However, some improvements could be readily achieved.</td></tr>
<tr><td>1 = Low</td><td>• Unit performance characteristics consistent with relevant international and/or national standards are available for some units over some of the range of operating heads, and relative unit performance characteristics based on index testing are available for some (i.e., 20% or less of total generation) of the remaining units.
• Some performance-related data, including power, headwater elevation, tailwater elevation, flow rate, water temperature, gate opening, and blade angle (where appropriate) is available for some units, but most flow rates are relative rather than absolute.
• Some personnel, budgets, systems, processes, and procedures are in place, but these are generally ineffective and/or inadequate.</td></tr>
<tr><td>0 = Zero</td><td>• No unit performance characteristics are available, and no attention is paid to performance-related instrumentation, data, or personnel.</td></tr>
<tr><td>Comments</td><td></td></tr>
</table>

Score	

Table 2.02-4: Aspect P2, Organizational Utilization of Performance Results

P2 – Utilization	
Proper utilization of valid performance results throughout the organization is required for cost-effective operations.	
Performance Processes Scoring	
5 = Highest	• Unit performance characteristics and past performance test results consistent with Aspect P1 are readily available to appropriate personnel (e.g., operations, maintenance, engineering, power management, water management, environmental management) and systems (e.g., monitoring system, automation system, optimization system, maintenance management system, environmental management system) within the organization and are used in the long-term, medium-term, short-term, and real-time optimization of unit/plant and system operations for relevant operational modes (e.g., specific power, specific flow, most efficient power, most efficient power within a range, conventional AGC, optimization-based AGC). • Real-time and archival performance-related data consistent with Aspect P1, as well as supplementary performance-related information (e.g., unit operational data; electrical, mechanical, and hydraulic operational limits; power/energy and ancillary services rates versus time; operational scheduling information such as unit status and schedule request;) are securely stored, appropriately backed-up, and readily available to appropriate personnel and systems within the organization. Systems, processes, and procedures are in place to periodically compare expected performance data for each unit with real-time and archival performance-related data and supplementary performance-related information to ensure that improvements and corrections to performance characteristics are incorporated in a timely fashion into all appropriate optimization systems and related procedures, such as operator guidelines. • Adequate personnel, budgets, systems, processes, and procedures are in place to properly manage and maintain performance-related communications infrastructure, archival software with appropriate data compression settings, operator-based and/or automation-based optimization infrastructure and software, including obsolescence management for hardware and software and succession planning for personnel; to periodically review performance-related data and information; to periodically evaluate and train relevant personnel; and to take timely and appropriate action when necessary.
3 = Medium	• Unit performance characteristics and past performance test results consistent with Aspect P1 are readily available to appropriate personnel and systems within the organization for most units (i.e., 50% or more of total generation) and are used for most units in the long-term, medium-term, short-term, and real-time optimization of unit/plant and system operations for relevant operational modes. • Real-time and archival performance-related data consistent with Aspect P1, as well as supplementary performance-related information, are securely stored, appropriately backed-up, and readily available to appropriate personnel and systems within the organization for most units. Systems and procedures are in place for most units to periodically compare expected performance data for each unit with real-time and archival performance-related data and supplementary performance-related information. • Significant personnel, budgets, systems, processes, and procedures are in place to properly manage and maintain performance-related communications infrastructure, archival software, and operator-based and/or automation-based optimization infrastructure and software. However, some improvements could be readily achieved.
1 = Low	• Unit performance characteristics and past performance test results are available to appropriate personnel and systems within the organization for some units (i.e., 20% or less of total generation) over some of the range of operating heads. • Real-time and archival performance-related data, as well as supplementary performance-related information, are stored and available to appropriate personnel and systems within the organization for some units and are used in the long-term, medium-term, short-term, and real-time optimization of unit/plant and system operations for relevant operational modes for some units. • Some personnel, budgets, systems, processes, and procedures are in place, but these are generally ineffective and/or inadequate.
0 = Zero	• No unit performance characteristics are available, and no attention is paid to performance-related instrumentation, data, or personnel.
Comments	

Score	

Table 2.02-5: Aspect P3, Integration with Business Policies, Processes, and Systems

P3 - Integration	
Integration of the performance data and related information into the organization's business policies, processes, and systems is required.	
Performance Processes Scoring	
5 = Highest	• Unit performance characteristics, consistent with Aspects P1 and P2, are used in the evaluation and quantification of economic losses associated with optimization systems, instrumentation, avoidable losses, unit/plant scheduling, environmental operations, and operational impacts on maintenance (e.g., AGC operation, exceeding cavitation limits, rough zone operation). • Systems, processes, and procedures, consistent with Aspects P1 and P2, are in place to compute quantitative performance metrics which ensure that relevant economic results are available for establishing maintenance priorities, developing capital equipment priorities, and evaluating operational policies, such as: (1) a timely comparison of actual operations to optimized operations under the same conditions; (2) a timely comparison of expected (i.e., historical) performance data for each unit with real-time and/or archival performance-related data to ensure that improvements and corrections to performance characteristics and instrumentation are incorporated in a timely fashion; (3) a timely evaluation of avoidable energy losses (e.g., trash rack fouling, penstock/tunnel fouling, penstock/tunnel degradation); (4) a timely evaluation of unit/plant scheduling. • Adequate personnel, budgets, systems, processes, and procedures are in place (1) to properly manage and maintain the infrastructure and software for integrating performance-related data and related information into the organization's business policies, processes, and systems, including obsolescence management for hardware and software and succession planning for personnel; (2) to periodically evaluate and train relevant personnel; and (3) to take timely and appropriate action when necessary.
3 = Medium	• Unit performance characteristics, consistent with Aspects P1 and P2, are used in the evaluation and quantification of economic losses associated with optimization, instrumentation, avoidable losses, and unit/plant scheduling for most units (i.e., 50% or more of total generation). • Systems, processes, and procedures, consistent with Aspects P1 and P2, are in place for most units to compute quantitative performance metrics. • Significant personnel, budgets, systems, processes, and procedures are in place to properly manage and maintain the infrastructure and software for integrating performance-related data and related information into the organization's business policies, processes, and systems. However, some improvements could be readily achieved.
1 = Low	• Unit performance characteristics are used in the evaluation and quantification of economic losses associated with optimization, instrumentation, avoidable losses, and unit/plant scheduling for some units (i.e., 20% or less of total generation). • Systems, processes, and procedures are in place for some units to compute quantitative performance metrics. • Some personnel, budgets, systems, processes, and procedures are in place, but these are generally ineffective and/or inadequate.
0 = Zero	• No unit performance characteristics are available, and no attention is paid to performance-related instrumentation, data, or personnel.
Comments	

Score	

Appendix 2.03 - Detailed Description of Optimization Engine for Performance Analyses

Revision 1.0, 11/16/2011

The optimization engine used for the optimization-based performance analyses computes the load allocation among a set of units to maximize overall plant efficiency for a given plant load and head.

The general optimized dispatch problem is represented by the equations below:

maximize

$$\sum_{i=1}^{N} P_i \Big/ \sum_{i=1}^{N} \gamma Q_i H_i \qquad (1)$$

subject to

(2)

$$P_{plant} = \sum_{i=1}^{N} P_i \qquad (3)$$

$$P_i \geq Min\ P_i \quad ; i = 1\ to\ N$$

$$P_i \leq Max\ P_i \quad ; i = 1\ to\ N \qquad (4)$$

where

P_i = unit power
Q_i = unit volumetric flow rate, function of unit power and unit head
H_i = unit head
γ = specific weight of water
N = number of units on line
P_{plant} = plant power.

This problem is non-linear and non-convex. Because the system of equations is non-convex, the solution for the system will not in general be a global maximum but will depend on the starting solution which is chosen for the system.

The optimization engine uses Solver, available in Microsoft Excel, in conjunction with pre- and post-processing routines. Solver is configured to use a non-linear solver, specifically the generalized reduced gradient algorithm. The pre- and post-processing routines involve a heuristic approach to determine which units to use in producing an optimized solution.

Figure 2.03-1 provides a flow chart outlining the computational approach.

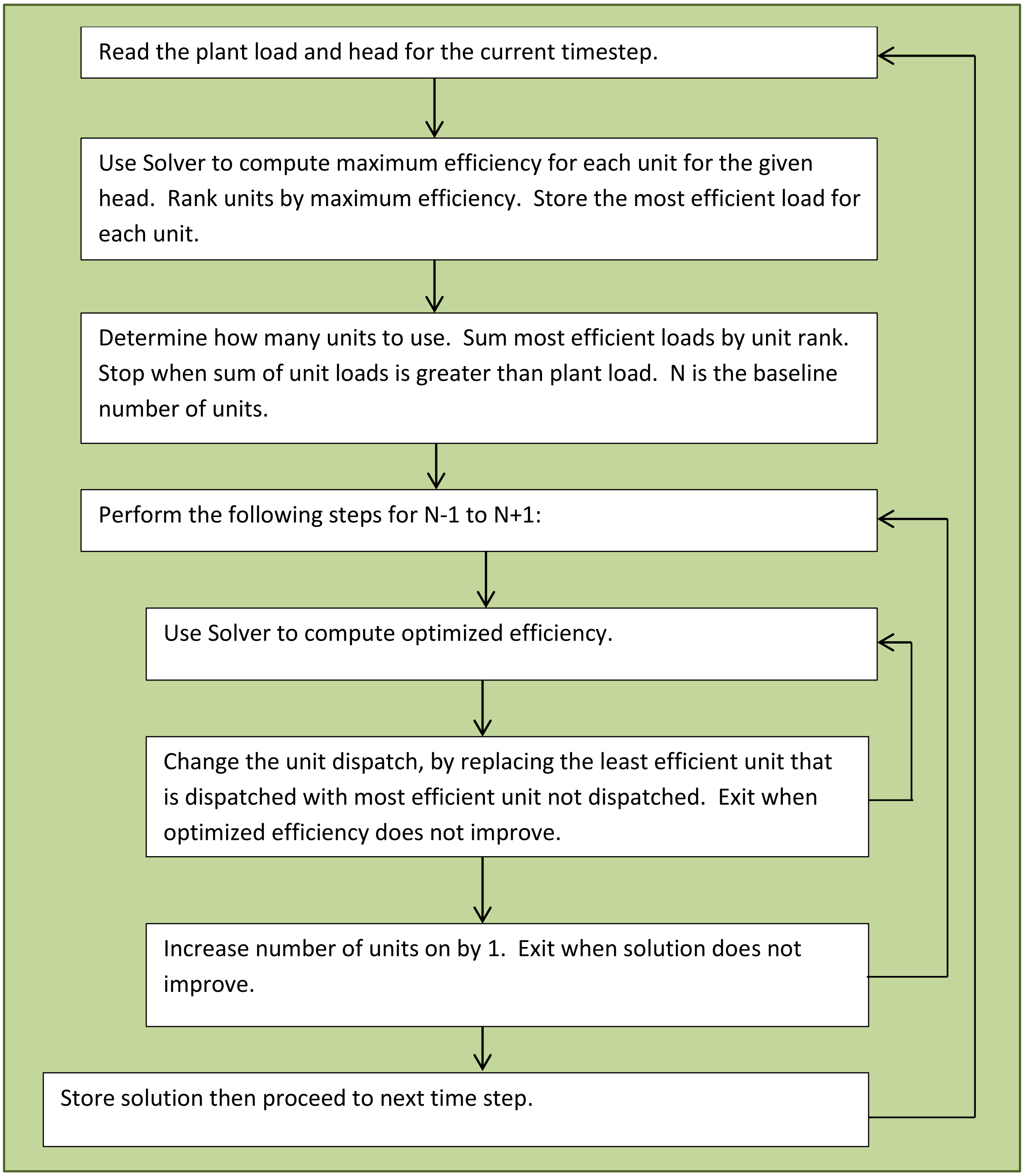


Figure 2.03-1: Steps for the Optimization Calculation

The unit characteristics file that specifies unit flow rate as a function of unit power and head is an important component of this computational approach. Polynomial functions are used to fit the power versus flow data for the purpose of generating a unit characteristics file. Third or fourth order polynomials are usually sufficient to fit the flow data closely.

An example showing a unit characteristics file is provided in Figure 2.03-2.

