Performance Assessment Manual

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1.0 Introduction

The Hydropower Advancement Project (HAP) was initiated by the Wind and Water Power Program within the Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) as a systematic approach to best practices implementation for improving the efficiency, capability, and water utilization of existing U.S. hydropower plants.

The HAP 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 Installed Performance Level is that achievable by the facility under design conditions immediately after commissioning (typically, the installed name-plate capacity performance). The Current Performance Level 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]. The Potential Performance Level is that which could be achieved under current operating constraints through installation of best available technology and implementation of best practices for operations and maintenance.

2.0 Overview of Performance Assessments and Analyses

The Hydropower Advancement Project is designed for both condition assessment and performance assessment of existing hydropower plants. The quantitative condition assessment aims to characterize and trend the asset conditions across the U.S. existing hydro fleet for identifying and evaluating the upgrading opportunities, as previously discussed. The performance assessments aim to quantify unit and plant performance and to investigate the opportunities for operations-based, equipment-based, and maintenance-based performance improvements leading to additional generation. This document, as the Performance Assessments section of the HAP Assessment Manual, addresses the processes and methodologies used for the performance assessments and the quantitative performance analyses.

In the context of the HAP, three types of performance assessments or analyses are conducted: (1) a performance process assessment; (2) hydrology-based performance analyses; and (3) optimization-based performance analyses. An overview of the hydrology-based performance analyses and the optimization-based performance analyses is shown in Figure 1.

