Performance Assessment Manual

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

Revision 1.1, 10/12/2012

Prepared by

HYDRO PERFORMANCE PROCESSES INC.
Doylestown, Pennsylvania 18901

and

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6283
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Contents

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

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

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

The Potential Performance Level (PPL) unit performance curves for U1, U2, and U3 are based on the CPL curve for the upgraded U2, with an additional assumed net head turbine efficiency improvement of 1% due to improved turbine technology and a maximum assumed generator efficiency of 98% due to improved generator technology. The PPL unit flow versus unit power curves for U1, U2, and U3 at gross heads of 55 ft, 60 ft, 65 ft, and 70 ft are presented in Figure 2.05-7, and the corresponding gross head unit efficiencies versus power for U1, U2, and U3 are provided in Figure 2.05-8.

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

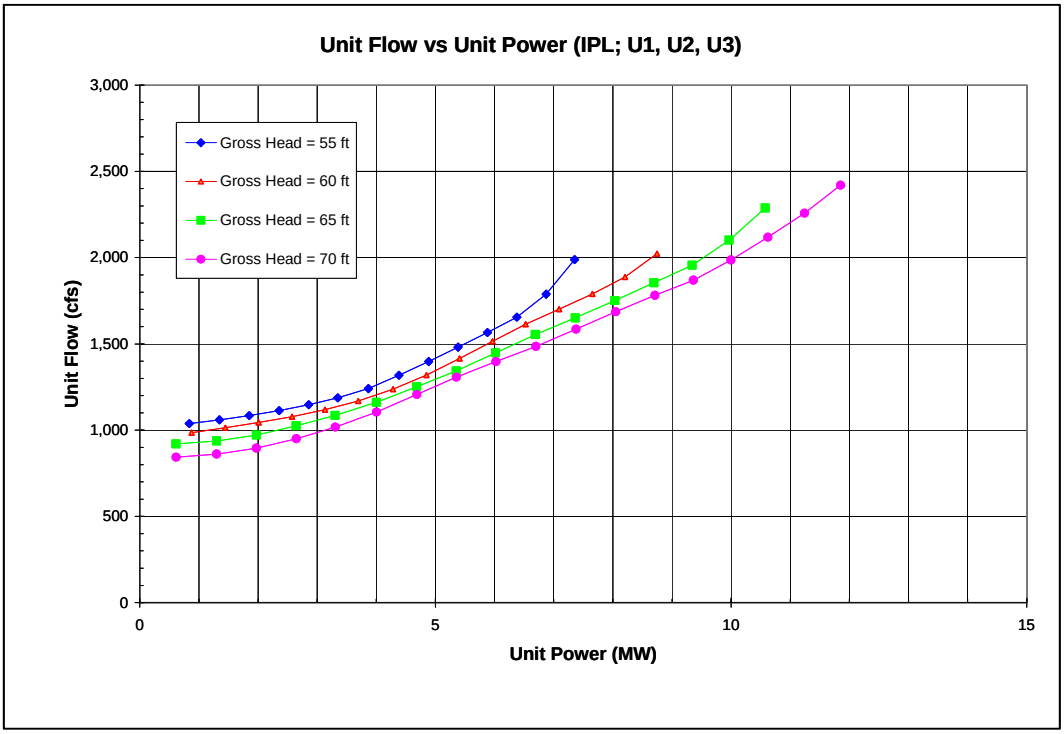


Figure 2.05-1: Unit Flow versus Unit Power (IPL; U1, U2, U3)

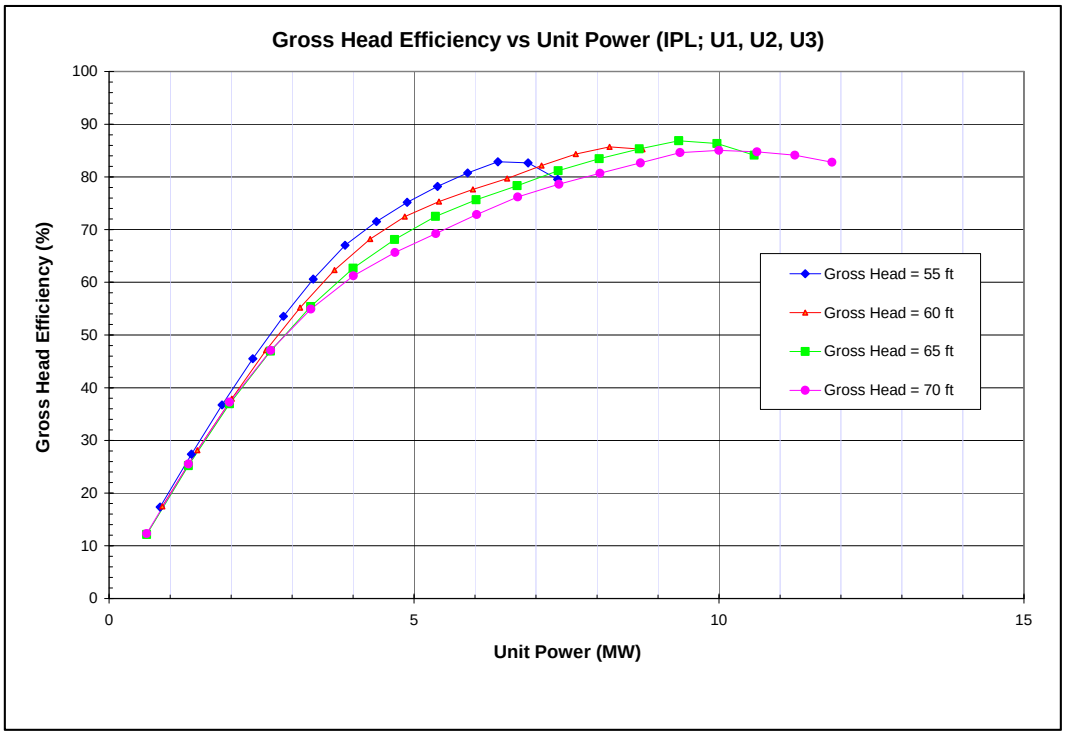


Figure 2.05-2: Unit Gross Head Efficiency versus Unit Power (IPL; U1, U2, U3)

