Quantification of Optimization Benefits from Detailed Unit Performance Testing at Multiunit Hydropower Facilities

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Operators of hydro plants typically assume that nominally identical units have identical performance characteristics. However, multiple factors can influence a unit's performance. Differences in construction of intakes, penstocks, spiral cases, stay vanes, wicket gates, throat rings, and draft tubes can lead to performance differences among units. Turbine fabrication errors, different operational patterns, and different maintenance experiences, such as cavitation repairs, impact the performance of nominally identical units. Also, unit performance results are often obtained at a few heads and scaled across the full head range, leading to potential errors. The U. S. Bureau of Reclamation's (USBR's) Flaming Gorge Plant was selected for the initial case study of a research project to evaluate and quantify potential optimization benefits from detailed unit performance testing and optimized dispatch at USBR hydropower facilities. USBR personnel conducted efficiency tests for Flaming Gorge Units 1, 2, and 3 in November 2015. Detailed unit efficiency results were also developed from 2008-2015 archival data (HW, TW, unit power, unit flow) and used to create a set of modified unit characteristics. The modified unit characteristics were used for operation efficiency analyses and generation scheduling analyses. Performance characteristics derived from archival data correlated well with field measurements. Operation efficiency analyses showed the potential for modest annual improvements of 0.4% from improved unit dispatch, corresponding to $48,000/year in power revenue. Generation scheduling analyses showed potential for significant annual improvements of 1.8% due to improved scheduling, corresponding to $210,000/year in power revenue. Similar comparisons are planned for additional USBR hydro plants, including Palisades and Glen Canyon.

1. Introduction

Accurate unit and plant performance characteristics are essential for proper plant operation and optimization. Accurate flow measurement is a key component for determining accurate unit and plant performance characteristics, and careful attention to unit flow measurements can improve operational efficiencies and generation [EPRI, 2015]. In addition, the unit and plant performance information must be properly utilized by operators and/or control systems. For example, during unit upgrades proper performance management requires application of old and new unit characteristics in a timely manner to maximize plant efficiency and generation.

Typically, owners/operators of hydroelectric power plants assume that a “family” of nominally identical units has identical performance characteristics for each unit. However, multiple factors can influence a unit’s performance and affect the validity of that assumption. For example, differences in construction of intakes, penstocks, spiral cases, stay vanes, wicket gates, throat rings, and draft tubes can lead to performance differences among units with identical turbine designs. Performance for individual units can be significantly affected by the cleanliness of trash racks, as shown by previous analyses of the USBR’s three-unit Flaming Gorge plant [March et al., 2012]. Turbine fabrication errors, different operating experiences, and different maintenance experiences (e.g., cavitation repairs) can impact the performance of nominally identical units. Localized irregularities in composition can lead to localized cavitation damage, blade distortion, and blade cracking, which can also affect performance adversely. In addition, unit performance results are typically obtained at a few opportunistic heads and then scaled across the full operational range, leading to potential errors in plant optimization, reduced generation, and reduced water in storage.

The USBR’s Flaming Gorge Dam and Powerplant was selected for the initial case study of a research project to evaluate and quantify potential operational and maintenance-related optimization benefits from detailed unit performance testing and optimized dispatch at several USBR hydropower facilities. Flaming Gorge Dam and Powerplant is located on the Green River in Daggett County, Utah. The Flaming Gorge Reservoir has a capacity of 3,788,700 acre-ft, and the plant has the 15th largest generation capacity (151 MW) among the 53 USBR plants. Flaming Gorge was constructed as part of the Colorado River Storage Project (CRSP) to provide storage and distribution of water to the upper Colorado River basin. Construction on the dam began in 1958, and Flaming Gorge was commissioned for operation in 1964.

The plant has three Francis turbine generating units. Originally, each unit had a rating of 36 MW. The generators were uprated between 1990 and 1992, and the turbines were modernized between 2005 and 2007. The current rating for each unit is 50.65 MW at a design net head of 440 ft. In addition, three large selective withdrawal structures were installed on the upstream face of the dam over the penstock intakes and trash rack structures in 1978, and the GSU transformers were replaced with larger capacity transformers in 2001.

Figure 1.1 shows a photograph of the Flaming Gorge Dam and Powerplant.

Figure 1-1: USBR's Flaming Gorge Dam and Powerplant

2. Review of Related Literature

There has been relatively little treatment in the technical literature of the potential optimization benefits from detailed performance testing for each one of a set of nominally identical units. Lamy and Néron [2003] discuss a variation of the pressure-time methodology as an approach to reducing field test costs for measuring performance of each unit at multiunit hydroplants. The authors note, "…tests done in different powerhouses at Hydro-Québec have shown that turbines assumed to be identical often have non-negligible differences in their turbine efficiency. This is particularly true for units produced before modern day blade manufacturing techniques using numerically controlled machine tools. Hydro-Québec is now turning to using individualized unit efficiency curves to improve plant efficiency [Lamy and Néron, 2003]." Curves are provided for each individual unit at three plants, including a five-unit plant, a nine-unit plant, and an eight-unit plant. For the five-unit plant (noted as "a plant in which particularly large differences in turbine efficiency are present amongst units reputed to be identical"), turbine efficiencies varied from 92.1% to 92.5%, and turbine power levels at best efficiency varied from 43 MW to 46 MW. For the nine-unit plant, turbine efficiencies varied from 95.0% to 95.3%, and turbine power levels at best efficiency varied from 264 MW to 270 MW. For the eight-unit plant, turbine efficiencies varied from 93.8% to 94.6%, and turbine power levels at best efficiency varied from 290 MW to 305 MW. Unfortunately, the scatter associated with the actual test data for these three plants is not provided in the paper, no statistical analyses are provided, and no quantification is provided for the potential benefits from utilizing the individual unit characteristics.

Similar to Lamy and Néron [2003], Almquist et al. [2005] examines the relatively inexpensive implementation of variations on the pressure-time methodology for comparing the performance among units of nominally identical design. Four variations were examined, and a preferred low-cost method called the “simple biased method” was identified for additional examination. However, only the standard code-compliant (see [ASME, 2011]) pressure-time methodology provided consistent, accurate results. Almquist et al. [2005] provides no quantification for the potential benefits from utilizing individual unit characteristics.

EPRI [2015] presents the first comprehensive examination of the effects of uncertainty in unit characteristics on the optimization of multiunit hydroplants. Operational data and unit performance data from sixteen hydroelectric plants analyzed during previous studies provided the basis for scaled unit characteristics in generalized two-unit, three-unit, five-unit, and seven-unit plant configurations with Francis units, diagonal flow units, fixed propeller units, and Kaplan units. Operational data from the sixteen hydroelectric plants also formed the basis for generalized annual generation patterns. Three annual generation patterns, including an hourly generation pattern, a moderate automatic generation control (AGC) generation pattern, and a heavy AGC generation pattern, were developed from the data. Operation and optimization for the two-unit, three-unit, five-unit, and seven-unit plant configurations were evaluated under the hourly generation pattern and the moderate AGC generation pattern with unit performance uncertainties of 1%, 2.5%, and 5% and with unit commitments based on equal unit power, simple operational rules, and unconstrained optimization. EPRI [2015] concludes that energy losses and revenue losses due to uncertainty in unit characteristics can be substantial for multiunit plants. For the plant configurations and unit types included in the analyses, annual energy losses based on flow modification uncertainties and power modification uncertainties are similar. For Francis plants, annual energy losses vary with assumed uncertainty from approximately 0.3%–1.2% for the two-unit plant configuration, from approximately 0.2%–1.3% for the three-unit plant configuration, from approximately 0.2%–1.4% for the five-unit plant configuration, and from approximately 0.3%-1.5% for the seven-unit plant configuration. Results demonstrate that optimized dispatch is an effective hedge against the potential for energy losses and revenue losses due to uncertainty in unit characteristics. Results from the evaluations with Francis units are also provided in March et al. [2016].