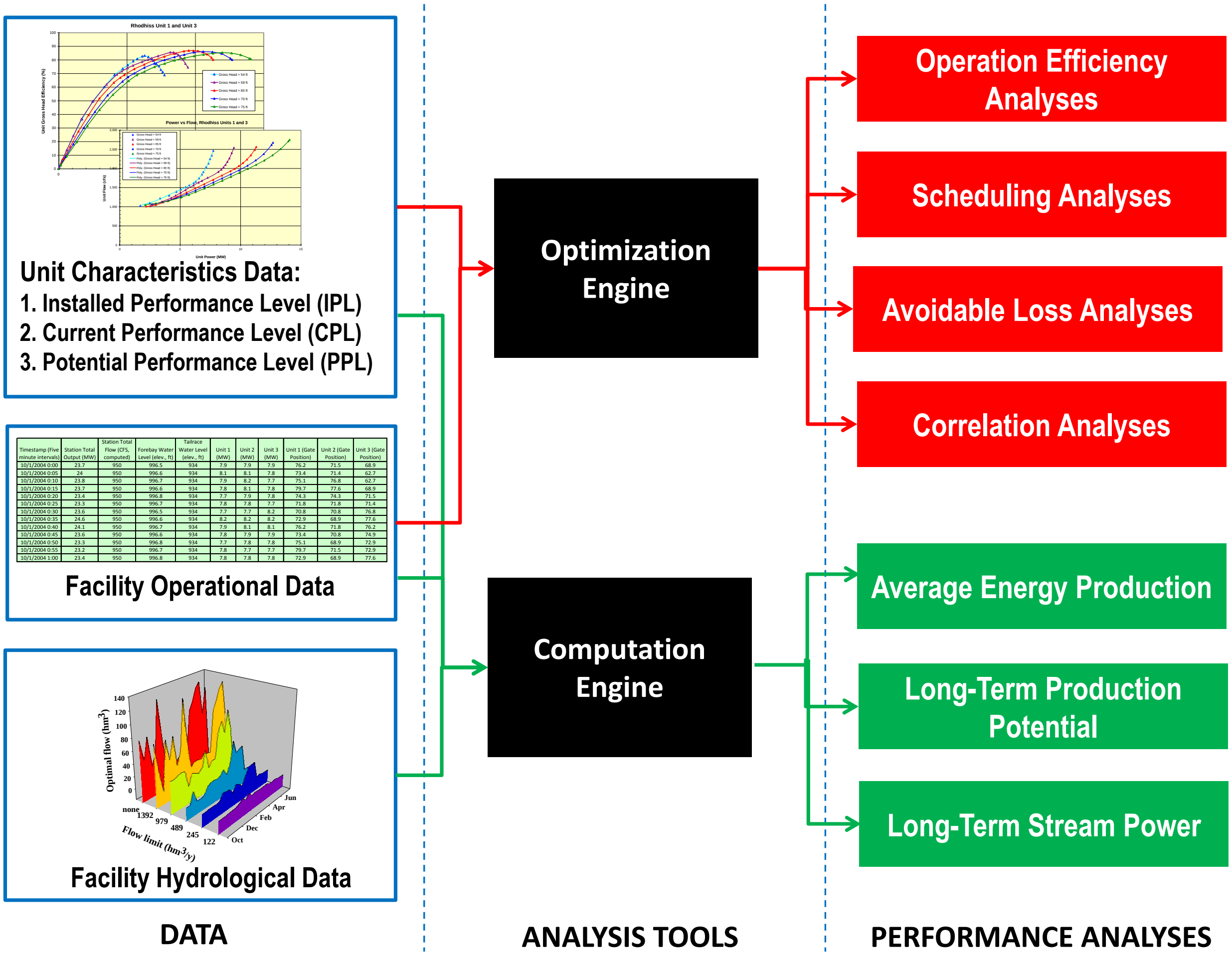

Figure 1: Overview of Performance Analyses

The performance process assessment, which is described in Appendix 2.01 and Appendix 2.02, is based on information from the condition assessment, discussed in another part of the HAP Assessment Manual. Unit characteristics, facility operational data, and facility hydrological data are discussed in Section 3, Data for Performance Analyses. Performance analysis tools are discussed in Section 4, Tools for Performance Analyses. Hydrology-based performance analyses are discussed in Section 5, and optimization-based performance analyses are discussed in Section 6.

3.0 Data for Performance Analyses

The primary data needs for performance analyses include unit characteristics data, facility operational data, and facility hydrological data. These data types 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 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 to the turbine, and H is the head across the unit.

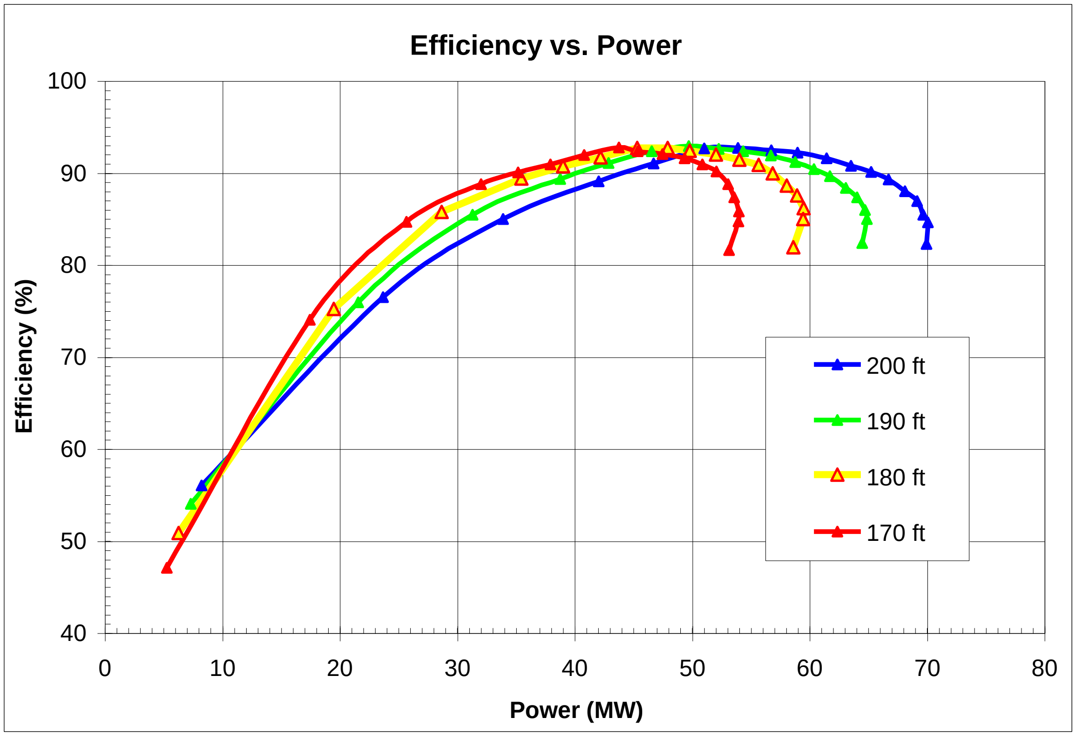

Figure 2: Example of Single Unit Efficiency Characteristics versus Head

As an example, Figure 2 shows the unit characteristics at multiple heads for a single, conventional Francis unit at an intermediate-head, two-unit, 120 MW hydroelectric plant. Efficiency curves such as these provide guidance for effective use of a hydro unit. In this case, the points of most efficient operation can be identified and the efficiency penalty for straying from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at another power level. When maximum power output is required, these curves show that there is a point at which very small gains in power result in drastic reductions in efficiency. Operation in this high-load, lower-efficiency region is also associated with increased cavitation damage to the turbine and accelerated bearing wear.