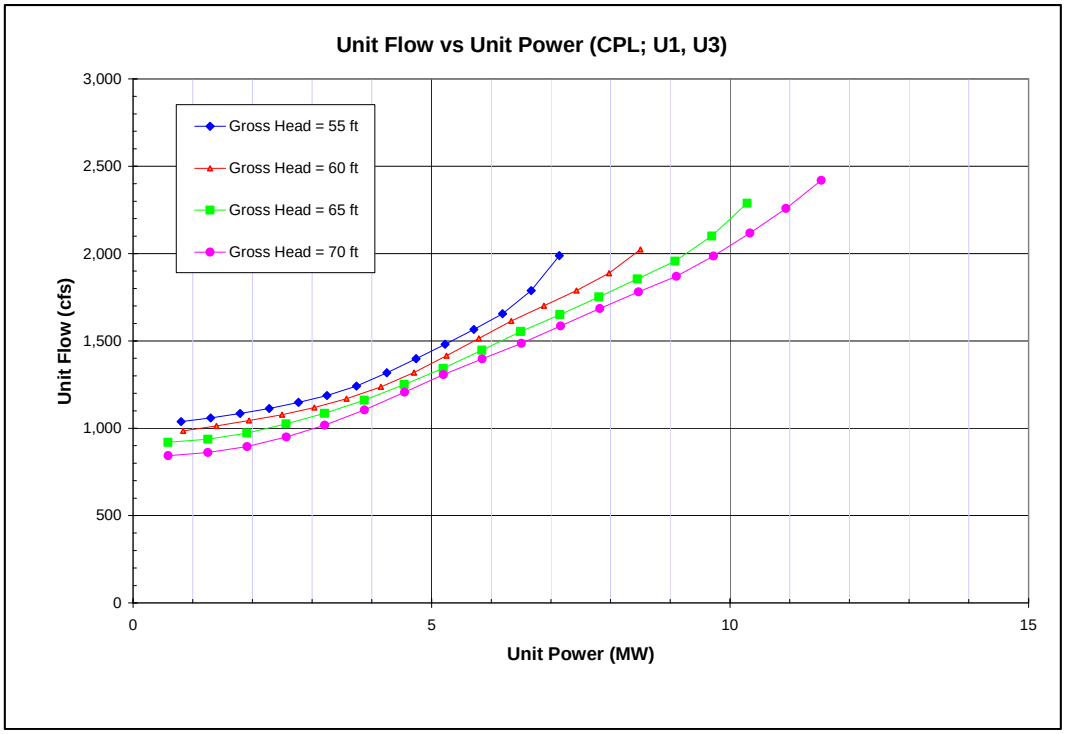


Figure 2.05-3: Unit Flow versus Unit Power (CPL; U1, U3)

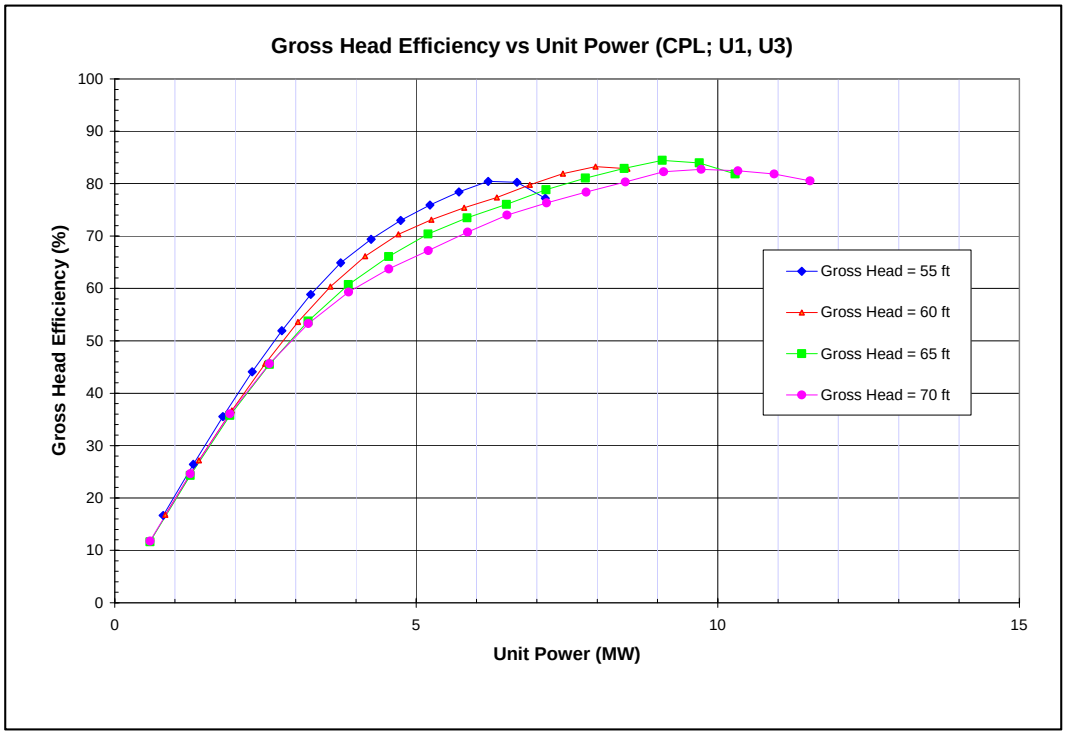


Figure 2.05-4: Unit Gross Head Efficiency versus Unit Power (CPL; U1, U3)