3. Overview of Performance Analyses

The performance analyses computed for this paper are based on a set of tools 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. The following subsections briefly address the processes and methodologies used for the quantitative performance analyses. Additional details are available in ORNL [2011], EPRI [2015], and elsewhere [March and Wolff, 2003; March and Wolff, 2004; EPRI, 2008; EPRI, 2012a; EPRI, 2012b; EPRI, 2012c; EPRI, 2012d; March et al., 2012; March et al., 2014; EPRI, 2014; March et al., 2016].

3.1 Data for Performance Analyses

The primary data needs for performance analyses include unit characteristics data and facility operational data, which are discussed in this subsection.

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 the 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 unit, 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 a different power level.

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

1. Timestamp;
2. Unit Power;
3. Unit Flow;
4. Headwater Level;
5. Tailwater Level; and
6. Unit Status (e.g., available, unavailable, condensing).

Figure 3-1 provides an example of unit characteristics previously computed from operational data for Flaming Gorge Unit 1 [March et al., 2012]. The expected efficiency versus unit power level is shown as the red line, and the measured efficiencies versus the unit power levels are shown as the blue triangles. The results indicate that the performance for the unit is approximately 1% lower than the expected performance, and the shape for the actual efficiency curve is somewhat flatter than expected. Figure 3-1 also shows limited performance results from flow measurements for Unit 1 before it was upgraded, providing a graphic indication of the significant performance gains achieved by the upgrade

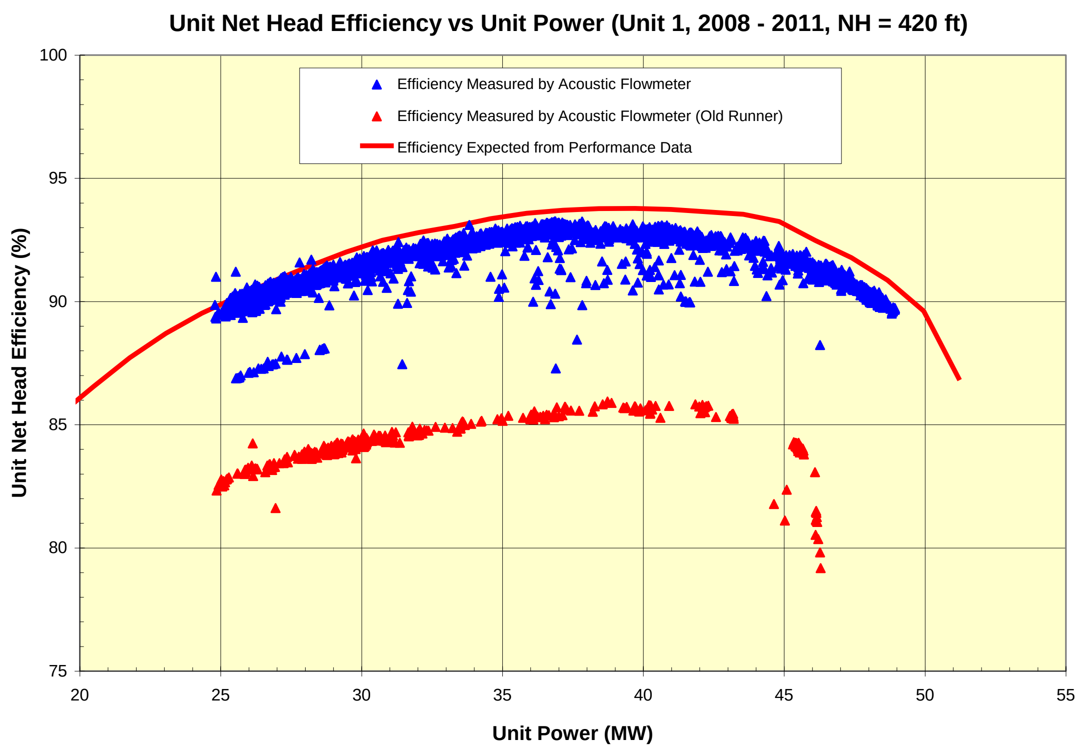

Figure 3-1: Example of Expected and Measured Efficiency versus Power

3.2 Tools for Performance Analyses

The primary tool for conducting performance analyses is the Hydroplant Performance Calculator (HPC). The HPC was developed to enable standardized metrics for hydro plant performance [March et al., 2014]. The Hydroplant Performance Calculator includes: (1) a setup module, HPC PlantBuilder, for developing unit and plant performance characteristics; and (2) a multi-unit optimization and analysis module, HPC Analyzer, for calculating operation efficiencies, generation scheduling analyses, and flow analyses. The data needs for HPC PlantBuilder and HPC Analyzer include unit performance data and facility operational data, as described in the previous subsection.

Figure 3-2 provides a graphical overview of HPC PlantBuilder, and Figure 3-3 provides a graphic overview of HPC Analyzer. Input data for the HPC PlantBuilder includes unit performance data (generator efficiency; turbine power and turbine flow versus head) and

