Evaluating the Effects of Uncertainty in Unit Characteristics on the Operation and Optimization of Multiunit Hydroplants

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Abstract

Operational data and unit performance data from sixteen hydroelectric plants provide the basis for scaled unit characteristics in generalized two-unit, three-unit, five-unit, and seven-unit plant configurations. Unit types include Francis units, diagonal flow units, fixed propeller units, and Kaplan units. Three annual generation patterns (an hourly generation pattern, a moderate AGC generation pattern, and a heavy AGC generation pattern) were developed from the operational data. For each unit type, operation and optimization for the two-unit, three-unit, five-unit, and seven-unit plant configurations were evaluated under the three generation patterns with unit performance uncertainties of 1.0%, 2.5%, and 5% and with unit commitments based on unconstrained optimization, simple operational rules, and equal unit power.

Results demonstrate that optimized unit commitment is an effective hedge against substantial energy losses and revenue losses due to uncertainty in unit characteristics. These extensive operation efficiency analyses enable owner/operators of hydroelectric plants to estimate the costs and benefits from (a) flow measurement improvements and/or unit performance testing; (b) control system improvements, including rules-based systems and integrated optimizer systems; (c) additional operator guidance and training; and (d) plant performance management during and after unit upgrades. The analyses also provide a template for using site-specific unit characteristics and site-specific operational data to quantify the value of these performance improvements.

Section 1: Introduction

Under previous projects, detailed plant performance analyses have been computed using unit and plant performance characteristics and plant operational data for five pumped storage plants and eleven conventional hydroplants. These sixteen case studies encompass three well-established markets (MISO, NYISO, and PJM) and two non-market regions (Northwest area, Southeast area). The diverse owners for the sixteen plants include four investor-owned utilities (eight plants), two state power authorities (two plants), an industrial utility (two plants), and the three main federal hydropower producers (four plants). The previous studies have provided (1) multi-year generating data under various market and non-market conditions; (2) unit performance characteristics for a range of original and upgraded units; and (3) a well-documented methodology and toolset for analyzing optimized and suboptimized plant performance [March and Wolff, 2003; March and Wolff, 2004; ORNL, 2011; EPRI, 2012a; EPRI, 2012b; EPRI, 2012c; EPRI, 2012d; EPRI, 2014; March et al., 2013; March et al. 2014].

Operational data and unit performance data from the 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. Unit types include Francis units, diagonal flow units, fixed propeller units, and Kaplan units. Operational data from the sixteen 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 three generation patterns 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.

Section 2: 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 opportunities for operations-based and equipment-based performance improvements, leading to additional generation. The following subsections briefly addresses the processes and methodologies used for the quantitative performance analyses. Additional details are available in EPRI [2015] and elsewhere [ORNL, 2011; March et al., 2012; March et al., 2014; EPRI, 2014].

2.1: 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 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. Essential operational data for operation efficiency analyses and generation scheduling analyses include:

1. Timestamp;

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

Figure 2-1 provides an example of unit characteristics computed from operational data. 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 2-1 also shows limited performance results from flow measurements for the old turbine before it was upgraded, providing a graphic indication of the significant performance gains achieved by the upgrade [March et al., 2012b]. For the current analyses, the facility operational data is included in the annual generation patterns (see Section 4).

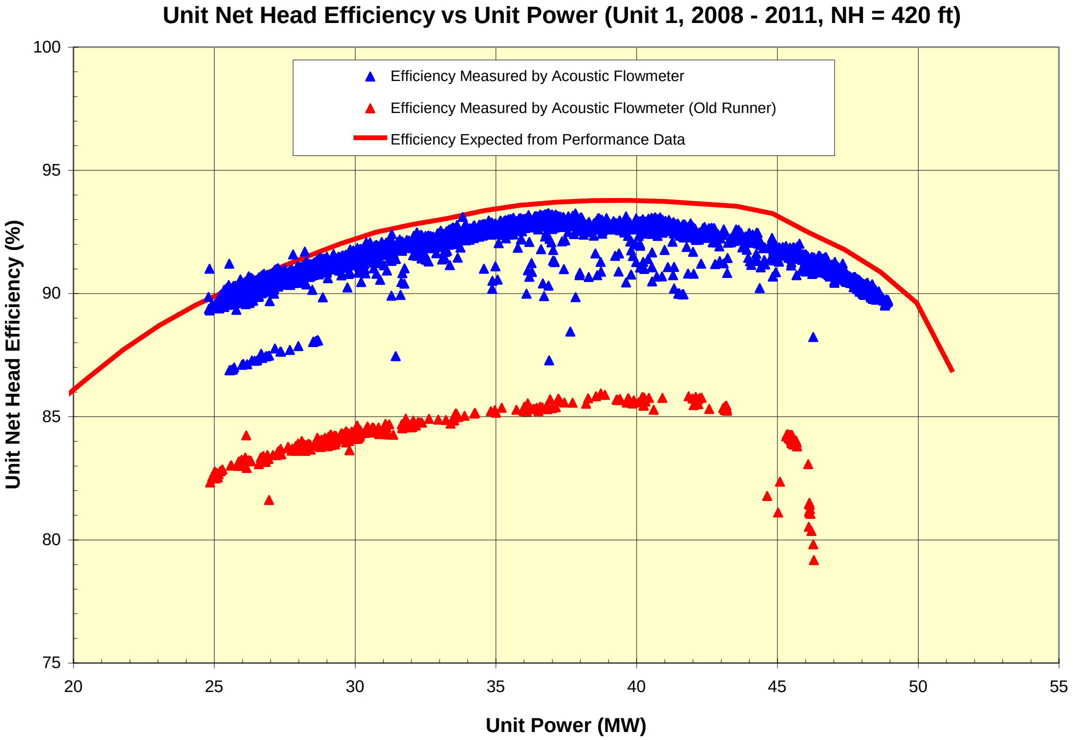

Figure 2-1: Example of Expected and Measured Efficiency versus Power

2.2: Tools for Performance Analyses

The primary tool for conducting the performance analyses is the Hydroplant Performance Calculator (HPC). The HPC was developed to enable standardized metrics for hydroplant 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.

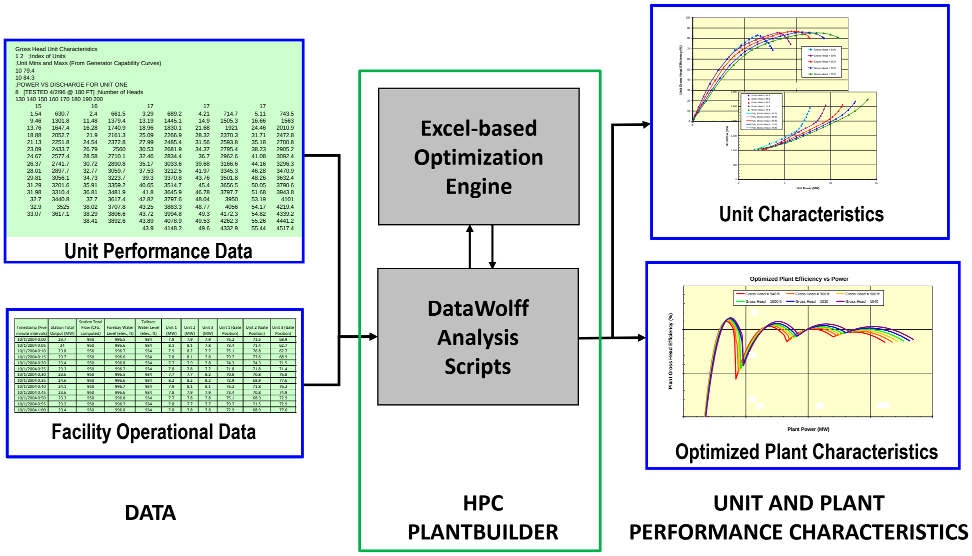

Figure 2-2: Overview of HPC PlantBuilder

Figure 2-2 provides a graphical overview of HPC PlantBuilder. Input data for the HPC PlantBuilder includes unit performance data (generator efficiency; turbine power and turbine flow versus head) and facility operational data (unit power and head versus time). The input data for HPC PlantBuilder also 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 [ORNL, 2011; 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.