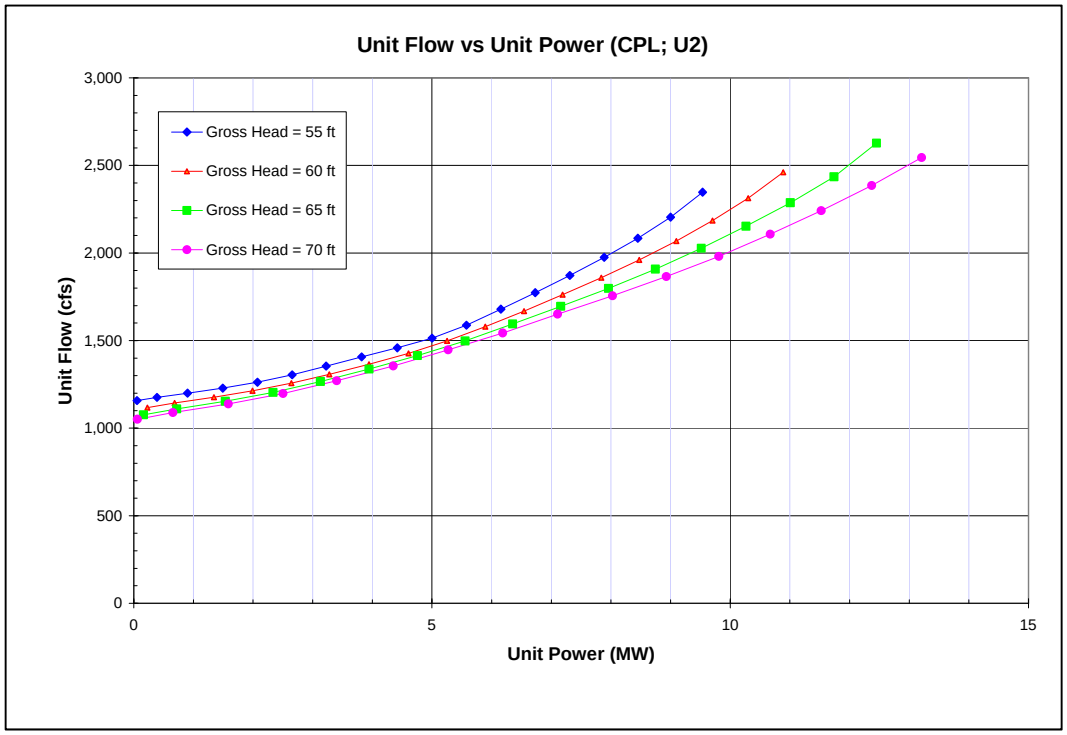


Figure 2.05-5: Unit Flow versus Unit Power (CPL; U2)

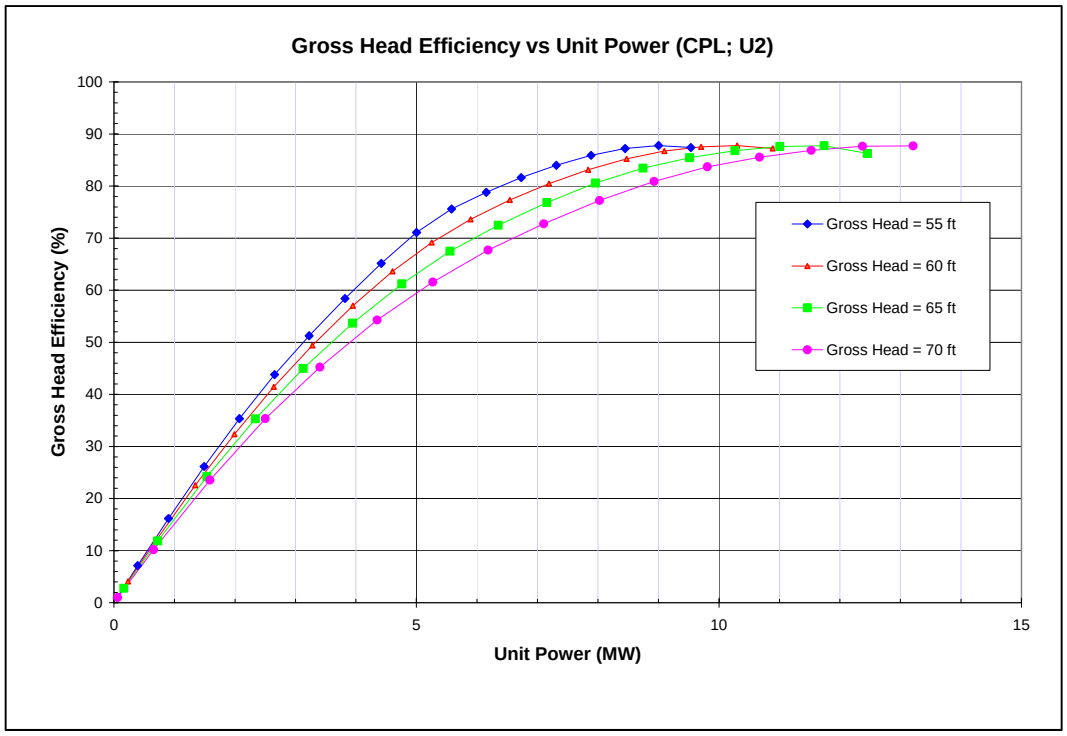


Figure 2.05-6: Unit Gross Head Efficiency versus Unit Power (CPL; U2)