Unit Indices	1	2	3			
Unit 1						
Head	Min Power	Max Power	C0	C1	C2	C3
800	100.0	386.0	803.4959483	12.95901452	-0.012516449	2.72475E-05
820	100.0	400.0	779.1287276	12.46492887	-0.010171889	2.2593E-05
840	100.0	413.3	762.2243831	12.04814701	-0.008525652	1.92943E-05
860	100.0	426.7	708.8377359	12.26894125	-0.009372311	1.88191E-05
880	100.0	441.2	653.7701053	12.55582708	-0.010748803	1.93791E-05
900	100.0	446.0	602.4557509	12.63716266	-0.011108693	1.89294E-05
920	100.0	446.0	550.7515091	12.74597635	-0.011494927	1.8455E-05
Unit 2						
Head	Min Power	Max Power	C0	C1	C2	C3
800	100.0	384.2	777.0271739	13.34584166	-0.013520041	2.73163E-05
820	100.0	398.2	759.3314157	12.84340597	-0.011366885	2.3142E-05
840	100.0	411.5	733.9298828	12.51138043	-0.010025859	2.02674E-05
860	100.0	424.8	712.3336132	12.08146238	-0.008299093	1.71127E-05
880	100.0	439.3	667.5928913	12.24233532	-0.009288537	1.74768E-05
900	100.0	446.0	603.9127511	12.64118968	-0.011206196	1.90267E-05
920	100.0	446.0	553.1554981	12.62465138	-0.010967545	1.77727E-05
Unit 3						
Head	Min Power	Max Power	C0	C1	C2	C3
800	100.0	376.2	796.2206324	12.59551737	-0.010575133	2.41302E-05
820	100.0	390.0	761.7030756	12.2917749	-0.009040099	2.05049E-05
840	100.0	402.9	723.4770205	12.22593026	-0.008811879	1.89345E-05
860	100.0	416.0	689.245344	12.11197056	-0.008323045	1.70889E-05
880	100.0	430.2	647.2029387	12.04819659	-0.007891678	1.54196E-05
900	100.0	444.5	580.684719	12.52468709	-0.010288174	1.76044E-05
920	100.0	446.0	501.9774617	13.05870716	-0.012634001	1.95113E-05

Figure 2.03-2: Example Showing Unit Characteristics File

Appendix 2.04 – Examples of Results from Hydrologic Analyses

Revision 1.0, 03/23/2012

Introduction

Appendix 2.04 provides an example of results from the hydrological analyses for a three-unit hydro plant. This includes the hydrological background information about the plant site, the discussions of approaches and methods used for hydrology-based assessment, and results for the metrics of Long-Term Stream Power (LTSP), Long-Term Production Potential (LTPP), and Average Power Production (APP). These performance metrics enable benchmarking and trending of performance across many facilities in a variety of river system, power system, and water availability contexts.

Site Hydrological Characteristics

Rhodhiss hydropower plant is situated on the Catawba River with a contributing watershed of 697,600 acres. Stream flow data from the USGS stream gauge 02140991, located on a tributary (John's River) to the Catawba River, was used to identify the hydrological trends in this watershed area for the period from 2007 through 2011. Other stream gauges on the main river did not have the full record of data for this time period. For the purpose of identifying hydrological variation trends in the area as opposed to absolute values, using a stream gauge in the vicinity of the dam is considered as appropriate. The gauge flow variations are trended (shown as the blue curves in Figure 2.04-4 and Figure 2.04-5).

Long-Term Stream Power (LTSP) Analysis

The calculation of the annual and Long-Term Stream Power (LTSP) is to determine the power potential at the plant site based on the historical gross heads and flows passing through the site. This total flow (so-called plant site flow or plant flow) includes turbine flows, spill flows, measurable leakages, bypass flows, etc. Ideally, the flows measured immediately downstream of a hydropower plant would be used for this calculation as they would represent the total flows actually passing through the plant site. However, many hydropower plants do not measure the flows, and often there are not any nearby USGS gauge measurements that can be utilized for historic site flows. In this case, the plant operations data would be used to retrieve the historic plant flows.

For the Rhodhiss hydropower plant, the historical records of unit operations with 15 minutes intervals are available, from which the time series of gross heads, the corresponding powerhouse flows (i.e., the flows passing through all the turbine units for energy generation), as well as the spill flows, can be obtained or retrieved. The sum of powerhouse flow and spill flow is used as plant flow to calculate the stream power potential at the plant site.

Long-Term Production Potential (LTPP) Analysis

Since the LTPP is a measure of power production for the three different performance levels of IPL, CPL, and PPL, a series of plant performance curves corresponding to each of these performance levels are needed. The performance curves relating the powerhouse flows to the plant efficiencies are discussed in Appendix 2.05. For the Rhodhiss case, four different performance curves under each performance level are provided, corresponding to gross heads of 55 ft, 60 ft, 65 ft, and 70 ft, respectively. These curves serve as the basis from which the values of plant efficiencies corresponding to other gross heads and powerhouse flows are interpolated. The plant efficiency curves are shown in Figures 2.04-1, 2, and 3 for the IPL, CPL, and PPL, respectively.

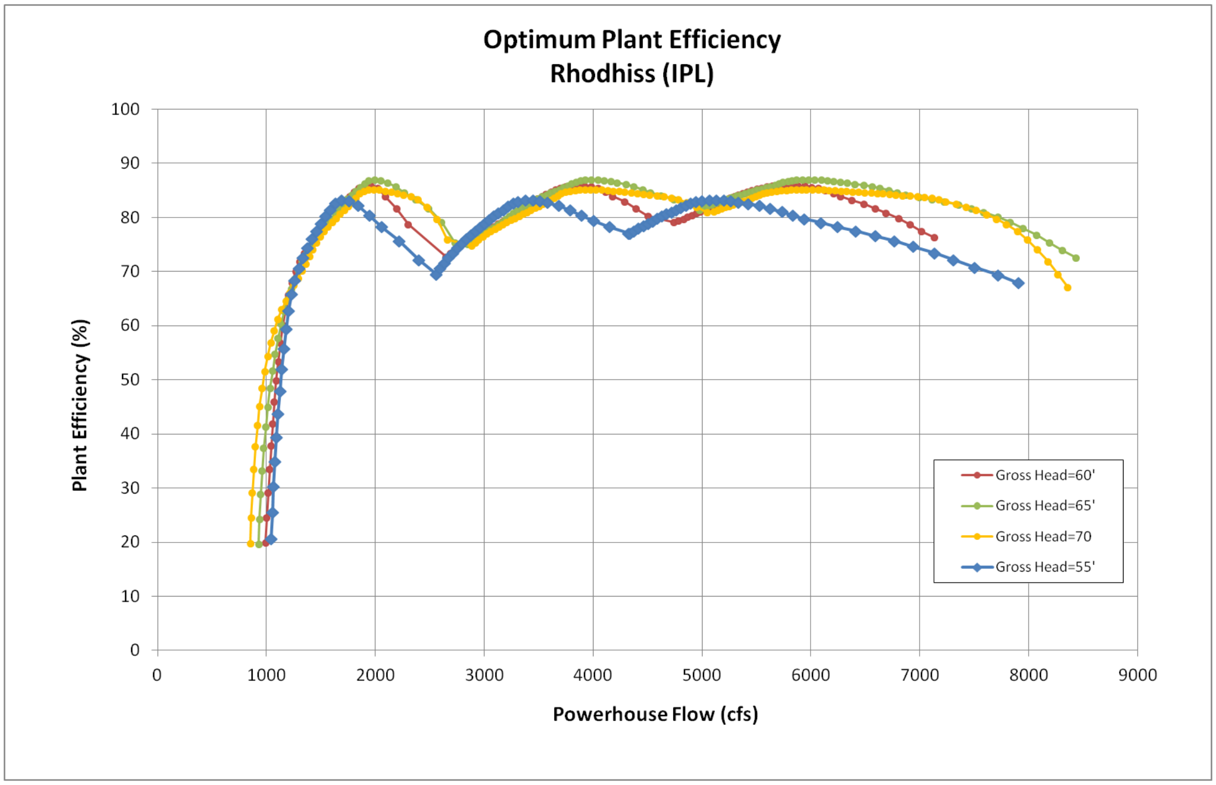


Figure 2.04-1: Powerhouse Flow versus Plant Efficiency (IPL; U1, U2, U3)

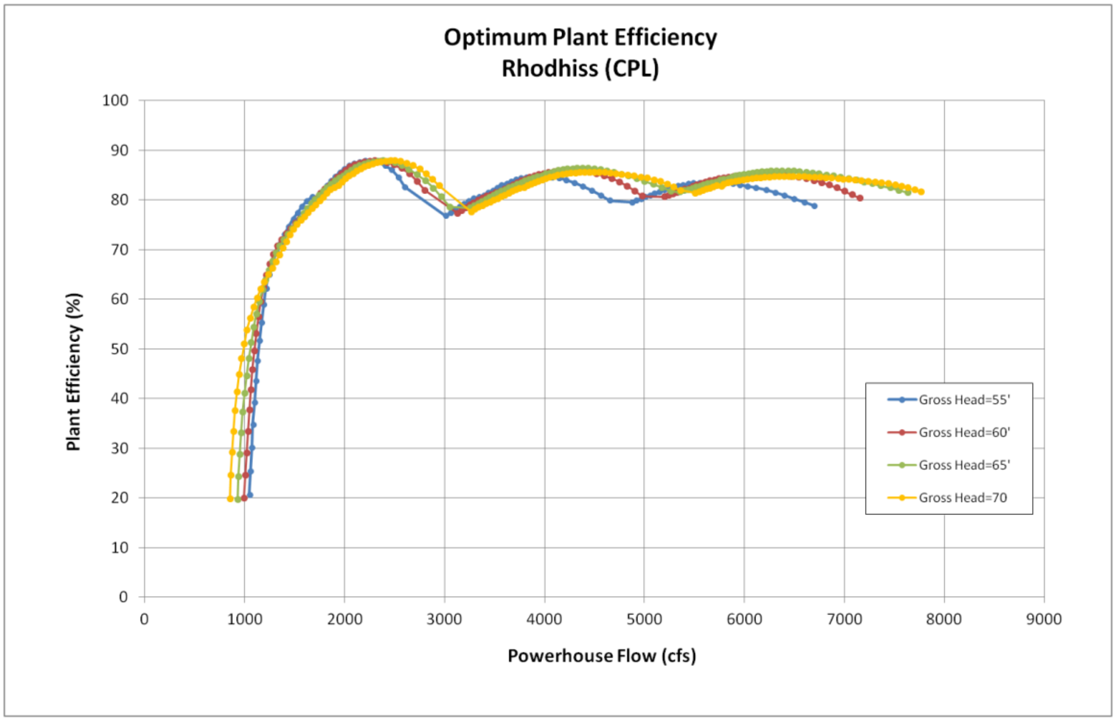


Figure 2.04-2: Powerhouse Flow versus Plant Efficiency (CPL; U1, U2, U3)

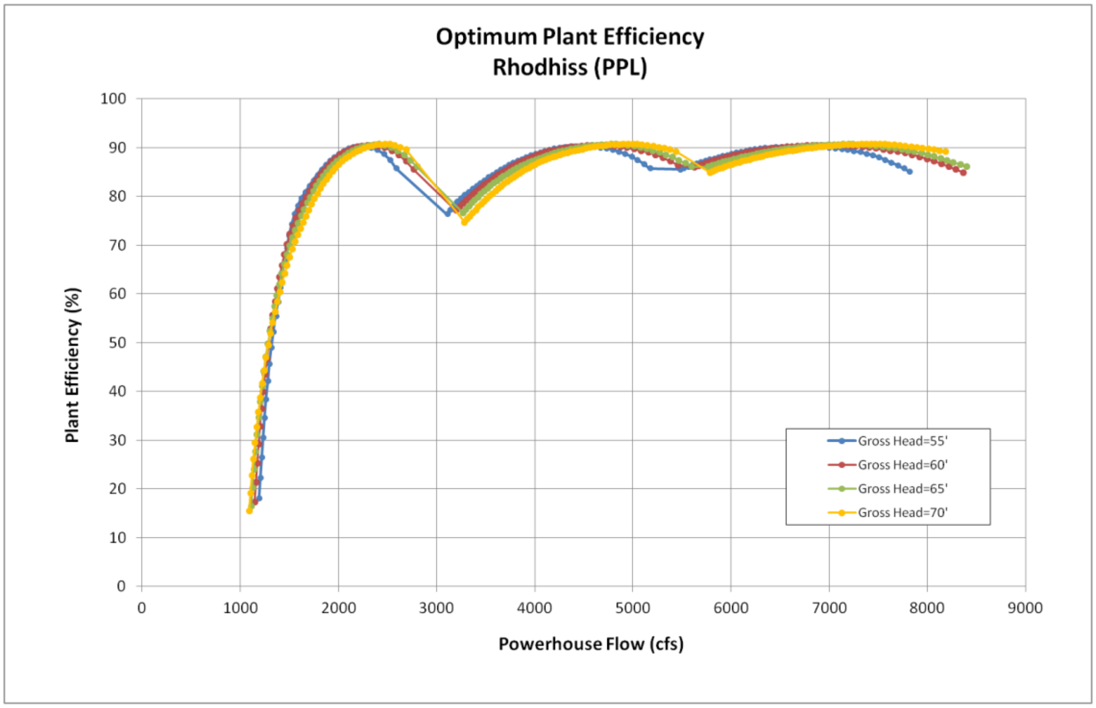


Figure 2.04-3: Powerhouse Flow versus Plant Efficiency (PPL; U1, U2, U3)

Based on the optimized efficiency curves provided in Figures 2.04-1 through 2.04-3, the method used to determine the plant efficiency for a given powerhouse flow assumes that the plant is operated at the peak efficiency point within each of the three curvatures on the optimized efficiency curves for the dispatch of one unit, two units, or three units. This is accomplished by "shifting" the actual time increment (15 minutes in this case) of a flow to a shorter or longer time period while conservation of water is maintained by allowing the same volume of water to be released for generating over different time durations with a higher efficiency. This method assumes that the total of the "extra" time resulted from this flow shifting does not exceed what is physically allowable over the course of the day, and hence any net changes of reservoir storage and water levels resulting from this flow shifting are negligible.

