Data-Based Performance Assessments for the DOE Hydropower Advancement Project

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Abstract

The U. S. Department of Energy's Hydropower Advancement Project (HAP) was initiated to characterize and trend hydropower asset conditions across the U.S.A.'s existing hydropower fleet and to identify and evaluate the upgrading opportunities. Although HAP includes both detailed performance assessments and condition assessments of existing hydropower plants, this paper focuses on the performance assessments.

Plant performance assessments provide a set of statistics and indices that characterize the historical extent to which each plant has converted the potential energy at a site into electrical energy for the power system. The performance metrics enable benchmarking and trending of performance across many projects in a variety contexts (e.g., river systems, power systems, and water availability). During FY2011 and FY2012, assessments will be performed on ten plants, with an additional fifty plants scheduled for FY2013. This paper focuses on the performance assessments completed to date, details the performance assessment process, and describes results from the performance assessments.

1. Introduction

The U. S. Department of Energy's (DOE's) Hydropower Advancement Project (HAP) was initiated to characterize and trend hydropower asset conditions across the U.S.A.'s existing hydropower fleet and to identify and evaluate the upgrading opportunities. Details of the HAP, including a project overview, a description of the hydropower technology taxonomy, the hydropower Best Practice Catalog, the hydropower Assessment Manual, and a sample assessment, are provided through Oak Ridge National Laboratory's (ORNL's) web site [ORNL, 2012].

The HAP includes both detailed performance assessments and condition assessments of existing hydropower plants. However, this paper focuses on the performance assessments. Performance metrics resulting from the assessments enable benchmarking and trending of performance across many projects in a variety contexts (e.g., river systems, power systems, and water availability). During FY2011 and FY2012, assessments will be performed on ten conventional hydropower plants, with an additional fifty plants scheduled for assessment during FY2013. This paper details the performance assessment process, focuses on the performance assessments for the three plants completed to date, and describes results from these performance assessments.

2. Overview of Performance Analyses

The performance assessments are based on a set of analyses to quantify unit and plant performance and to enable the investigation of potential opportunities for operations-based and equipment-based performance improvements, leading to additional generation. This report addresses the processes and methodologies used for the quantitative performance analyses. An overview of the optimization-based performance analyses is shown in Figure 2-1.

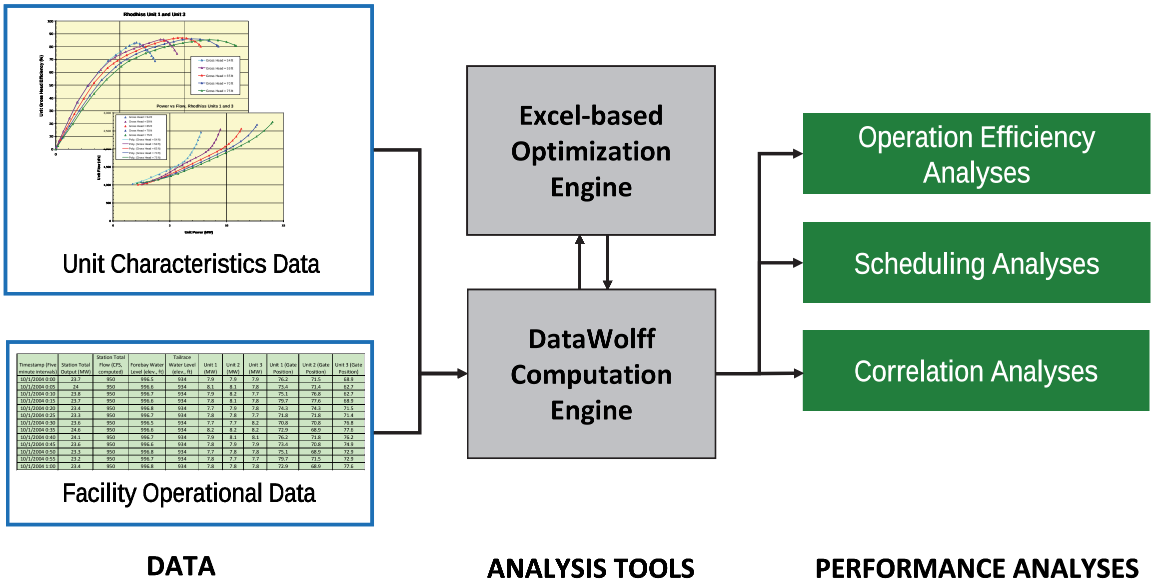

Figure 2-1: Overview of Performance Analyses

Unit characteristics and facility operational data are discussed in Section 3, “Data for Performance Analyses.” The performance analysis tools are discussed in Section 4, “Tools for Performance Analyses.” Optimization-based performance analyses are discussed in Section 5, and results from performance analyses are provided in Section 6. Section 7 summarizes and discusses the results.

3. Data for Performance Analyses

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

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

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

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

Efficiency curves provide guidance for the effective use of a hydropower unit or facility. The points of most efficient operation can be identified, and the efficiency penalty for operating away from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at another power level. The HAP typically 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_{IPL}) 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 some facilities across the U.S., the installed performance characteristics may be the only formal documentation available to describe unit and plant performance.
>
> CPL performance characteristics (η_{CPL}) can be used in performance analyses if recent performance tests results for the units are available. The CPL 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].
>
> PPL performance characteristics (η_{PPL}) 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 the best available technology.

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

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

4. Tools for Performance Analyses

As shown previously in Figure 2-1, the primary tools for performance analyses include an optimization engine and a computation engine, which are 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 included below, and a detailed explanation is included elsewhere [DOE, 2011].

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

Computation Engine – The primary computation engine is DataWolff, an Excel-based program that enables the automating of multiple data analyses. Additional configuration of the computation engine with specific analysis scripts and calculation libraries is required for each particular type of analysis. The optimization-based performance analyses use the procedures described in Section 5 and provided in detail by the Performance Assessment Manual [DOE, 2011].

5. Optimization-Based Performance Analyses

Optimization technologies and recent advances in automated data analyses provide the tools for conducting 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, generation scheduling 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 5-1, and the specific analyses are described in the following subsections.