The optimized plant performance characteristics are a primary input for HPC Analyzer, as discussed in the following section. Figure 2-3 provides a graphical overview of HPC Analyzer. Input data for the HPC Analyzer includes optimized plant performance data (computed by HPC PlantBuilder) and facility operational data (unit power and head versus time, from the heavy AGC, moderate AGC, and hourly annual generation patterns; see Section 4). For this paper, HPC Analyzer was used to compute operation efficiency analyses, as described in EPRI [2015].

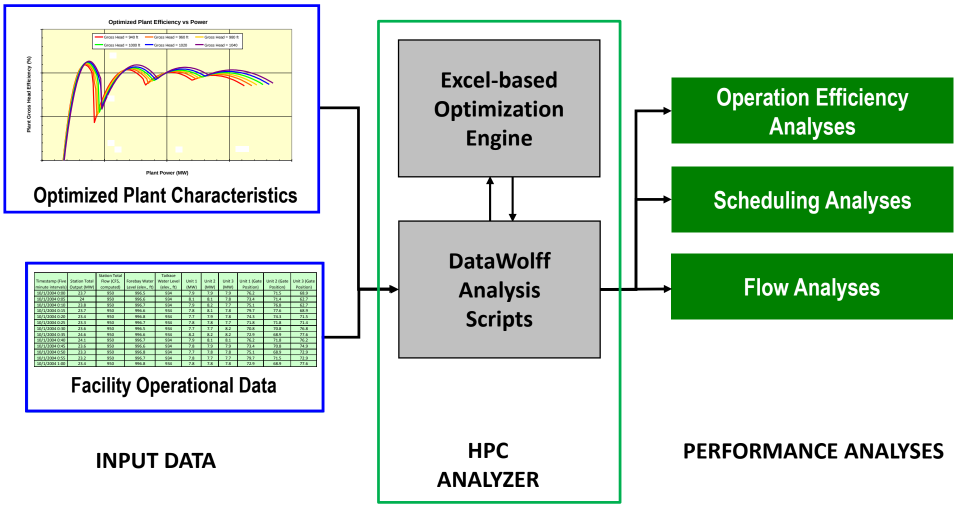

Figure 2-3: Overview of HPC Analyzer

Section 3: Development of Generalized Unit and Plant Characteristics

3.1: Data Sources for Unit Characteristics

Under previous projects, detailed plant performance analyses have been computed using unit and plant performance characteristics and plant operational data for five pumped storage plants and eleven conventional hydroplants [March and Wolff, 2003; March and Wolff, 2004; ORNL, 2011; EPRI, 2012a; EPRI, 2012b; EPRI, 2012c; EPRI, 2012d; March et al., 2013; March et al. 2014].

3.2: Single Unit Performance and Plant Performance

The single unit performance data for the sixteen plants were typically supplied by the facility owners. This performance data came from a variety of sources, including physical modeling, numerical modeling, and field testing of existing and upgraded turbines or pump-turbines. Performance curves for Francis units, diagonal flow units, fixed propeller units, and Kaplan units provided the basis for the generalized unit characteristics.

Selected data for each unit type was normalized to a midrange head of 100 ft. The scaled single unit characteristic curves for a head range from 90 ft to 110 ft are provided for the generalized Francis unit in Figure 3-1 (Flow vs Power) and Figure 3-2 (Efficiency vs Power). The single unit characteristic curves are provided for the generalized diagonal flow units, fixed propeller units, and Kaplan units in the comprehensive report which provides the basis for this paper [EPRI, 2015]. A comparison of the four unit types is shown in Figure 3-3 for a gross head of 100 ft.

The scaled single unit characteristics were used to develop the generalized two-unit, three-unit, five-unit, and seven-unit Francis-type plant configurations. The Hydroplant Performance Calculator (see Section 2) was used to compute optimized plant gross head efficiencies for the two-unit, three-unit, five-unit, and seven-unit plant configurations, assuming all units to be identical. For Francis units, Figures 3-4, 3-5, 3-6, and 3-7 show the optimized plant gross head efficiencies versus plant power at multiple gross heads for the two-unit, three-unit, five-unit, and seven-unit plants, respectively. The optimized plant gross head efficiencies versus plant power at multiple gross heads are provided for diagonal flow units, fixed propeller units, and Kaplan units in EPRI [2015].

For each head and each plant configuration, the first peak in Figures 3-4 through 3-7 corresponds to the operation of the most efficient unit (or any unit, under the assumption that the units are identical), the second peak corresponds to the most efficient operation of the two most efficient units, etc. As more units operate, the peaks become broader.

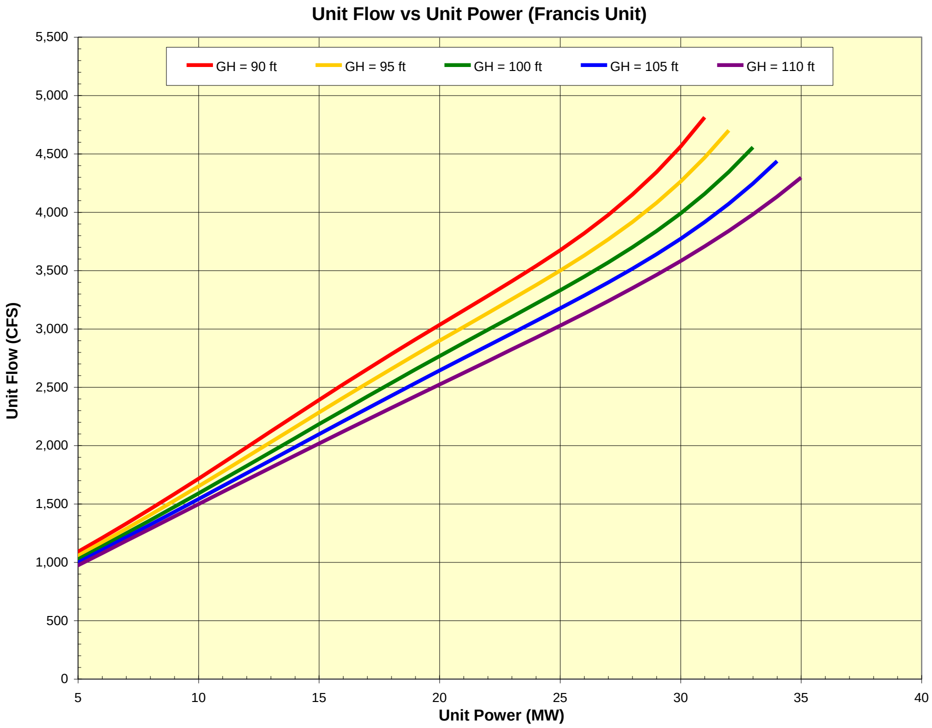

Figure 3-1: Scaled, Generalized Francis Unit Characteristics (Flow vs Power)