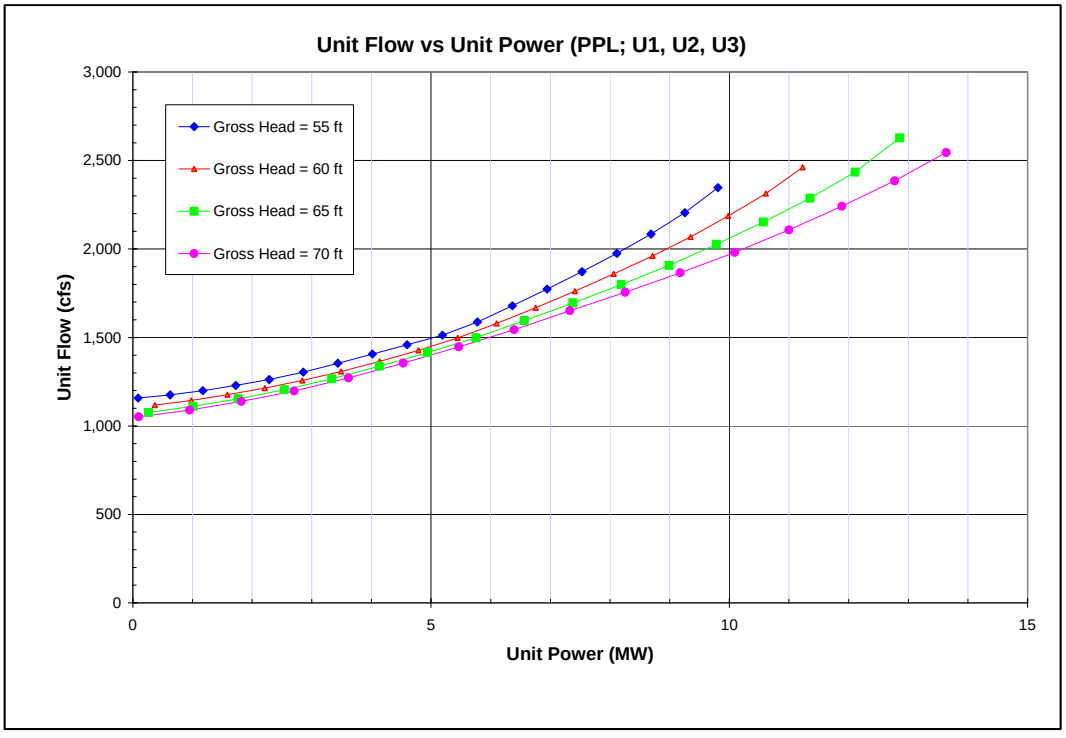


Figure 2.05-7: Unit Flow versus Unit Power (PPL; U1, U2, U3)

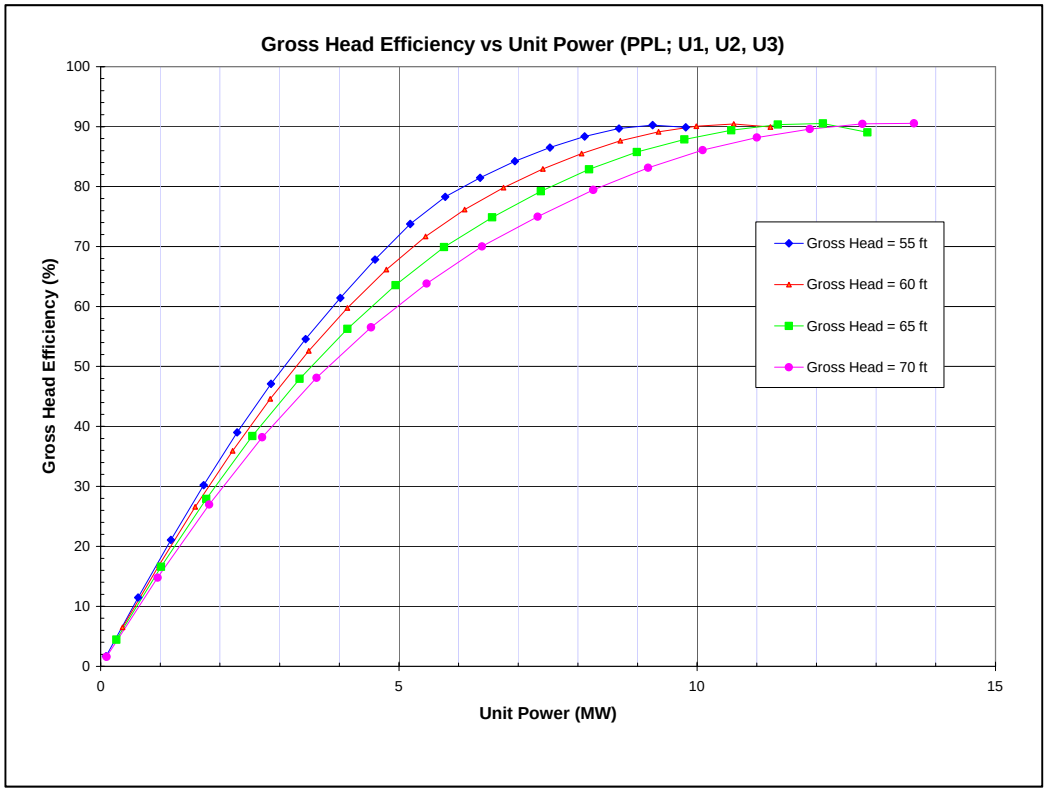


Figure 2.05-8: Unit Gross Head Efficiency versus Unit Power (PPL; U1, U2, U3)

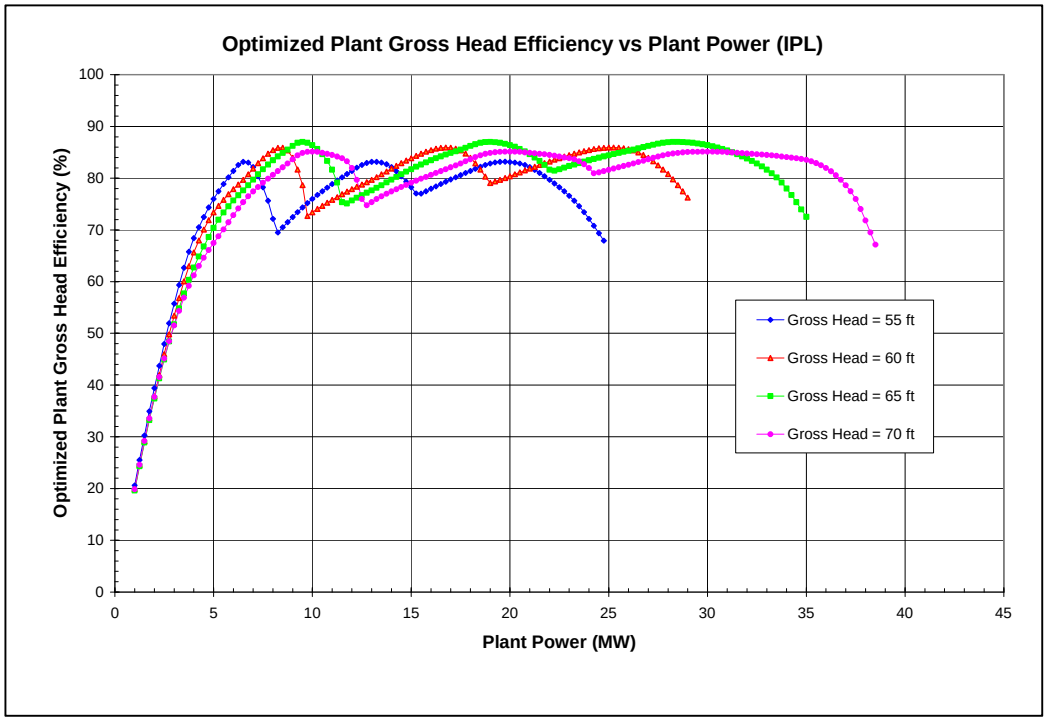


Figure 2.05-9: Optimized Plant Gross Head Efficiency versus Plant Power (IPL)