However, information from the single-unit efficiency characteristics alone is not sufficient for achieving effective operations in a multi-unit plant. This is illustrated in Figure 2, which shows overall plant efficiency characteristics, assuming all units are available, at multiple heads for generating mode operation of reversible Francis units at a high-head, six-unit, 3,000 MW plant with one new unit and five original units. The overall plant efficiency is dramatically affected by the plant load and head. For example, when operating at 1140 feet of head, a 500 MW load is quite inefficient for this plant, with an efficiency penalty of about 5%.

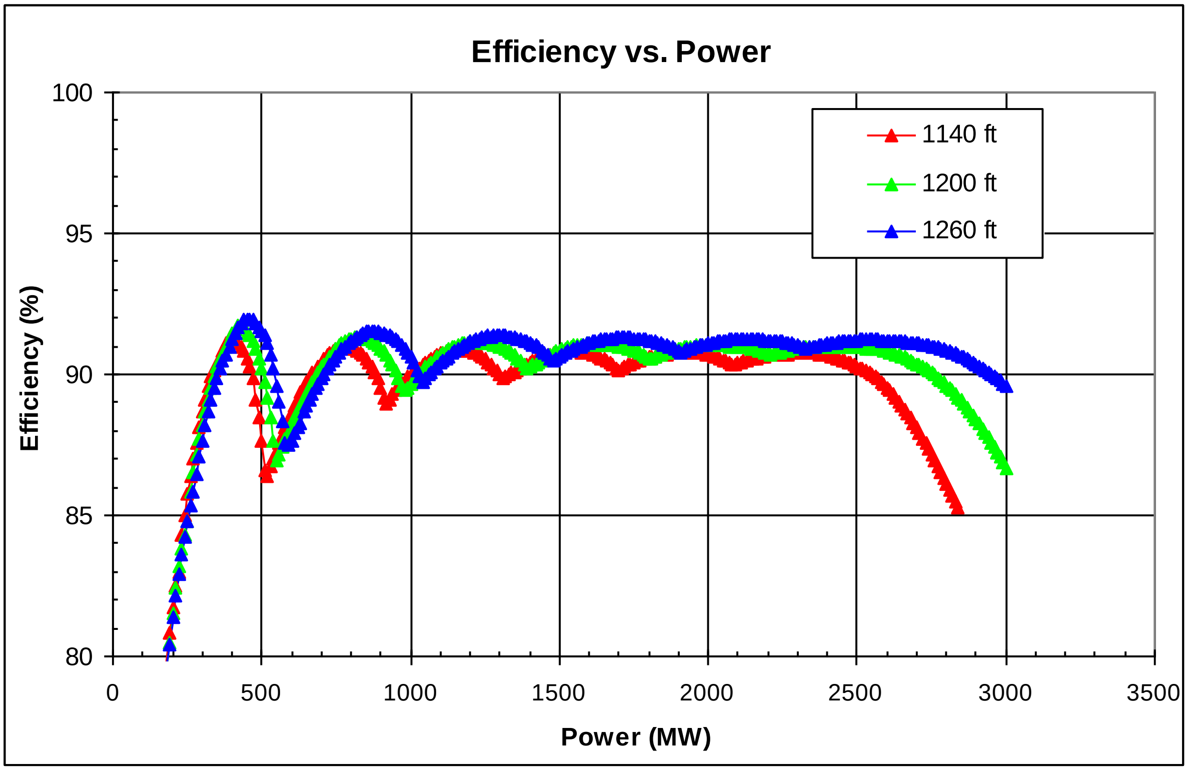

Figure 3: Example of Overall Plant Efficiency Characteristics versus Head

As discussed in Section 1, the HAP 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_I) 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 a non-trivial number of facilities across the U.S., the installed performance characteristics are the only formal documentation available to describe unit and plant performance. In many cases, the installed performance characteristics may be based entirely on model tests of unit performance.
>
> ***Actual performance characteristics (***η_A) can be used in performance analyses if recent performance tests results for the units are available. The actual performance characteristics provide reduced uncertainty to performance analyses examining the overall plant performance under conditions of optimal commitment and dispatch.
>
> ***State-of-the-art performance characteristics*** (η_0) 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 best available technology. The state-of-the-art changes over time, so performance results based on the state-of-the-art represent a “moving target.”