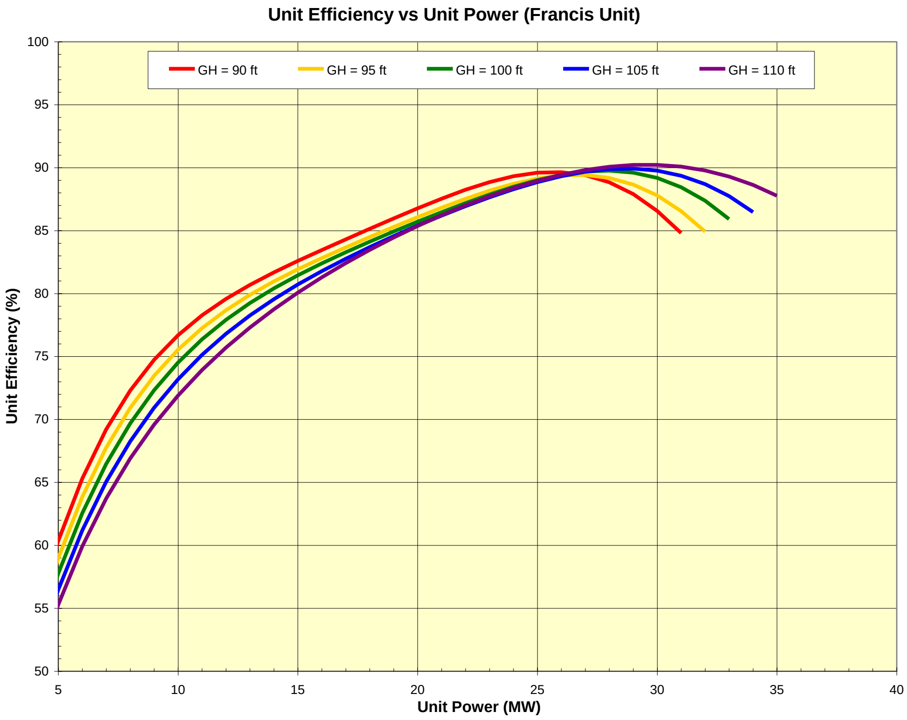

Figure 3-2: Scaled, Generalized Francis Unit Characteristics (Efficiency vs Power)

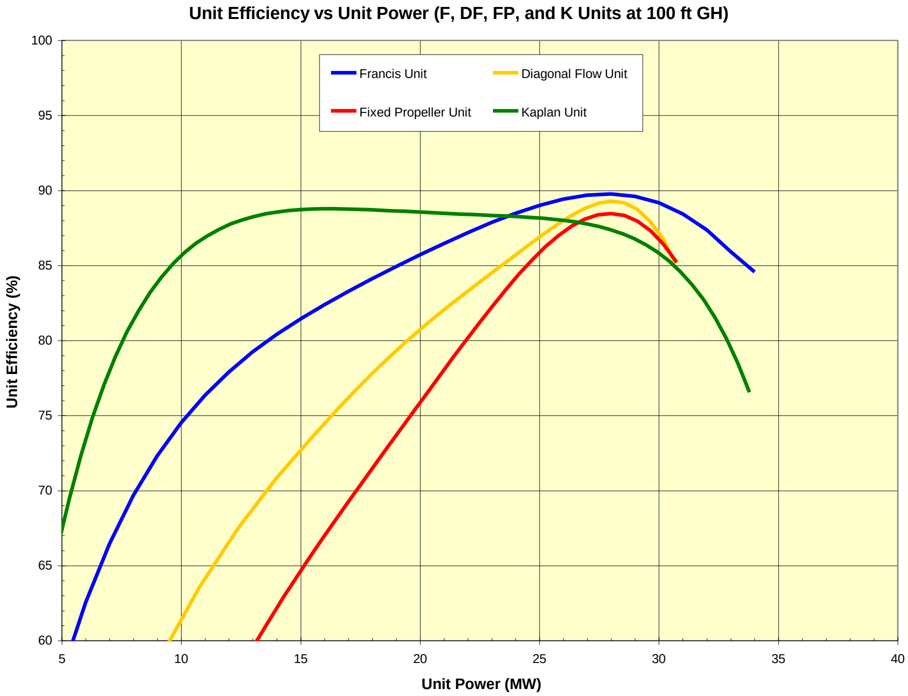

Figure 3-3: Comparison of Unit Efficiency versus Unit Power for Gross Head of 100 ft

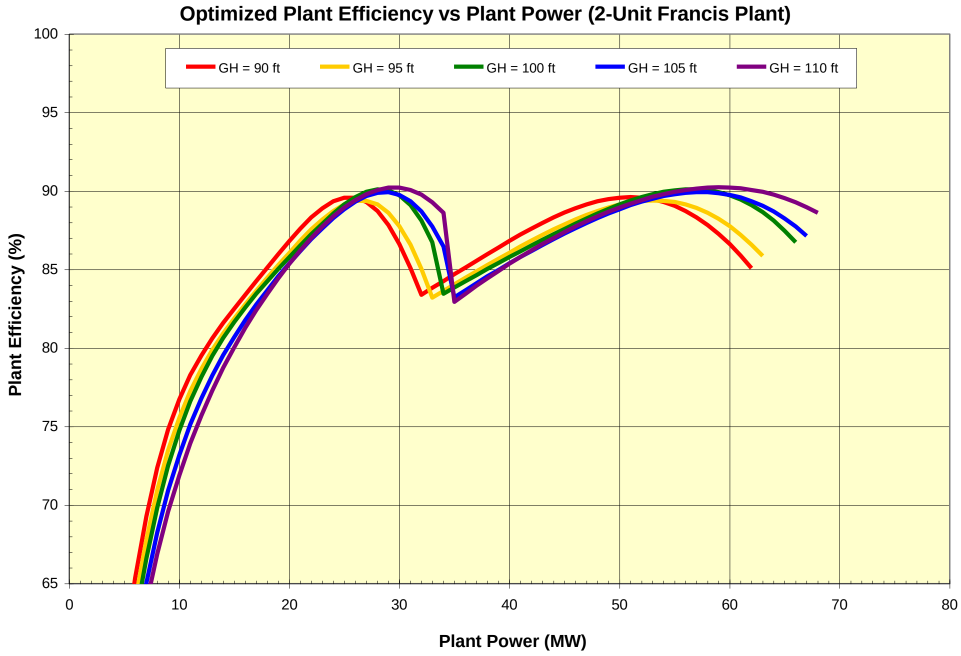

Figure 3-4: Optimized Plant Gross Head Efficiency versus Plant Power for Two-Unit Francis Plant

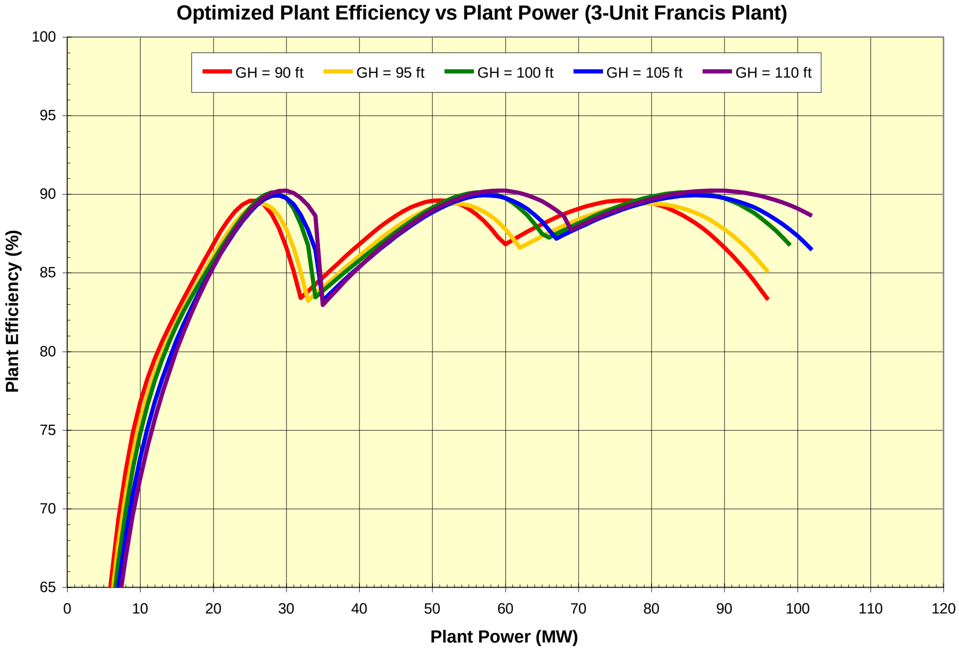

Figure 3-5: Optimized Plant Gross Head Efficiency versus Plant Power for Three-Unit Francis Plant