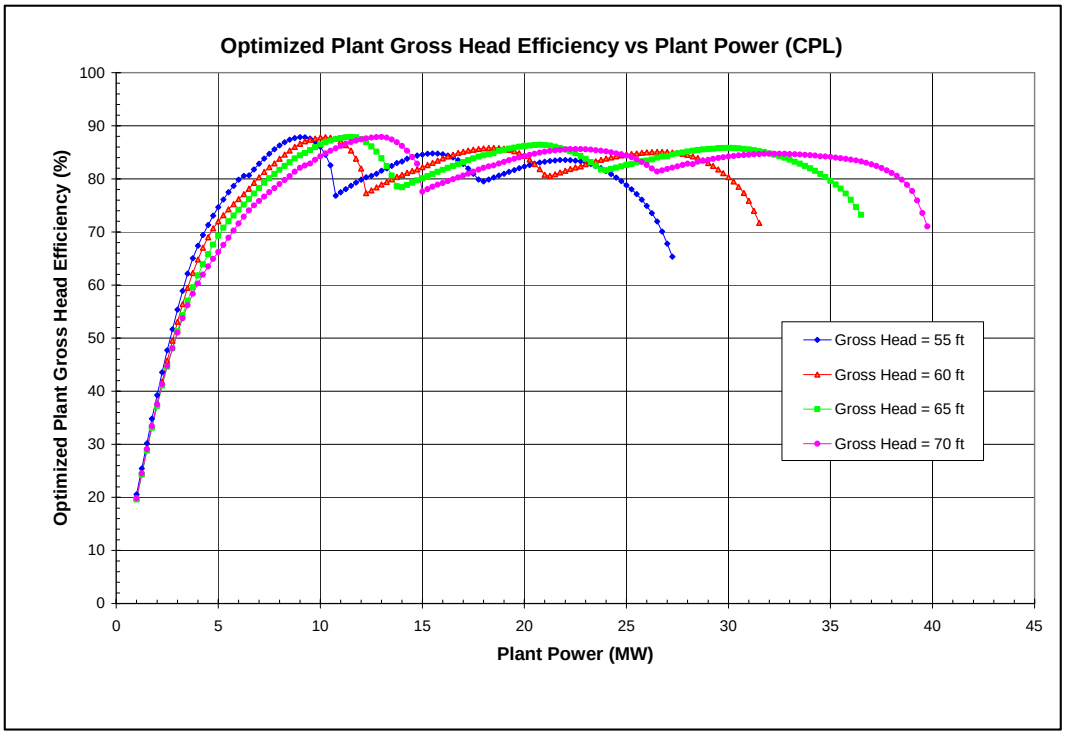


Figure 2.05-10: Optimized Plant Gross Head Efficiency versus Plant Power (CPL)

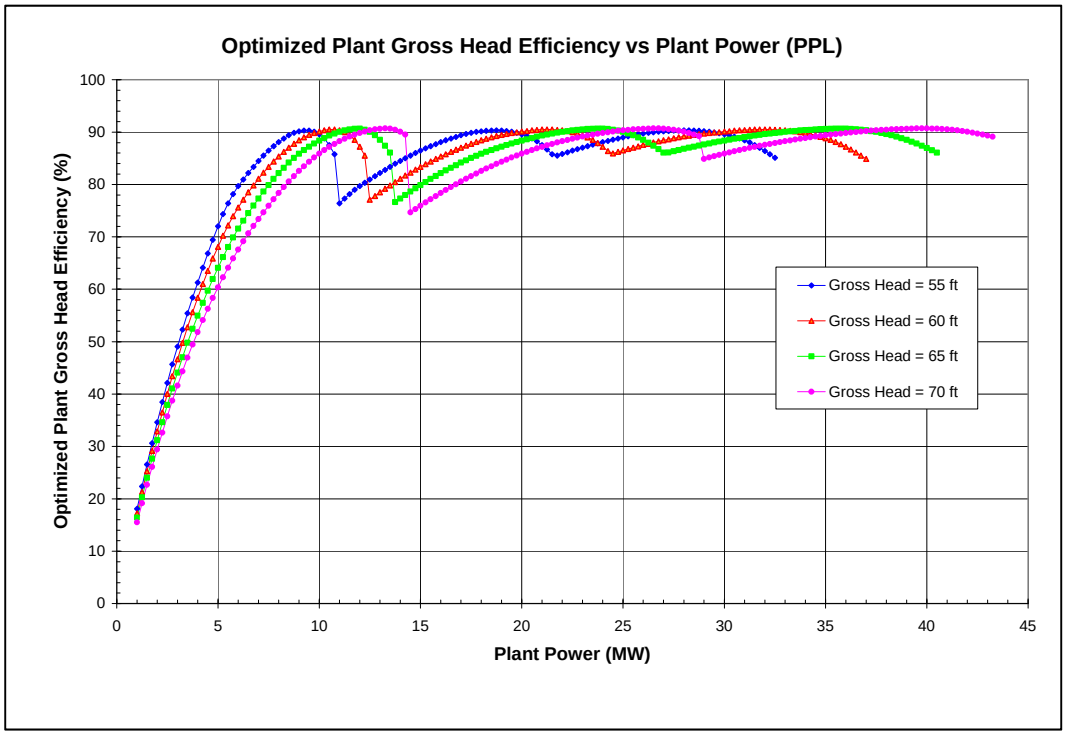


Figure 2.05-11: Optimized Plant Gross Head Efficiency versus Plant Power (PPL)