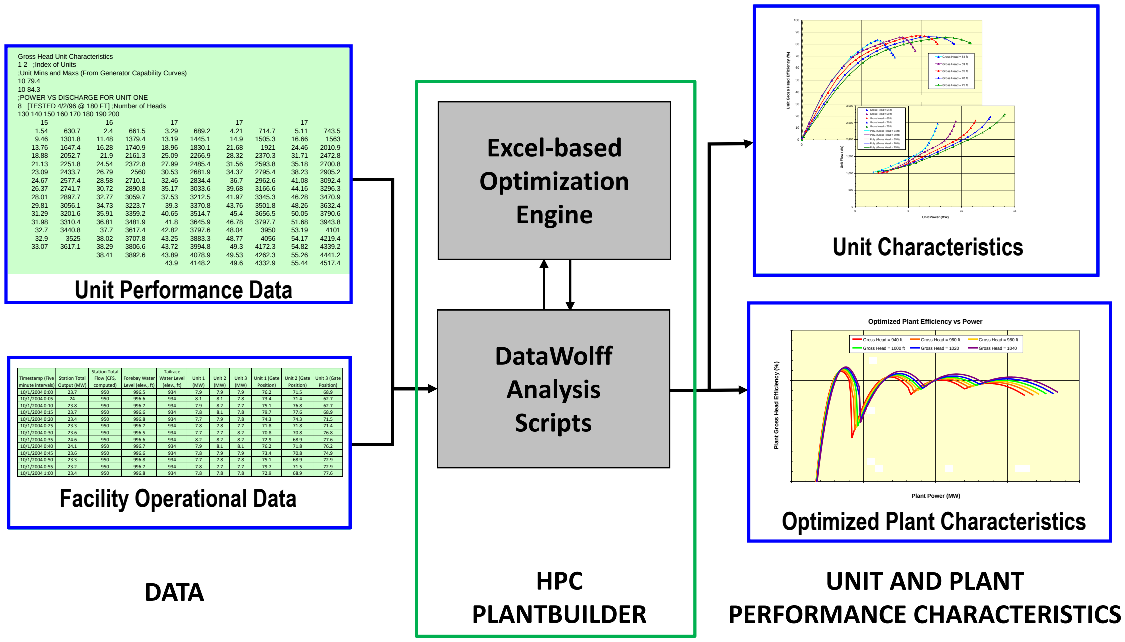

Figure 3-2: Overview of HPC PlantBuilder

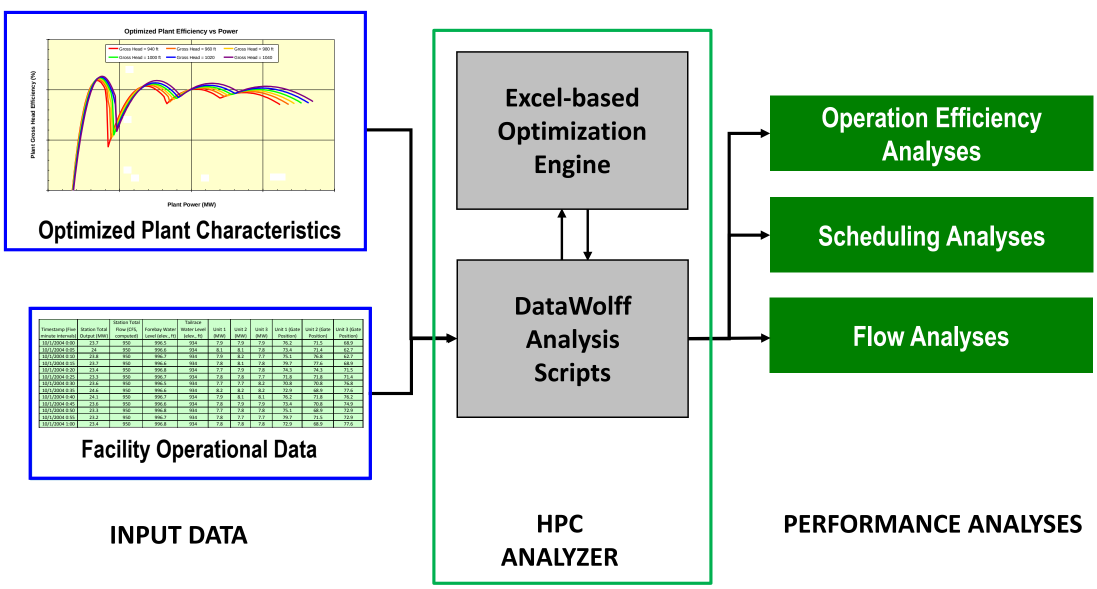

Figure 3-3: Overview of HPC Analyzer

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

Additional details are available in EPRI [2015] and elsewhere [March et al., 2012b; March et al., 2014; EPRI, 2014]. An Excel interface for HPC PlantBuilder provides an efficient, consistent, and systematic approach to creating unit and plant performance characteristics from performance data and plant operational data.

Input data for the HPC Analyzer includes optimized plant performance data, as computed by HPC PlantBuilder, and facility operational data (unit power and head versus time). For this paper, HPC Analyzer was used to compute operation efficiency analyses and generation scheduling analyses, as described in ORNL [2011] and March et al. [2014].

4. Results from Performance Analyses

4.1 Flow Correlation Analyses

Hourly measurements of flow rate (cfs) from acoustic time-of-flight flowmeters were available for each unit at Flaming Gorge for the period from January 2008 through November 2015. Additional hourly measurements included unit power (MW), headwater elevation (ft), and tailwater elevation (ft). Correlation analyses were used to derive unit performance characteristics for comparison with expected unit performance characteristics from the turbine manufacturer (VA TECH) and measured unit efficiencies from field performance tests conducted by USBR personnel in November 2015.

Previous correlation analyses for Flaming Gorge have shown that correlation efficiencies for the plant are uniformly high. Figure 4.1, for example, shows correlation efficiencies for Unit 1, Unit 2, and Unit 3 for the period from 2008 through 2011 [March et al., 2012].

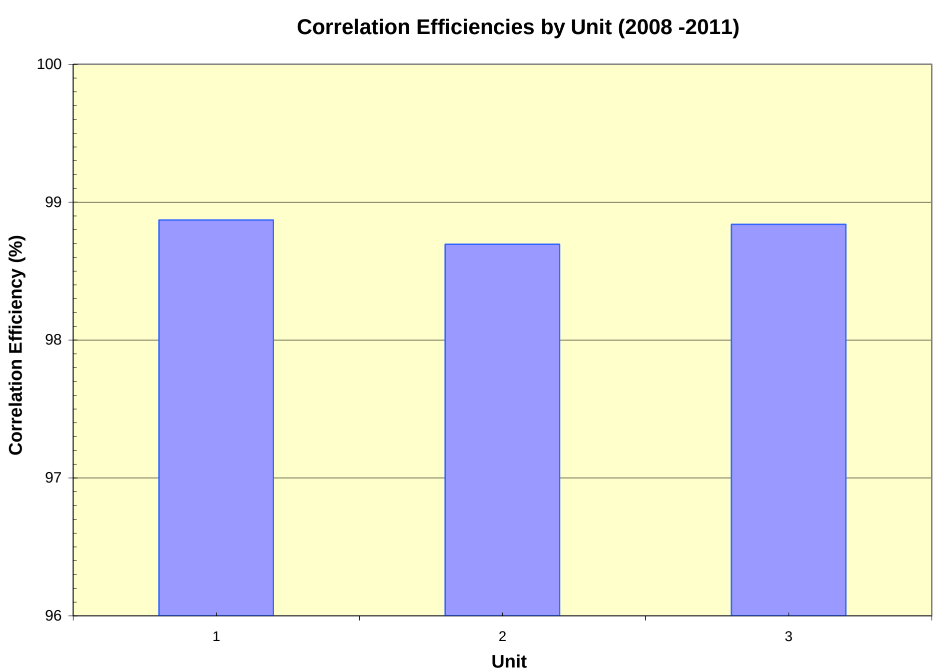

Figure 4.1: Flaming Gorge Correlation Efficiencies (2008 – 2011)

Figure 4.2 provides results from the current correlation analyses for Flaming Gorge Unit 1, using data from January 2008 through November 2015. The red line in Figure 4.2 shows the computed Unit 1 efficiency curve at a head of 420 ft, derived from 2008-2015 hourly archival data for unit flow, unit power, headwater, and tailwater. The small blue triangles show average efficiency values at 0.5 MW intervals, and the black error bars show the precision error for the 2008-2015 archival data for the given power level. Below about 25 MW, significant scatter can be observed in the efficiency results because operation in this range is typically a transient condition during ramp-up and ramp-down. Consequently, the hourly flow data is not adequate to characterize these transitions. The green triangles show the Unit 1 efficiencies measured during the November 2015 field performance tests. The unit efficiencies from the field tests agree closely with the efficiencies derived from the archival data.