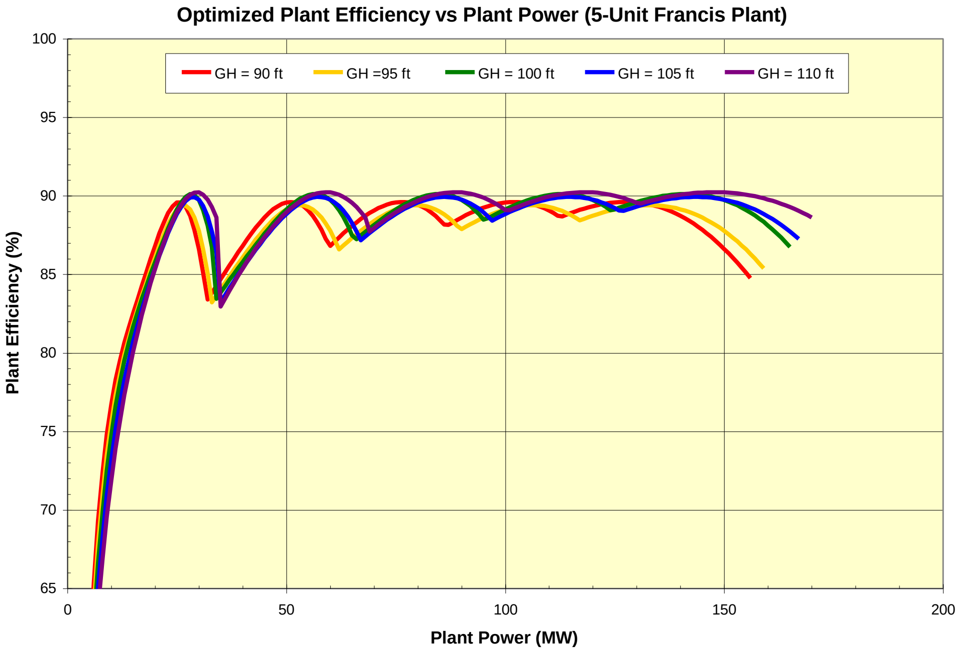

Figure 3-6: Optimized Plant Gross Head Efficiency versus Plant Power for Five-Unit Francis Plant

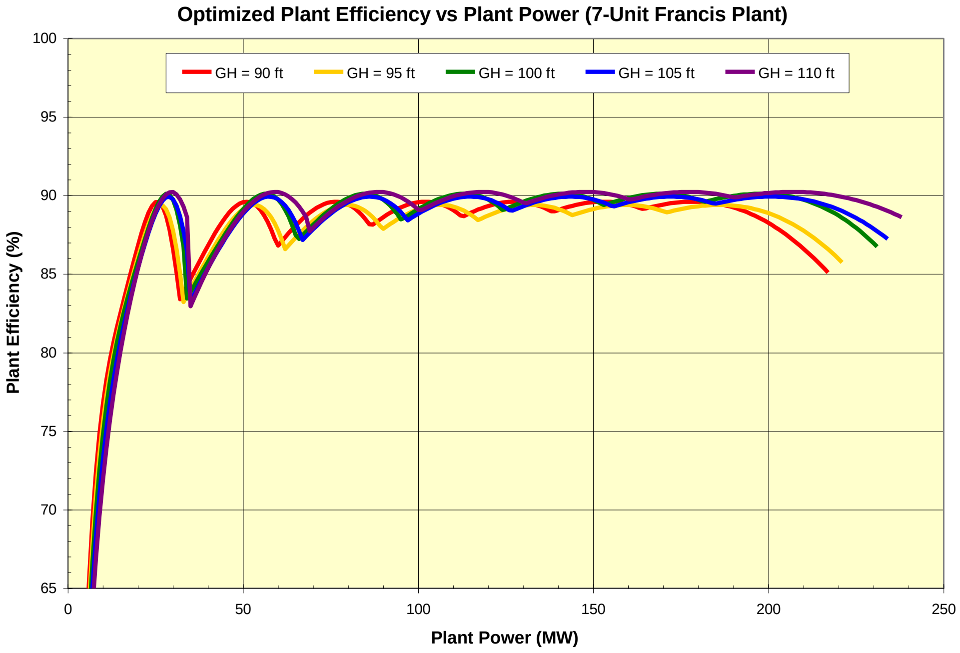

Figure 3-7: Optimized Plant Gross Head Efficiency versus Plant Power for Seven-Unit Francis Plant

3.3: Application of Flow and Power Uncertainty

Based on extensive experience from field tests, uncertainties in both flow and power were assumed to produce lower than expected unit efficiencies. For the single unit characteristics, the flow uncertainties of 1%, 2.5%, and 5% were modeled by adding 1%, 2.5%, and 5%, respectively, to the flow at each power level and each head. Similarly, the power uncertainties of 1%, 2.5%, and 5% were modeled by subtracting 1%, 2.5%, and 5%, respectively, from the power at each flow level and each head.

Figure 3-8 provides a typical example showing the application of the 5% uncertainty to flow and to power for single Francis unit characteristics at a head of 100 ft. Note that the flow uncertainty modification lowers the maximum efficiency but does not shift the power level at which the maximum efficiency occurs. The power uncertainty modification both lowers the maximum efficiency and lowers the power level at which the maximum efficiency occurs.

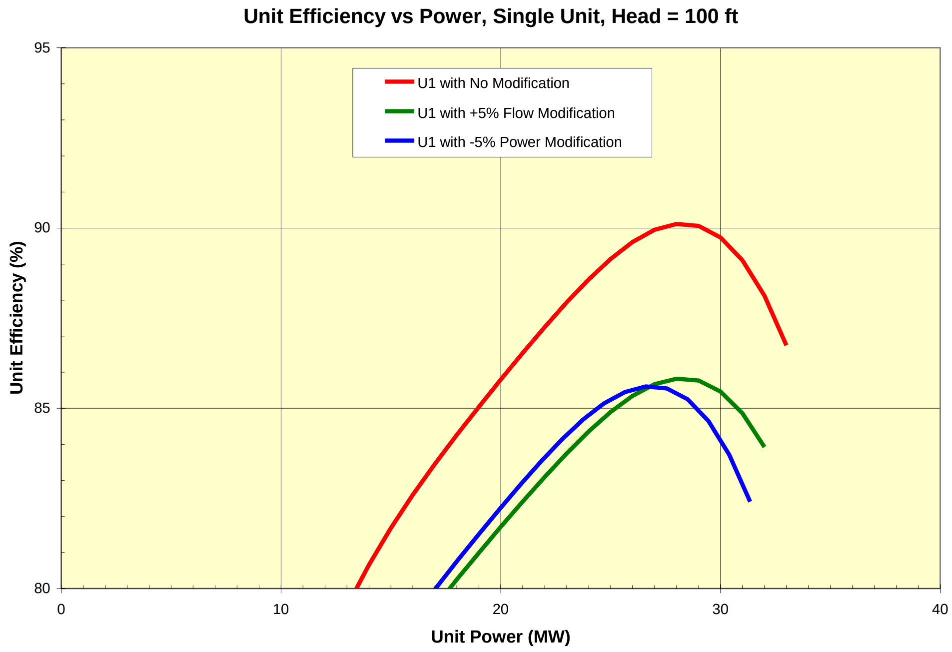

Figure 3-8: Unit Efficiency versus Plant Power with Application of 5% Uncertainty to Flow and Power for a Single Francis Unit

The scaled single unit characteristics with flow and power uncertainties of 1%, 2.5%, and 5% were used to compute the optimized plant performance for the two-unit, three-unit, five-unit, and seven-unit Francis-type plant configurations. The Hydroplant Performance Calculator (see Section 2) was used to compute optimized plant gross head efficiencies for the two-unit, three-unit, five-unit, and seven-unit plant configurations, under the following cases:

1. The flow uncertainties of 1%, 2.5%, and 5% are applied to U1 for the two-unit configuration, to U1 and U2 for the three-unit configuration, to U1, U2, and U3 for the five-unit configuration, and to U1, U2, U3, and U4 for the seven-unit configuration;
2. The power uncertainties of 1%, 2.5%, and 5% are applied to U1 for the two-unit configuration, to U1 and U2 for the three-unit configuration, to U1, U2, and U3 for the five-unit configuration, and to U1, U2, U3, and U4 for the seven-unit configuration.