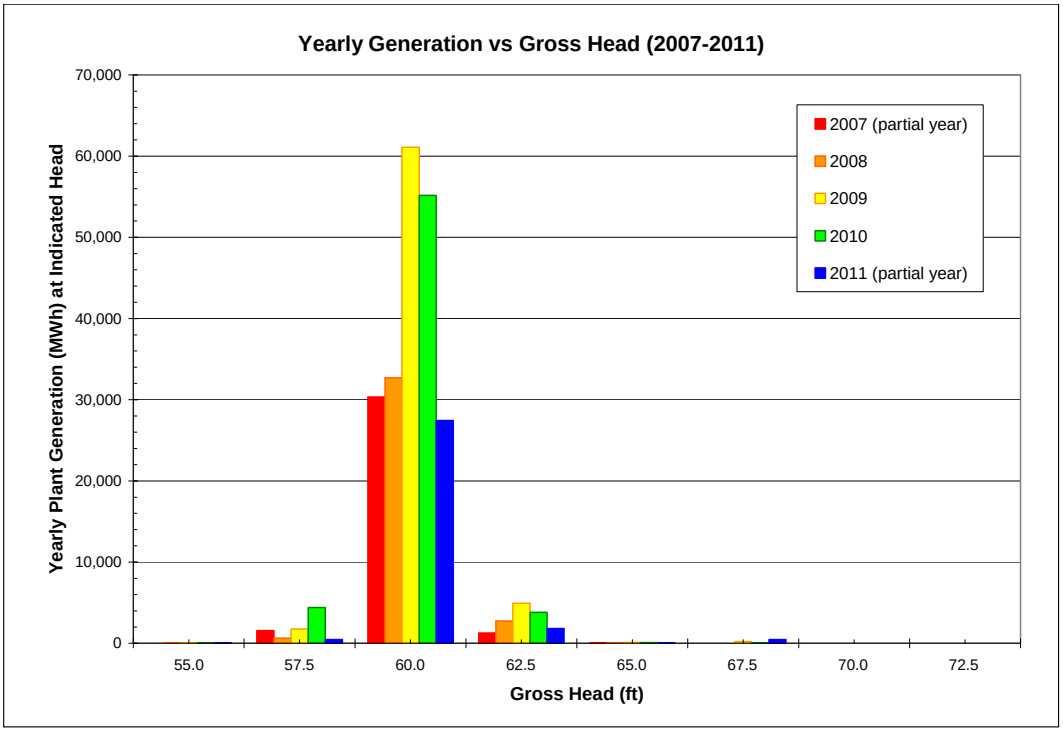


Figure 2.05-12: Distribution of Yearly Generation with Gross Head (2007 – 2011)

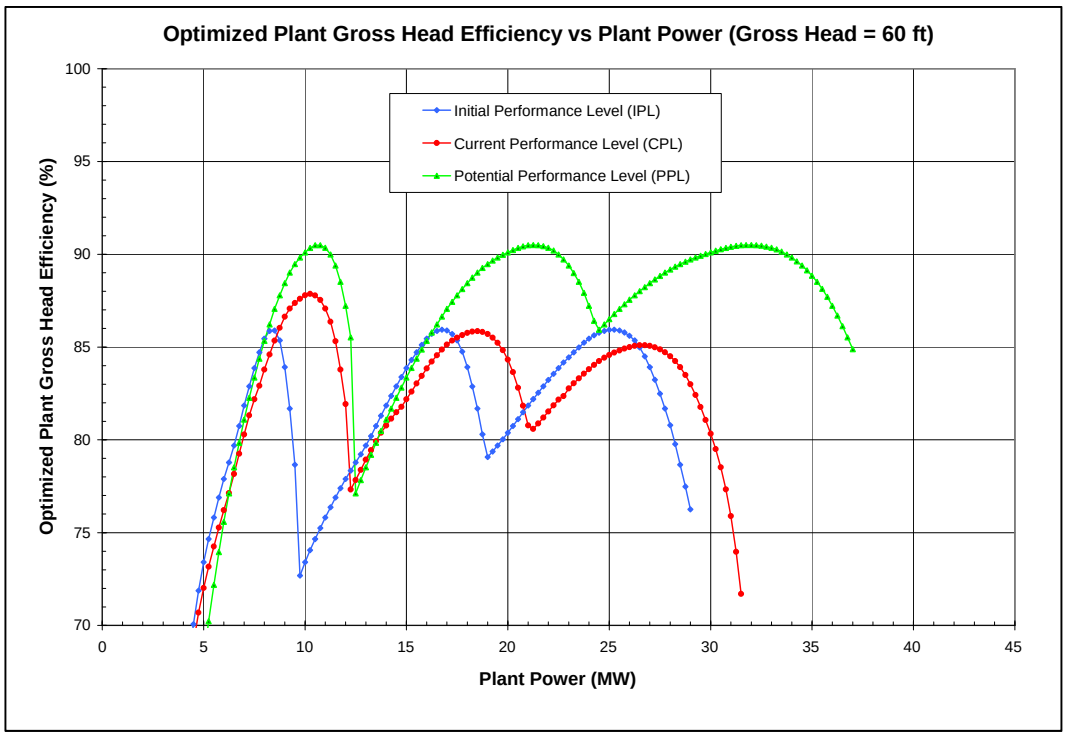


Figure 2.05-13: Optimized Plant Gross Head Efficiency versus Plant Power (GH = 60 ft)

Operation Efficiency Analyses – The Operation Efficiency Analyses use unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch. Computational steps for determining the operation efficiency are discussed in the Performance Assessment Manual. At each time step of the archival data, the optimized plant efficiency is computed, apportioning the total plant load among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the actual plant load, matching the head, and operating each unit within minimum and maximum power limits). Energy gains due to water savings from optimized dispatch are computed by assuming that the water is converted into energy at the optimized plant efficiency and head for the time step in which the potential energy gain occurs.