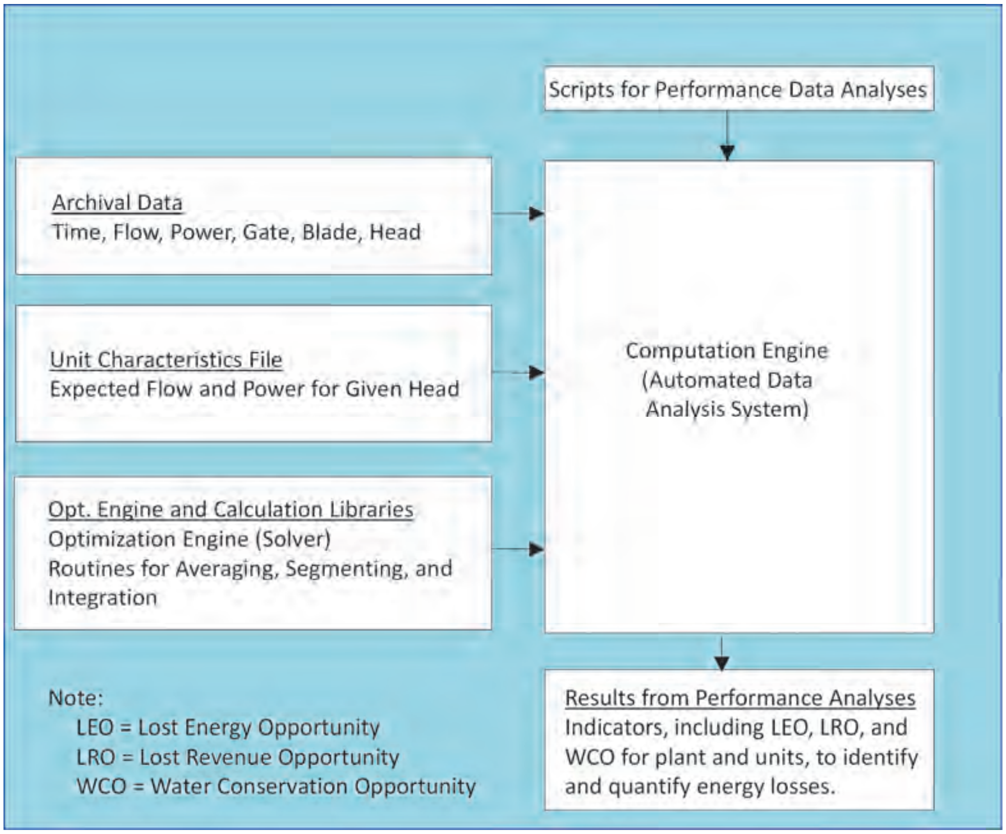

Figure 5-1: Process Diagram for Optimization-Based Performance Analyses

<u>Operation Efficiency Analyses</u> – 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 provided in the Performance Assessment Manual [DOE, 2011]. 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).

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].

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

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 performance with the expected unit performance characteristics [March and Wolff, 2004; Jones and Wolff, 2007]. Computational steps for the correlation analyses are provided in the Performance Assessment Manual [DOE, 2011]. 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.

6. Typical Results from Performance Analyses

Overview of Facilities – Through April 2012, detailed HAP performance assessments have been completed for three hydropower facilities. One three-unit plant, located in North Carolina, is owned by Duke Energy and operated primarily for generation. Another three-unit plant, located in Tennessee, is owned by the U. S. Army Corps of Engineers (USACE) and operated primarily for flood control and recreation. Another three-unit plant, located in Utah, is owned by the U. S. Bureau of Reclamation (USBR) and operated primarily for flow releases and recreation. Due to the confidential nature of the performance data, some results from the assessments are not available for public distribution.

Single Unit Performance and Plant Performance - The IPL and CPL single unit performance data for the three plants, if available, was supplied by the facility owners. Expected PPL performance was developed from the CPL data, from the condition assessment results for each facility, and from upgrading experience with similar facilities. Based on the IPL, CPL, and PPL unit performance curves, the optimization engine (see Section 4) was used to compute optimized plant gross head efficiencies for each facility.

Figure 6-1 shows the optimized plant gross head efficiencies at the CPL versus plant power at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft for Plant 1. For each head, the first peak in Figure 6-1 corresponds to the operation of the most efficient unit, the second peak corresponds to the most efficient operation of the two most efficient units, and the third peak corresponds to the most efficient operation of all three units. As more units operate, the peak efficiencies fall, and the peaks become broader.

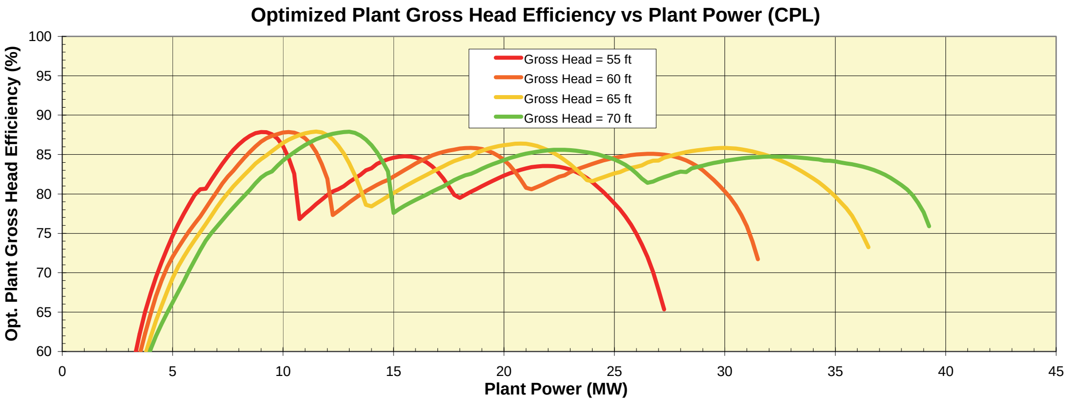

Figure 6-1: Optimized Plant Gross Head Efficiency versus Plant Power (CPL), Plant 1

Figure 6-2 compares the optimized plant gross head efficiency versus plant power for IPL, CPL, and PPL at a gross head of 60 ft, where approximately 90% of Plant 1's generation occurs. The CPL improvement over IPL is largely due to the replacement of Unit 2 with a turbine of relatively modern design. The PPL improvement over CPL is based on the CPL curve for the upgraded Unit 2, with an additional assumed net head turbine efficiency improvement of 1%, due to improved turbine technology, and a maximum assumed generator efficiency of 98%, due to improved generator technology.