Facility Operational Data – Facility operational data is typically obtained from multiple sources, including plant personnel, central engineering staff, and load control personnel (if applicable). A preliminary data survey is desirable to determine “what, how, where, and who:”

- What performance-related parameters are measured?
- How well are the parameters measured?
- Where is the archival data stored?
- Who is the proper contact for obtaining the archival data?

Essential operational data for operation efficiency analyses and schedule analyses include:

1. Timestamp;
2. Unit Power;
3. Headwater Level (by unit if appropriate);
4. Tailwater Level (by unit if appropriate);
5. Unit Status (e.g., available, unavailable, condensing).

Additional operational data may also be required, depending on the facility. The additional data could include:

- Unit Wicket Gate Opening;
- Unit Winter-Kennedy Differential, Acoustic Flow Meter Output, or Other Unit Flow Rate;
- Spill Flow (if any);
- Unit Trash Rack Differential;
- Unit Blade Angle (for Kaplan Units);
- Unit Valve(s) Position (for Pelton Units);
- Unit Air Status (on/off) and Unit Air Flow Rate (for aerating units);
- Facility Environmental Flows (e.g., minimum flows, fish attraction flows, fish spill flows);
- Facility Leakage Flows.

In general, “snapshot” data are preferable to hourly averages. For most facilities, a few years’ data is sufficient to capture operational patterns. However, for some facilities more years may be appropriate to capture longer term events (e.g., market effects on dispatch, excessive outages due to reliability problems, hydrology-related patterns, etc.). Additional information should be solicited to determine how the facility’s units are dispatched (e.g., generation, ancillary services, both), to establish the unit operational constraints (e.g., cavitation and vibration constraints, generator constraints, transmission constraints), and to understand the environmental constraints (e.g., minimum flows, DO and TDG constraints, fish attraction flows, etc.).

Facility Hydrological Data – Facility hydrological data is required for the hydrology-based performance analyses, for example to quantify the total plant inflows and outflows. For many facilities, the total outflow is not measured but rather computed from unit power data and the unit characteristics (typically in the form of flow tables) that relate the unit flow to unit power and head. Flows bypassing the turbines, which include spill flows, environmental flows, and leakage flows, are also required for determining the total plant outflow. In some cases, it may also be beneficial to compute total plant outflow by performing a flow balance on the reservoir. This requires measured inflows, the measured reservoir elevations, reservoir bathymetric data, and evaporation from the reservoir.

4.0 Tools for Performance Analyses

As shown previously in Figure 1, the primary tools for performance analyses include an optimization engine and a computation engine, as 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 described below, and a detailed explanation is included in Appendix 2.03.

The optimization engine is used to determine how a given plant load 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 load allocation that meets the given plant load with the lowest possible water usage, providing the highest possible plant efficiency.

Computation Engine – The computation engine is an Excel-based program that enables the automating of multiple data analyses. Additional configuration of the computation engine with an analysis script and calculation libraries is required for each particular type of analysis. The specific analyses can be configured to compute both the hydrology-based performance analyses (see Section 5) and the optimization-based performance analyses (see Section 6), using the equations and procedures described in the relevant sections.

5.0 Hydrology-Based Performance Analyses

The hydrology-based performance analyses produce a set of statistics and indices that characterize the historical extent to which a facility has converted the potential energy at a site to electrical energy for the electric power system. These statistics and indices are similar and, in some cases, identical to those used in design, decision-support, and scheduling for hydropower plants and units. As defined below, the performance metrics enable benchmarking and trending of performance across many facilities in a variety of river system, power system, and water availability contexts. The typical hydrology-based performance analyses include the Average Energy Production, the Long-Term Production Potential, and the Long-Term Stream Power.