As examples of the computed plant performance, Figures 3-9, 3-10, 3-11, and 3-12 show the optimized Francis plant gross head efficiencies versus plant power at a head of 100 ft for case 3 (flow adjustment to some units) and case 4 (power adjustment to some units).

Figure 3-9: Optimized Plant Gross Head Efficiency versus Plant Power with Application of 5% Uncertainty to Flow and Power for Two-Unit Francis Plant

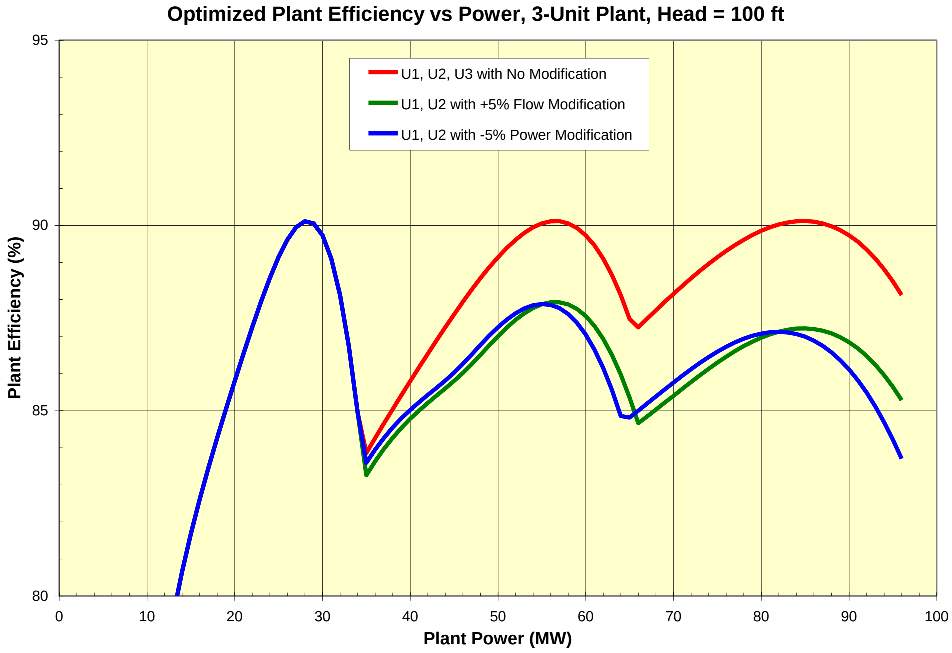

Figure 3-10: Optimized Plant Gross Head Efficiency versus Plant Power with Application of 5% Uncertainty to Flow and Power for Three-Unit Francis Plant

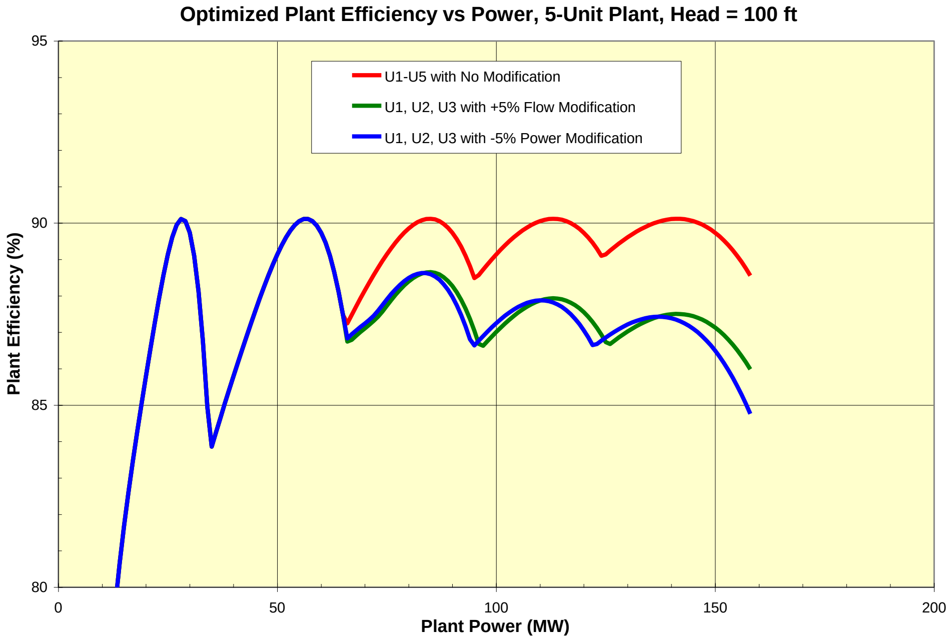

Figure 3-11: Optimized Plant Gross Head Efficiency versus Plant Power with Application of 5% Uncertainty to Flow and Power for Five-Unit Francis Plant

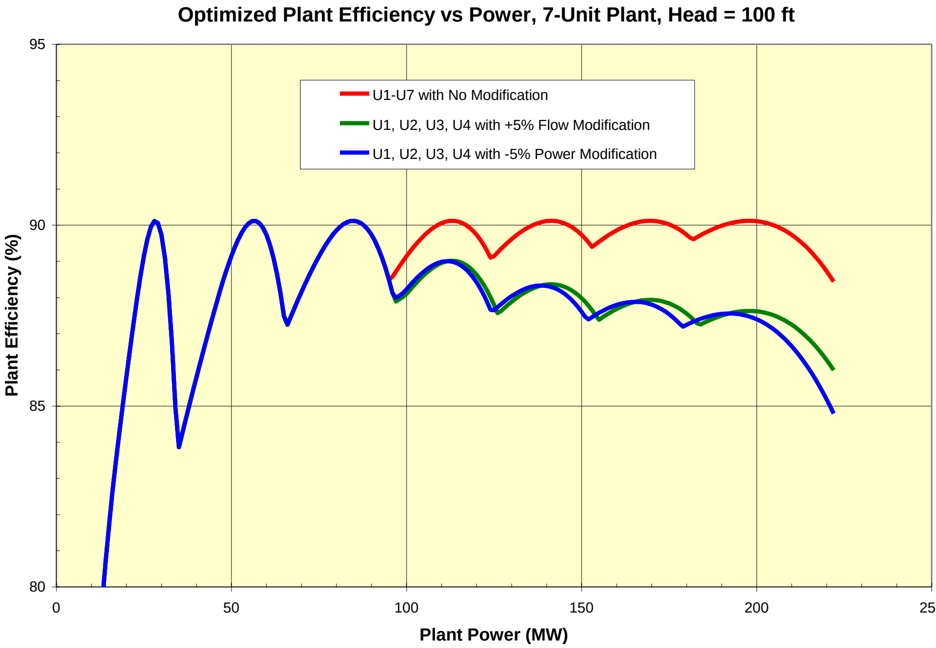

Figure 3-12: Optimized Plant Gross Head Efficiency versus Plant Power with Application of 5% Uncertainty to Flow and Power for Seven-Unit Francis Plant

In Figure 3-12, the first three peaks correspond to the most efficient units, U5, U6, and U7, where the flow and power uncertainty modifications have not been applied. The next four peaks correspond, in no particular order, to U1, U2, U3, and U4, where the flow and power uncertainty modifications have been applied. For U1, U2, U3, and U4, the flow uncertainty lowers the maximum efficiency but does not shift the power level at which the maximum efficiency occurs. The power uncertainty both lowers the maximum efficiency and lowers the power level at which the maximum efficiency occurs. These comments also apply to Figures 3-9, 3-10, and 3-11.

The corresponding 2-unit, 3-unit, 5-unit, and 7-unit plant performance curves for the diagonal flow, fixed propeller, and Kaplan plants are provided in EPRI [2015].