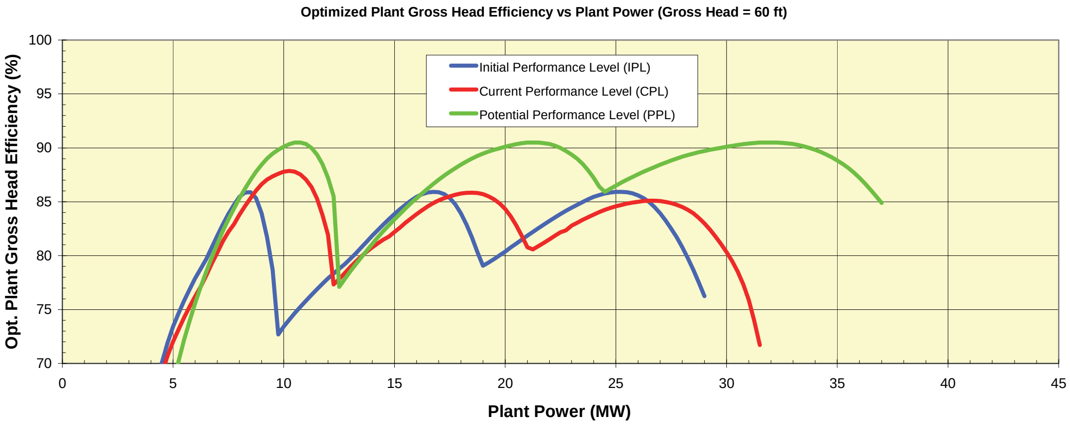

Figure 6-2: Opt. Plant Gross Head Efficiency versus Plant Power (GH = 60 ft), Plant 1

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 [DOE, 2011]. 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.

Typical results from the operation efficiency analyses for Plant 1 (see Table 6-1) are provided in Figures 6-2 through 6-5. In these figures, the red line represents the actual Unit 1 generation, the blue line represents the actual Unit 2 generation, and the violet line represents the actual Unit 3 generation. The dashed red line represents the optimized Unit 1 generation, the dashed blue line represents the optimized Unit 2 generation, and the dashed violet line represents the optimized Unit 3 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.

Much of this plant's generation occurs with Unit 1 and Unit 2 operating near, but not at, the optimized power levels, as shown in Figure 6-2. Minor adjustments in the Unit 1 and Unit 2 power levels result in plant efficiency improvements ranging from 0.3% to 1.2%. On numerous occasions, Unit 1 is the only unit in operation but Unit 2 is more efficient, as shown in Figure 6-3. Here, the potential improvements in plant efficiency range from 2% to 10.4%. Figure 6-4 presents an example showing the plant generating with Unit 1 and Unit 2 only, when significant efficiency improvements, ranging from 2.2% to 12.5%, could be achieved with the proper combination of Unit 1, Unit 2, and Unit 3. (At this plant, Unit 1 and Unit 2 are remotely operated, but Unit 3 must be manually operated at the site.) Figure 6-5 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.

Results from the operation efficiency analyses for the three facilities are summarized in Table 6-1. The potential plant generation improvements due to plant efficiency improvements from direct optimization while producing the same power at the same time ranged from 1.5% to 3.0% for Plant 1, which operates for generation in an integrated power system; from 0.02% to 0.05% for Plant 2, which operates according to a fixed, pre-determined schedule; and from 0.1% to 0.4% for Plant 3, which operates according to water demands. Much of Plant 1's potential generation improvements from direct optimization should be achievable through automation and control system improvements.