Appendix 2.04 provides examples of results from the hydrology-based performance analyses for a three-unit facility.

Average Power Production – Produced power is a measure of the energy actually delivered to the power system by the facility. It is computed using historical generation data (PΔt in kWh):

$$P_A \equiv \sum_{i=1}^{M}[P\Delta t] \bigg/ \sum_{i=1}^{M}\Delta t$$

Long-Term Stream Power – The baseline measure of energy at a plant site is the Long-Term Stream Power (LTSP), P_S:

$$P_S \equiv \sum_{i=1}^{M}[(\rho g h_i Q_i)\Delta t] \bigg/ \sum_{i=1}^{M}\Delta t$$

The LTSP is computed over a sufficient number of time steps M to characterize the variances of the total releases (powerhouse, spillway, leakage and other flows) from the plant (Q) and the gross head (h) at the plant. The LTSP includes a weak functional dependence on the dam and reservoir geometry via the gross head history, but it is primarily a function of the site hydrology and physical relief and not related to the technology installed at the site. Because the LTSP is defined in terms of the plant releases rather than unregulated inflows, it is also influenced by the water management strategy implemented in regulated river systems. The practical import of this dependence on water management strategy is that performance metrics defined in terms of the LTSP are "local" to the plant. In other words, metrics using the LTSP as a baseline indicate how well the plant is able to convert energy from the flows and storage (gross head) dictated by the river system and water management strategy.

The LTSP will most often be computed using hourly data (Δt = 1 hour), although for some run-of-river plants with persistent flows a daily time step (Δt = 24 hours) may be appropriate. In cases where flow, gross head, and load vary significantly or often within the hour, the appropriate time step of the computation (and that of the required data) could be less than one hour. The most common LTSP parameter will be the multi-year LTSP (M>>8760 hours). When the duration is M = 8760 hours and corresponds to a water year or calendar year time frame, the resulting LTSP parameter is termed an annual stream power (ASP) for a specific year. A related statistic is the monthly or seasonal LTSP computed over N years of data:

$$P_{S,j} \equiv \sum_{i=1}^{N}\sum_{k=1}^{M_j}\left[\left(\rho g h_{k,i,j} Q_{k,i,j}\right)\Delta t\right] \Big/ \sum_{i=1}^{N}\sum_{k=1}^{M_j}\Delta t$$

j ϵ [Jan, Feb, …, Dec; Winter, Spring, Summer, Fall; Irrigation, Non-Irrigation]

in which M_j is the number of time steps in month or season j.

Long-Term Production Potential – Not all of the water moving past the plant site is available for power generation. Only the water passing through the powerhouse (Q_{PH}) is available as potential energy for conversion to electrical energy. As with any power production, conversion of potential and mechanical energy to electrical energy by hydroelectric technology is less than complete. The hydroelectric units in the powerhouse are assumed to be optimally committed and dispatched to produce the maximum amount of energy from the powerhouse flow in each time step, thereby defining a set of plant performance characteristics $\eta = f(h, Q_{PH})$ that quantify the ability of a plant with its set of units to convert energy over a range of gross head and powerhouse flow conditions. It is then possible to define the Long-Term Production Potential (LTPP) for a plant:

$$P_P \equiv \sum_{i=1}^{M}\left[\rho g\left(\eta h_i Q_{PH,i}\right)\Delta t\right] \Big/ \sum_{i=1}^{M}\Delta t$$

The appearance of the plant performance characteristics η in the LTPP formula means that the LTPP is a function of the technology installed at the site. One can select different plant performance characteristics corresponding to assumptions about the condition of the technology present over the duration M of the computation:

These performance assumptions can also be used in a monthly or seasonal LTPP computation:

$$P_{P,j} \equiv \sum_{i=1}^{N}\sum_{k=1}^{M_j}\left[\rho g\left(\eta h_{k,i,j} Q_{k,i,j}\right)\Delta t\right] \Big/ \sum_{i=1}^{N}\sum_{k=1}^{M_j}\Delta t$$

j ϵ [Jan, Feb, …, Dec; Winter, Spring, Summer, Fall; Irrigation, Non-Irrigation]

The use of performance characteristics in the monthly or seasonal computation highlights the possibility that installed, state-of-the-art, or actual performance characteristics are not necessarily constant throughout annual cycles as different operational modes are activated. Examples include performance characteristics that depend upon seasonally-deployed turbine aeration systems or fish exclusion screens in unit intakes.

