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Component Indicators for an Optimization-Based Hydro Performance Indicator

by

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INTRODUCTION

In *What Management Is*, Joan Magretta writes, "It may be the oldest saw in the book, yet it remains absolutely true: What gets measured gets managed. Without measurement, there is no performance." Typically, the performance measures for a hydroelectric generating facility or system include readily measured items such as expenditures and schedules for major capital projects, reductions in overall operations and maintenance expenses, bus-bar generation costs, and improvements to the equivalent forced outage rate. Although electricity generation is a primary production element, generation is typically tracked, but not used as a performance measure. Wide variations in annual hydrology, changing operational patterns due to market conditions, a variety of power system needs, and regulatory requirements for instream flows, recreational flows, fish spills, etc., can obscure the "line of sight" between individual actions, unit operations, plant operations, water resource system operations, and overall power system production.

Water resource systems are typically operated to achieve a balance among a variety of conflicting objectives, including navigation, flood control, power production, water supply, water quality, and recreation. With the advances in electronics and computers over the past several decades, many hydro systems now have on-line operating data for every unit and a sustained commitment to ensure accurate unit performance characteristics and appropriate use of the available performance information. Indicators can be constructed from these data to assess the performance of the hydro system at any desired level of detail.

This paper describes a hierarchical, optimization-based hydro performance indicator (OHPI) with four components, the operation efficiency, correlation efficiency, scheduling efficiency, and avoidable loss efficiency. The operation efficiency and correlation efficiency are fully implemented (March and Wolff, 2003; Wolff et al., 2002), and the scheduling efficiency and avoidable loss efficiency are currently being demonstrated and refined. These indicators enable managers and employee teams to evaluate how closely the actual plant dispatch matches the optimized plant dispatch, how closely archival unit characteristics match those derived from on-line data, how closely the actual plant load aligns with plant peak efficiency operating points, and whether appropriate maintenance activities, such as trash rack cleaning, are being implemented in a timely manner to minimize avoidable losses. These component indicators can be viewed hierarchically to understand performance at the unit level, the plant level, or the overall system level, and the component indicators can be displayed in easily understood units, including lost energy opportunity (LEO, in MWh), water conservation opportunity (WCO, in acre-feet), and lost revenue opportunity (LRO, in $).

The OHPI and its component indicators are computed using plant operational data, archival unit performance characteristics, an optimization engine, and an automated data analysis system (March and Wolff, 2003). The plant operational data is typically obtained from continuous, real-time monitoring systems that provide results with very high temporal resolution. The unit performance characteristics are derived from a combination of sources which include numerical and physical model tests, index (i.e., relative efficiency) tests, and absolute efficiency tests.

The OHPI provides an efficient means for benchmarking, prioritizing, and troubleshooting performance issues for a hydro plant or a system of plants, whether fully automated, partially automated, or manually operated. This ensures that the limited human and capital resources can be applied to identify and correct the most significant problems. The OHPI and its four component indicators are described in the following section. As examples, the paper presents operation efficiency and correlation efficiency results for a system with two different plants, including: (1) Plant 1, a run of the river plant with four Kaplan units; and (2) Plant 2, a run of the river plant with eighteen Francis units and three propeller units. The scheduling efficiency is evaluated for another run of the river plant with four Kaplan units, and the avoidable loss efficiency is presented for four Kaplan units of an eight unit powerhouse. The resulting analyses and subsequent test results demonstrate how these indicators can be used in ranking the plants and units in a hydro system to rapidly determine the largest contributors to lost energy production and to provide information for determining the root causes of the lost efficiency.

OHPI AND THE COMPONENT INDICATORS

This paper discusses four component indicators of the OHPI, including operation efficiency, correlation efficiency, scheduling efficiency, and avoidable loss efficiency. The OHPI is created from these indicators to represent the gains from achievable plant improvements in units that are directly relevant to management and plant personnel (i.e., energy, water, and revenue). When applied to different utilities or to different organizations within a utility, the OHPI and its components can be modified to accurately quantify only those performance measures applicable to a particular group. The OHPI provides the framework to analyze years of archival data, to obtain information and knowledge from the data, to prioritize actions, and to accurately quantify the effects those actions have on a utility's profitability.

Operation Efficiency

The operation efficiency compares the measured plant efficiency to the optimized plant efficiency while meeting the actual plant generation. The WaterView® optimization engine is used to compute the optimized plant efficiency using archival data. For each time step of the archival data, the optimization engine apportions the total plant load among the units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the measured plant load; matching the net head; operating each unit within minimum and maximum power limits; and meeting reactive power requirements). Note that the deficit in operation efficiency (100 minus the operation efficiency) represents the efficiency gain achievable by continuously optimizing the plant load. Water savings from optimized dispatch are converted into energy gains by assuming the water is converted into energy at the optimized plant efficiency, plant generation, and net head of the time step in which it occurs.

Correlation Efficiency

Optimized plant dispatch depends on accurate unit characteristics and well-maintained instrumentation, which are evaluated with a component indicator of the OHPI, the correlation efficiency. At each time step and for each unit within the system, a unit correlation efficiency deficit is computed as the absolute value of the difference between the expected unit characteristics used by the optimization engine and the measured unit characteristics acquired by on-line measurements of unit load, unit flow, unit gate and blade settings, headwater, and tailwater.

Linking the deficit in unit correlation efficiency to the efficiency losses associated with plant dispatch and caused by errors in unit characteristics is an important step in computing the correlation efficiency. With this link established, the energy losses for each unit can be computed, and the units within a system responsible for the largest energy losses can be identified. Currently, the simplifying assumption is made that a one percent correlation efficiency deficit will produce a corresponding one percent unit efficiency loss. In reality, the effects of errors in unit characteristics on optimized plant dispatch will depend on the plant configuration, the schedule request, and the distribution of the correlation efficiency deficit among the units. A previous analysis, which examined the effects of errors in unit characteristics on optimized dispatch, suggests that the assumption is an upper bound.

Scheduling Efficiency

The scheduling efficiency, which evaluates how closely actual plant loads align with the peak efficiency points for a plant, is the third component of the OHPI. Figure 1 presents individual unit efficiency curves and an overall plant efficiency curve. The 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. This curve shows that there are operating regions with plant efficiencies a few percent higher than the cusps of the curve. By scheduling plant loads to align with peak operating efficiency regions, more efficient energy generation is achieved.

The scheduling efficiency is computed by first determining the location of the actual plant load with respect to the various regions on the overall plant efficiency curve. Regions are separated by the cusps on the plant efficiency curve. For example region 2 of Figure 1 is located in the interval from 27 to 44 MW with an associated peak efficiency of 89.7%. Energy generated at the plant's maximum sustainable load (MSL) is not included in the computation because MSL is a constraint imposed by system power demands or by excessive inflows to a reservoir. Energy gains are computed by converting the water used for a given time step to energy at the peak plant efficiency and at the measured plant head. The difference between the peak and actual plant energy generation quantifies the gains achievable with optimized plant scheduling. This analysis is particularly applicable to larger systems in which changes in load at one plant can be compensated by other plants.