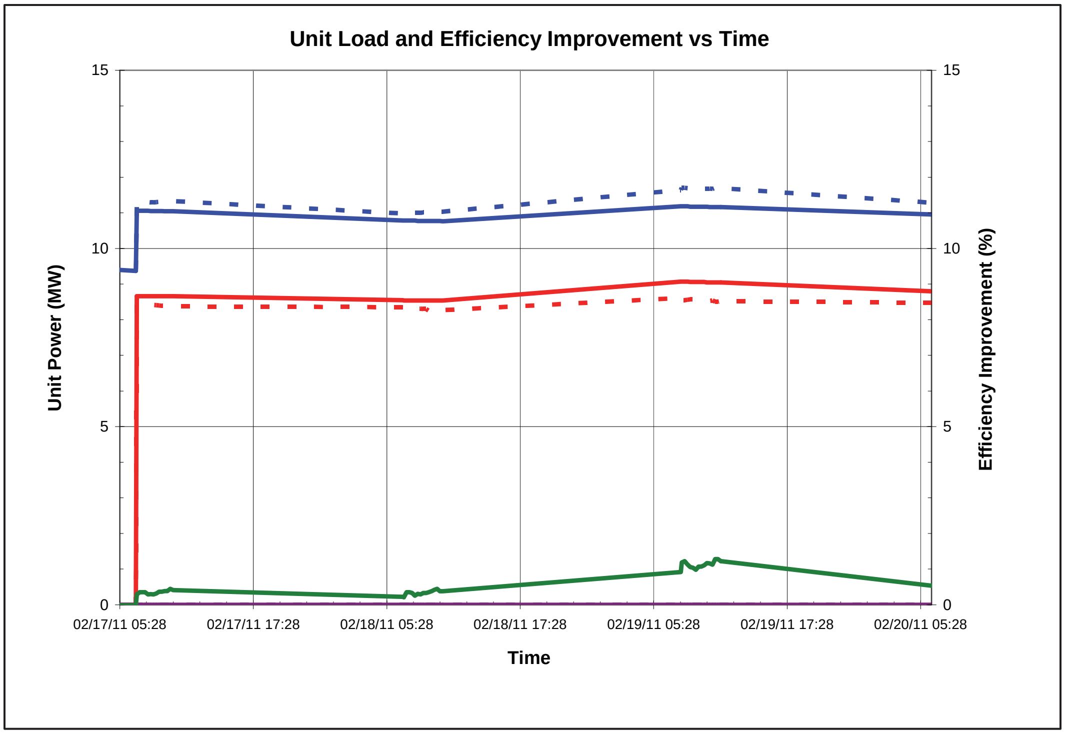

Figure 6-2: Typical Operation Efficiency Results (February 17-20, 2011), Plant 1

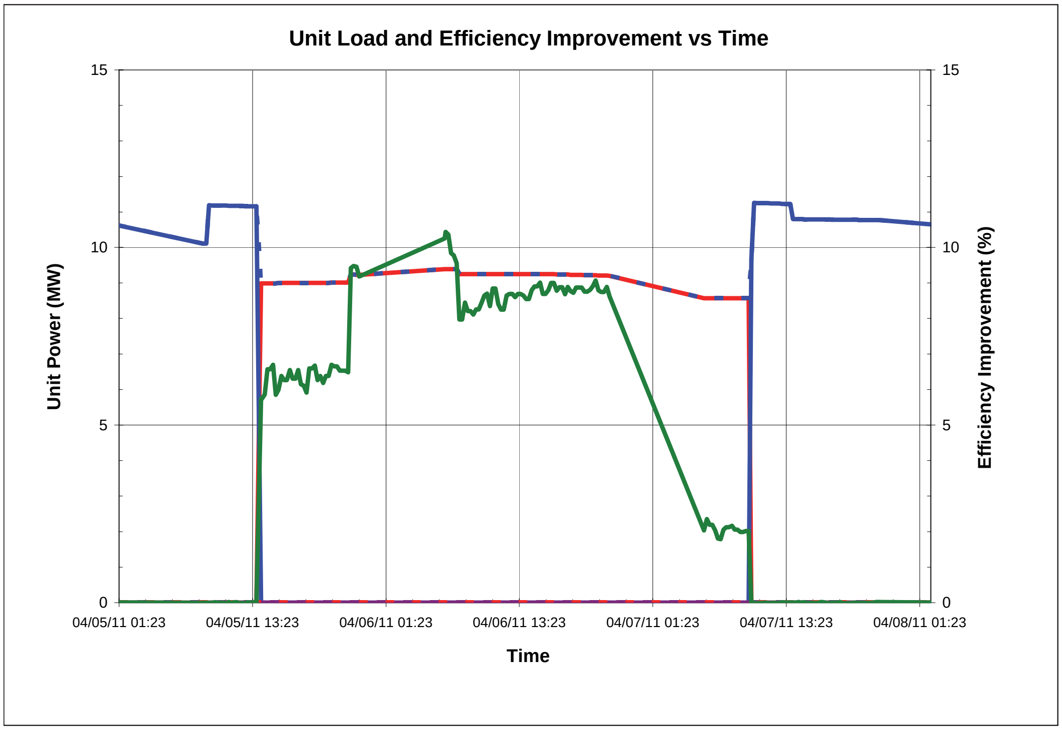

Figure 6-3: Typical Operation Efficiency Results (April 5-7, 2011), Plant 1

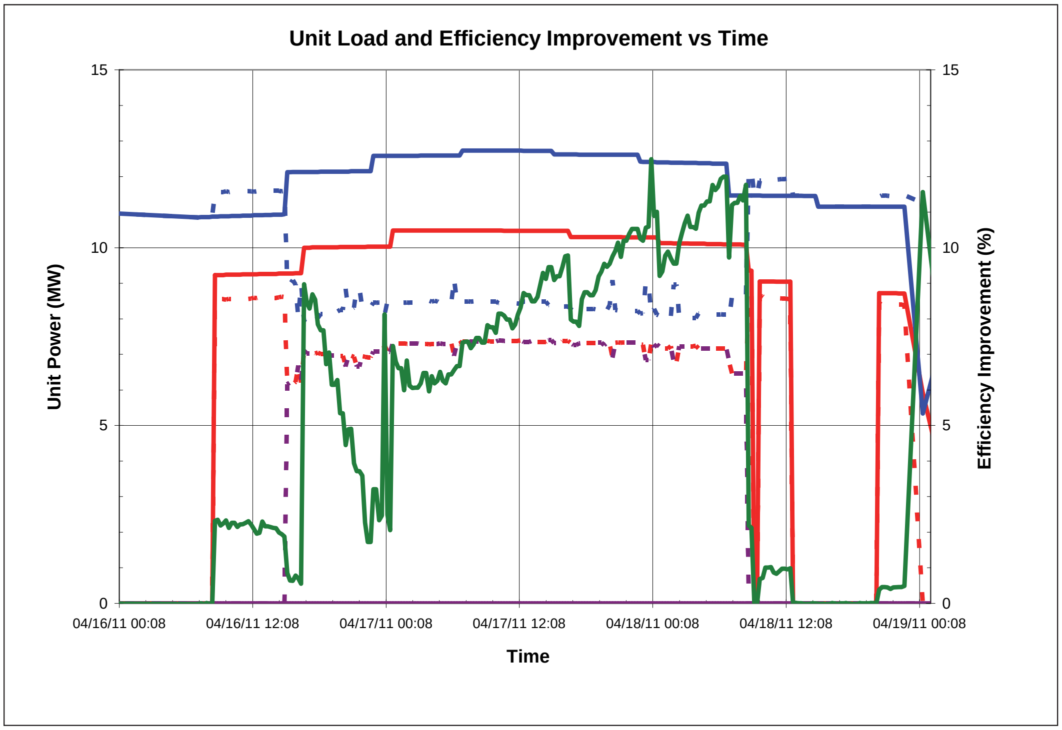

Figure 6-4: Typical Operation Efficiency Results (April 16-18, 2011), Plant 1

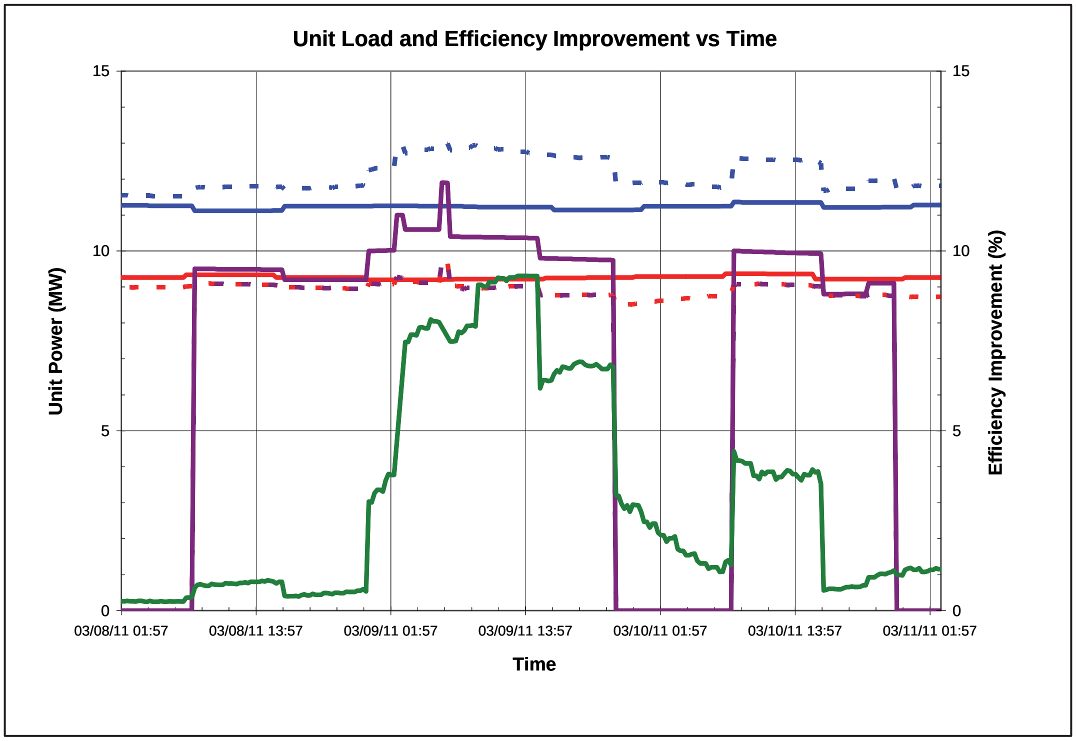

Figure 6-5: Typical Operation Efficiency Results (March 9-11, 2011), Plant 1

Plant 1		
Year	**Computed Improvement (MWh)**	**Computed 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 Jan. 1, 2007, through June 30, 2007.
2. The 2011 results only include generation from Jan. 1, 2011, through Aug. 22, 2011.
3. Operation efficiency results show potential improvements while continuously meeting the actual generation.

Plant 2		
Year	**Computed Improvement (MWh)**	**Computed Improvement (%)**
2009	175	0.05
2010	101	0.04
2011	73	0.02

Note:

1. Operation efficiency results show potential improvements while continuously meeting the actual generation.

Plant 3		
Year	**Computed Improvement (MWh)**	**Computed Improvement (%)**
2008	1,330	0.4
2009	728	0.2
2010	493	0.1
2011	1,742	0.3

Note:

1. Operation efficiency results show potential improvements while continuously meeting the actual generation.

Table 6-1: Summary of Results from Operation Efficiency Analyses for Three Plants

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

Figures 6-6, 6-7, and 6-8 provide typical results from generation scheduling analyses, showing results for Plant 1, Plant 2, and Plant 3, respectively. In each figure, the optimized plant gross head efficiency for the particular head is shown in red, the actual monthly generation versus plant power is shown in blue, and the optimized monthly generation versus plant power is shown in green. The optimized generation occurs at or near the peak efficiencies corresponding to the number of operating units. For all three plants, the actual generation beyond the three-unit efficiency peak is typically associated with flood control operations. The wide range of generation values for Plant 3 reflects the plant's priority for flow releases.