Section 4: Generalized Annual Generation Patterns and Unit Commitment Patterns

4.1: Overview

The generation pattern for a hydroplant depends on a variety of factors, including hydrology, market requirements, market opportunities, the owner's needs for support of other generating facilities, system needs for automatic generation control (AGC), etc. A review of the detailed operational data from sixteen hydroelectric plants was conducted, and three annual generation patterns were developed from the data.

In addition, unit commitment patterns are an important factor in analyzing the effects of uncertainty in unit characteristics on the optimization of multiunit hydroplants. Previous work has shown that plants with optimizers integrated into the control systems operate more efficiently than plants incorporating operational rules in the control systems under both steady and variable generation conditions [EPRI, 2012d]. Based on experience, three unit commitment patterns were selected for these analyses, including equal unit power, simple operational rules, and unconstrained optimization.

The three annual generation patterns and the three unit commitment patterns are discussed in the following sections.

4.2: Annual Generation Patterns

An annual generation pattern from the hydroplant with the most significant AGC operation was selected as the "Heavy AGC" generation pattern, with the power levels normalized at one-minute time intervals to the plant's maximum power capacity.

To ensure comparable generation patterns and consistent water utilization, the "Moderate AGC" pattern was derived as ten-minute averages of the one-minute data from the Heavy AGC pattern. Similarly, the "Hourly" pattern was derived as sixty-minute averages of the one-minute data from the Heavy AGC pattern. Figure 4-1 shows a 24-hour comparison for the Heavy AGC, the Moderate AGC, and the Hourly generation patterns.

Previous work compared analyses of the Heavy AGC pattern (one-minute intervals) and the Moderate AGC pattern (ten-minute intervals) for two-unit, three-unit, five-unit, and seven-unit hydroplants with Francis units [EPRI, 2014]. Results from the ten-minute (Moderate AGC) analyses and the one-minute (Heavy AGC) analyses were basically identical [EPRI, 2014], so only the Moderate AGC analyses and Hourly analyses were conducted in this study to reduce computational complexity.

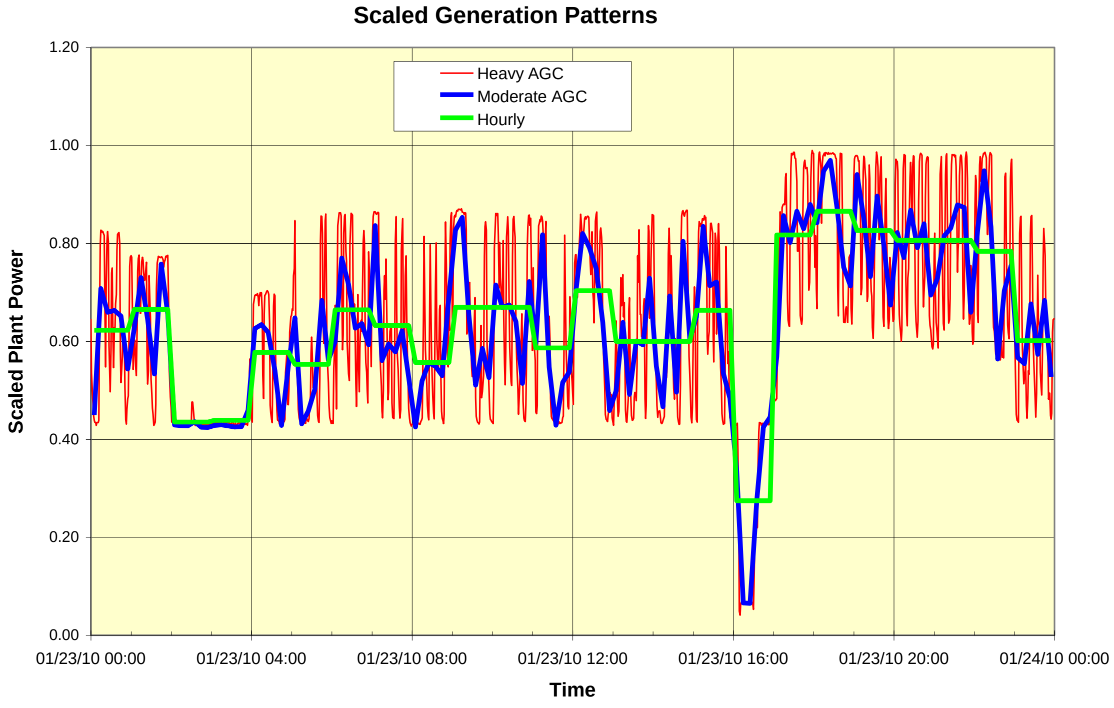

Figure 4-1: 24-Hour Example for Three Scaled Generation Patterns

4.3: Unit Commitment Patterns

Equal Unit Power – Under this unit commitment pattern, all of the units are operating, and the plant power is divided equally among the units. The number of operating units is selected to ensure that the minimum unit power is greater than or equal to 2.0 MW.

Simple Operational Rules – For this unit commitment pattern, the simple operational rules were developed from discussions with hydroplant managers and unit operators. The rules assumed for a five-unit plant are listed below:

1. A threshold power (P_T) is determined for each unit type, based on peak efficiencies from the unit characteristics (Francis = 28 MW; diagonal flow = 28 MW; fixed propeller = 28 MW; Kaplan = 20 MW; see Figures 3-2, 3-4, 3-6, and 3-8).

2. If the plant power is less than or equal to P_T then two units are operating.

3. If the plant power is between P_T and $2 \times P_T$ then three units are operating.

4. If the plant power is between $2 \times P_T$ and $3 \times P_T$ then four units are operating.

5. If the plant power is equal to or greater than $3 \times P_T$ then five units are operating.

6. With the required number of units in operation, power is shared equally among the operating units.

Unconstrained Optimization - For this unit commitment pattern, the optimized combination of units to provide the plant power at the highest efficiency is computed for each time period, with additional units added or removed as necessary. Optimization details are provided in EPRI [2015].

Section 5: Results from Performance Analyses

5.1: Overview

The performance analysis results are provided in tabular form. The tabular results combine two-unit, three-unit, five-unit, and seven-unit details for equal unit power commitment, simple rules commitment, and optimized unit commitment, with separate tables for the flow uncertainty modifications and the power uncertainty modifications. Unit types include Francis units, diagonal flow units, fixed propeller units, and Kaplan units. Multiple examples are included to show how performance assessment results can be used by owner/operators of hydroelectric plants to estimate the benefits of site-specific performance analyses, flow measurement improvements, unit performance testing, and control system improvements, including rules-based systems and integrated optimizer systems.

5.2: Results

Francis Units - Table 5-1 includes all of the performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using equal unit power commitment and flow uncertainty assumptions, and Table 5-2 includes all of the performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using equal unit power commitment and power uncertainty assumptions. Table 5-3 includes all of the performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using simple rules commitment and flow uncertainty assumptions, and Table 5-4 includes all of the performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using simple rules commitment and power uncertainty assumptions. Table 5-5 includes all of the performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using optimized commitment and flow uncertainty assumptions, and Table 5-6 includes all of the performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using optimized commitment and power uncertainty assumptions.