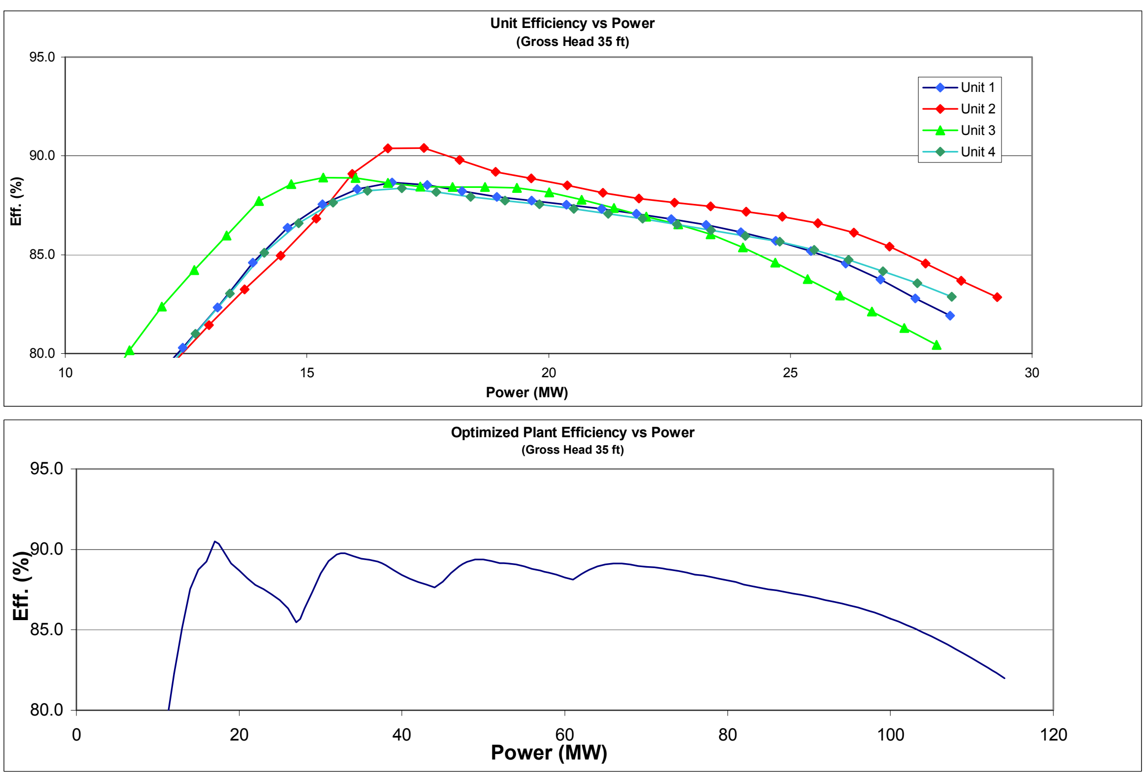

Figure 1: Individual Unit and Optimized Plant Efficiency Curves

Avoidable Loss Efficiency

The avoidable loss efficiency quantifies energy losses that can be minimized with appropriate maintenance activities. Trash rack fouling is the most common avoidable loss occurring in hydroplants. Penstock fouling caused by biological growth and losses due to penstock or tunnel degradation can also be addressed with this indicator.

This component indicator is computed by first quantifying the head loss that occurs for the base case, or "clean" condition. By comparing the on-line differential head measurement to the base case differential head measurement, the energy losses produced by the fouling can be determined. The avoidable loss efficiency is computed by dividing the actual energy generation by the energy generation that would have been achieved with the same quantity of water while operating at the base case condition. Details of the head loss calculations are presented elsewhere (Jones and March, 1997).

Calculating the Optimization-Based Hydro Performance Indicator

The Optimization-Based Hydro Performance Indicator is computed by first summing, for the entire system, the energy losses derived from the appropriate component indicators. The total system energy (which is the total energy that would have been generated if the plant produced energy at only peak plant efficiency points, if all units in all plants were optimized based on unit characteristics with no errors, and if there were no avoidable energy losses) is also required. The OHPI is computed from these terms by subtracting the summed losses from the total energy and then dividing the resulting value by the system energy. This result, created from data for all units within a system for the time period of interest, represents how well the system has been optimized.

The efficiency gains identified by the OHPI and for each indicator are converted into three measures: (1) lost energy opportunity (LEO); (2) lost revenue opportunity (LRO); and (3) water conservation opportunity (WCO). The lost energy opportunity represents the additional energy that would have been generated if the energy losses identified by the indicators were eliminated. The WCO represents the water that could have been saved by optimized dispatch and stored rather than used to produce additional energy. LRO is the corresponding revenue that would have been gained from the additional energy, based on the spot market price for the given time step. These measures represent gains from achievable plant improvements in units that are directly relevant to management and plant personnel (i.e., energy, water, and revenue).

The supporting analyses for the component indicators mirror the hierarchical structure of the hydro system. For example, Figure 2 presents the structure that is used for the correlation efficiency analysis. The data used are individual unit data, separated into head intervals which are within a Zone 1 tolerance as defined in the ASME performance test code for hydroturbines, PTC 18-2002 (ASME, 2002). This allows the proper application of the appropriate affinity relationships to flow and power data. For a given head level, the data are presented in a series of plots comparing expected performance to measured performance. The LEO, LRO, and WCO measures are computed at the head level and summed to the unit, plant, and system level. The hierarchical data structure enables a manager or performance engineer to rapidly rank the plants and units by performance, to identify the poorest performing plants and units, and to establish root causes for the poor performance.

The multi-level structure is adapted to a specific system by adding nodes at each level in a manner similar to adding file directories within widely used file management programs for personal computers. For example, Figure 3 presents a four-level structure adapted to a hypothetical two-plant system with each plant containing a different number of units and with one nominal head interval for each unit. Most systems are considerably more complex, but even complex systems can be readily configured and analyzed with this approach.

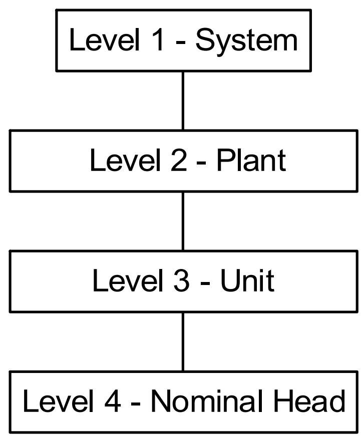

Figure 2: Four-Level, Hierarchical Data Analysis Structure

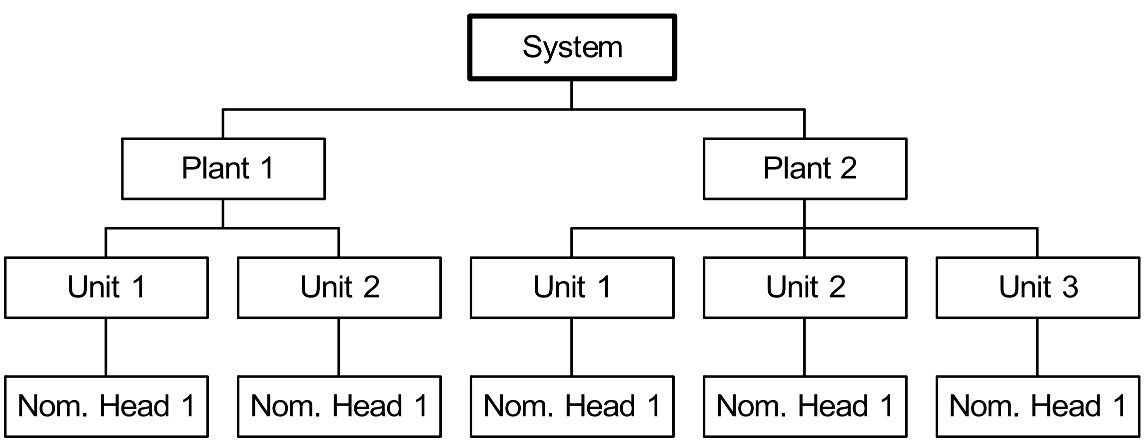

Figure 3: Four-Level Structure Configured for a System

Figure 4 presents a process diagram for the data analyses. DataWolff™, an Excel-based general-purpose program for automated data analyses, performs the overall OHPI analyses. DataWolff is configured with an analysis script that creates the hierarchical structure and defines the analysis steps (for example, defining the data to import, defining the filters, specifying the calculations, and defining which plots to create). Because all calculation procedures are contained in external libraries, analysis scripts can support a wide variety of computations. Within the OHPI analysis script, the WaterView optimization module computes optimized plant efficiencies for the operation efficiency indicator. Once the script is created, the data analyses can be fully automated. The analysis results are contained in a series of Excel workbooks corresponding to the hierarchical structure of the analyses.