For the efficiency curve corresponding to the last unit dispatched (in this case – the third curvature), the powerhouse flows that exceed the peak efficiency point are not shifted to the peak efficiency. Instead, the actual flows and their corresponding efficiencies are used in the calculation of annual and long term production potentials. This reflects a hydropower facility's typical operation during the periods where flows at this large magnitude may represent the passage of a flood. The priority of passing the flood must be considered and the shifting of flows towards smaller ones to gain better efficiency values would not be appropriate in this case.

Historical powerhouse flows that are less than the minimum flow point on the plant efficiency curves are neglected for the calculation of plant production potential. The minimum flow point is associated with the turbine operating limits to avoid turbine vibration and cavitation. In addition, shifting these small flows to those corresponding to the peak efficiencies would result in extremely small and unrealistic periods of run-time. Historical powerhouse flows greater than the maximum value exceeding the endpoint of the plant efficiency curves utilize the endpoint efficiency on the curve.

For the case of Rhodhiss, none of the historical gross head values fall outside of the 55 ft and 70 ft envelope of gross heads.

Average Power Production (APP) Calculation

The calculation of the Average Power Production (APP) simply requires the time-series of historical generation data. For the Rhodhiss data, only positive values of reported generation are used in this computation. Generation values of zero within the time-series are also included in the average.

Summary of Results

The actual productions in megawatt-hours (MWh), in addition to the average hourly MW for each of the years, are calculated. Table 2.04-1 summarizes the annual generations (in MWh) through the years from 2007 to 2011, respectively, for the historical recorded plant production, the plant production potentials at IPL, CPL and PPL, and the stream hydropower potential.

Table 2.04-2 summarizes the annual power potentials (in MW) for each year from 2007 to 2011, respectively, for historical recorded production, plant production potentials at IPL, CPL and PPL and the stream hydropower potential. The bottom array shows the long-term power potentials (in MW) over the years from 2007 to 2011.

Table 2.04-3 summarizes the absolute and relative increases in annual generation (MWh) at each of the IPL, CPL, and PPL levels, potentially gained from optimization of plant operations.

Table 2.04-1: Summary of Results for Annual Generation

	Actual Annual Generation	Optimized Annual Generation (IPL)	Optimized Annual Generation (CPL)	Optimized Annual Generation (PPL)	Annual Stream Power Potential
	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)
2007	32,866	34,067	34,573	36,315	40,650
2008	35,398	36,507	36,651	38,685	42,821
2009	67,517	69,896	70,442	74,446	83,232
2010	63,360	65,921	66,923	70,212	78,270
2011	29,768	30,695	31,063	32,515	36,799

Notes:

1. The 2007 results include generation and flow from January 1, 2007, through June 30, 2007, only.
2. The 2011 results include generation and flow from January 1, 2011, through August 31, 2011, only.
3. Some missing hours were found on the first and last day for the year 2008 and 2011. These values account for less than 0.25% of the entire yearly data.

Table 2.04-2: Summary of Results for APP, LTPP and LTSP

	APP	LTPP IPL	LTPP CPL	LTPP PPL	LTSP
	(MW)	(MW)	(MW)	(MW)	(MW)
2007	7.57	7.85	7.96	8.37	9.36
2008	4.04	4.16	4.18	4.41	4.89
2009	7.72	7.99	8.05	8.51	9.51
2010	7.24	7.53	7.65	8.03	8.95
2011	5.31	5.48	5.54	5.80	6.57
All Years	6.32	6.55	6.62	6.97	7.78

Notes:

1. The 2007 results include generation and flow from January 1, 2007, through June 30, 2007, only.
2. The 2011 results include generation and flow from January 1, 2011, through August 31, 2011, only.
3. Some missing hours were found on the first and last day for the year 2008 and 2011. These values account for less than 0.25% of the entire yearly data.

Table 2.04-3: Summary of Generation Increases for Optimized IPL, CPL, and PPL Performance Levels

	Improvement (IPL)	Improvement (CPL)	Improvement (PPL)	Improvement (IPL)	Improvement (CPL)	Improvement (PPL)
	(MWh)	(MWh)	(MWh)	(%)	(%)	(%)
2007	1,201	1,707	3,449	3.65	5.19	10.49
2008	1,109	1,253	3,287	3.13	3.54	9.29
2009	2,379	2,925	6,929	3.52	4.33	10.26
2010	2,561	3,563	6,852	4.04	5.62	10.81
2011	927	1,295	2,740	3.11	4.35	9.20

The monthly averaged actual power production (APP), plant production potential, and stream power potential are plotted in Figures 2.04-4, 2.04-5, and 2.04-6, respectively. These monthly variation trends are compared across the years from 2007 to 2011, which shows the overall production and power potential were the lowest in 2008 and the highest in 2009, the same finding as indicated in Table 2.04-2. As expected, the APP calculated from historical generation records (Figure 2.04-4) trended consistently with the stream power potential that is calculated from the plant site flows (Figure 2.04-6). This is because at the Rhodhiss site there was little spill and no releases other than for power generation purposes. Also as expected, the monthly variations of plant production potential for each year (Figure 2.04-5) follow the similar pattern and trend of stream power potential (Figure 2.04-6). The major difference between the two plots is that plant production potential takes the plant efficiency into account.

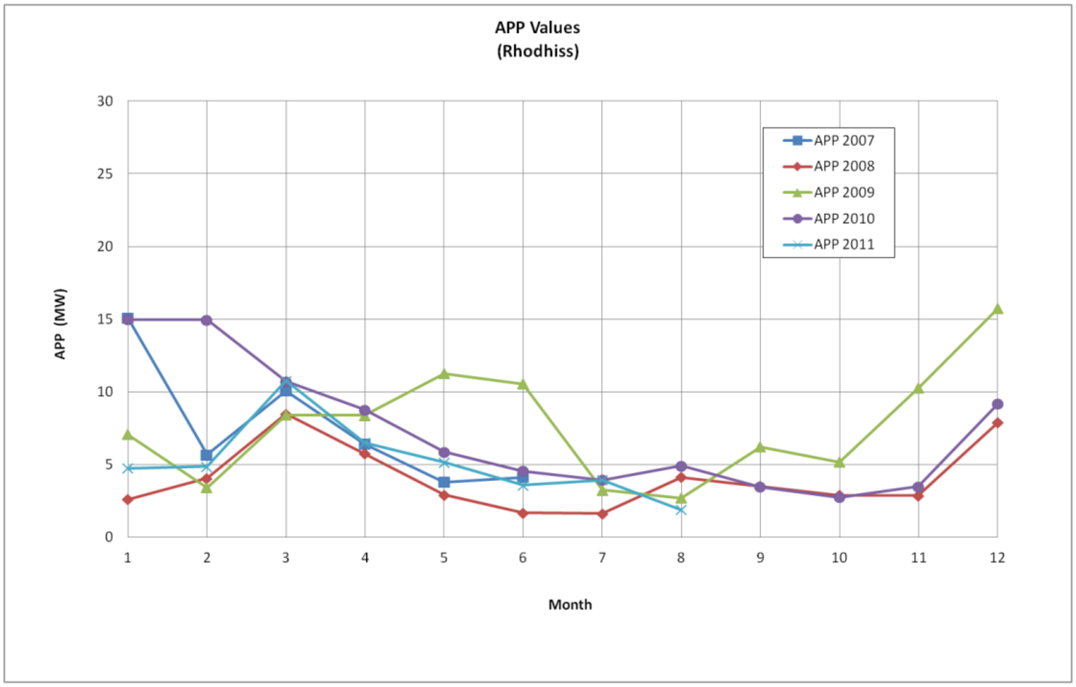


Figure 2.04-4: Monthly averaged APP trend for 2007-2011

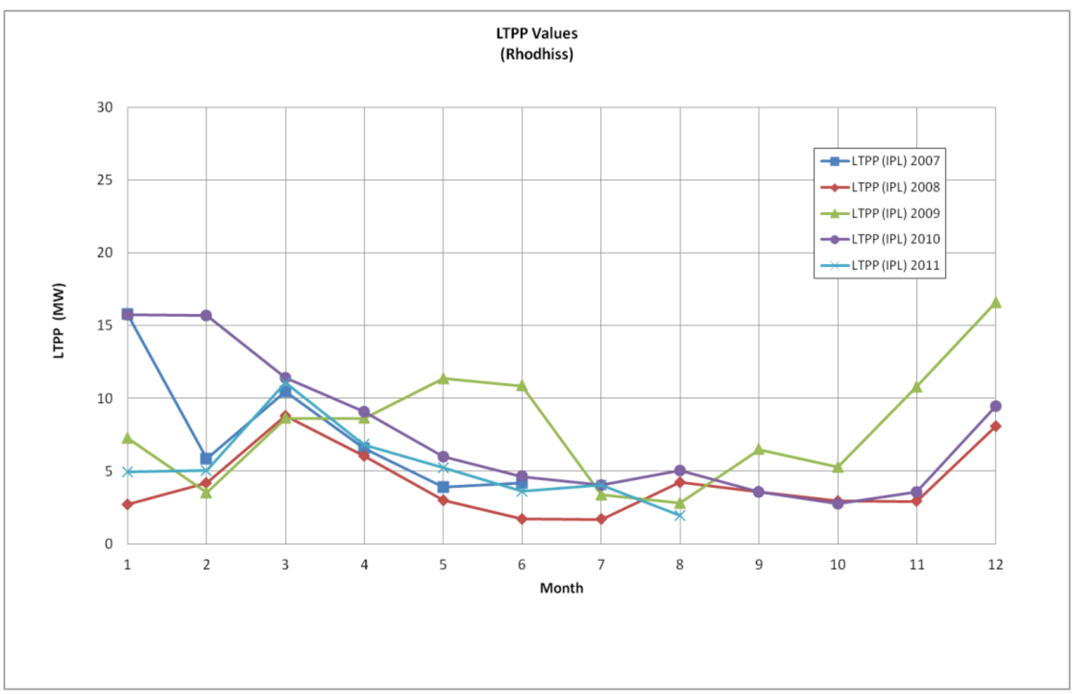


Figure 2.04-5: Monthly averaged plant production potential trend for 2007-2011

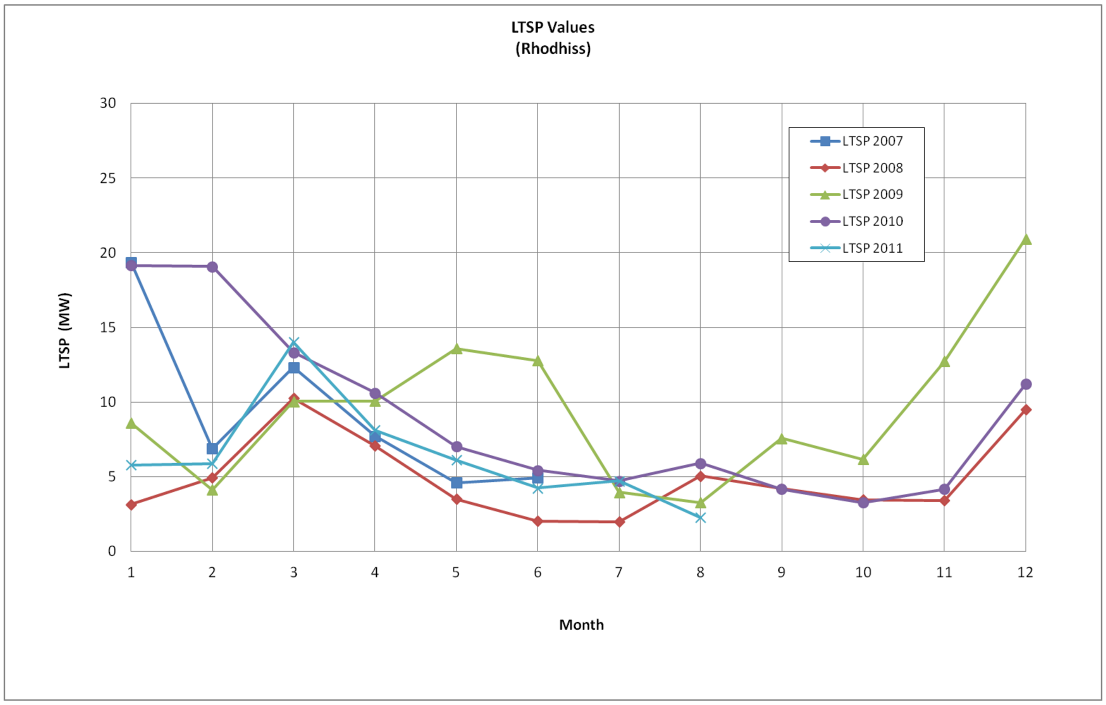


Figure 2.04-6: Monthly averaged stream power potential trend for 2007-2011

Discussion of Results

The increasing trend in the results for the annual optimized generation in Table 2.04-1 from IPL to CPL and to PPL is as expected. This is also reflected in the LTPP values in Table 2.04-2. An indication that the plant was not operated at an optimized schedule is reflected in the comparatively smaller values for the actual annual generation as compared to the optimized annual generation. Optimized generation for all of the years indicate an average performance increase over actual generation of about 3.5%, 4.6%, and 10.0% at the IPL, CPL, and PPL levels, respectively. This corresponds to average increase in annual generation by about 1635 MWh, 2149 MWh, and 4651 MWh for the five year period at each of the respective performance levels.