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

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

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

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

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

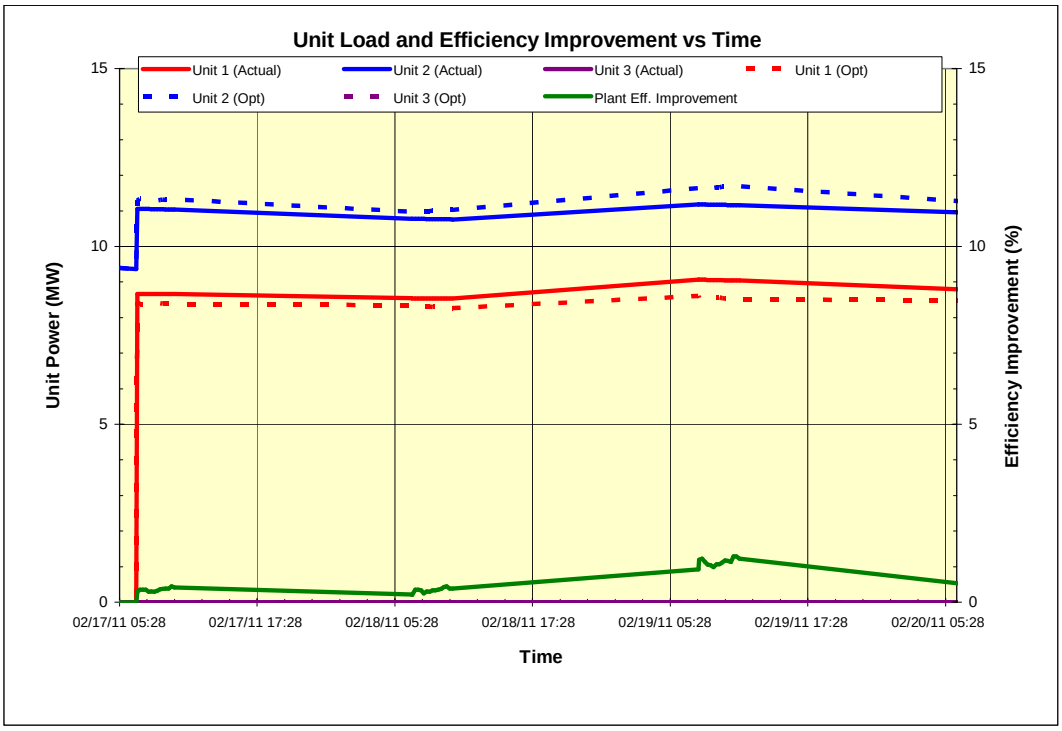


Figure 2.05-14: Typical Operation Efficiency Results (February 17-20, 2011)

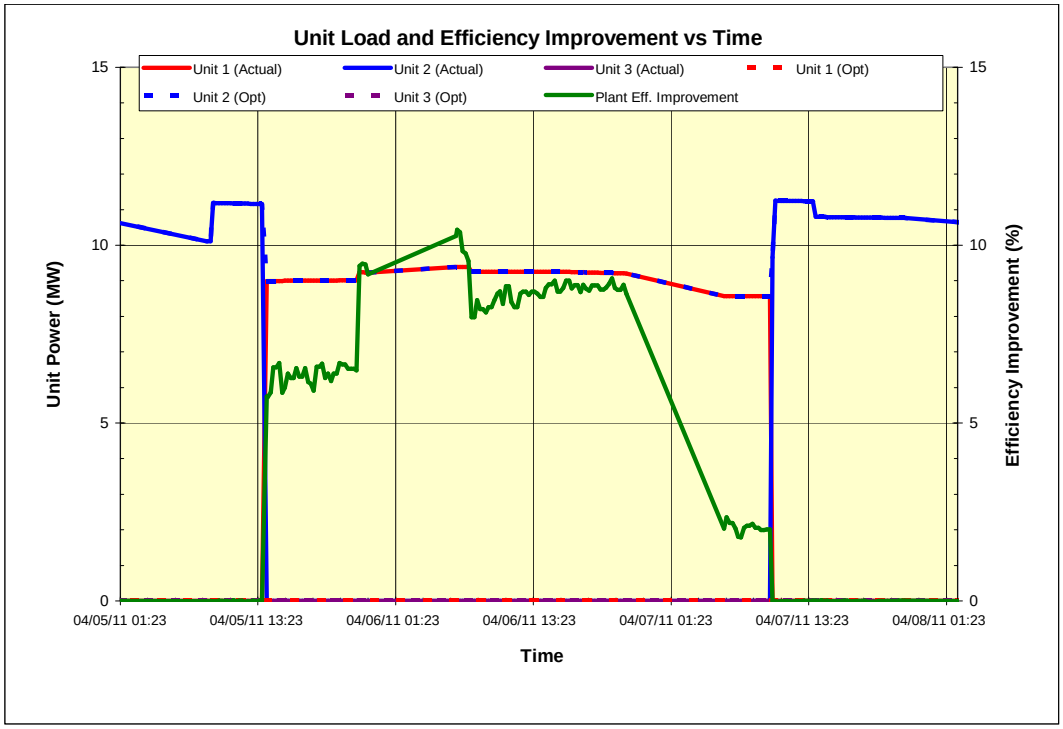


Figure 2.05-15: Typical Operation Efficiency Results (April 5-7, 2011)

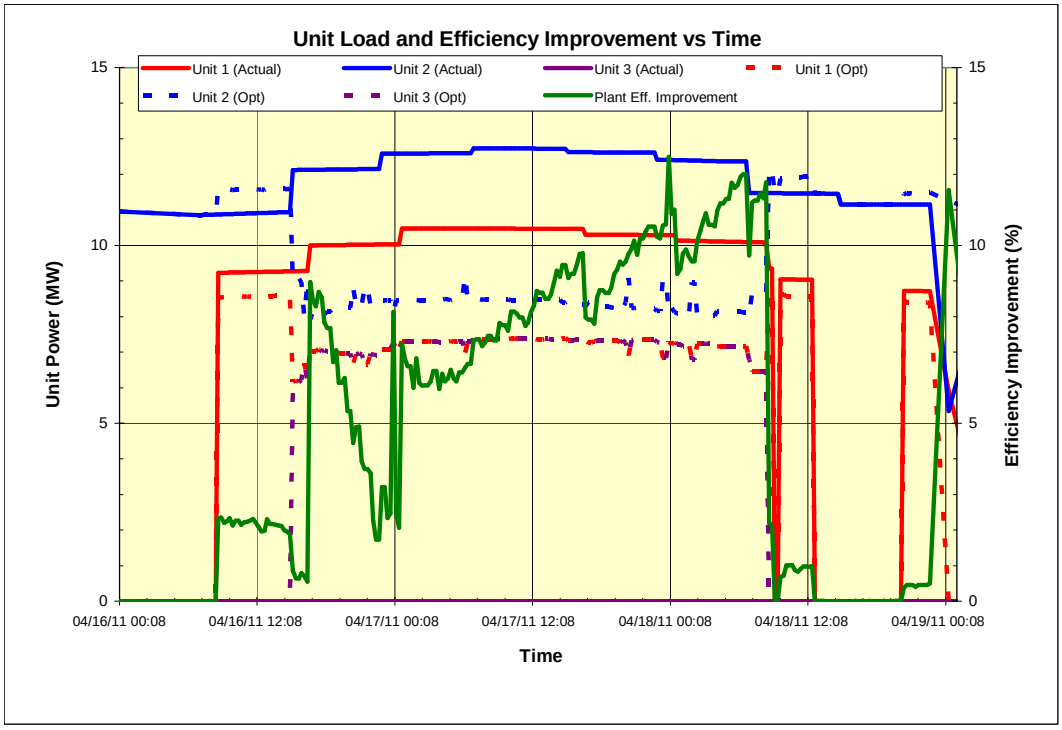


Figure 2.05-16: Typical Operation Efficiency Results (April 16-18, 2011)