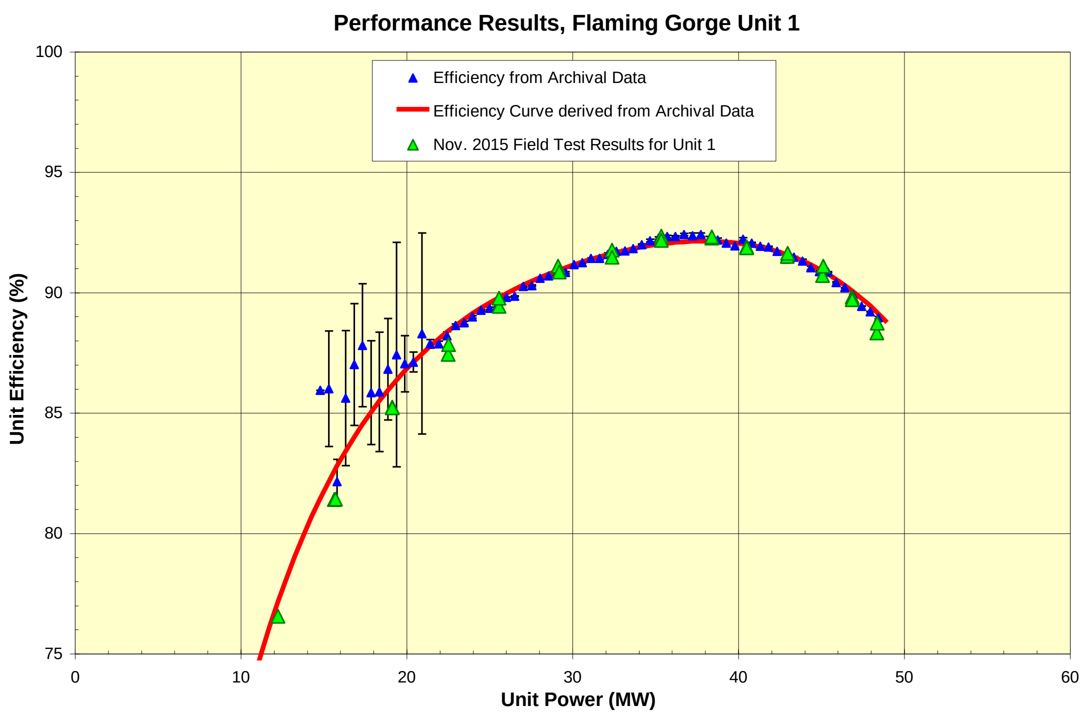

Figure 4.2: Performance Results for Flaming Gorge Unit 1 (GH = 420 ft)

Similarly, Figures 4.3 and 4.4 provide results from the current correlation analyses for Flaming Gorge Unit 2 and Unit 3, respectively. As with Unit 1, the unit efficiencies from the field tests for Unit 2 and Unit 3 agree closely with the corresponding derived efficiencies. For Unit 2, additional scatter in the derived efficiency values can be observed in some of the data above a power level of 25 MW. Similar results, previously observed with 2008-2011 analyses of Flaming Gorge archival data for Unit 2, were attributed to occasional trash rack fouling events [March et al., 2012].

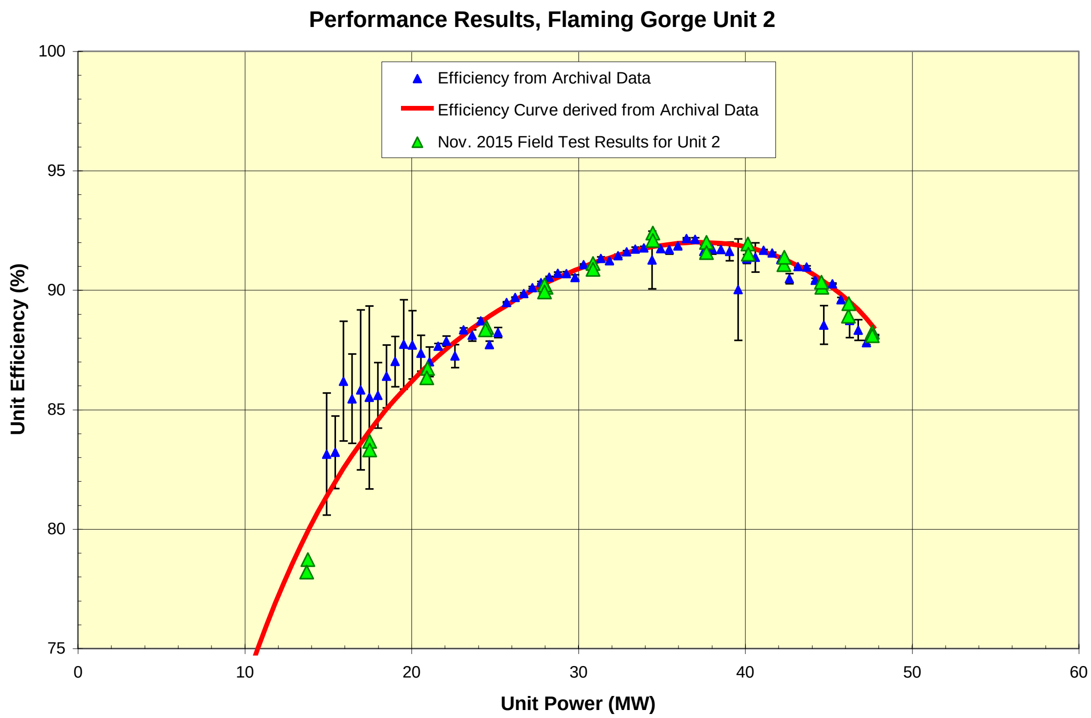

Figure 4.3: Performance Results for Flaming Gorge Unit 2 (GH = 420 ft)