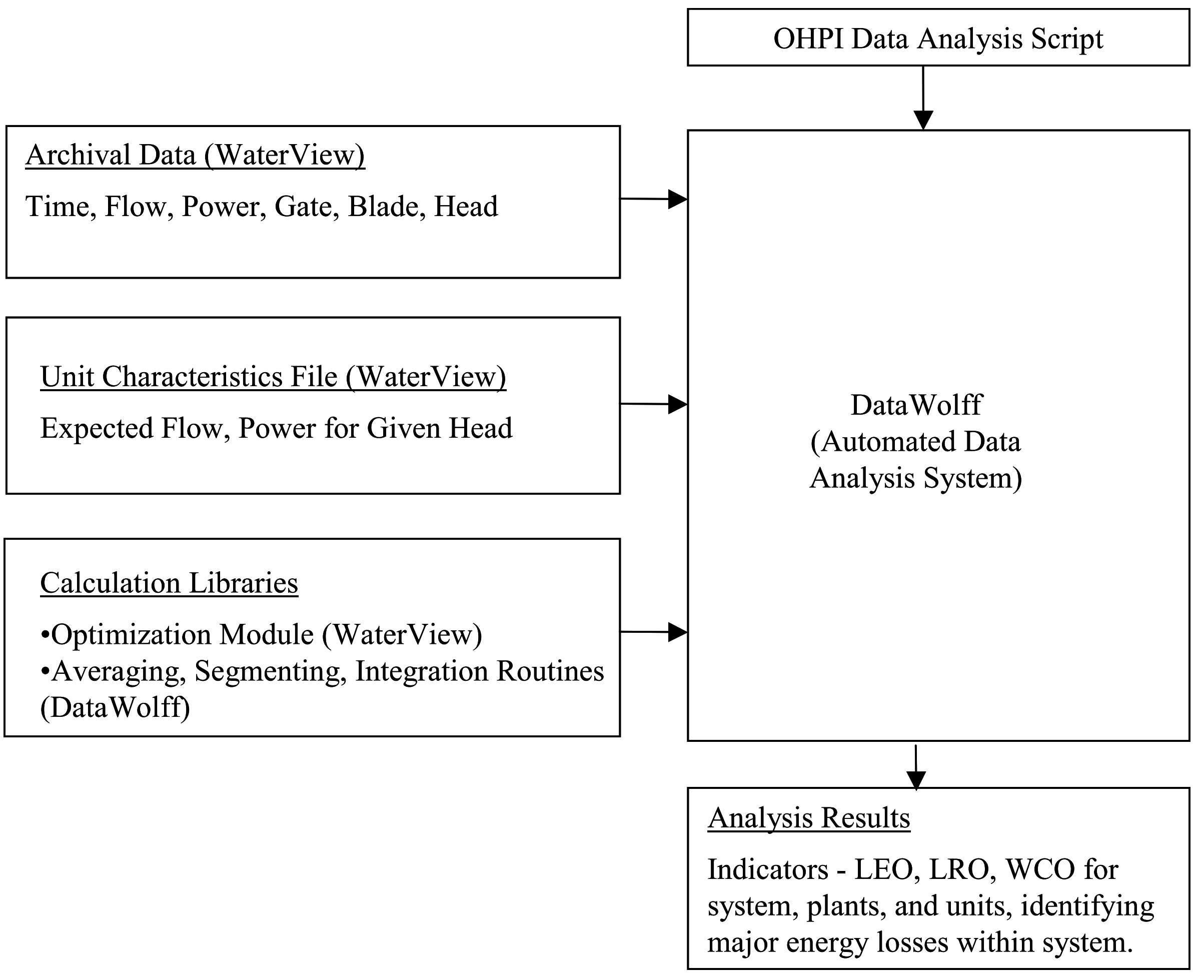

Figure 4: Data Analysis Process Diagram

RESULTS FROM INDICATOR ANALYSES AND SUBSEQUENT TESTS

The following results illustrate three different applications of the OHPI and its component indicators. The first example demonstrates the operation and correlation efficiencies for a hydro system with two hydro plants: (1) Plant 1, a plant with four Kaplan units; and (2) Plant 2, a plant with eighteen Francis units and three propeller units (March and Wolff, 2003). The second example demonstrates the scheduling efficiency component for a run of the river hydro plant with four Kaplan units. The third example demonstrates an avoidable loss efficiency analysis to evaluate trash rack losses for four of the horizontal bulb units in an eight unit powerhouse. These analyses were performed with archival data acquired at 5 to 15 minute intervals over the course of several years. The following discussion demonstrates the utility of the OHPI results in rapidly identifying and ranking the more poorly performing plants and units within a system and in troubleshooting the root causes for the various performance losses.

Example 1 – Operation Efficiency, Correlation Efficiency, and OHPI

The system level of the analysis contains an overall OHPI, which has a value of 93.1% for the year. This represents a deficit of 6.9% from a fully optimized system and merits further investigation. Figure 5 shows three plots that separate the OHPI into the operation and correlation efficiencies at both the system level and the plant level. The system operation efficiency of 97.3% shows that improvements in optimization are possible.

The operation efficiencies for Plant 1 and Plant 2, presented in Figure 5, are 99.9% and 96.6%, respectively, with corresponding LEO values of 500 MWh and 73,500 MWh. The LEO for Plant 2 of 73,500 MWh corresponds to a LRO of $1,740,000 and a WCO of 731,000 acre-feet. This demonstrates that there is significant room for improvement at Plant 2, while little optimization gain appears to be achievable at Plant 1. Plant 1's high operation efficiency, approaching 100%, can be readily understood by examining Figure 6, which presents unit characteristics for Plants 1 and 2 for a given head. Because all units in Plant 1 have almost identical unit characteristics, which are relatively flat over most of the operating region, optimized plant dispatch is achieved easily. In contrast, Plant 2 includes multiple units with significantly different characteristics, so this plant presents a much greater challenge in optimizing the generation.

Plant 2, which is used extensively for automatic generation control (AGC), has been typically set to operate with a base load and a participation (swing) load. The individual units are manually configured to match the plant's overall AGC requirements. Typically, the base load remains constant, and an AGC control signal varying between –1 and +1 controls the swing load. The minimum control setting can decrease each unit's base load up to the swing load, and the maximum control can increase the base load up to the swing load (Wolff et al., 2002).