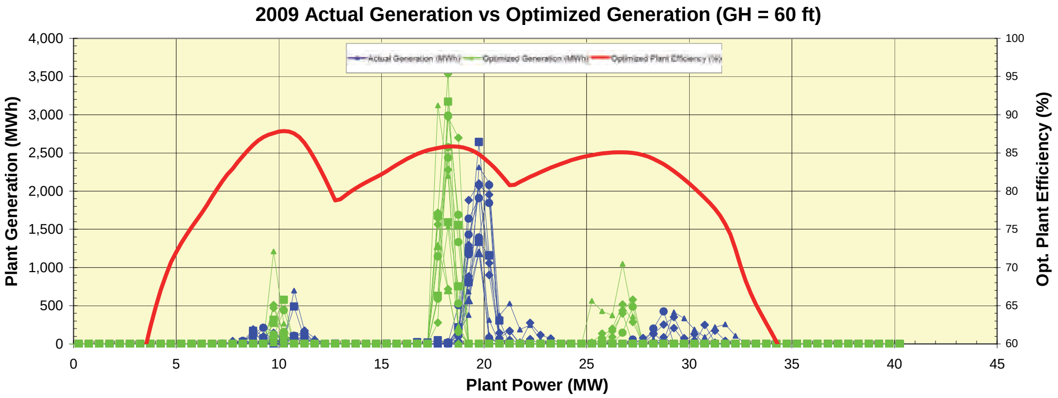

Figure 6-6: Typical Results from Scheduling Analyses, Plant 1

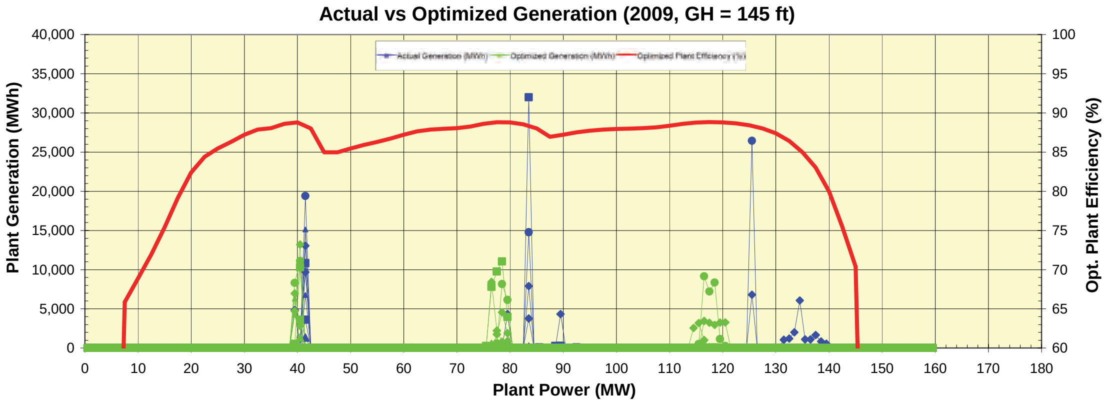

Figure 6-7: Typical Results from Scheduling Analyses, Plant 2

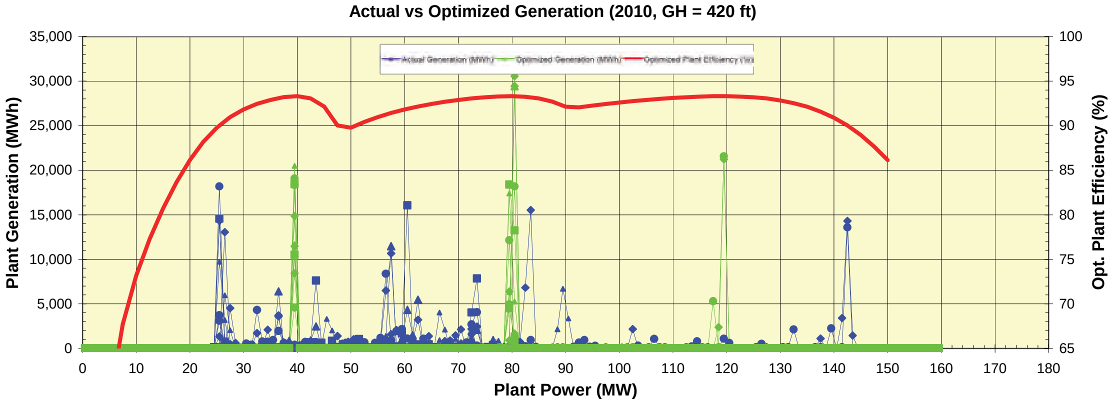

Figure 6-11: Typical Results from Scheduling Analyses, Plant 3

For each plant, quantitative analyses were conducted by using the CPL unit performance characteristics, the optimized plant efficiency curves over the head range, and the archival plant data. The actual quantities of water used for generation per hour for the entire data set were computed. Those quantities of hourly "fuel" were applied to the optimized plant gross head efficiency curves for the appropriate heads to compute optimized generation. Results from the generation analyses for the three plants are provided in Table 6-2, using the actual annual generation as the baseline for each year. For Plant 1, the potential generation improvements range from a low of 1,076 MWh (3.1%) in 2008 to a high of 3,781 MWh (6.0%) in 2010, with a three-year (2008-2010) total of 8,065 MWh and a three-year average of 4.6%. For Plant 2, the potential generation improvements range from a low of 2,522 MWh (0.6%) in 2011 to a high of 4,170 MWh in 2009, with a three-year total of 9,558 MWh and a three-year average of 1.0%. For Plant 3, the potential generation improvements range from a low of 6,321 MWh (1.4%) in 2009 to a high of 15,341 (2.3%) MWh in 2011, with a 2008 – 2011 total of 38,513 MWh and an average of 2.0%.

Plant 1				
Year	**Actual Annual Generation (MWh)**	**Optimized Annual Generation (MWh)**	**Computed Improvement (MWh)**	**Computed 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 scheduling analyses show potential improvements while using the actual amount of water per hour.

Plant 2				
Year	**Actual Annual Generation (MWh)**	**Optimized Annual Generation (MWh)**	**Computed Improvement (MWh)**	**Computed Improvement (%)**
2009	380,290	384,460	4,170	1.1
2010	251,808	254,674	2,866	1.1
2011	392,999	395,521	2,522	0.6

Note:
1. The scheduling analyses show potential improvements while using the actual amount of water per hour.

Plant 3				
Year	**Actual Annual Generation (MWh)**	**Optimized Annual Generation (MWh)**	**Computed Improvement**	**Computed Improvement (%)**
2008	371,373	380,700	9,326	2.5
2009	459,505	465,827	6,321	1.4
2010	411,231	418,755	7,524	1.8
2011	679,404	694,746	15,341	2.3

Note:
1. The scheduling analyses show potential improvements while using the actual amount of water per hour.

Table 6-2: Summary of Results from Generation Scheduling Analyses

<u>Avoidable Loss Analyses</u> – 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 these three plants, insufficient data was available to evaluate avoidable losses except as noted in the following section.

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 Plant 1 and Plant 2, unit flows are not measured. Unit flows for Plant 3 are measured using acoustic flowmeters, so data was available for correlation analyses.

Correlation efficiencies over the entire 2008 – 2011 period, shown in Figure 6-12, are uniformly high for Plant 3 (98.9% for Unit 1, 98.7% for Unit 2, and 98.8% for Unit 3), indicating good overall agreement between measured efficiencies and expected efficiencies.