Figure 2.04-7 depicts and compares the trends of monthly average stream flows and monthly average plant production potential at IPL, CPL, and PPL. Because the majority of the stream flow passing Rhodhiss is used for power generation, the variation of plant production potential over time trended consistently with the hydrological variation in the vicinity. This comparison also helps to identify significant periods of plant outage or periods for which plant operations data are missing (e.g., July-Dec. 2007). In addition, the variation of yearly average stream flows, as shown in Figure 2.04-8, clearly explains why the annual power potentials for the year of 2008 and 2011 are significantly lower than those of 2007, 2009, and 2010 (see in Table 2.04-2). Observation of the annual variation of stream flows indicates that 2008 and 2011 are "dry" years, while the 2009 is a "wet" year which provides a power potential 92% higher than that of 2008 and 46% higher than that of 2011.

Corresponding to the highest peak of hydrological flow (see the blue curve in Figure 2.04-7) for the period from April to July in 2009, the significantly higher actual production can be found for the same period in Figure 2.04-4. The second highest hydrologic peak in Figure 2.04-7 for the time period from November 2009 to May 2010 also corresponds to the relatively higher production in Figure 2.04-4.

Comparison of results from Appendix 2.04 and Appendix 2.05 reveals an overall difference is less than 1% in IPL, CPL, and PPL related optimized annual generation values over the five Calendar years. The slight differences in both results are attributed to subsequent refinement of methods associated with filtering the 15 minutes data and inputting flows as compared to the calculations reported in Appendix 2.05.

Some of the turbine flow data extracted from the time-condensed data files provided by the plant owner appear erroneous (e.g., some reported generation values exceed what is possible to achieve by the reported flows, and in some instances non-zero generation amount is reported during periods of zero flow). Thus, the turbine flows used for these hydrological analyses are based on the reported plant generation.

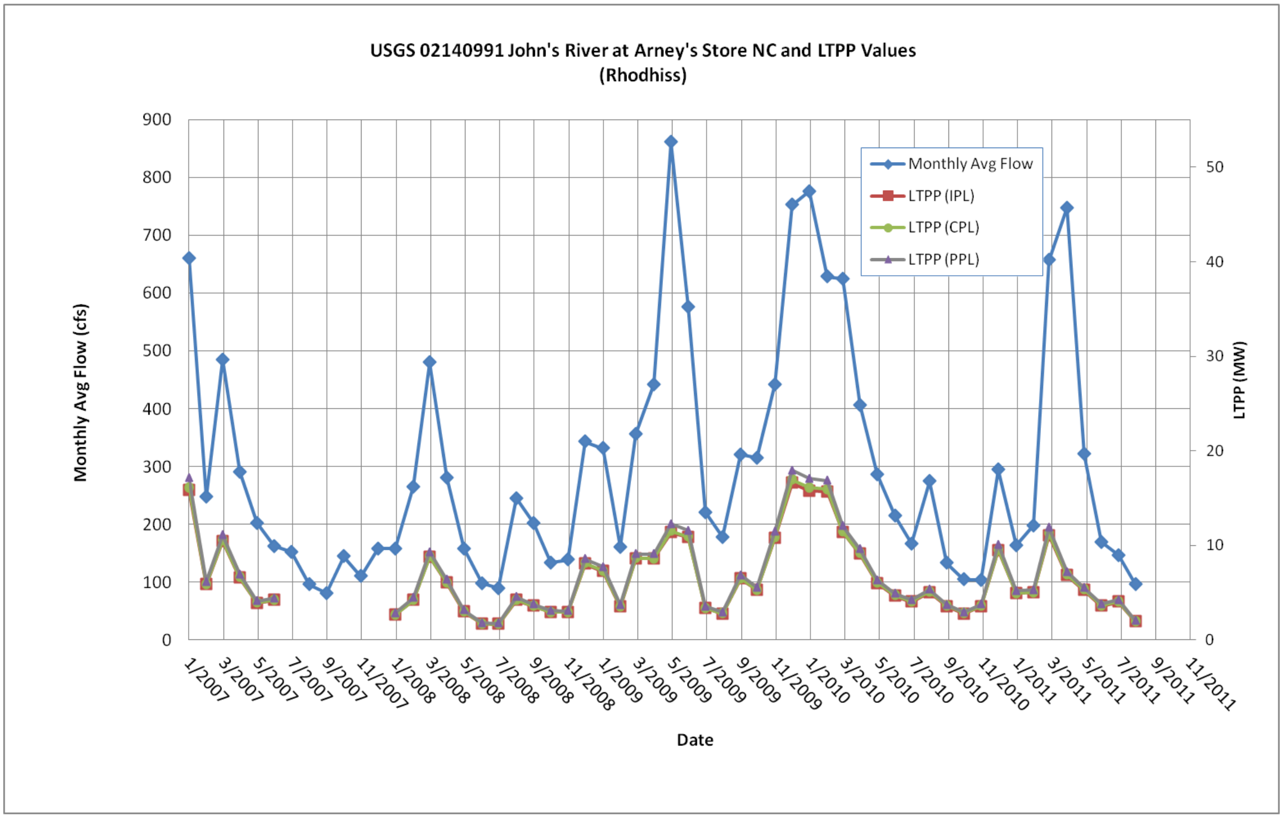


Figure 2.04-7: Monthly average hydrological flow and plant production potential trend for 2007-2011

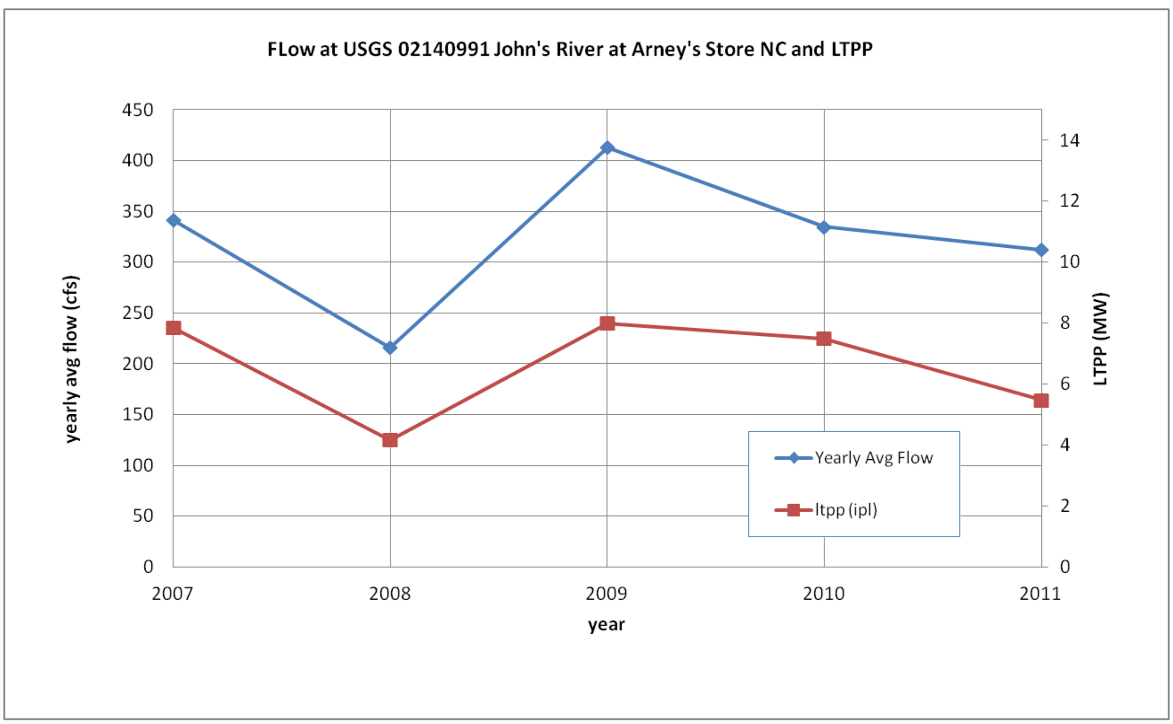


Figure 2.04-8: Yearly average flow and LTPP trend for 2007-2011

Appendix 2.05 – Examples of Results from Optimization-based Performance Analyses

Revision 1.1, 10/12/2012

Introduction – Appendix 2.05 provides some typical examples of results from optimization-based performance analyses for a three-unit hydro plant. The results include unit performance curves, optimized plant performance curves, operation efficiency analyses, and scheduling analyses.

Unit and Plant Performance Curves – The Initial Performance Level (IPL) unit performance curves are based on turbine net head efficiency data from S. Morgan Smith Company dated July 9, 1930, generator efficiency data from Westinghouse Electric & Manufacturing Company dated February 28, 1927, and intake/penstock head loss information from American Hydro's response to Specification 00003.03.0112.00-F14-001. The derived IPL unit flow versus unit power curves at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft are presented in Figure 2.05-1, and the corresponding gross head unit efficiencies versus power are provided in Figure 2.05-2.

The Current Performance Level (CPL) unit performance curves for U1 and U3 are based on the IPL curves, with an additional assumed degradation (i.e., a net head turbine efficiency loss) of 2.5%. The derived CPL unit flow versus unit power curves for U1 and U3 at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft are presented in Figure 2.05-3, and the corresponding gross head unit efficiencies versus power for U1 and U3 are provided in Figure 2.05-4. The Current Performance Level (CPL) unit performance curves for U2 are based on the IPL generator curve and the net head turbine efficiency curves provided by the turbine manufacturer, American Hydro Corporation, at the time of the runner upgrade and included in American Hydro's response to Specification 00003.03.0112.00-F14-001. The CPL unit flow versus unit power curves for U2 at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft are presented in Figure 2.05-5, and the corresponding gross head unit efficiencies versus power for U2 are provided in Figure 2.05-6.

The Potential Performance Level (PPL) unit performance curves for U1, U2, and U3 are based on the CPL curve for the upgraded U2, 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. The PPL unit flow versus unit power curves for U1, U2, and U3 at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft are presented in Figure 2.05-7, and the corresponding gross head unit efficiencies versus power for U1, U2, and U3 are provided in Figure 2.05-8.

Based on the IPL, CPL, and PPL unit performance curves, the optimization engine (see Appendix 2.03) was used to compute optimized plant gross head efficiencies. The IPL, CPL, and PPL optimized plant gross head efficiencies versus plant power at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft are presented in Figures 2.05-9 through 2.05-11, respectively. Figure 2.05-12 shows the distribution of yearly generation with gross head for 2007 through 2011. Typically, 90% or more of the plant's generation occurs at a gross head of 60 ft. Figure 2.05-13 compares optimized plant gross head efficiency versus plant power for IPL, CPL, and PPL at a gross head of 60 ft.

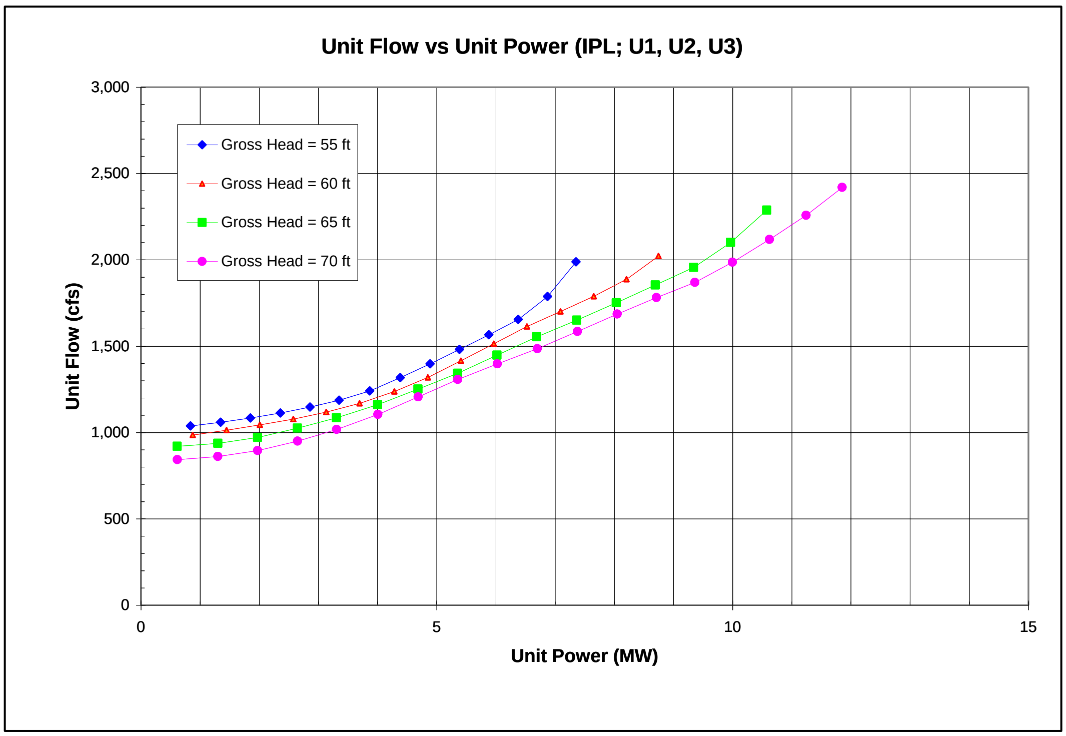


Figure 2.05-2: Unit Flow versus Unit Power (IPL; U1, U2, U3)