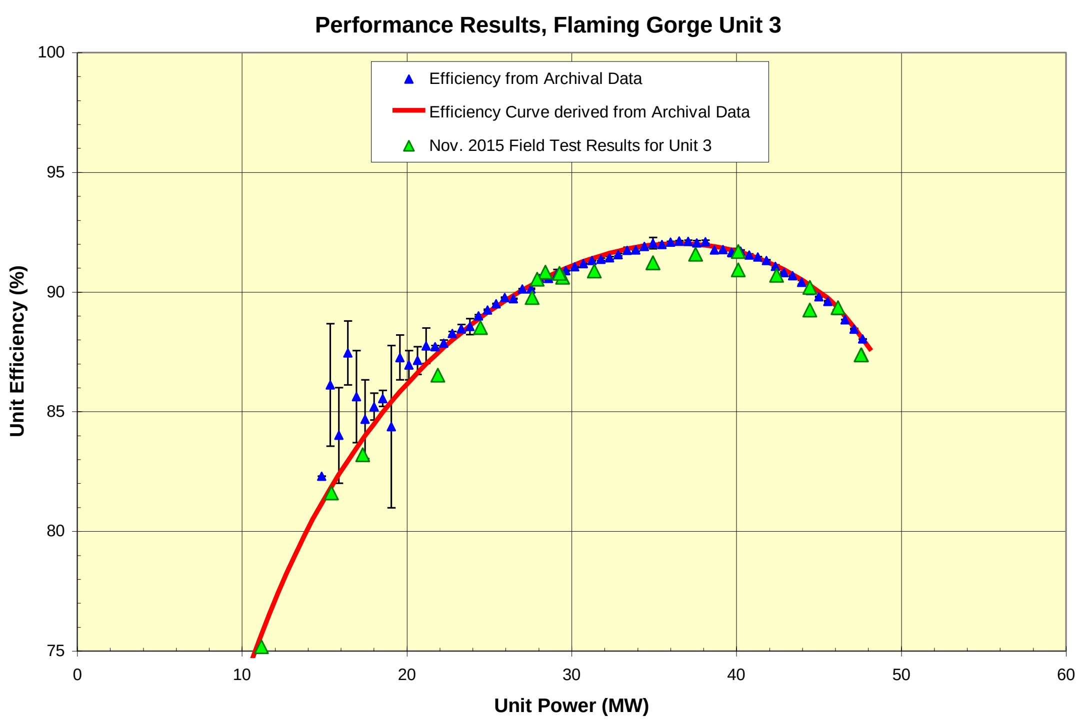

Figure 4.4: Performance Results for Flaming Gorge Unit 3 (GH = 420 ft)

Figure 4.5 shows a comparison among curve fits of performance results for Flaming Gorge at a gross head of 420 ft. The red line in Figure 4.5 is the expected performance provided by the turbine manufacturer, VA TECH. The blue line shows the Unit 1 performance curve derived from the 2008 – 2015 archival data, the green line shows the Unit 2 derived performance curve, and the yellow line shows the Unit 3 derived performance curve. The HPC was used to develop optimized plant efficiency curves based on the VA TECH unit characteristics and based on the derived unit characteristics.

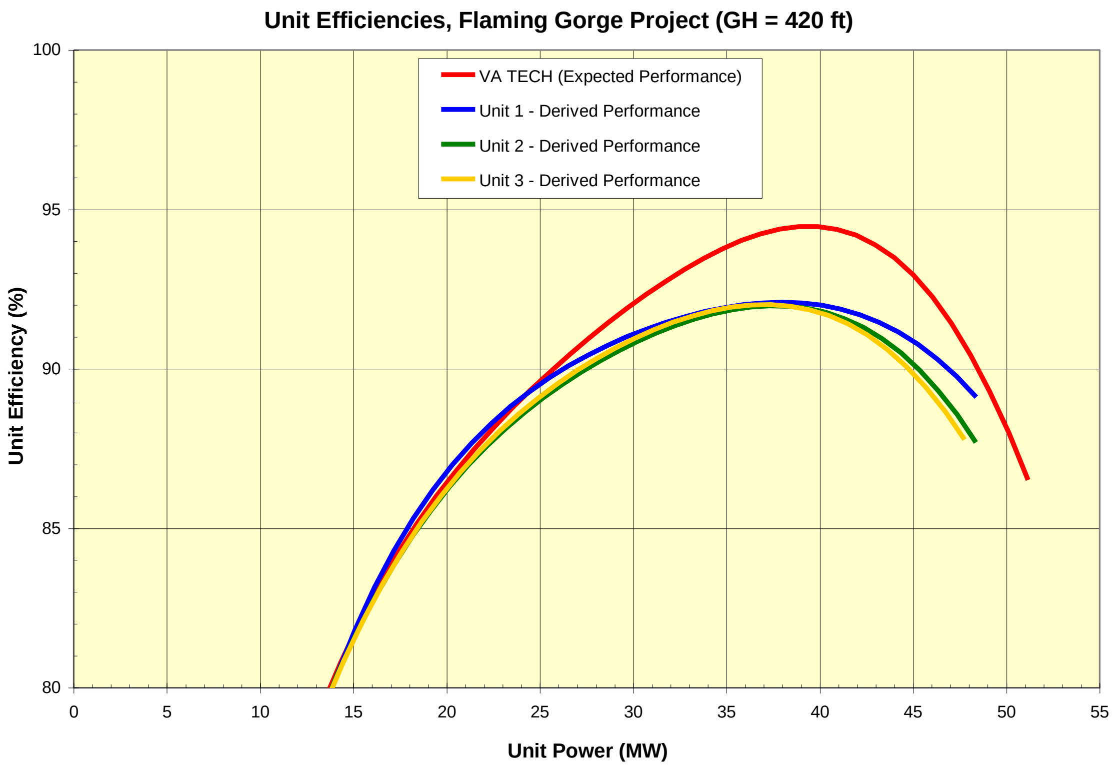

Figure 4.5: Comparison of Unit Performance Curves for Flaming Gorge (GH = 420 ft)

Typical optimized plant efficiency curves for Flaming Gorge, at a gross head of 420 ft, are provided in Figure 4.6. Note the shift in the power levels for minimum and maximum values of optimized plant efficiency for the VA TECH efficiency curve compared to the derived efficiency curve.

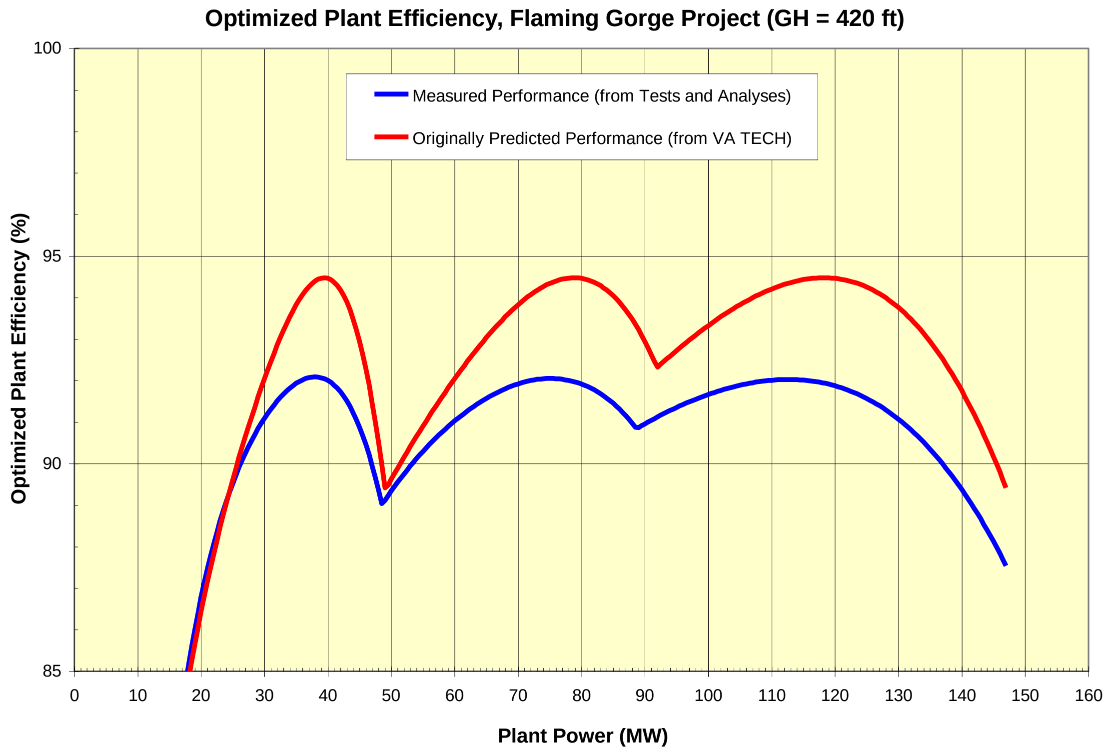

Figure 4.6: Comparison of Plant Performance Curves for Flaming Gorge (GH = 420 ft)

4.2 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. Detailed computational steps for determining the operation efficiency are discussed elsewhere [ORNL, 2011]. At each time step of the archival data, the optimized plant efficiency is computed, apportioning the total plant power among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the actual plant power, 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 computed energy gain occurs.