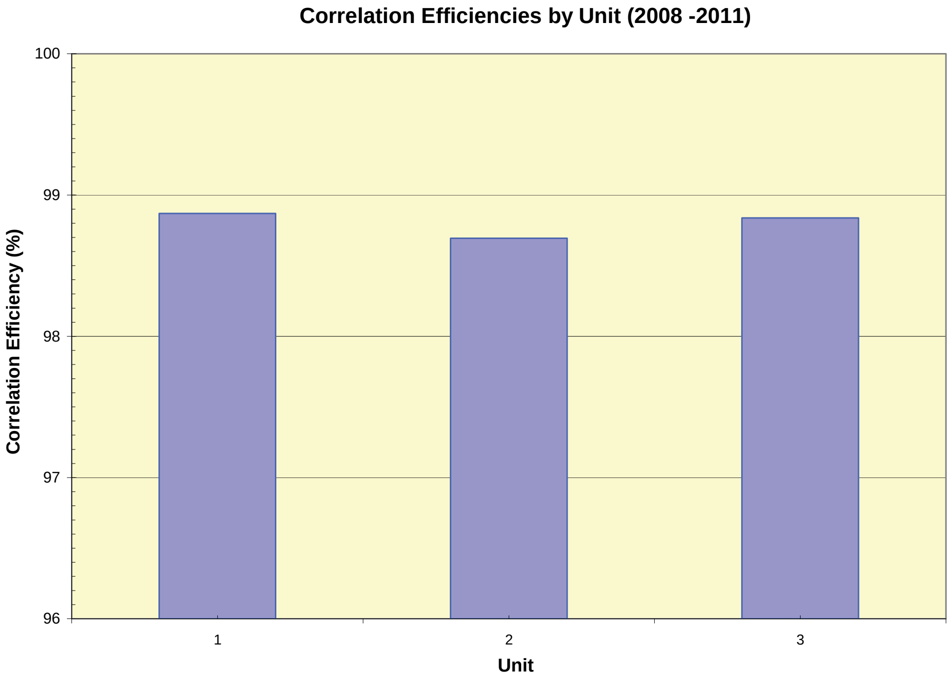

Figure 6-12: Correlation Efficiencies for Plant 3 (2008 - 2011)

Performance comparisons for Plant 3's Unit 1, Unit 2, and Unit 3 are provided in Figure 6-13, Figure 6-14, and Figure 6-15, respectively. The expected net head efficiencies versus unit power levels are shown as the red lines, and the measured net head efficiencies versus the unit power levels are shown as the blue triangles. The results from the correlation analyses indicate that the performance for each unit is approximately 1% lower than the expected performance across the head range from 410 ft to 430 ft, and the shapes for the actual efficiency curves are somewhat flatter than expected. Figure 6-13 also shows limited performance results from Unit 1 flow measurements in 2007 (red triangles) for the old Unit 1 turbine before it was upgraded, providing a graphic indication of the significant performance gains achieved by the upgrade.

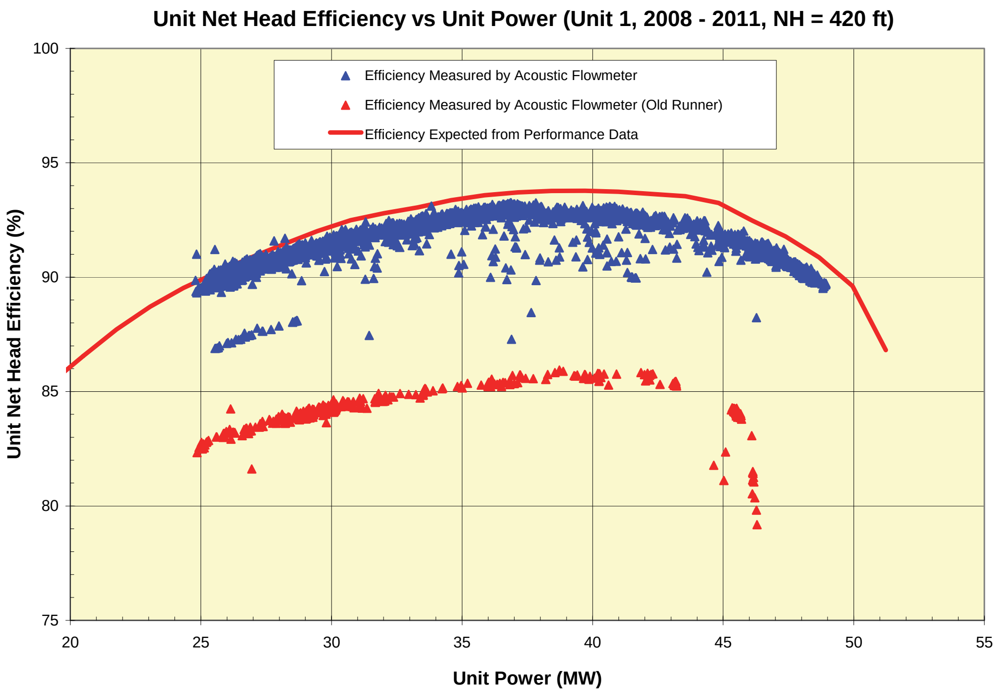

Figure 6-13: Expected and Measured Efficiency versus Power, Plant 3 (Unit 1, 2008 – 2011, NH = 420 ft)