Optimizing a diverse set of units is readily achievable with optimization programs and automation systems (Adams et al., 1999). Re-computing the optimized plant dispatch on a continual basis as the plant load request changes and setting the load for each unit accordingly provides a more efficient means for providing automatic generation control. This approach is called optimization-based automatic generation control, or OGC (Giles et al., 2003). Additional analyses indicate that Plant 2's operations under the current form of conventional AGC are responsible for approximately 60% of the plant's avoidable energy losses (Wolff et al., 2002).

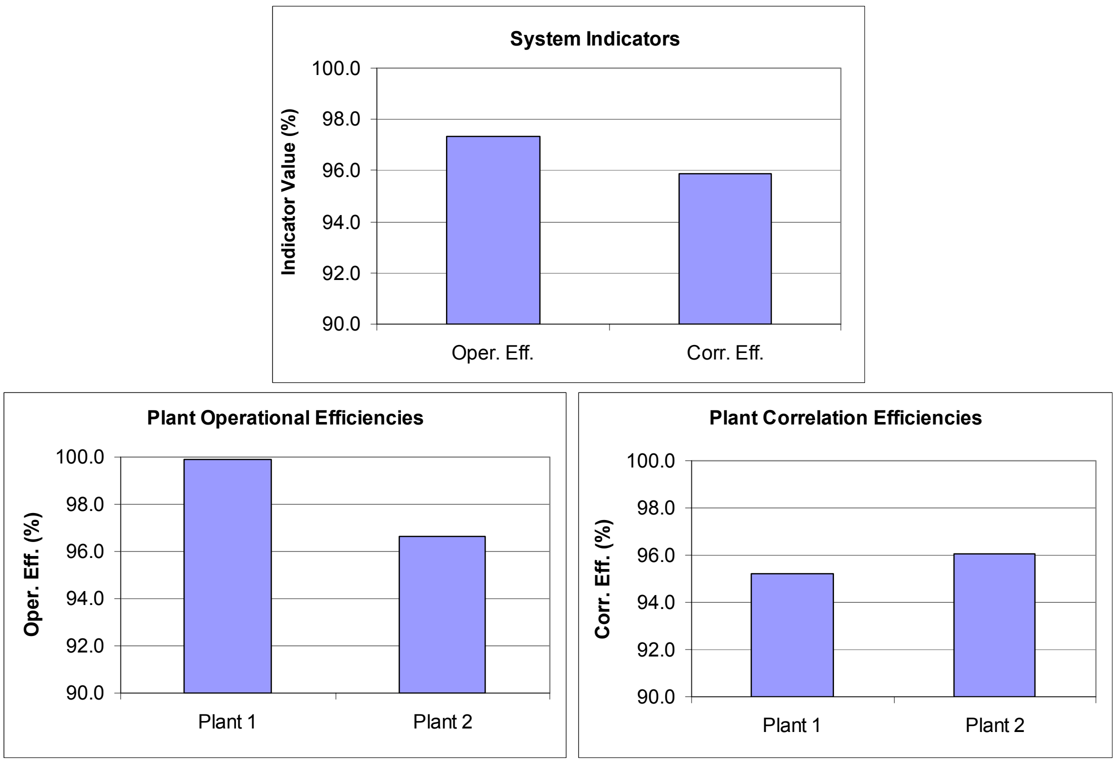

Figure 5: System and Plant Indicators

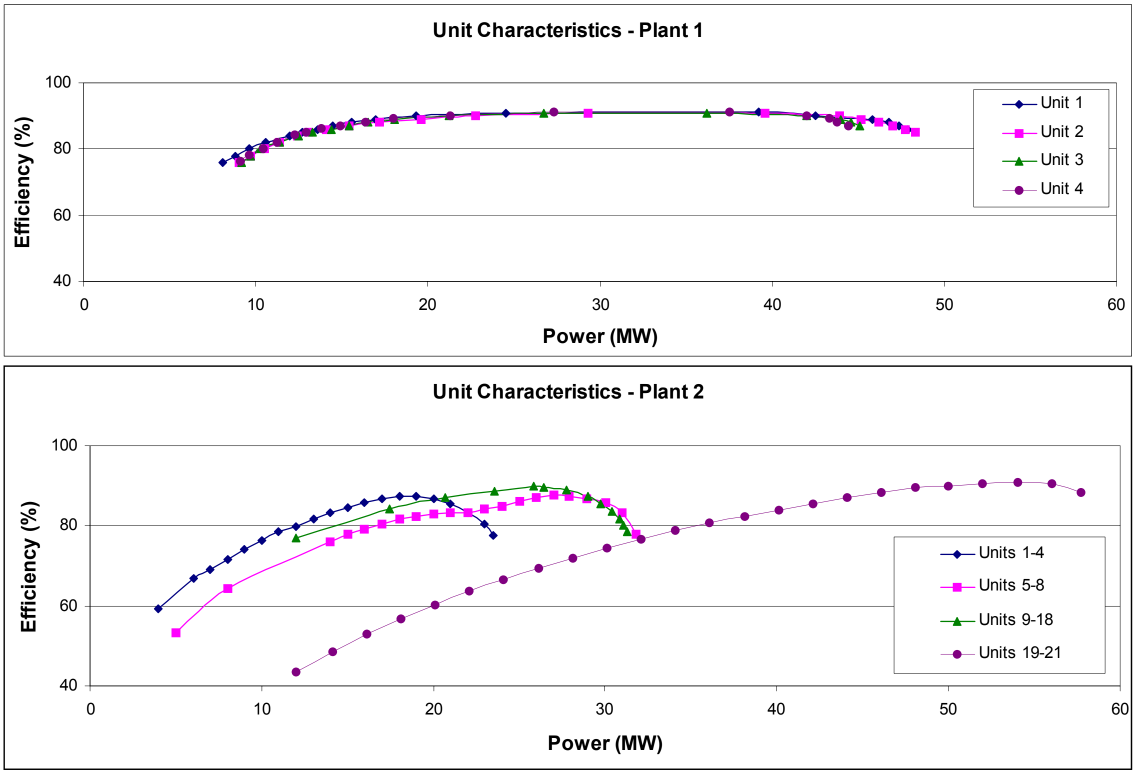

Figure 6: Representative Unit Characteristics for Units within Two Plants

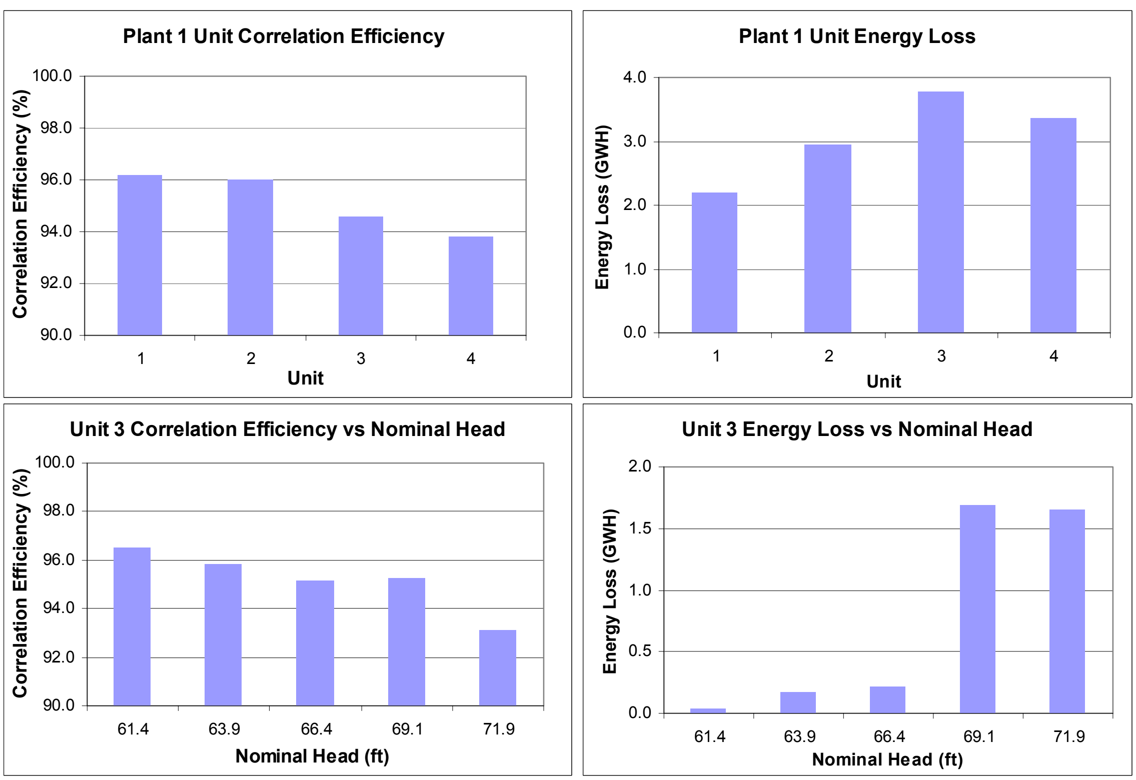

Figure 7: Unit and Nominal Head Indicators for Plant 1, Unit 3

In this example, the second major component of the OHPI is the correlation efficiency. For the plants used in this example, the correlation efficiency has a system value of 95.9% and values of 95.2% and 96.1% for Plants 1 and 2, respectively. Figure 7 presents correlation efficiencies versus unit for Plant 1, showing that Unit 3 has a correlation efficiency of 94.6% with an associated LEO of 3,800 MWh. This unit was chosen for further investigation because it had the highest energy loss and thus had significant potential for improvement, as demonstrated by the low correlation efficiency. Figure 7 also shows the energy losses and the correlation efficiencies versus nominal head. A nominal head of 69.1 ft contains the largest energy loss, indicating that the unit operated for a large portion of the time at this head and that a significant amount of data exists for this head interval.