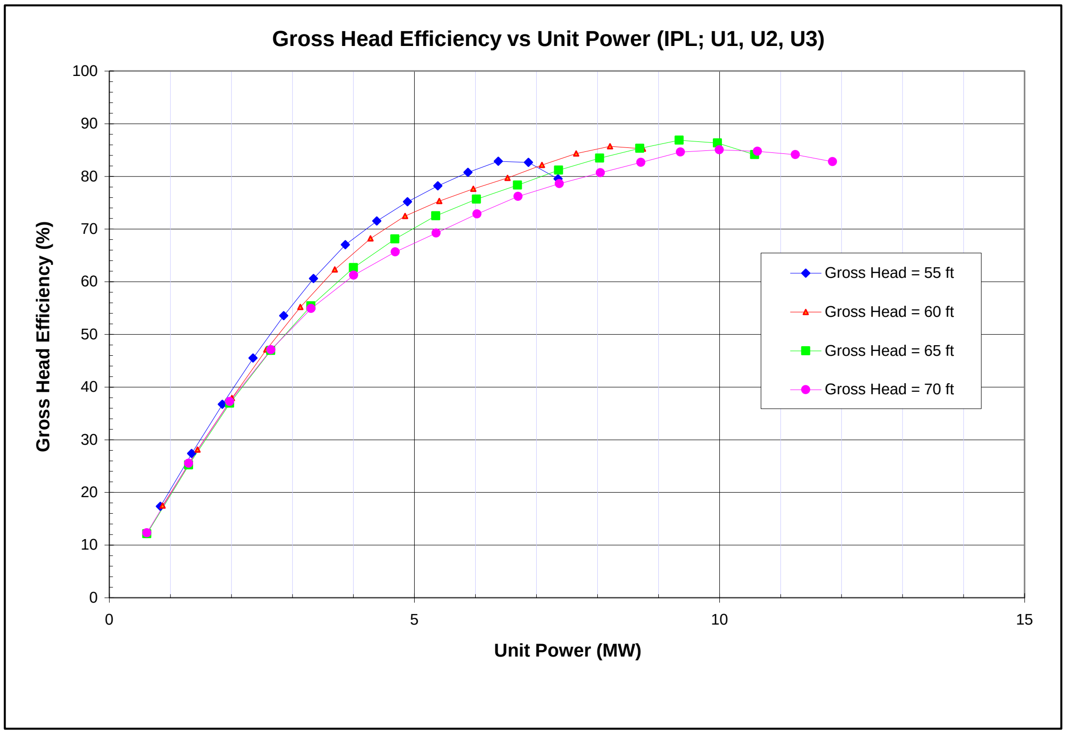


Figure 2.05-2: Unit Gross Head Efficiency versus Unit Power (IPL; U1, U2, U3)

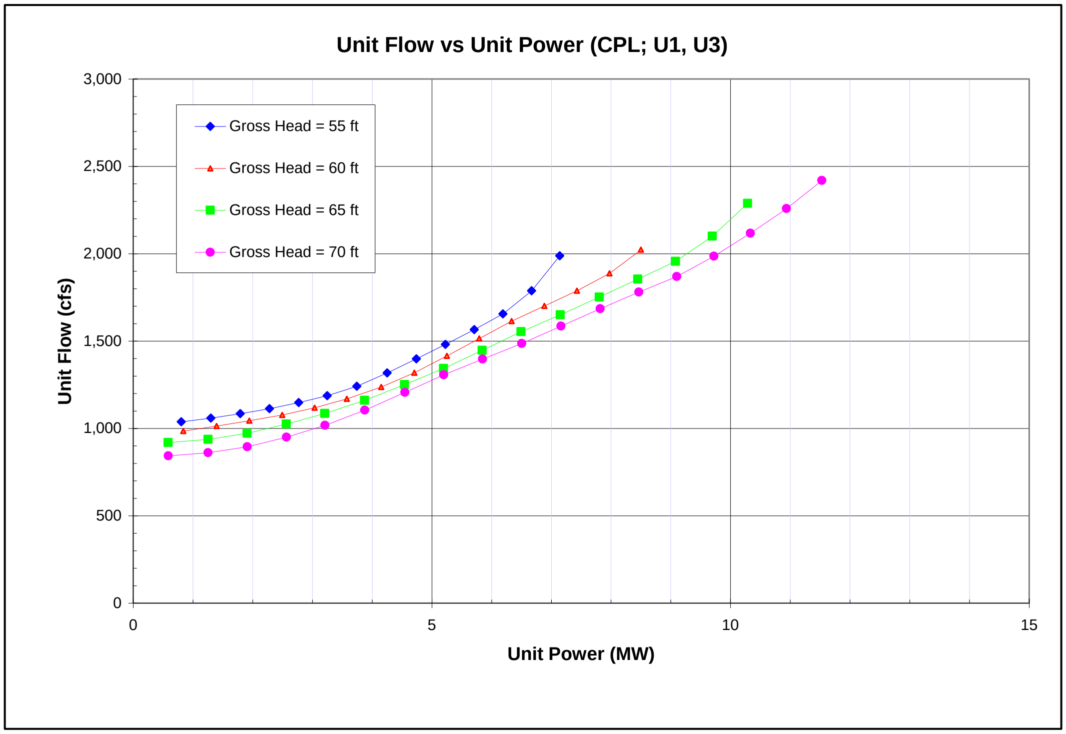


Figure 2.05-3: Unit Flow versus Unit Power (CPL; U1, U3)

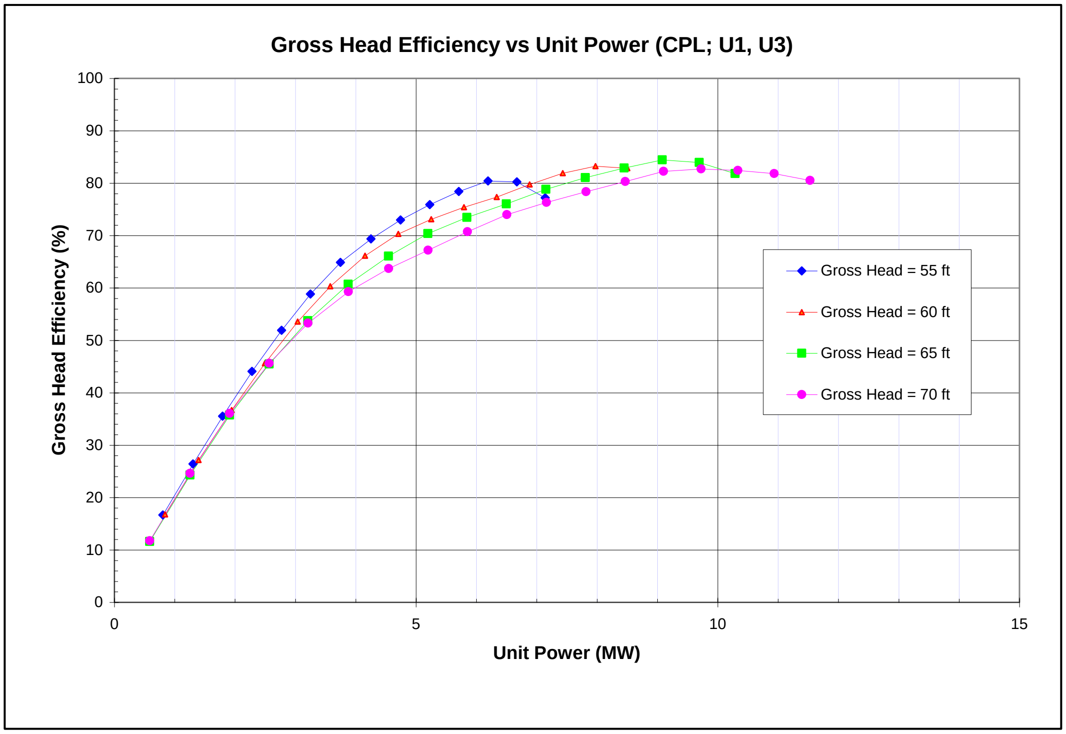


Figure 2.05-4: Unit Gross Head Efficiency versus Unit Power (CPL; U1, U3)

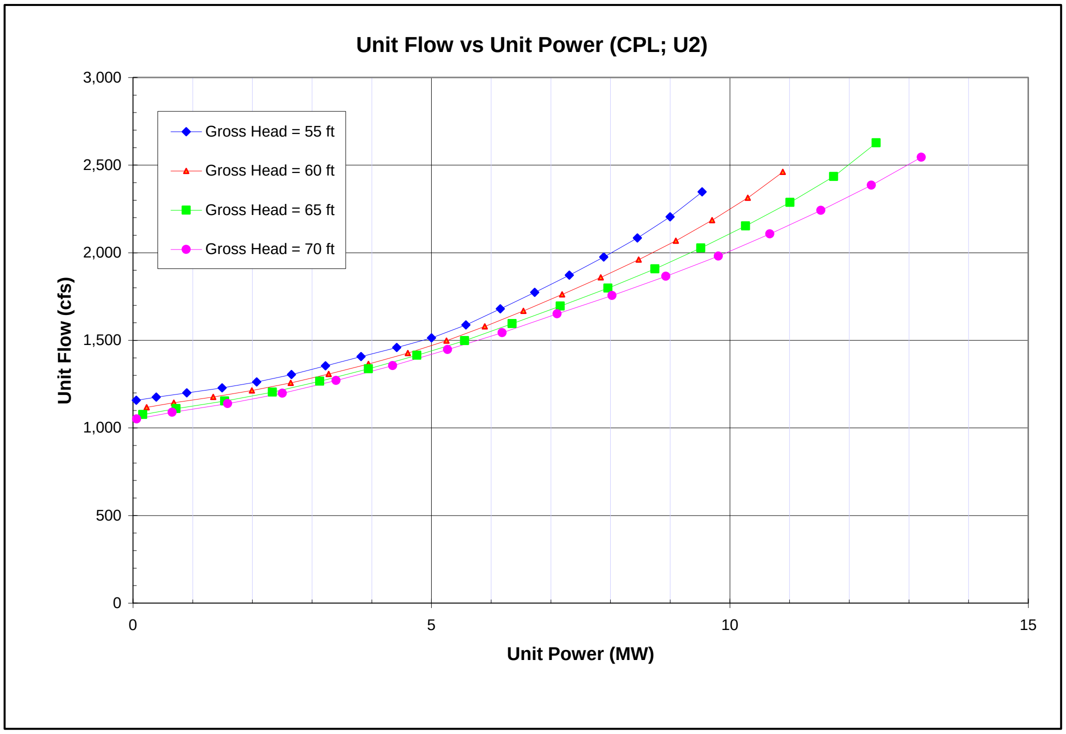


Figure 2.05-5: Unit Flow versus Unit Power (CPL; U2)

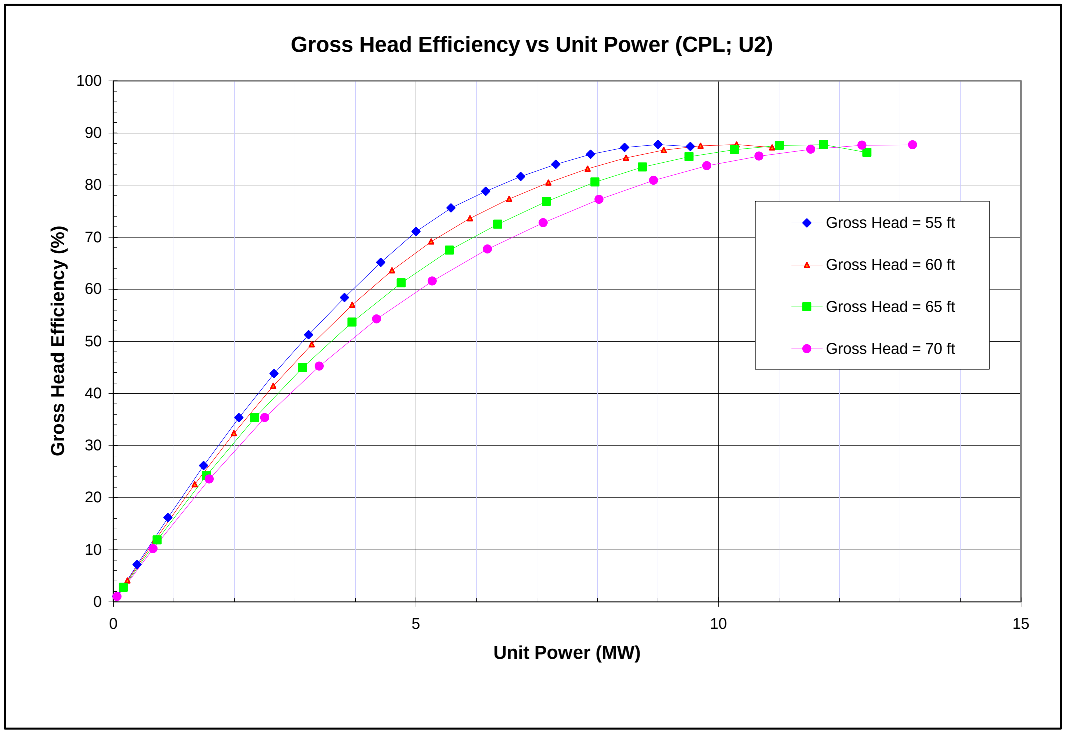


Figure 2.05-6: Unit Gross Head Efficiency versus Unit Power (CPL; U2)