Operation efficiency analyses were computed with the HPC Analyzer for Flaming Gorge using the 2008-2015 hourly archival data of unit flow, unit power, headwater, and tailwater and the derived unit characteristics. Results from these operation efficiency analyses are summarized in Table 4.1. Figure 4.7 provides a bar chart for the lost energy opportunity (LEO, in MWh) by year, and Figure 4.8 shows a bar chart for the corresponding water conservation opportunity (WCO, in acre-ft).

Table 4.1: Summary of Operation Efficiency Analyses for Flaming Gorge (2008-2015)

Year	Total Lost Energy Opportunity (MWh)	Total Lost Revenue Opportunity ($)	Total Water Conservation Opportunity (acre-ft)	Actual Energy Production (MWh)	Potential Increase in Energy Production (%)
2008	1,708	51,236	4,185	368,495	0.5
2009	997	29,907	2,402	457,274	0.2
2010	1,084	32,533	2,602	395,614	0.3
2011	3,198	95,954	7,544	674,662	0.5
2012	1,641	49,220	3,869	97,612	1.7
2013	809	24,283	2,002	299,601	0.3
2014	1,284	38,515	3,046	418,674	0.3
2015	1,988	59,646	4,720	450,339	0.4
TOTAL (2008-2015)	**12,710**	**381,293**	**30,370**	**3,162,271**	**0.4**

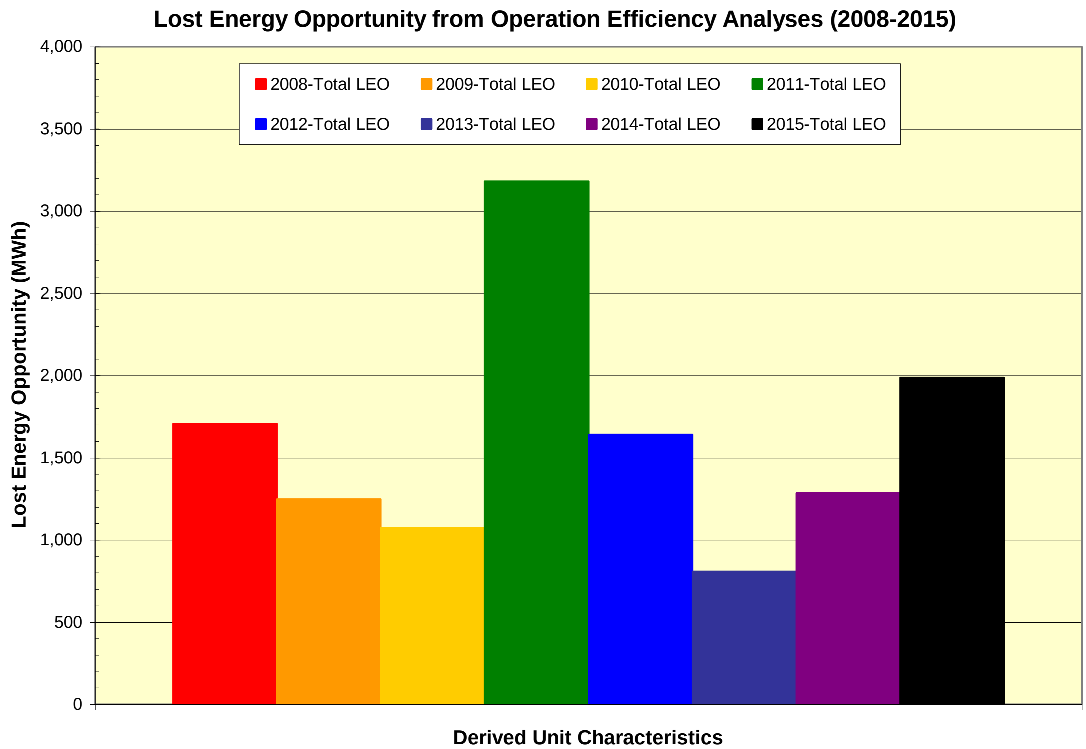

Figure 4.7: Lost Energy Opportunity from Operation Efficiency Analyses (2008-2015)

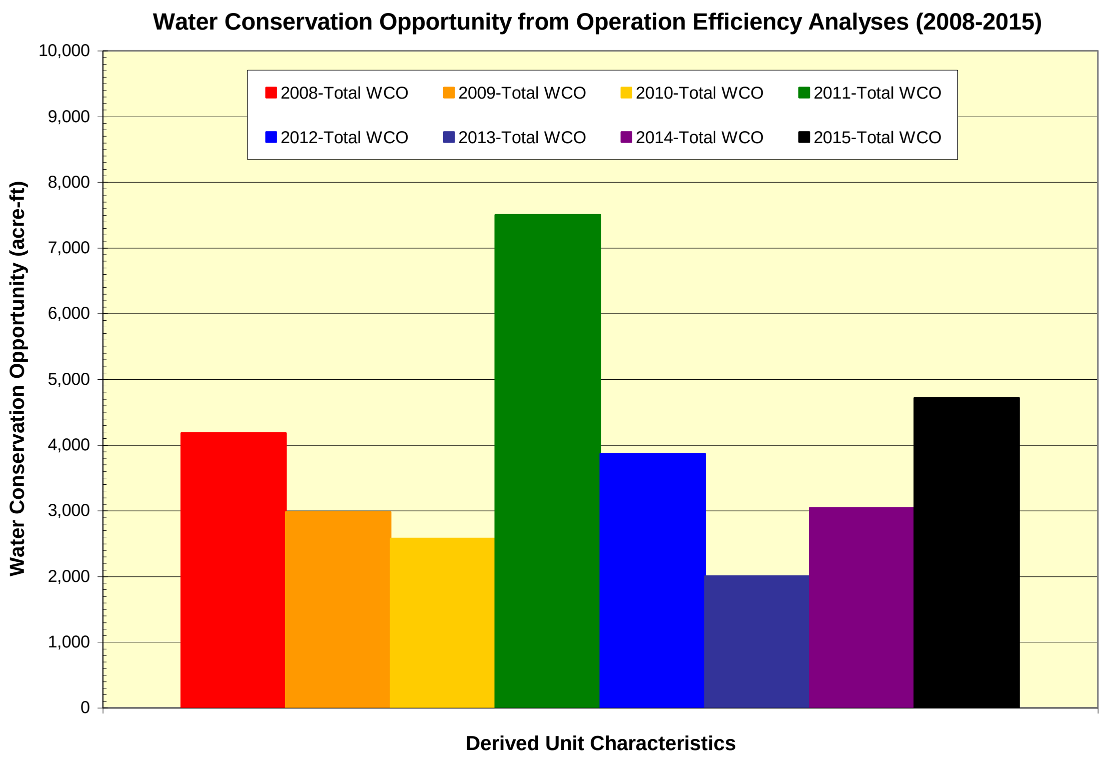

Figure 4.8: Water Conservation Opportunity from Operation Efficiency Analyses (2008-2015)