Figure 8 presents plots of efficiency versus power, flow versus power, power versus gate, and blade versus gate for a nominal head of 69.1 ft. The efficiency and flow versus power curves clearly indicate that there is a discrepancy between the expected flow from the unit characteristics and the measured flow from the Winter-Kennedy relative flow meter.

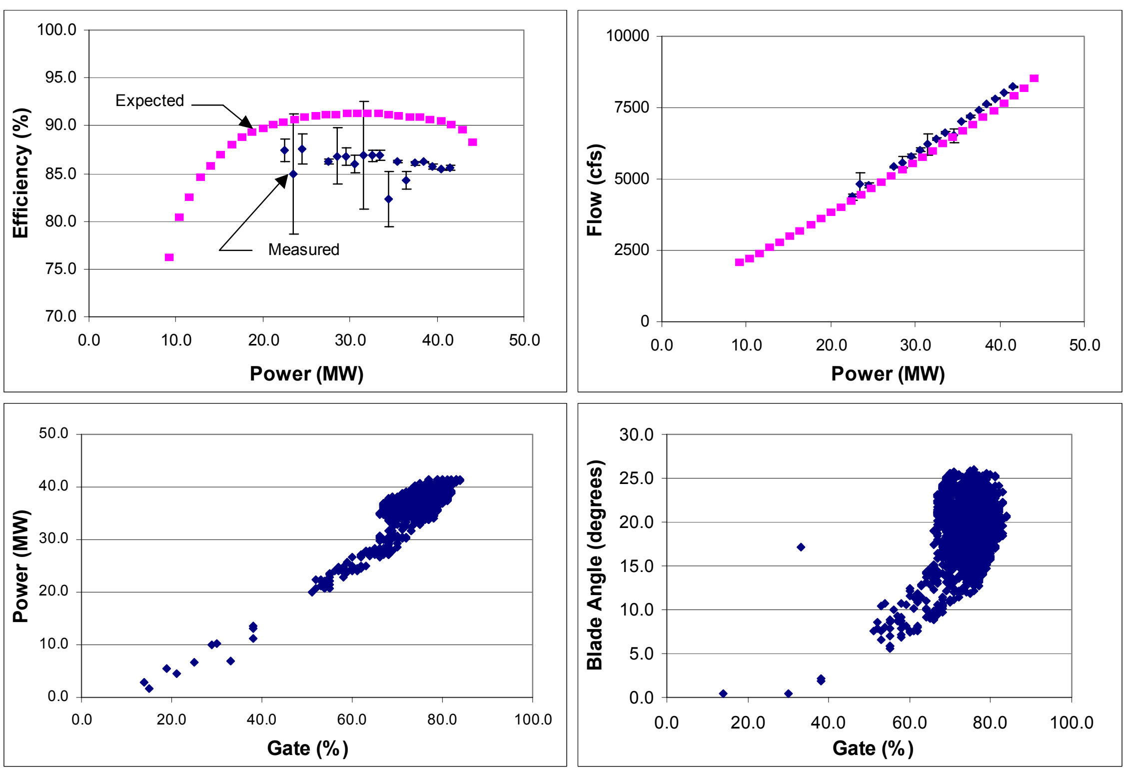

Figure 8: Unit 3 Data for Nominal Head of 69.1 ft

In addition, the blade versus gate curve shows other probable causes for the poor correlation efficiency. For a given head, the blade-gate curve should be a well-defined line. This is not the case, suggesting problems with either the blade and gate instrumentation or improper operation of the blade-gate cam. Because the power versus gate curve demonstrates similar scatter, it was judged likely that the problems were associated with the cam rather than with the instrumentation.

Performance engineers conducted follow-up testing to further investigate the poor correlation efficiencies computed for Unit 3 at Plant 1. Two remote index tests were conducted. For these tests, the data were acquired in five-second intervals from the WaterView monitoring and optimization system while the unit was stepped through several gate settings and held at each gate setting for approximately five minutes. Prior to the tests, the unit's instrumentation was checked by inspecting the blade-gate cam, bleeding air from the Winter-Kennedy piezometer lines, and checking calibrations.