Table 5-1: Results for Two-Unit, Three-Unit, Five-Unit, and Seven-Unit Francis Plants Using Equal Unit Power Commitment and Flow Uncertainty Assumptions

Unit Configuration	Hourly		Moderate AGC	
	Efficiency Loss (%)	On/Off per Unit	Efficiency Loss (%)	On/Off per Unit
Two Unit, Base Case	2.89	346	2.85	528
Two Unit, U1 +1% Flow	3.13	346	3.08	528
Two Unit, U1 +2.5% Flow	3.34	346	3.29	528
Two Unit, U1 +5% Flow	3.72	346	3.67	528
Three Unit, Base Case	5.09	323	4.91	490
Three Unit, U1 U2 +1% Flow	5.26	323	5.07	490
Three Unit, U1 U2 +2.5% Flow	5.50	323	5.30	490
Three Unit, U1 U2 +5% Flow	5.91	323	5.70	490
Five Unit, Base Case	6.74	309	6.49	464
Five Unit, U1 U2 U3 +1% Flow	6.91	309	6.65	464
Five Unit, U1 U2 U3 +2.5% Flow	7.17	309	6.89	464
Five Unit, U1 U2 U3 +5% Flow	7.62	309	7.33	464
Seven Unit, Base Case	7.44	306	7.16	459
Seven Unit, U1 U2 U3 U4 +1% Flow	7.62	306	7.33	459
Seven Unit, U1 U2 U3 U4 +2.5% Flow	7.88	306	7.59	459
Seven Unit, U1 U2 U3 U4 +5% Flow	8.36	306	8.05	459

Table 5-2:Results for Two-Unit, Three-Unit, Five-Unit, and Seven-Unit Francis Plants Using Equal Unit Power Commitment and Power Uncertainty Assumptions

Unit Configuration	Hourly		Moderate AGC	
	Efficiency Loss (%)	On/Off per Unit	Efficiency Loss (%)	On/Off per Unit
Two Unit, Base Case	2.89	346	2.85	528
Two Unit, U1 -1% Power	3.09	346	3.04	528
Two Unit, U1 -2.5% Power	3.26	346	3.21	528
Two Unit, U1 -5% Power	3.58	346	3.54	528
Three Unit, Base Case	5.09	323	4.91	490
Three Unit, U1 U2 -1% Power	5.17	323	5.00	490
Three Unit, U1 U2 -2.5% Power	5.29	323	5.12	490
Three Unit, U1 U2 -5% Power	5.53	323	5.36	490
Five Unit, Base Case	6.74	309	6.49	464
Five Unit, U1 U2 U3 -1% Power	6.83	309	6.58	464
Five Unit, U1 U2 U3 -2.5% Power	6.96	309	6.71	464
Five Unit, U1 U2 U3 -5% Power	7.24	309	6.99	464
Seven Unit, Base Case	7.44	306	7.16	459
Seven Unit, U1 U2 U3 U4 -1% Power	7.53	306	7.25	459
Seven Unit, U1 U2 U3 U4 -2.5% Power	7.67	306	7.39	459
Seven Unit, U1 U2 U3 U4 -5% Power	7.96	306	7.68	459

Table 5-3: Results for Two-Unit, Three-Unit, Five-Unit, and Seven-Unit Francis Plants Using Simple Rules Commitment and Flow Uncertainty Assumptions

Unit Configuration	Hourly		Moderate AGC	
	Efficiency Loss (%)	**On/Off per Unit**	**Efficiency Loss (%)**	**On/Off per Unit**
Two Unit, Base Case	2.89	346	2.85	528
Two Unit, U1 +1% Flow	3.13	346	3.08	528
Two Unit, U1 +2.5% Flow	3.34	346	3.29	528
Two Unit, U1 +5% Flow	3.72	346	3.67	528
Three Unit, Base Case	3.48	382	3.40	548
Three Unit, U1 U2 +1% Flow	3.66	382	3.58	548
Three Unit, U1 U2 +2.5% Flow	3.93	382	3.84	548
Three Unit, U1 U2 +5% Flow	4.40	382	4.28	548
Five Unit, Base Case	2.86	467	2.68	967
Five Unit, U1 U2 U3 +1% Flow	3.07	467	2.88	967
Five Unit, U1 U2 U3 +2.5% Flow	3.37	467	3.18	967
Five Unit, U1 U2 U3 +5% Flow	3.91	467	3.70	967
Seven Unit, Base Case	2.16	511	2.03	1,171
Seven Unit, U1 U2 U3 U4 +1% Flow	2.39	511	2.25	1,171
Seven Unit, U1 U2 U3 U4 +2.5% Flow	2.73	511	2.59	1,171
Seven Unit, U1 U2 U3 U4 +5% Flow	3.33	511	3.17	1,171

Table 5-4: Results for Two-Unit, Three-Unit, Five-Unit, and Seven-Unit Francis Plants Using Simple Rules Commitment and Power Uncertainty Assumptions

Unit Configuration	Hourly		Moderate AGC	
	Efficiency Loss (%)	**On/Off per Unit**	**Efficiency Loss (%)**	**On/Off per Unit**
Two Unit, Base Case	2.89	346	2.85	528
Two Unit, U1 -1% Power	3.09	346	3.04	528
Two Unit, U1 -2.5% Power	3.26	346	3.21	528
Two Unit, U1 -5% Power	3.58	346	3.54	528
Three Unit, Base Case	3.48	382	3.40	548
Three Unit, U1 U2 -1% Power	3.58	382	3.51	548
Three Unit, U1 U2 -2.5% Power	3.73	382	3.66	548
Three Unit, U1 U2 -5% Power	4.02	382	3.96	548
Five Unit, Base Case	2.86	467	2.68	967
Five Unit, U1 U2 U3 -1% Power	2.99	467	2.82	967
Five Unit, U1 U2 U3 -2.5% Power	3.19	467	3.02	967
Five Unit, U1 U2 U3 -5% Power	3.59	467	3.42	967
Seven Unit, Base Case	2.16	511	2.03	1,171
Seven Unit, U1 U2 U3 U4 -1% Power	2.31	511	2.19	1,171
Seven Unit, U1 U2 U3 U4 -2.5% Power	2.55	511	2.42	1,171
Seven Unit, U1 U2 U3 U4 -5% Power	3.01	511	2.88	1,171

Table 5-5: Results for Two-Unit, Three-Unit, Five-Unit, and Seven-Unit Francis Plants Using Optimized Unit Commitment and Flow Uncertainty Assumptions

Unit Configuration	Hourly		Moderate AGC	
	Efficiency Loss (%)	On/Off per Unit	Efficiency Loss (%)	On/Off per Unit
Two Unit, Base Case	0.00	434	0.00	1,204
Two Unit, U1 +1% Flow	0.30	434	0.29	1,204
Two Unit, U1 +2.5% Flow	0.60	434	0.60	1,204
Two Unit, U1 +5% Flow	1.14	436	1.16	1,227
Three Unit, Base Case	0.00	510	0.00	1,364
Three Unit, U1 U2 +1% Flow	0.25	503	0.24	1,350
Three Unit, U1 U2 +2.5% Flow	0.61	508	0.58	1,355
Three Unit, U1 U2 +5% Flow	1.23	504	1.17	1,354
Five Unit, Base Case	0.00	521	0.00	1,433
Five Unit, U1 U2 U3 +1% Flow	0.26	553	0.25	1,518
Five Unit, U1 U2 U3 +2.5% Flow	0.65	528	0.62	1,473
Five Unit, U1 U2 U3 +5% Flow	1.34	523	1.27	1,455
Seven Unit, Base Case	0.00	518	0.00	1,458
Seven Unit, U1 U2 U3 U4 +1% Flow	0.27	541	0.26	1,519
Seven Unit, U1 U2 U3 U4 +2.5% Flow	0.68	520	0.66	1,478
Seven Unit, U1 U2 U3 U4 +5% Flow	1.41	513	1.35	1,458

Table 5-6: Results for Two-Unit, Three-Unit, Five-Unit, and Seven-Unit Francis Plants Using Optimized Unit Commitment and Power Uncertainty Assumptions

Unit Configuration	Hourly		Moderate AGC	
	Efficiency Loss (%)	On/Off per Unit	Efficiency Loss (%)	On/Off per Unit
Two Unit, Base Case	0.00	434	0.00	1,204
Two Unit, U1 -1% Power	0.28	447	0.28	1,290
Two Unit, U1 -2.5% Power	0.54	461	0.56	1,440
Two Unit, U1 -5% Power	1.02	486	1.04	1,652
Three Unit, Base Case	0.00	510	0.00	1,364
Three Unit, U1 U2 -1% Power	0.24	513	0.22	1,374
Three Unit, U1 U2 -2.5% Power	0.60	516	0.56	1,386
Three Unit, U1 U2 -5% Power	1.26	539	1.19	1,453
Five Unit, Base Case	0.00	521	0.00	1,433
Five Unit, U1 U2 U3 -1% Power	0.26	557	0.24	1,536
Five Unit, U1 U2 U3 -2.5% Power	0.65	554	0.62	1,516
Five Unit, U1 U2 U3 -5% Power	1.40	539	1.34	1,500
Seven Unit, Base Case	0.00	518	0.00	1,458
Seven Unit, U1 U2 U3 U4 -1% Power	0.27	552	0.26	1,551
Seven Unit, U1 U2 U3 U4 -2.5% Power	0.69	538	0.67	1,520
Seven Unit, U1 U2 U3 U4 -5% Power	1.50	529	1.46	1,509

Diagonal Flow, Fixed Propeller, and Kaplan Units - EPRI [2015] provides performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using equal unit power commitment and flow uncertainty assumptions and performance analysis results for two-unit, three-unit, five-unit, and seven-unit plants using equal unit power commitment and power uncertainty assumptions.