6.0 Optimization-Based Performance Analyses

Optimization technologies and recent advances in automated data analyses provide the opportunity to conduct 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, Scheduling Analyses, Avoidable Loss 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 3, and the specific analyses are described in the following subsections.

Appendix 2.05 provides examples of results from optimization-based performance analyses for a three-unit facility.

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. Computational steps for determining the operation efficiency are shown in Figure 4.

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).

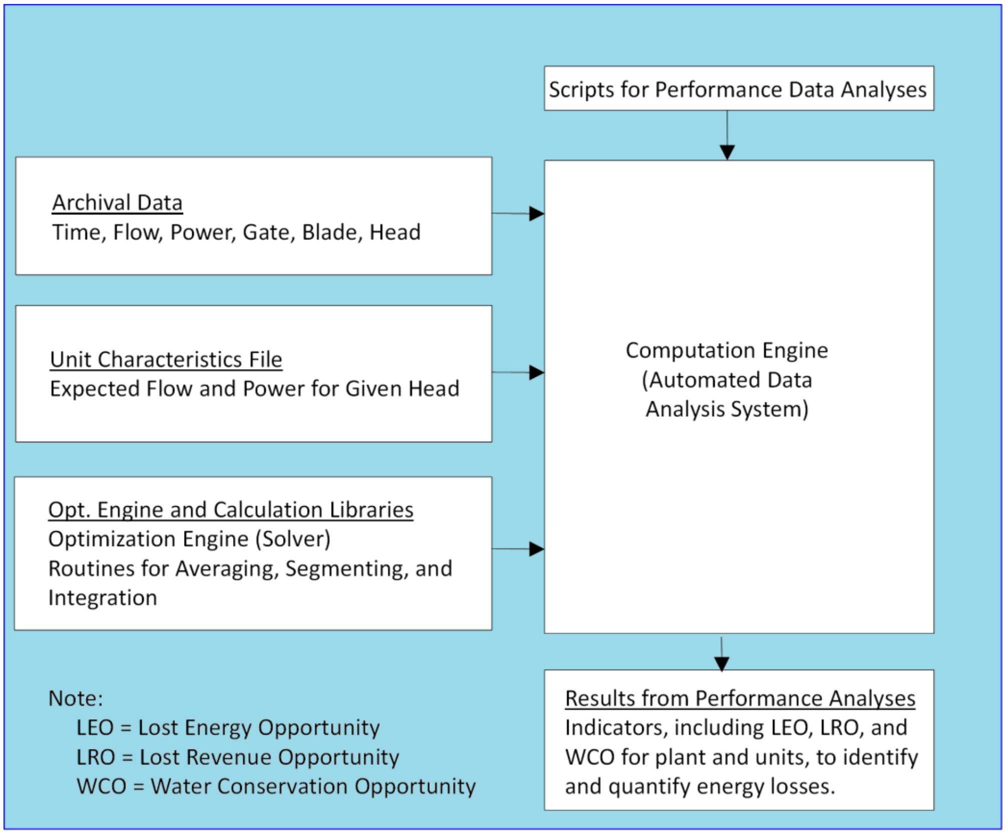

Figure 3: Process Diagram for Optimization-Based Performance Analyses

- Operation Efficiency determines how closely the actual dispatch matches the optimized dispatch
- Computational Steps:
  - Inputs are head, power, unit performance curves
  - Compares actual dispatch to optimal plant dispatch while meeting the actual load
  - Optimized dispatch requires less water
  - Water saved is converted into power at same head in the time step during which it occurs
  - Operation efficiency = 100 * (Actual Energy) / (Optimized Energy)

Figure 4: Operation Efficiency Analyses

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].

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 efficiency are shown in Figure 5. 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.

- Scheduling Analyses determine how closely the plant load request matches the points of peak plant efficiency
- Computational Steps:
  - Compute the optimized plant efficiency curve for the range of heads
  - Create a scheduling table that defines the peak plant efficiencies, the peak efficiency loads, and the minimum efficiency loads as a function of head and the number of units on line
  - Using the plant load and head as inputs, interpolate to compute peak efficiencies and minimum efficiency loads for the given head
  - Determine the number of units to dispatch by comparing the plant load to the minimum efficiency load; find the lowest plant efficiency load that is greater than the plant load (the number of units at which this occurs is the reference number of units)
  - Compute the efficiency difference between the optimized plant efficiency for the given load and the maximum scheduling efficiency
  - Assume the water used for the given timestep is utilized to create energy at the maximum scheduling efficiency
  - Scheduling Efficiency = 100 * (Optimized Energy) / (Optimized Schedule Energy)

Figure 5: Scheduling Analyses

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. The computational steps for the Avoidable Loss Analyses are shown in Figure 6.