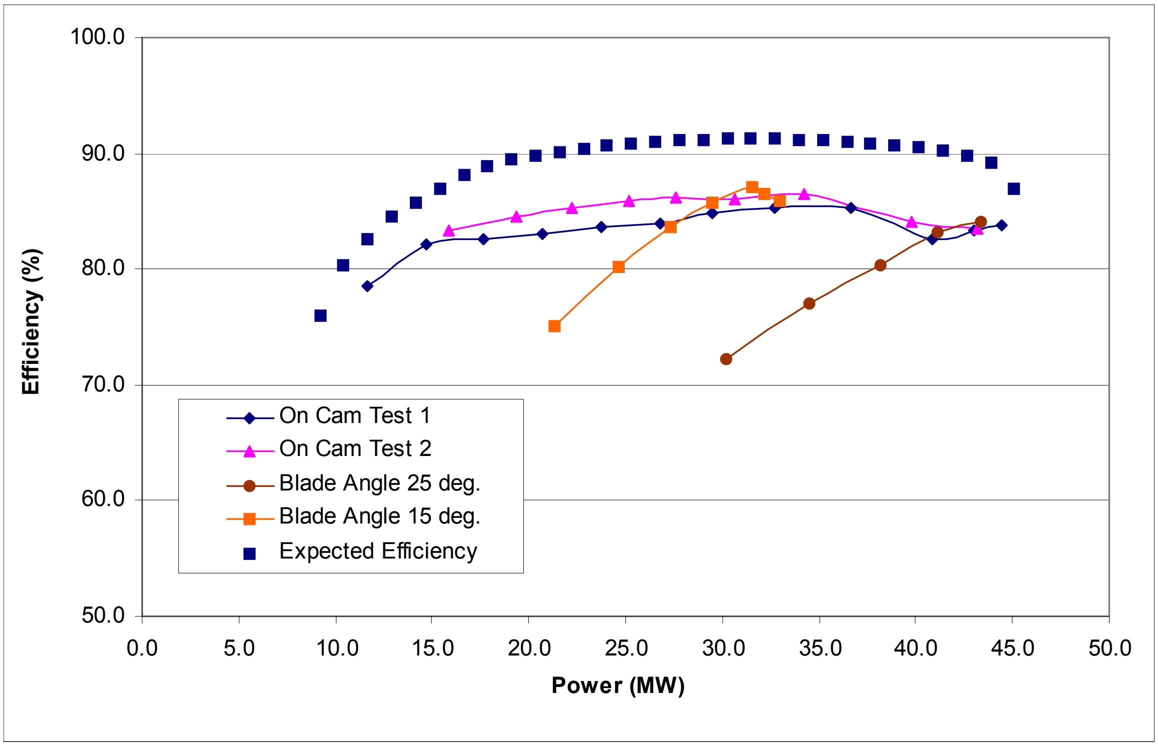

Figure 9: Unit 3 Index Test Results

Figure 9 presents the results from the remote index test. These results are consistent with the OHPI analyses based on the WaterView archival data. Both archival analyses and the remote index test results demonstrate a similar discrepancy between the measured and expected efficiencies, which is a primary cause of the low correlation efficiency.

The remote index tests also confirmed that this unit would benefit from more emphasis on proper cam maintenance. The two on-cam tests were conducted when the head levels were close enough to apply ASME Zone 1 corrections. However, the on-cam efficiency versus power curves are different. The blade versus gate relationship changed in the time interval between the two on-cam tests, as verified by blade versus gate plots from the two tests. In addition, the fixed-blade tests demonstrated higher peak efficiencies than the on-cam tests, indicating that a properly optimized cam was not in place for either of the on-cam tests.

Significant improvements in unit characteristics are also possible for Plant 2, as indicated by the relatively low correlation efficiency of 96.1% shown in Figure 5. Figure 10 presents the correlation efficiencies versus unit power level and demonstrates that Units 19-21 have the lowest correlation efficiencies and the highest energy losses. Unit 19 was chosen to further demonstrate the utility of the correlation efficiency because it produced one of the largest energy losses and because it was available for testing.

Figure 10 also presents energy loss for Unit 19 as a function of nominal head. The largest energy loss occurred at a nominal head of 90.7 ft, indicating that the unit operated a large portion of the time at that head and that a significant amount of data exists.