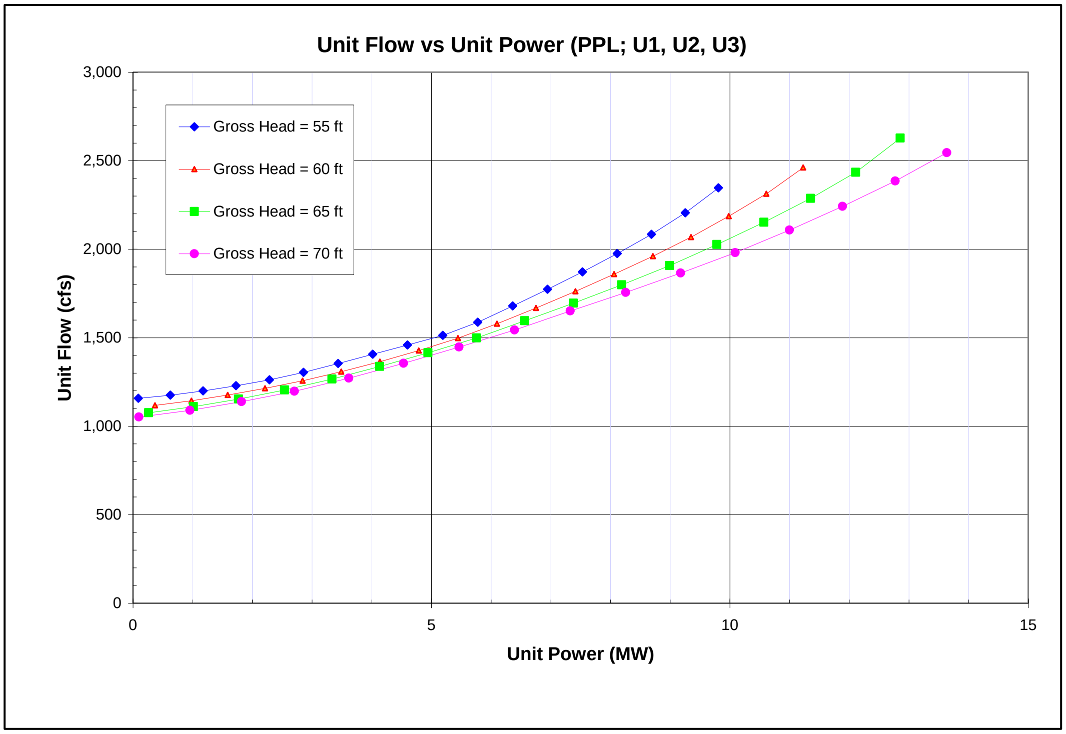


Figure 2.05-7: Unit Flow versus Unit Power (PPL; U1, U2, U3)

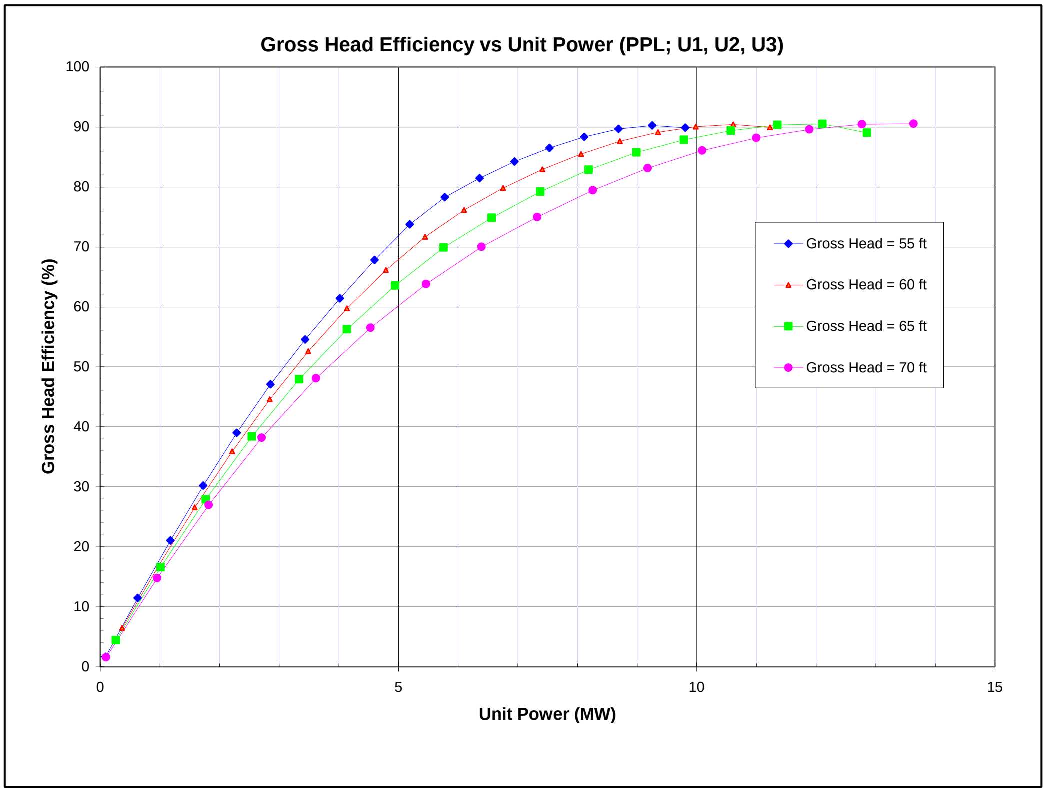


Figure 2.05-8: Unit Gross Head Efficiency versus Unit Power (PPL; U1, U2, U3)

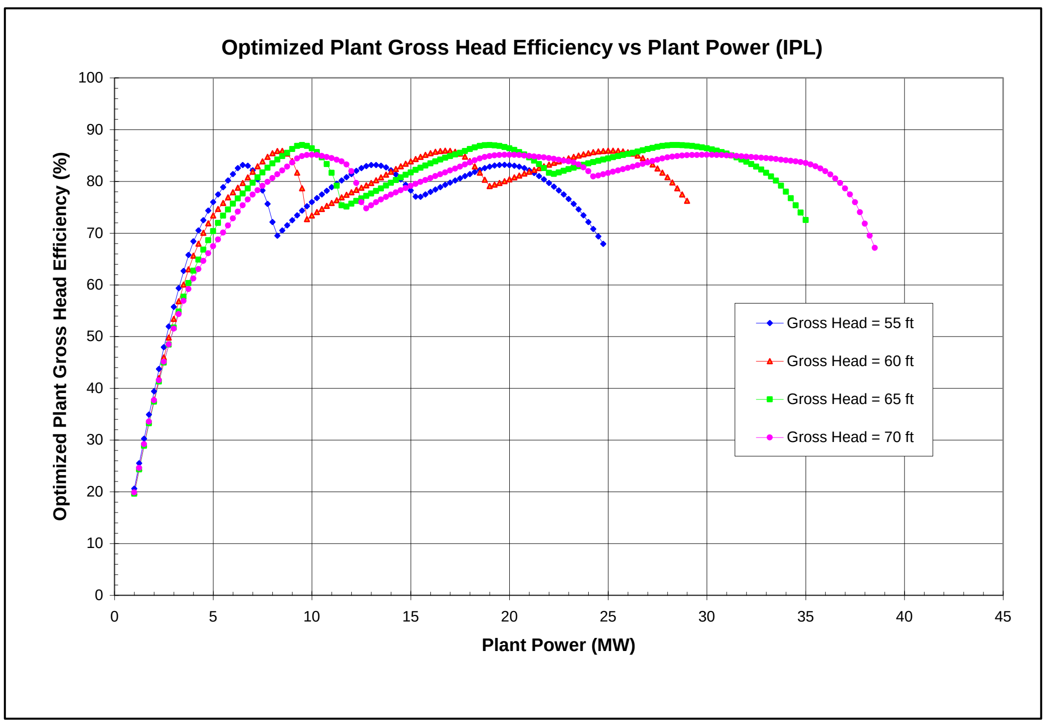


Figure 2.05-9: Optimized Plant Gross Head Efficiency versus Plant Power (IPL)

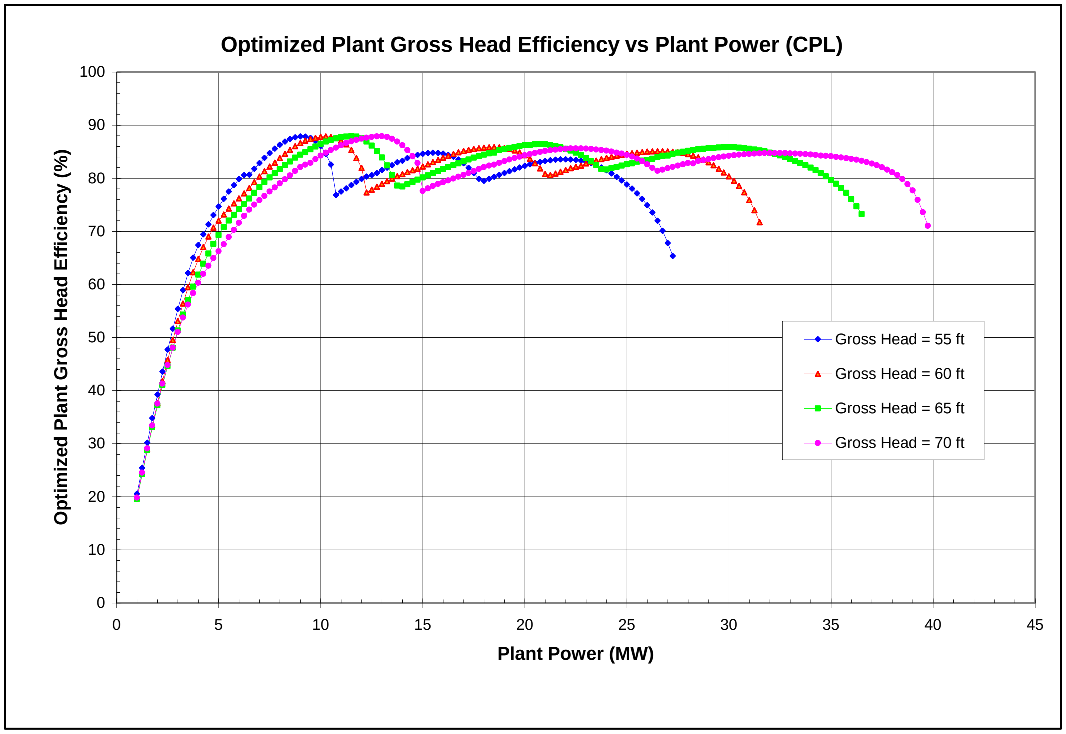


Figure 2.05-10: Optimized Plant Gross Head Efficiency versus Plant Power (CPL)

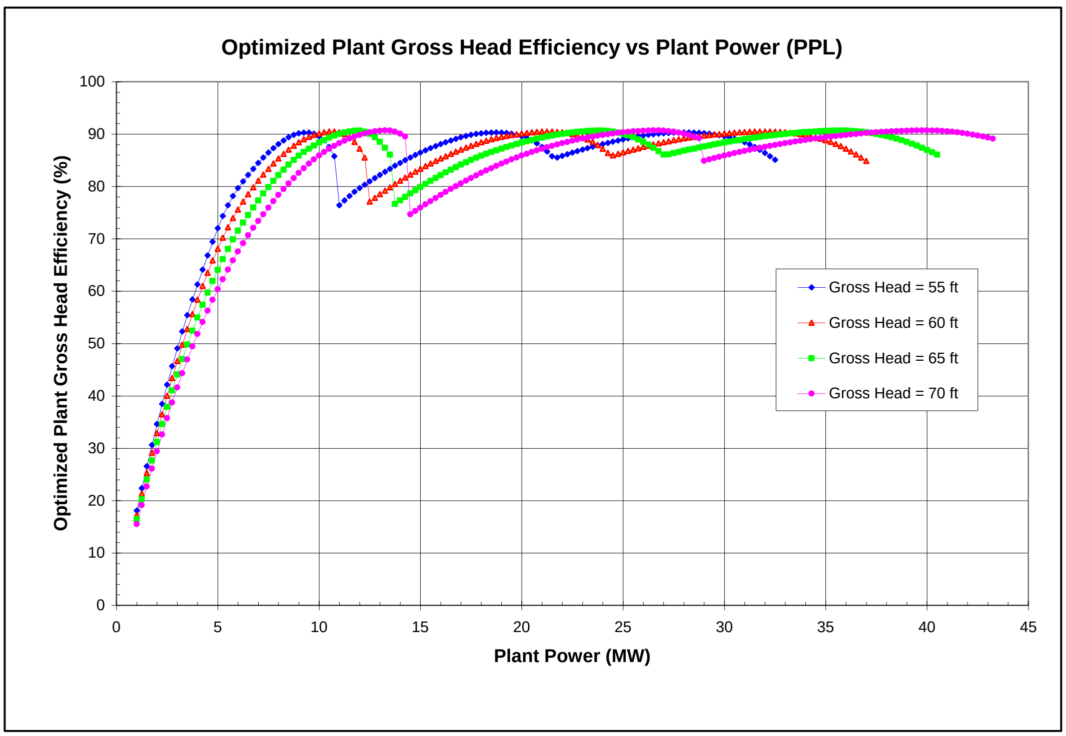


Figure 2.05-11: Optimized Plant Gross Head Efficiency versus Plant Power (PPL)