Overall, the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.2% for 2008 to a high of 1.7% for 2012, with an average of 0.4% and an eight-year total of 12,710 MWh, corresponding to a greenhouse gas emissions reduction of 8,764 metric tons of Carbon Dioxide Equivalent [EPA, 2016]. The 1.7% efficiency improvement for 2012 is based on a partial data set that includes data from 1/1/2012 through 2/23/2012. The water conservation opportunity ranges from a low of 2,002 acre-ft/year for 2013 to a high of 7,544 acre-ft/year for 2011, with an eight-year total of 30,370 acre-ft.

4.3 Generation Scheduling Analyses

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

Figure 4.9 provides typical results from the scheduling analyses conducted for Flaming Gorge, showing 2010 results for a gross head of 420 ft. The optimized plant gross head efficiency for 420 ft, based on the derived unit characteristics, is shown in green. The actual 2010 monthly generation versus plant power at that head is shown in blue, and the optimized 2010 monthly generation versus plant power at that head is shown in red. The actual generation values (blue triangles) tend to occur at a wide variety of power levels corresponding to specific release flows. The optimized generation values (red triangles) correspond to the peak efficiencies for one-unit, two-unit, and three-unit operation.

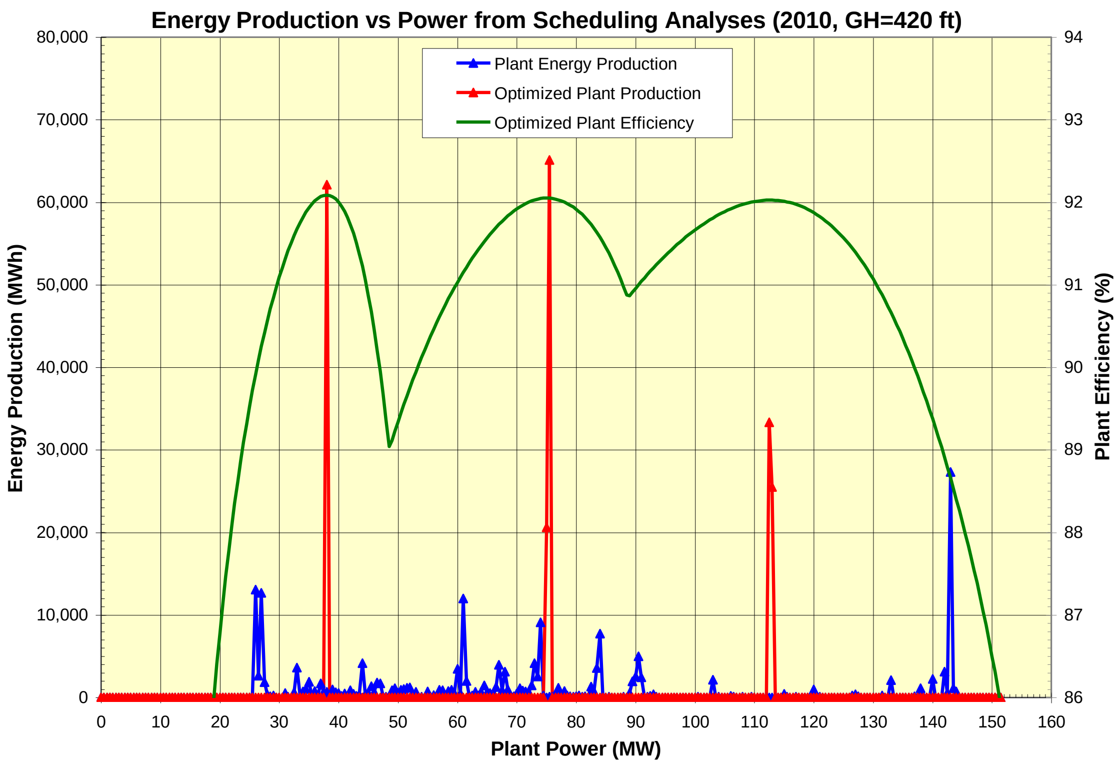

Figure 4.9: Typical Energy Production versus Power from Generation Scheduling Analyses (2010, Gross Head = 420 ft)

Results from these scheduling analyses are summarized in Table 4.2. Figure 4.10 provides a bar chart for the lost energy opportunity (LEO, in MWh) by year, and Figure 4.11 shows a bar chart for the corresponding water conservation opportunity (WCO, in acre-ft). The potential generation improvements are significant, ranging from a low of 1,254 MWh (1.3%) in 2012 to a high of 15,286 MWh (2.3%) in 2011, with an average of 1.8% and an eight-year total of 55,963 MWh, corresponding to a greenhouse gas emissions reduction of 38,589 metric tons of Carbon Dioxide Equivalent [EPA, 2016]. The water conservation opportunity ranges from a low of 2,936 acre-ft/year for 2012 to a high of 36,341 acre-ft/year for 2011, with an eight-year total of 133,320 acre-ft.

Table 4.2: Summary of Scheduling Analyses for Flaming Gorge (2008-2015)

Year	Total Lost Energy Opportunity (MWh)	Total Lost Revenue Opportunity ($)	Total Water Conservation Opportunity (acre-ft)	Actual Energy Production (MWh)	Potential Increase in Energy Production (%)
2008	7,830	234,895	18,744	368,495	2.1
2009	5,355	160,656	12,722	457,274	1.2
2010	6,032	180,956	14,292	395,614	1.5
2011	15,286	458,591	36,341	674,662	2.3
2012	1,254	37,614	2,936	97,612	1.3
2013	7,103	213,101	17,228	299,601	2.4
2014	7,590	227,697	18,092	418,674	1.8
2015	5,512	165,368	12,965	450,339	1.2
TOTAL (2008-2015)	**55,963**	**1,678,878**	**133,320**	**3,162,271**	**1.8**