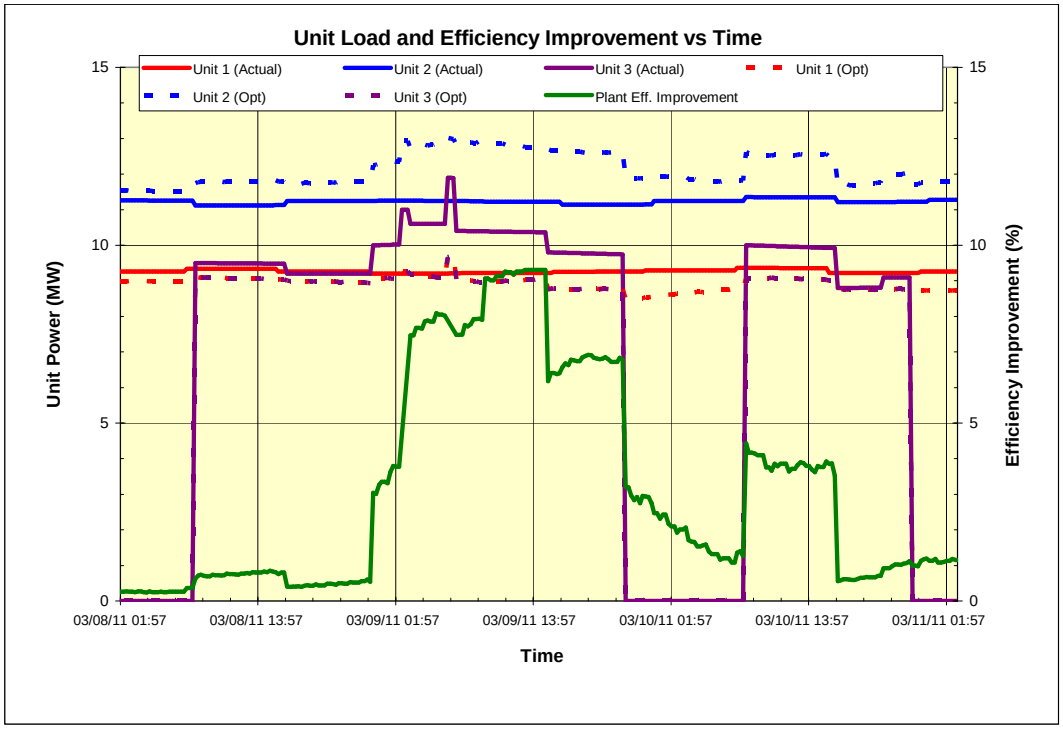


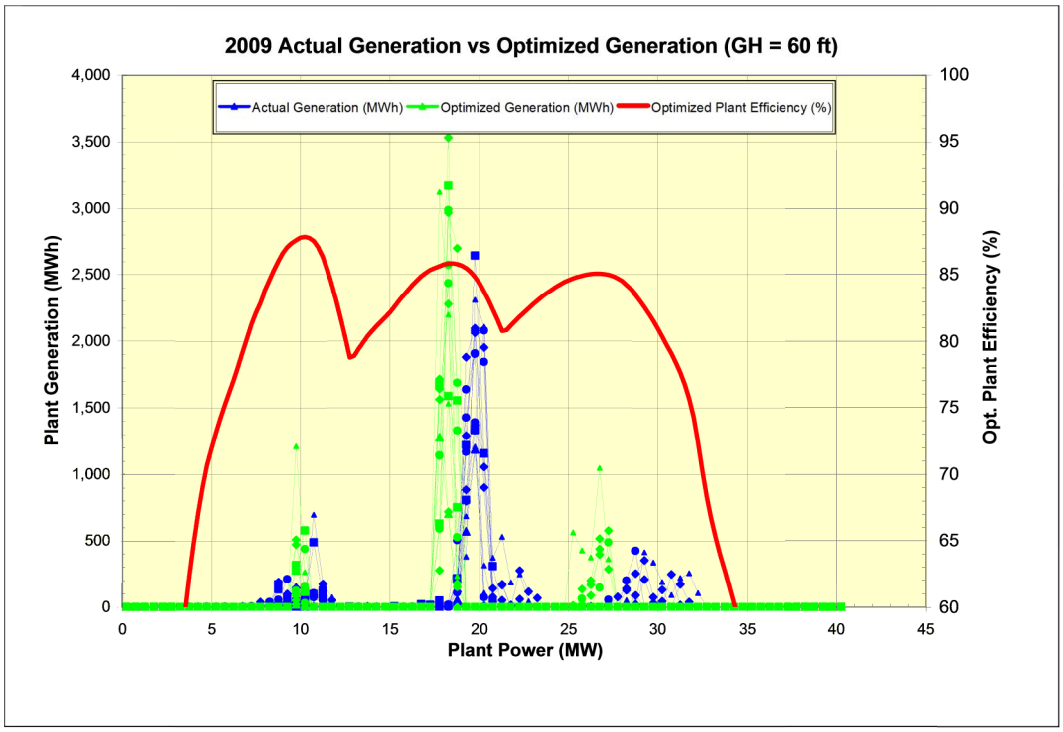
Figure 2.05-17: Typical Operation Efficiency Results (March 9-11, 2011)

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

Discussion of Results from Performance Assessments And Analyses

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

For overall questions
please contact:

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

or

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