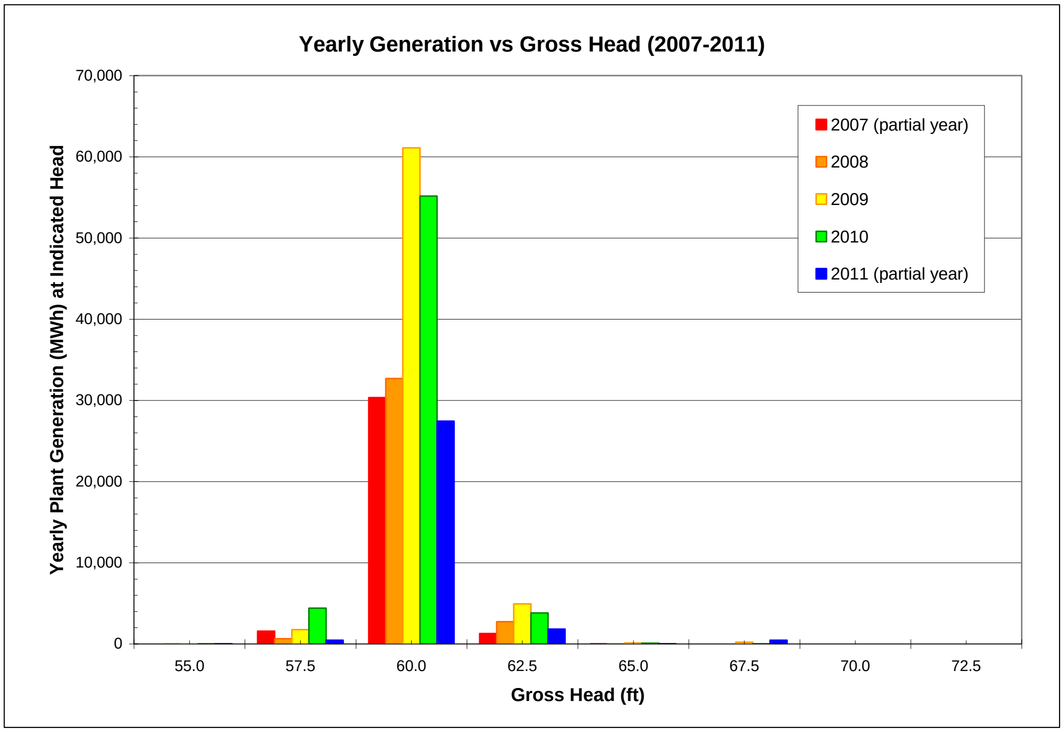


Figure 2.05-12: Distribution of Yearly Generation with Gross Head (2007 – 2011)

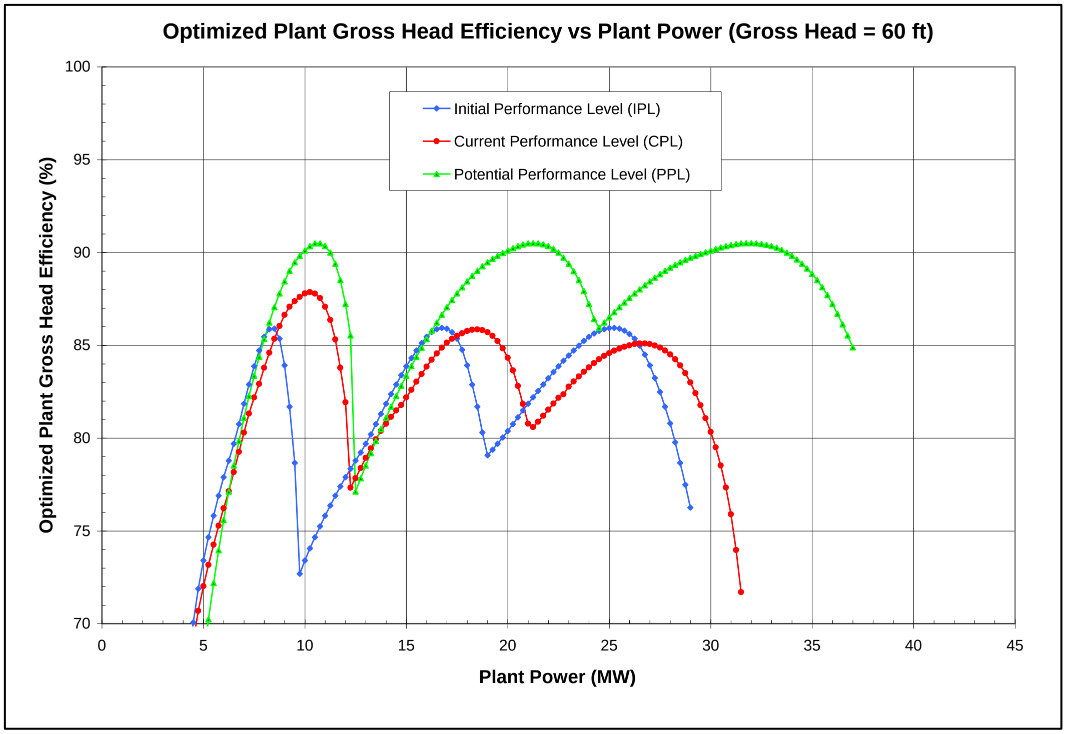


Figure 2.05-13: Optimized Plant Gross Head Efficiency versus Plant Power (GH = 60 ft)

Operation Efficiency Analyses – The Operation Efficiency Analyses use unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch. Computational steps for determining the operation efficiency are discussed in the Performance Assessment Manual. 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.

Results from the operation efficiency analyses are summarized in Table 2.05-1. Potential efficiency improvements due to improved optimization, while producing the same power at the same time, range from a low of 1.5% for 2008 to a high of 3.0% for 2010, with an average of 2.3%.

Year	Improvement (MWh)	Improvement (%)
2007	1,074	2.6
2008	633	1.5
2009	1,542	2.1
2010	2,027	3.0
2011	757	2.3

Notes:
1. The 2007 results only include generation from January 1, 2007, through June 30, 2007.
2. The 2011 results only include generation from January 1, 2011, through August 22, 2011.
3. Operation efficiency results show potential improvements while continuously meeting the actual generation.
4. Aeration effects are not included in the operation efficiency analyses.

Table 2.05-1: Summary of Results from Operation Efficiency Analyses

Typical results from the operation efficiency analyses are provided in Figures 2.05-14 through 2.05-17. In these figures, the red line represents the actual U1 generation, the blue line represents the actual U2 generation, and the violet line represents the actual U3 generation. The dotted red line represents the optimized U1 generation, the dotted blue line represents the optimized U2 generation, and the dotted violet line represents the optimized U3 generation. In addition, the green line refers to the secondary axis on the right and represents the potential plant efficiency improvement due to optimized generation.

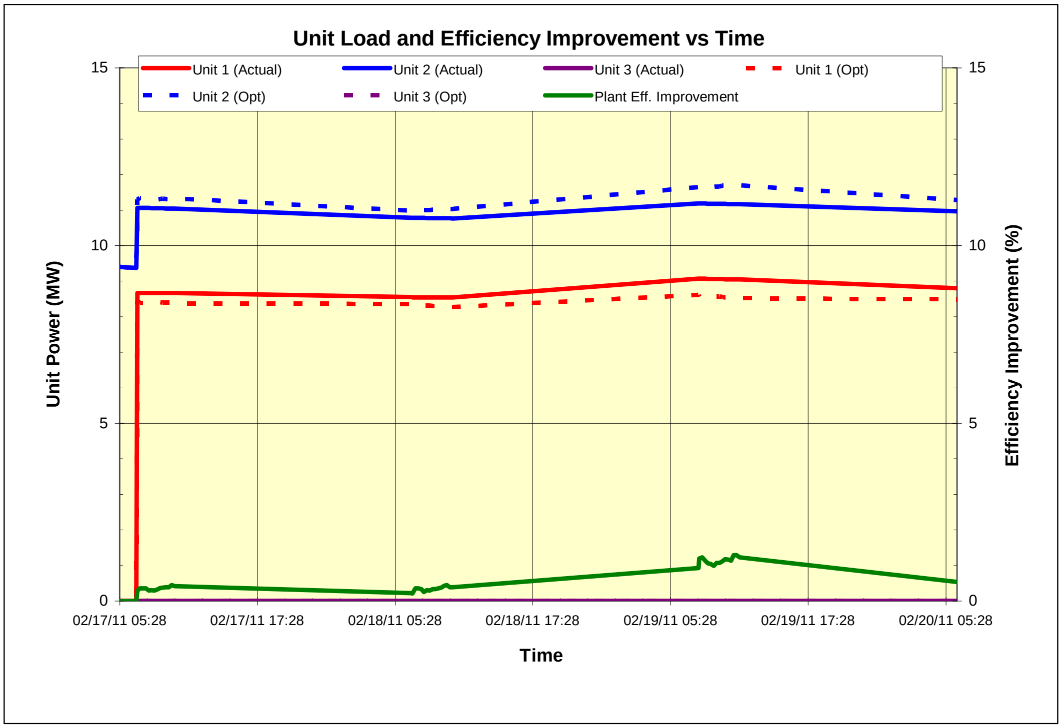


Figure 2.05-14: Typical Operation Efficiency Results (February 17-20, 2011)

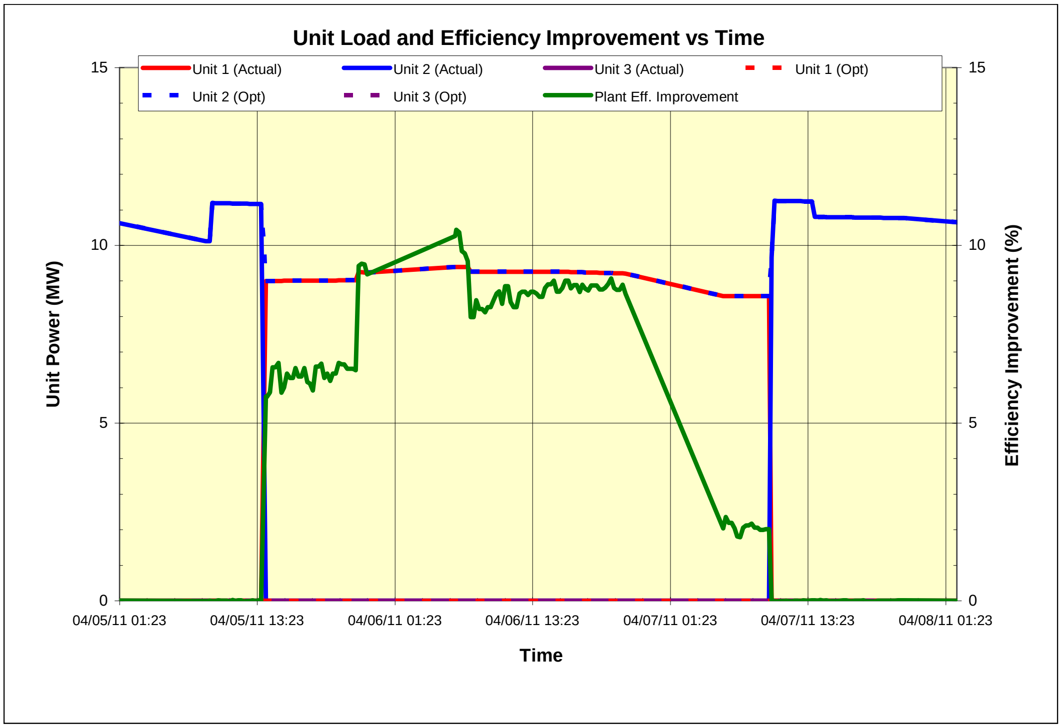


Figure 2.05-15: Typical Operation Efficiency Results (April 5-7, 2011)