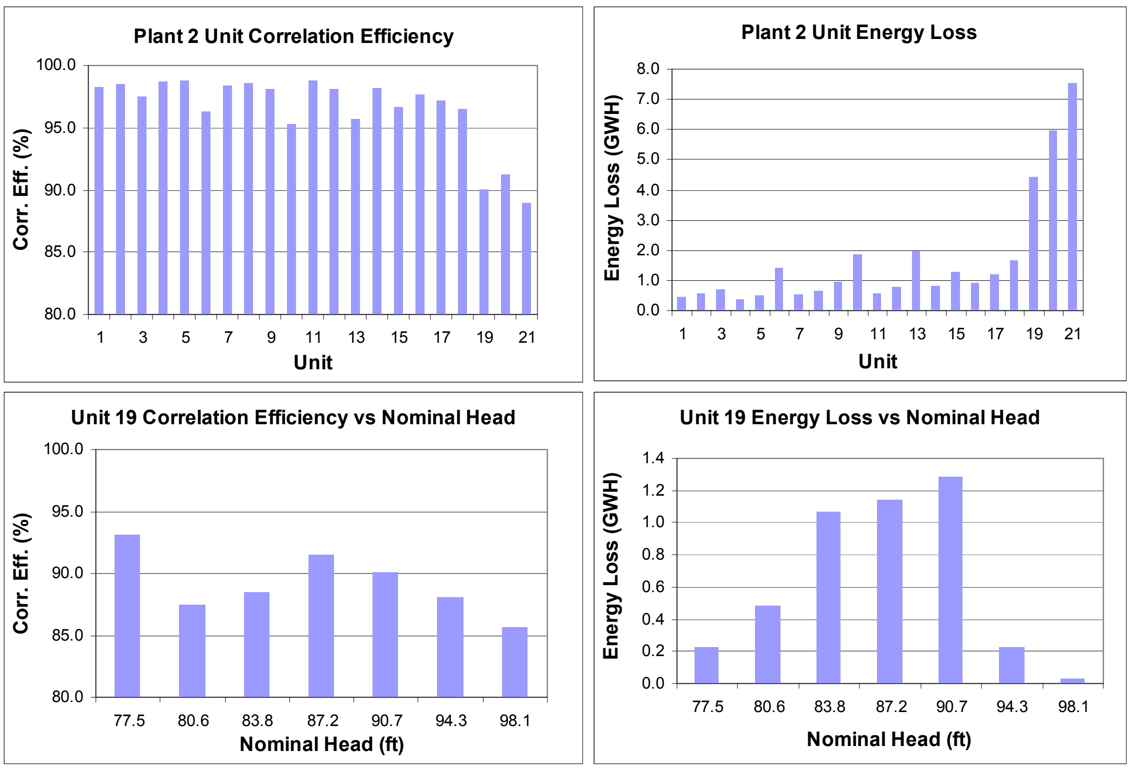

Figure 10: Unit and Nominal Head Characteristics for Plant 2

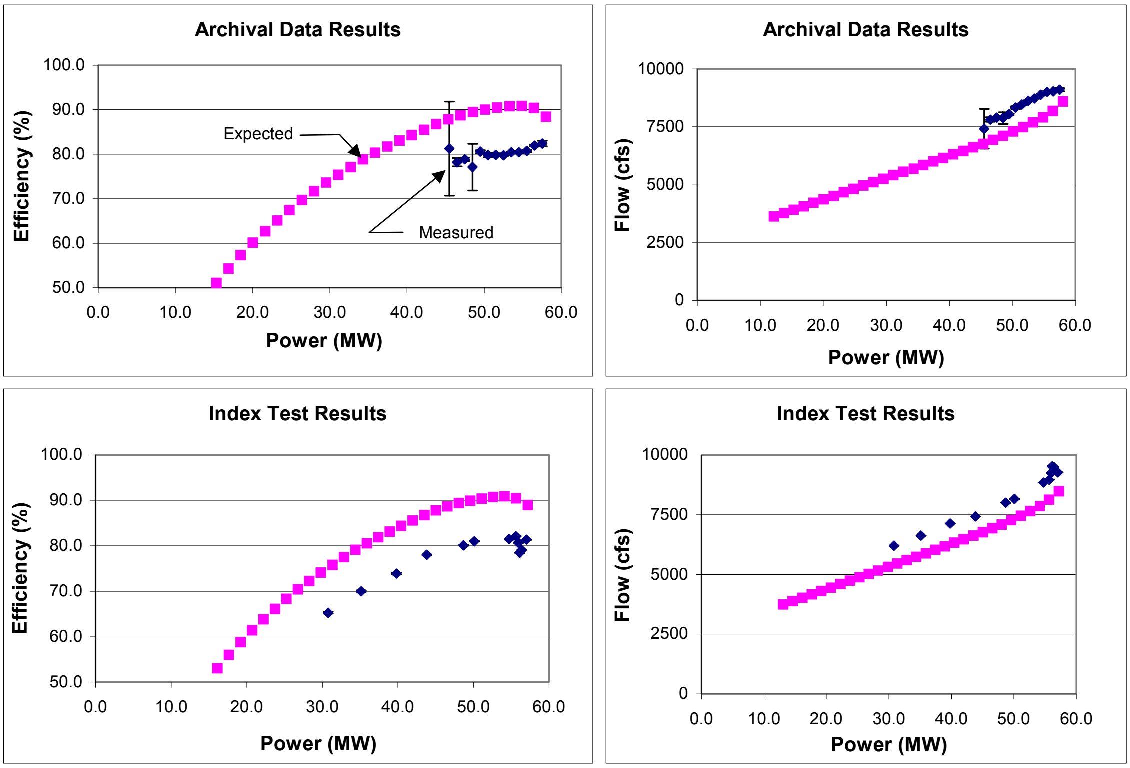

Figure 11: Comparison of Archival Analysis and Index Test, Unit 19, Plant 2

Figure 11 presents efficiency versus power results from the remote index test of Plant 2's Unit 19 and the expected efficiency versus power from the archival unit characteristics data. These plots demonstrate that the primary cause for the low correlation efficiency is a discrepancy between the measured flow rate and the expected flow rate.

Example 2 – Scheduling Efficiency

Example 2 presents results of a scheduling efficiency analysis based on one year of archival data. Figure 12 presents four different plots that contain the scheduling energy and revenue loss; the plant energy generation and hourly energy price; and the optimized plant efficiencies and plant energy generation versus power for two gross head values. The scheduling efficiency energy loss (LEO) for 2003 is 2,250 MWh which is equivalent to $74,500 (LRO), based on the hourly energy prices shown in Figure 12. The non-MSL energy generation was 195,000 MWh while the total plant energy generation was 926,000 MWh. The scheduling energy loss and the non-MSL energy generation represent a scheduling efficiency of 98.9%. The lower plots of Figure 12 present optimized plant efficiencies and plant energy generation versus power for gross heads of 45 ft and 50 ft. This plant generates a significant amount of energy at loads for which the plant efficiency is a few percent lower than the adjacent peak efficiency.

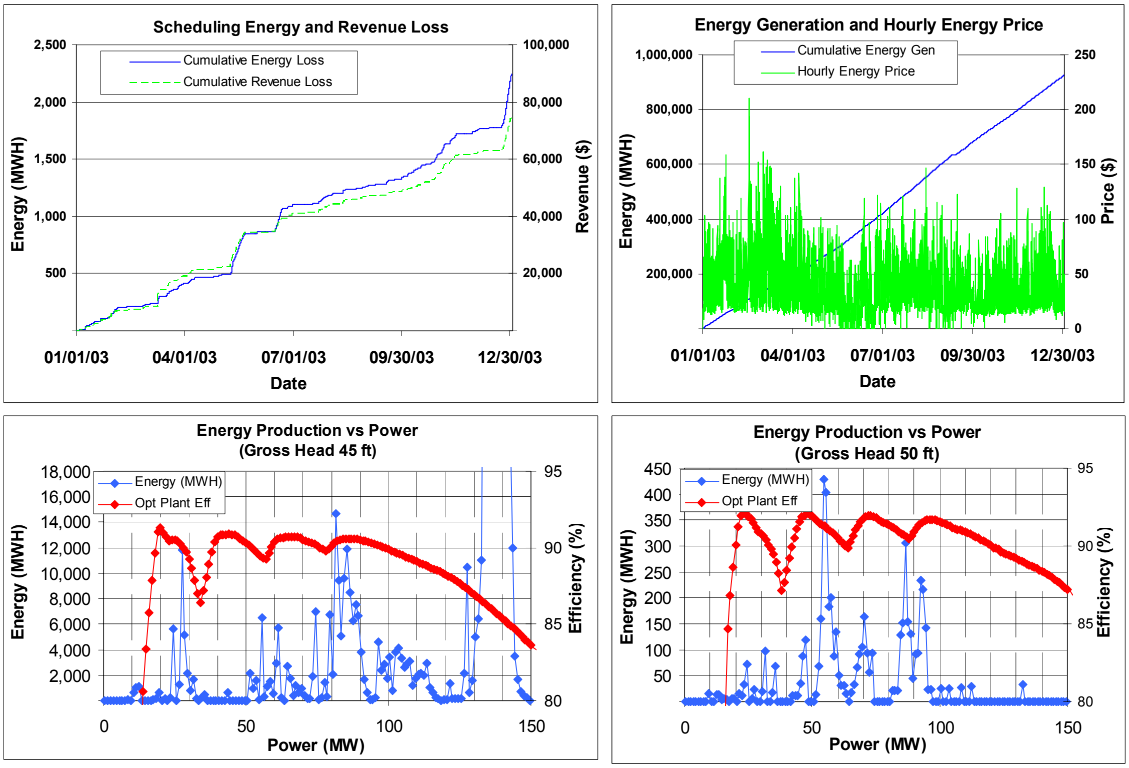

Figure 12: Energy Production vs Optimized Plant Efficiency

Example 3 – Avoidable Loss Efficiency

This example presents the results of an avoidable loss efficiency analysis performed for four horizontal bulb units of an eight unit powerhouse which experiences significant trash rack fouling caused by aquatic milfoil. During this time period, the trash racks were manually cleaned by divers. Figure 13 presents trends of the trash rack loss coefficients for the time period from 1/1/2002 through 1/1/2004. These plots illustrate significant trash rack fouling events, which typically occur in the Fall. Figure 14 presents the avoidable loss efficiency and the associated economic impacts. The economic impacts for this plant accrue from both reduced energy generation and from reduced capacity revenue. The utility receives revenue based on the maximum capacity of each unit. The lost revenue produced by trash rack fouling for these four units totals to over $2,000,000 for the 2002 and 2003 analysis period.

The avoidable loss efficiency presents a consistent measure of the effectiveness of the trash rack cleaning program. During the two years shown in the figures, the avoidable loss efficiency provides relatively consistent results. This is expected because the trash racks were routinely cleaned by divers for both years. In contrast, more substantial changes occur in energy and capacity gains and in unit revenue, which depend on other factors not specifically related to trash rack fouling (primarily market prices and unit capacity factors).