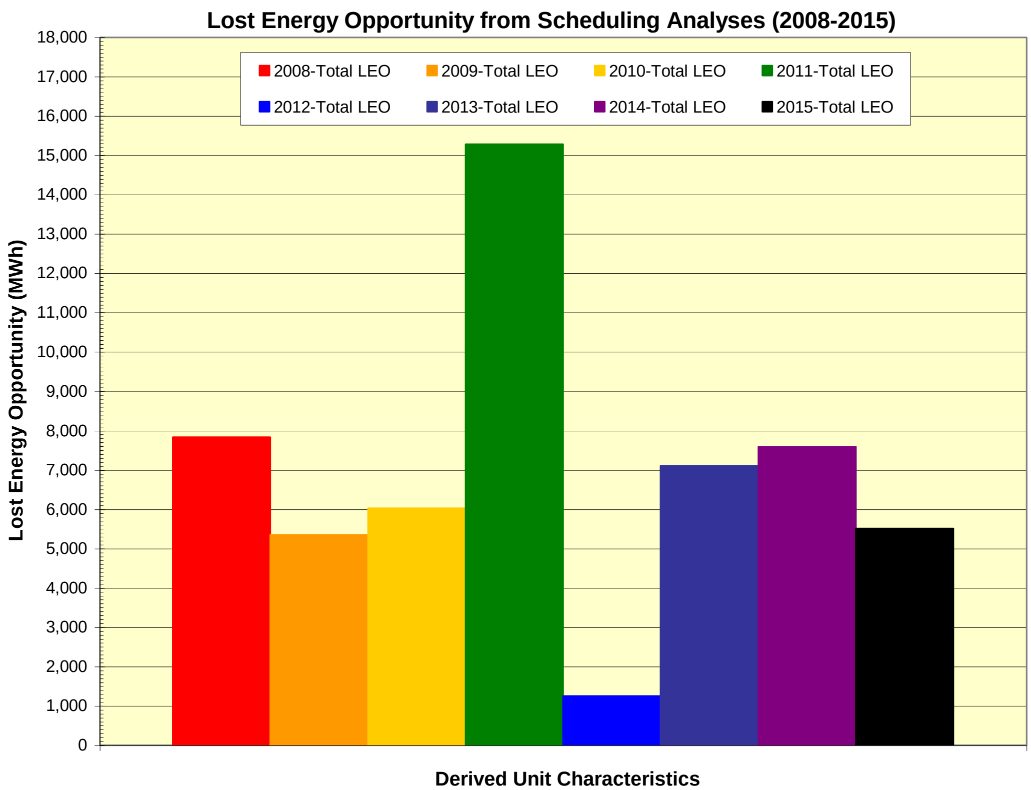

Figure 4.10: Lost Energy Opportunity from Generation Scheduling Analyses (2008-2015)

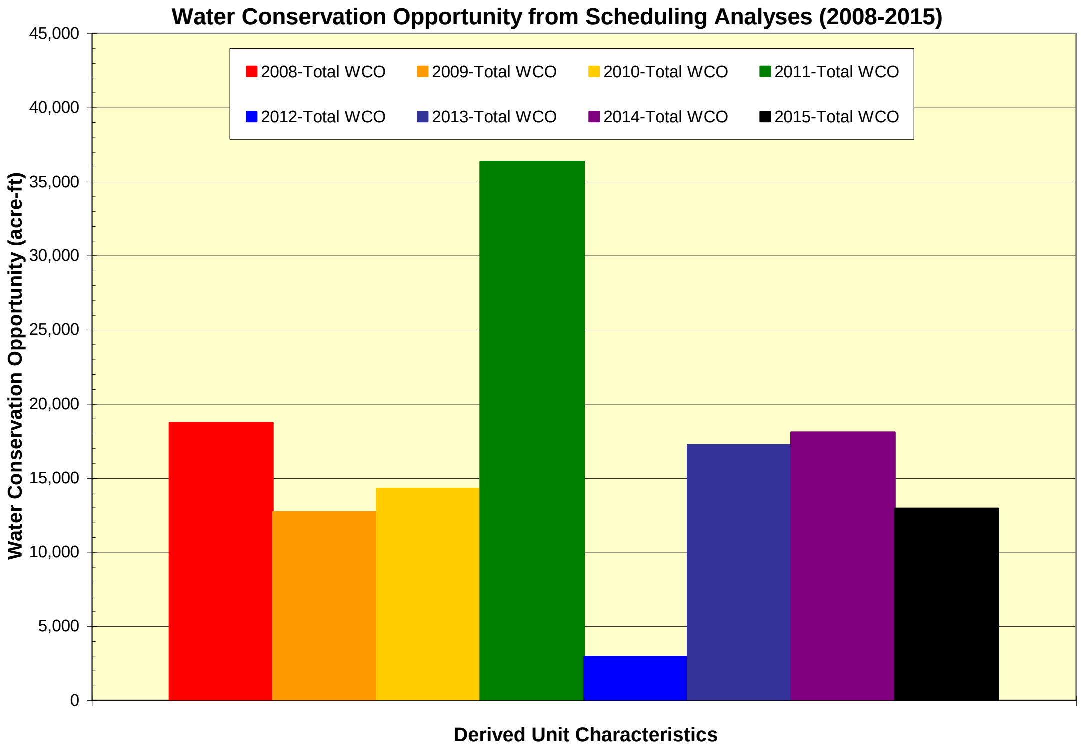

Figure 4.11: Water Conservation Opportunity from Generation Scheduling Analyses (2008-2015)

5. Summary and Recommendations

5.1 Summary of Results

Efficiency tests were conducted for Flaming Gorge Units 1, 2, and 3 in November 2015. Detailed unit characteristics were also developed from archival data (2008-2015), including HW, TW, unit power, and unit flow. The derived unit characteristics and the Hydroplant Performance Calculator were used to produce operation efficiency analyses and generation scheduling analyses.

Results are summarized below:

1. Performance characteristics derived from archival data correlate well with field measurements.
2. A performance comparison between the VA TECH curves and the derived performance curves shows an average annual energy difference of 1.6%, corresponding to a $190,000/year power revenue loss.
3. Operation efficiency analyses show the potential for modest annual improvements of approximately 0.4% from improved unit dispatch, corresponding to a $48,000/year power revenue increase and a 2008-2015

greenhouse gas emissions reduction of 8,764 metric tons of Carbon Dioxide Equivalent [EPA, 2016].

4. Generation scheduling analyses show potential for significant annual improvements of approximately 1.8%, corresponding to a $210,000/year power revenue increase and a 2008-2015 greenhouse gas emissions reduction of 38,589 metric tons of Carbon Dioxide Equivalent [EPA, 2016].

5.2 Suggested Actions based on Results

Flaming Gorge has high quality instrumentation for the plant's on-line systems, producing an accurate and valuable archival data set. The data are archived at one hour intervals, which is appropriate for Flaming Gorge because plant power changes generally occur on hourly intervals as the hour changes. Gaps that were identified as part of these analyses, and recommendations based on those gaps, include the following:

1. Flaming Gorge does not currently compute and review hydro performance indicators. Three important performance indicators for consideration include the operation efficiency, the generation scheduling efficiency, and the correlation efficiency.
2. The operation efficiency should be computed and reviewed on monthly intervals. This would help ensure that the unit dispatch is continually optimized. Because Flaming Gorge operates at fixed power levels for extended periods of time, it should be possible to reduce energy losses from non-optimized dispatch to less than one-tenth of a percent.
3. Modification to the plant power schedule is currently under review by USBR, based on the results from these analyses. If USBR determines that optimized plant power scheduling is feasible, the optimized scheduling performance should be computed and reviewed on a monthly basis to ensure that the scheduling efficiency is continually optimized.
4. Correlation efficiencies should be computed and reviewed on a monthly basis to ensure that unit characteristics are accurate and that the unit instrumentation is functioning properly. In addition, correlation efficiencies can be a useful component of a predictive maintenance program, including identification of trash rack fouling.

6. References

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