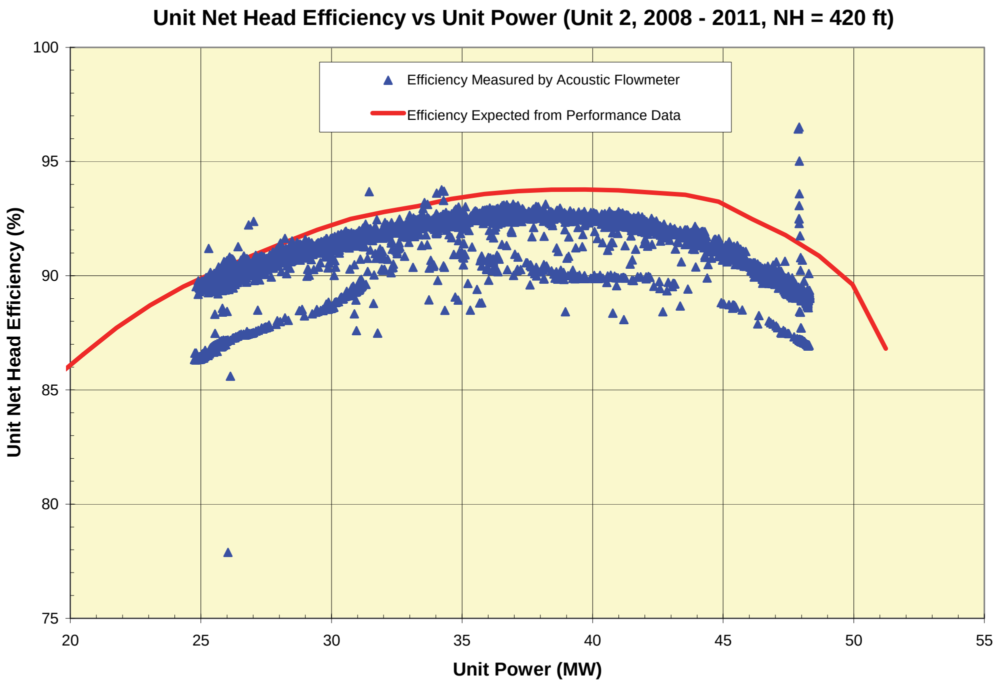

Figure 6-14: Expected and Measured Efficiency versus Power, Plant 3 (Unit 2, 2008 – 2011, NH = 420 ft)

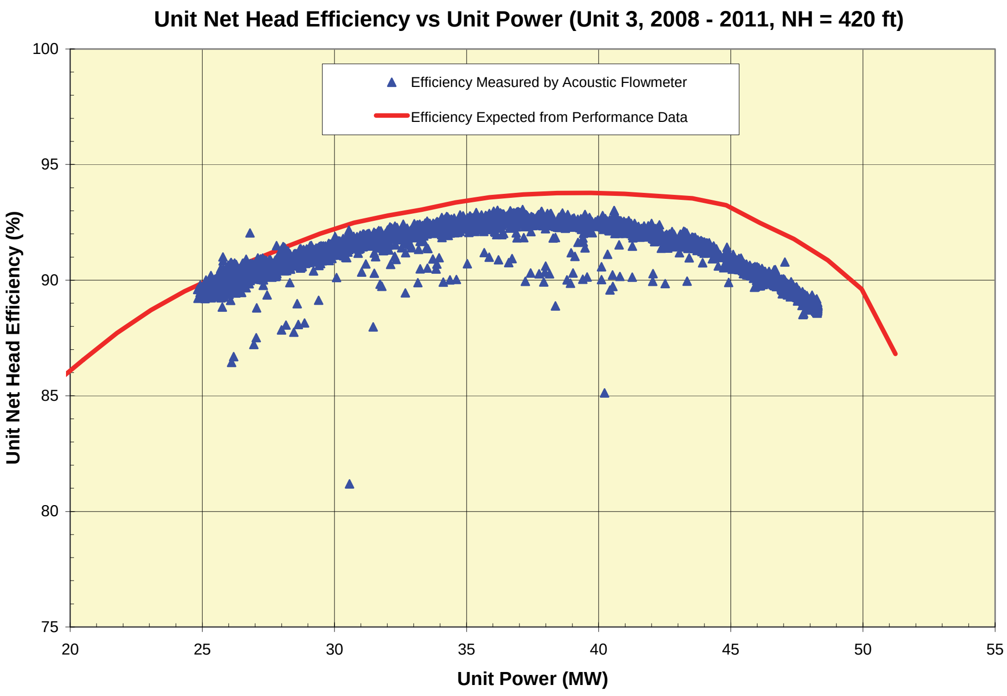

Figure 6-15: Expected and Measured Efficiency versus Power, Plant 3
(Unit 3, 2008 – 2011, NH = 420 ft)

Figure 6-13 also shows a period of reduced efficiency for Unit 1, and Figure 6-14 shows a period of reduced efficiency for Unit 2. Trash rack fouling is the most likely explanation for these periods of reduced efficiency. The installation and monitoring of differential pressure transducers to directly measure the trash rack losses could be considered by the Plant 3 owner. Alternatively, periodic calculation and review of correlation efficiencies would serve the same purpose without the capital cost, installation cost, and maintenance cost of additional instrumentation.

7. Conclusions and Recommendations

This report summarizes results from optimization-based performance analyses conducted for three hydroelectric facilities as part of the DOE's Hydropower Advancement Project. Conclusions and recommendations based on these results are listed below:

1. Potential plant generation improvements due to plant efficiency improvements from direct optimization, while producing the same power at the same time, ranged from 1.5% to 3.0% for Plant 1, which operates for generation in an integrated power system; from 0.02% to 0.05% for Plant 2, which operates according to a fixed, pre-determined schedule; and from 0.1% to 0.4% for Plant 3, which operates according to water flow requirements. Much of Plant 1's potential generation improvements from direct optimization should be achievable through automation of Unit 3 and control system improvements.

2. Based on generation scheduling analyses, the potential generation improvements for Plant 1 due to modified scheduling range from a low of 1,076 MWh (3.1%) in 2008 to a high of 3,781 MWh (6.0%) in 2010, with a three-year (2008-2010) total of 8,065 MWh and a three-year average of 4.6%. For Plant 2, the potential generation improvements range from a low of 2,522 MWh (0.6%) in 2011 to a high of 4,170 MWh in 2009, with a three-year total of 9,558 MWh and a three-year average of 1.0%. The potential generation improvements for Plant 3 range from a low of 6,321 MWh (1.4%) in 2009 to a high of 15,341 (2.3%) MWh in 2011, with a 2008 – 2011 total of 38,513 MWh and an average of 2.0%.
3. Correlation analyses for Plant 3, which utilizes acoustic flowmeters to measure unit flows, indicate that the actual performance for each unit is about 1% lower than the expected performance. The shapes for the efficiency curves are also somewhat flatter than expected. In addition, the results from the correlation analyses show periodic efficiency losses, probably due to trash rack fouling.
4. Where appropriate, plant owners should consider improving their operational performance by continuously measuring unit flows and by periodically comparing expected and measured unit performance.
5. The HAP performance assessment methodology is providing useful information to facility owners, the hydropower industry, and DOE. Additional assessments will provide additional information and context.

8. References

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