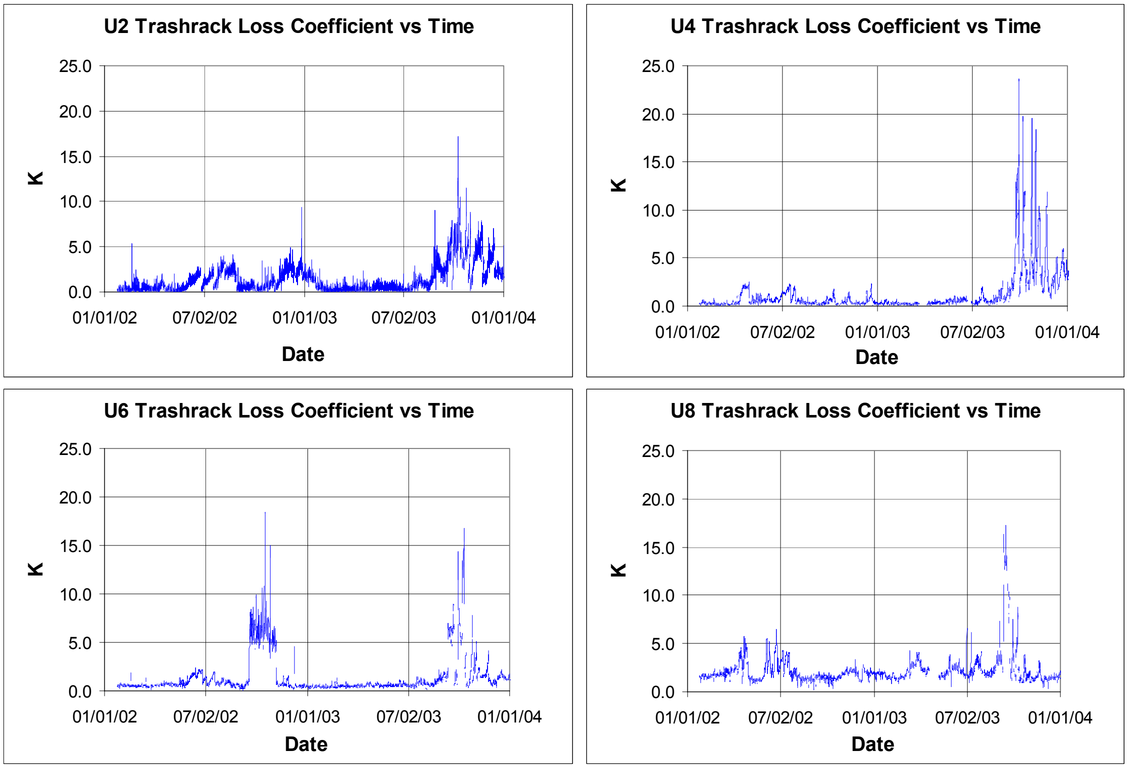

Figure 13: Trash Rack Fouling Loss Coefficients vs Time

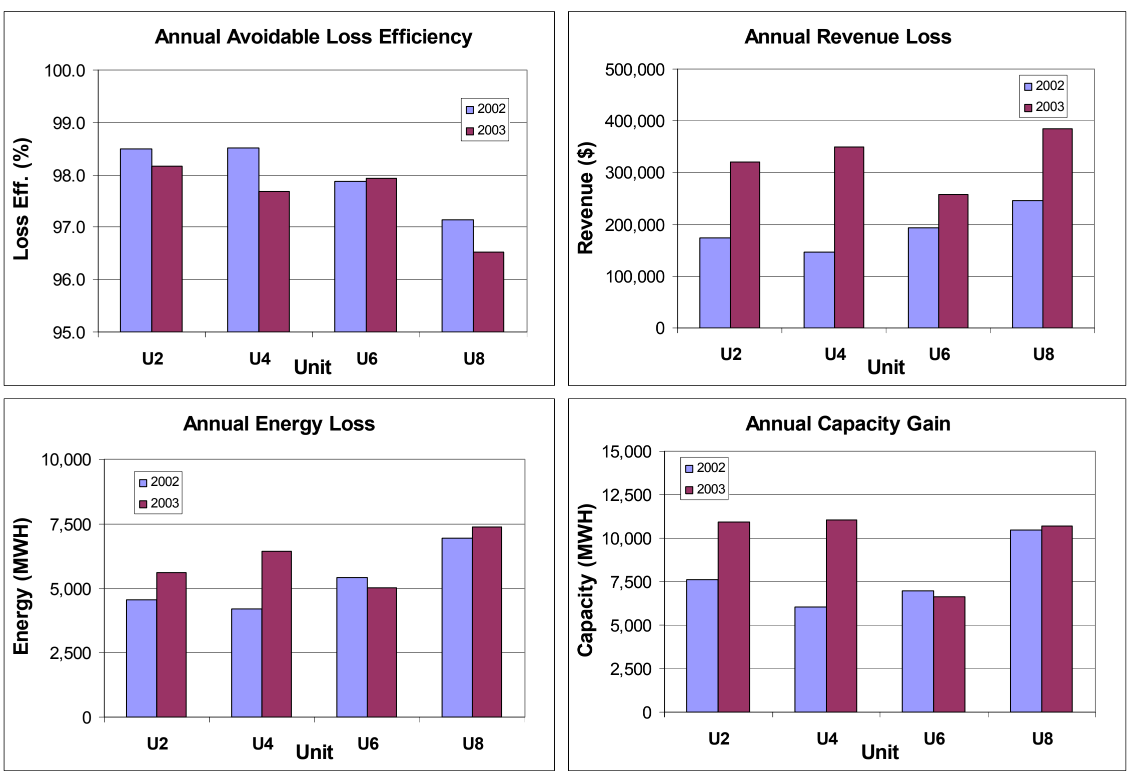

Figure 14: Avoidable Loss Efficiency for Trash Rack Analysis

CONCLUSIONS

The optimization-based hydro performance indicator (OHPI) and its component indicators provide an effective tool for measuring and managing a hydro system. The four component indicators discussed in this paper include the operation efficiency, the correlation efficiency, the scheduling efficiency, and the avoidable loss efficiency. The operation efficiency measures how efficiently all of the units in all of the plants within a system are operated to meet the requested loads, while the correlation efficiency evaluates the accuracy of all unit characteristics and related instrumentation within the system. The scheduling efficiency evaluates the gains that could be achieved by changing a plant's generation to align with peak plant efficiencies, and the avoidable loss efficiency quantifies the effectiveness of maintenance tasks for minimizing energy losses. Trash rack fouling is the most common application for the avoidable loss efficiency.

Archival operating data, an optimization engine, and automated data analysis software are utilized in conducting the OHPI analyses. The analyses are based on a comprehensive data set with high temporal resolution, including power, flow, headwater, tailwater, gate, and blade (for Kaplan units) data from every unit within the system. A key feature of the OHPI is that the structure of the hydro system is mirrored in the hierarchical structure of the data analyses. For example, the correlation efficiency is based on a four-level structure that summarizes performance at the system level, at the plant level, at the unit level, and at various levels for nominal head. The hierarchical structure enables a performance engineer to rank the plants and units within a given system by avoidable energy losses and to diagnose the root causes for the losses.

OHPI results from several years of archival data for four plants demonstrate the utility of this indicator. For example, the operation efficiencies for one of the described plants show that significant gains are achievable with improved optimization. The correlation efficiencies for two of the described plants provide an effective tool for locating the units within each plant that produced the highest energy losses in plant dispatch due to errors in their unit characteristics and associated instrumentation. This approach was used to identify a unit with an improperly operating blade-gate cam and two units that demonstrated significant discrepancies in the measurements of flow rate. Subsequent index testing confirmed the problems initially identified from the archival data by using the OHPI and two component indicators, the operation efficiency and the correlation efficiency. For an additional described plant, the scheduling efficiency demonstrates and quantifies the benefits from more efficient plant scheduling. In another example, the avoidable loss efficiency provides a quantitative measure for the effectiveness of trash rack cleaning procedures.

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