5.3: Examples for the Application of Performance Analysis Results

Two examples are provided for the practical application of these performance analysis results. Each example provides information for a hypothetical plant and shows how to use the analysis results to estimate the benefits of site-specific performance analyses, flow measurement improvements, unit performance testing, and control system improvements, including rules-based systems and integrated optimizer systems. Additional examples for plants with diagonal flow, fixed propeller, and Kaplan units are included in EPRI [2015].

Example 1: Two-Unit Francis Plant

This hypothetical two-unit, 20 MW Francis plant operates to provide energy, but no regulation services. Two original units provide 10 MW each. The average annual generation is 52,560 MWh, and the typical energy value is $50/MWh. Unit performance testing has never been conducted, and no performance information is available. A remote operator controls the units on an hourly basis to provide approximately equal unit power.

> Step 1, estimate the uncertainty level: Because no performance data is available, the combined power and flow uncertainty is likely to be relatively high. Assume 5%.
>
> Step 2, determine the appropriate unit commitment pattern and generation pattern: The plant uses equal unit power commitment and operates under an hourly generation pattern.
>
> Step 3, estimate the annual efficiency loss: For a two-unit Francis plant with equal unit power commitment operating under an hourly generation pattern, refer to Table 5-1. Table 5-1 indicates an estimated annual efficiency loss of about 3.7%.
>
> Step 4, compute the estimated annual value from performance improvements: Multiply the annual efficiency loss (3.7%) times the average annual generation (52,560 MWh) and the typical energy value ($50/MWh). The resulting value ($97,236/yr) represents an estimate of the annual value from performance improvements to reduce the uncertainty in the unit characteristics and improve the utilization of performance information. The performance improvements could include site-specific performance analyses to further identify and quantify opportunities, detailed unit performance testing, installation of absolute or relative flow monitoring equipment, operator guidance and training, and the addition of appropriate control system rules.

Example 2: Eight-Unit Francis Plant

This hypothetical eight-unit, 236 MW Francis plant operates to provide energy and heavy AGC within a utility's power system. Six original units provide 28 MW each, and two upgraded units provide 34 MW each. The average annual generation is 710,000 MWh, and the typical energy value is $50/MWh. No direct compensation is provided for the AGC support. Original unit performance information is available, and index tests were conducted on the new units. The plant has historically operated with equal unit power.

> Step 1, estimate the uncertainty level: If only original performance data and index test data are available, the combined power and flow uncertainty is likely to be high. Assume the uncertainty range is 2% to 5%.
>
> Step 2, determine the appropriate unit commitment pattern and generation pattern: Based on the hypothetical information, the plant uses equal unit power commitment and operates under a heavy AGC generation pattern.
>
> Step 3, estimate the annual efficiency loss: EPRI [2014] showed that results for a heavy AGC pattern are comparable to results for a moderate AGC pattern. For an eight-unit Francis plant with equal unit power commitment operating under a heavy AGC generation pattern, refer to the seven-unit results for the moderate AGC in Table 5-1. Table 5-1 indicates an estimated annual efficiency loss of about 8%.
>
> Step 4, compute the estimated annual value from performance improvements: Multiply the annual efficiency loss (8%) times the average annual generation (710,000 MWh) and the typical energy value ($50/MWh). The resulting value ($2,840,000/yr) represents an estimate of the annual value from performance improvements to reduce the uncertainty in the unit characteristics and to improve the utilization of performance information. The performance improvements could include site-specific performance analyses to further identify and quantify opportunities, detailed unit performance testing, installation of flow monitoring equipment, and improvements to the control system rules or optimizer.

Section 6: Summary, Conclusions, and Recommendations

6.1: Summary

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 Francis-type plant configurations. 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 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 Francis 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. Results from similar evaluations with diagonal flow, fixed propeller, and Kaplan units are provided in EPRI [2015].

6.2: Conclusions

Conclusions based on these results are described below:

1. Energy losses and revenue losses due to uncertainty in unit characteristics can be substantial.

2. The reported results provide screening-level guidance and show the value of performance analyses for owner/operators of hydroelectric plants in estimating the benefits of unit performance testing, flow measurement improvements, improved operator training, and control system improvements, including rules-based systems and integrated optimizer systems. With dissimilar units (due to, for example, cavitation repairs, wear and tear, different unit design, etc.), energy losses will be higher than reported here.

3. Similar performance analyses using site-specific unit characteristics and site-specific operational data will more accurately quantify the value of improved unit characteristics (e.g., through field testing, improved flow metering, etc.), improved control system rules, improved optimization, and/or additional operator guidance and training.

4. 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. However, the computed energy losses are slightly higher for the power modification uncertainties.

5. For the commitment pattern based on equal power, annual energy losses from the hourly and moderate AGC analyses are similar for the flow modification uncertainties and the power modification uncertainties. For Francis plants, annual energy losses vary from approximately 2.8%–3.7% for the two-unit plant configuration, from approximately 4.9%–5.9% for the three-unit plant configuration, from approximately 6.5%–7.6% for the five-unit plant configuration, and from approximately 7.2%–8.4% for the seven-unit plant configuration.

6. For the simple rules commitment pattern, the hourly and the moderate AGC analyses are similar for the flow modification uncertainties and the power modification uncertainties. For Francis plants, annual energy losses vary from approximately 2.8%–3.7% for the two-unit plant configuration, from approximately 3.4%–4.4% for the three-unit plant configuration, from approximately 2.7%–3.9% for the five-unit plant configuration, and from approximately 2.0%–3.3% for the seven-unit plant configuration.

7. For the optimized commitment pattern, the hourly and the moderate AGC analyses are similar for the flow modification uncertainties and the power modification uncertainties. For Francis plants, annual energy losses vary 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.

8. For all of the unit commitment patterns, unit on/off cycling increases substantially for the moderate AGC generation pattern compared to the hourly generation pattern (see Table 5-1 through Table 5-6 and EPRI [2015]). Benefits from improved optimization should be weighed against potential problems due to unit cycling.

9. Results demonstrate that optimized dispatch is an effective hedge against energy losses and revenue losses due to uncertainty in unit characteristics.

10. For identical units, well-informed and simple operational rules can often achieve much of the benefit from an integrated, real-time optimizer. However, changing constraints (e.g., unit outages, seasonal head changes, etc.) may require changes to the operational rules.

6.3: Recommendations

Recommendations based on the performance analysis results include:

1. The results for generic plants with Francis, diagonal flow, fixed propeller, and Kaplan units should be supplemented with detailed case studies showing the application of performance analyses for identifying, quantifying, prioritizing, and monitoring performance improvement projects at hydroelectric plants.

2. Performance improvement workshops should be conducted in conjunction with National Hydropower Association (NHA) regional meetings or annual industry conferences. The workshops would provide results from generic and specific performance analyses, train participants to estimate benefits from performance improvements at their hydroplants, and describe best practices for performance improvement projects. The workshops would also provide opportunities to gain additional information from participants on their current practices and needs.

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