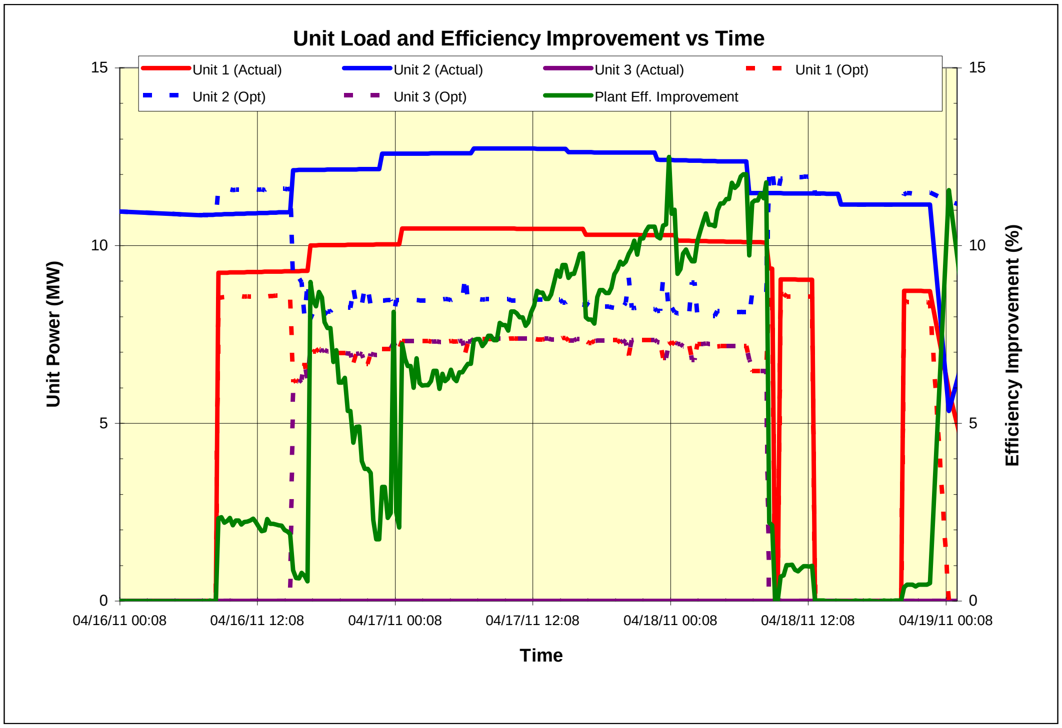


Figure 2.05-16: Typical Operation Efficiency Results (April 16-18, 2011)

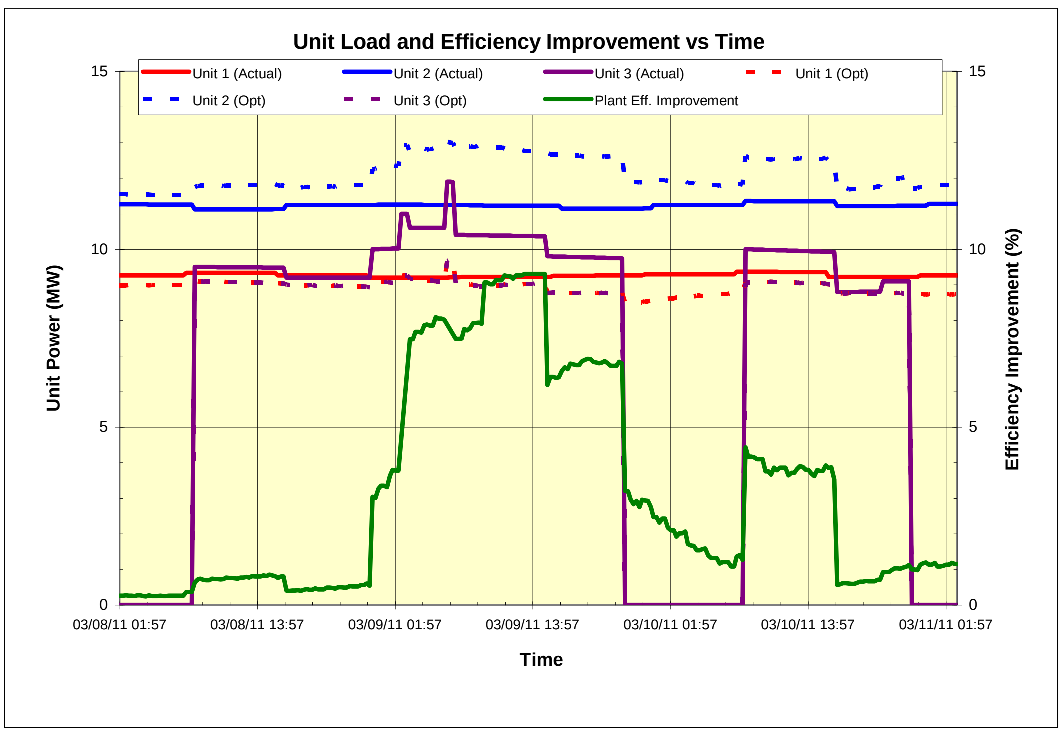


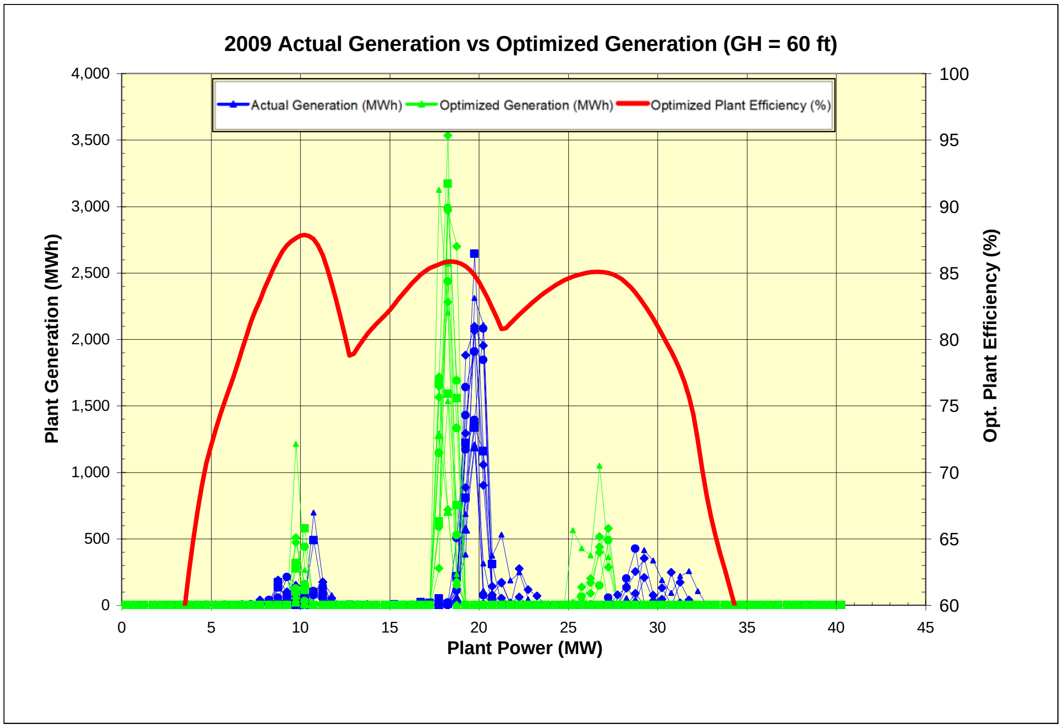
Figure 2.05-17: Typical Operation Efficiency Results (March 9-11, 2011)

Much of the plant's generation occurs with U1 and U2 operating near – but not at – the optimized power levels, as shown in Figure 2.05-14. Minor adjustments in the U1 and U2 power levels result in plant efficiency improvements ranging from 0.3% to 1.2%. On numerous occasions, U1 is the only unit in operation but U2 is more efficient, as shown in Figure 2.05-15. Here, the potential improvements in plant efficiency range from 2% to 10.4%. Figure 2.05-16 presents an example showing the plant generating with U1 and U2 only, when significant efficiency improvements, ranging from 2.2% to 12.5%, could be achieved with the proper combination of U1, U2, and U3. Figure 2.05-17 shows plant operation when all three units are operating. With adjustments in the unit power levels, plant efficiency improvements ranging from 0.5% to 9.3% could be achieved.

Scheduling Analyses – 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 scheduling analyses are shown in the Performance Assessment Manual. 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, market conditions, and other restrictions permit, more efficient energy generation is achieved.

Figure 2.05-18 provides typical results from scheduling analyses, showing 2009 results for a gross head of 60 ft. The optimized plant gross head efficiency for 60 ft is shown in red, the actual 2009 monthly generation versus plant power is shown in blue, and the optimized 2009 monthly generation versus plant power is shown in green. Note that the actual generation values tend to occur at power levels past the peak efficiencies for one-unit, two-unit, and three-unit operation, while the optimized generation values correspond to the peak efficiencies.

Using IPL, CPL, and PPL optimized plant efficiency curves, quantitative generation analyses were conducted. Using the CPL characteristics and the archival plant data, the quantity of water used per hour was computed for the entire 2007-2011 data set. That quantity of hourly "fuel" was applied to the appropriate IPL, CPL, or PPL optimized plant gross head efficiency curve to compute optimized generation. Results from the generation analyses are provided in Tables 2.05-2 through 2.05-4 for IPL, CPL, and PPL plant characteristics, respectively. In each table, the actual generation is used as the baseline.



Year	Actual Annual Generation (MWh)	Optimized Annual Generation (IPL) (MWh)	Improvement (MWh)	Improvement (%)
2007	33,472	34,880	1,408	4.2
2008	35,313	36,328	1,015	2.9
2009	67,362	70,545	3,183	4.7
2010	63,291	66,529	3,238	5.1
2011	29,377	30,457	1,081	3.7

Notes:
1. The 2007 results only include generation from January 1, 2007, through June 30, 2007.
2. The 2011 results only include generation from January 1, 2011, through August 22, 2011.
3. The generation analyses show potential improvements while using the actual amount of water per hour.
4. Aeration effects are not included in the generation analyses.

Table 2.05-2: Summary of Results from Generation Analyses (IPL)

Year	Actual Annual Generation (MWh)	Optimized Annual Generation (CPL) (MWh)	Improvement (MWh)	Improvement (%)
2007	33,472	35,096	1,624	4.9
2008	35,313	36,389	1,076	3.1
2009	67,362	70,570	3,208	4.8
2010	63,291	67,071	3,781	6.0
2011	29,377	30,709	1,332	4.5

Notes:
1. The 2007 results only include generation from January 1, 2007, through June 30, 2007.
2. The 2011 results only include generation from January 1, 2011, through August 22, 2011.
3. The generation analyses show potential improvements while using the actual amount of water per hour.
4. Aeration effects are not included in the generation analyses.

Table 2.05-3: Summary of Results from Generation Analyses (CPL)

Year	Actual Annual Generation (MWh)	Optimized Annual Generation (PPL) (MWh)	Improvement (MWh)	Improvement (%)
2007	33,472	36,800	3,329	9.9
2008	35,313	38,344	3,031	8.6
2009	67,362	74,371	7,010	10.4
2010	63,291	70,243	6,952	11.0
2011	29,377	32,115	2,738	9.3

Notes:
1. The 2007 results only include generation from January 1, 2007, through June 30, 2007.
2. The 2011 results only include generation from January 1, 2011, through August 22, 2011.
3. The generation analyses show potential improvements while using the actual amount of water per hour.
4. Aeration effects are not included in the generation analyses.

Table 2.05-4: Summary of Results from Generation Analyses (PPL)

Avoidable Loss Analyses – The Avoidable Loss Analyses determine how the optimized dispatch could be improved by reducing avoidable losses. Avoidable losses typically include excessive trash rack losses, excessive penstock losses, and excessive tunnel losses. For this plant, insufficient data was available to evaluate avoidable losses.

Correlation Analyses – When continuous measurements of relative or absolute flow rate are available for each unit, correlation analyses can be computed to compare the measured efficiencies with the expected unit performance characteristics. For this plant, insufficient data was available for correlation analyses.

Discussion of Results from Performance Assessments And Analyses

For the plant analyses reported in this appendix, the potential plant generation improvements due to plant efficiency improvements from direct optimization, while producing the same power at the same time, averaged about 2.3% for the analyzed years, while the potential generation improvements from using the available water at the peak plant efficiencies averaged about 4.7%. The potential generation improvements from the combination of improved optimization, improved scheduling, and state of the art turbines and generators averaged about 9.8%. Because no aeration-related performance information was available, these performance analyses were conducted without considering aeration. Aeration-related performance testing should be conducted, and additional performance analyses should be completed to investigate the effects of aeration on the current performance level and to estimate the anticipated effects of aeration on the potential performance level.

For overall questions
please contact:

Brennan T. Smith, Ph.D., P.E.
Water Power Program Manager
Oak Ridge National Laboratory
865-241-5160
smithbt@ornl.gov

or

Qin Fen (Katherine) Zhang, Ph. D., P.E.
Hydropower Engineer
Oak Ridge National Laboratory
865-576-2921
zhangq1@ornl.gov