- Avoidable Loss Analyses determine how the optimized dispatch could be improved by reducing avoidable losses (e.g., excessive trash losses, excessive penstock losses, and excessive tunnel losses)
- Computational Steps:
  - Inputs are head, power, unit performance curves, and piezometric heads corresponding to trash losses, penstock losses, tunnel losses
  - Energy losses for each component are based on piezometric heads and computed flow rates
  - Avoidable Loss Efficiency = 100 * (Actual Energy) / (Actual Energy + Avoidable Energy Loss)

Figure 6: Avoidable Loss Analyses

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 [March and Wolff, 2004; Jones and Wolff, 2007]. Computational steps for the correlation analyses are shown in Figure 7. 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.

- Correlation Analyses evaluate the accuracy of the unit characteristics and unit instrumentation
- Computational Steps:
  - Inputs are flow, head, power, and unit characteristics (wicket gate and blade data provide additional information for troubleshooting)
  - Measured efficiencies are compared to expected efficiencies
  - Deviations are assumed to be an efficiency loss
  - Efficiency losses are converted to energy losses based on unit power production
  - Correlation Efficiency = 100 * (Actual Power – Power Loss) / (Actual Power)

Figure 7: Correlation Analyses

7.0 Outcome from Performance Assessments and Analyses

The performance assessment results are used as input to two of the three Impact Indices, namely the Efficiency Impact Index, representing the potential of generating performance improvement, and the Cost Impact Index, representing the level of dollar cost for upgrading/replacing an asset in terms of $/kW or $/kWh. These two Impact Indices, in conjunction with the Reliability Impact Index, can collectively provide a base for decision-making on further assessment or studies and for prioritizing the investment opportunities at a facility.

8.0 References

ASME, *Performance Test Code 18: Hydraulic Turbines and Pump-Turbines*, ASME PTC 18-2011, New York, New York: American Society of Mechanical Engineers (ASME), 2011.

Giles, J. E., P. A. March, and P. J. Wolff, "An Introduction to Optimization-Based AGC," *Proceedings of Waterpower XIII*, Kansas City, Missouri: HCI Publications Inc., July 2003.

IHA, *Compliance Protocol (Sustainability Guidelines)*, London, England: International Hydropower Association (IHA), February 2004.

IHA, *Sustainability Assessment Protocol*, London, England: International Hydropower Association (IHA), July 2006.

Jones, R. K., and P. J. Wolff, "Maintaining Accurate Hydroturbine Operating Characteristics Utilizing Fleetwide Monitoring and Analysis Tools," *Proceedings of Waterpower XV*, Kansas City, Missouri: HCI Publications, July 2007.

March, P. A., "Best Practice Guidelines for the Hydro Performance Process and Implications for Incremental Hydropower," 2004 World Renewable Energy Conference, Denver, Colorado, September 2004.

March, P. A., *Hydropower Technology Roundup Report: Case Study on Hydro Performance Best Practices*, EPRI Report No. 1015807, Palo Alto, California: Electric Power Research Institute, December 2008.

March, P. A., C. W. Almquist, and P. J. Wolff, "Best Practice Guidelines for Hydro Performance Processes," *Proceedings of Waterpower XIV*, Kansas City, Missouri: HCI Publications, July 2005.

March, P. A., and P. J. Wolff, "Optimization-Based Hydro Performance Indicator," *Proceedings of Waterpower XIII*, Kansas City, Missouri: HCI Publications Inc., July 2003.

March, P. A., and P. J. Wolff, "Component Indicators for an Optimization-Based Hydro Performance Indicator," *Proceedings of HydroVision 2004*, Kansas City, Missouri: HCI Publications Inc., August 2004.

Schofield, E. W., and P. A. March, "From Assessment to Indicators: A Case Study in Hydro Performance Improvements at Ketchikan Public Utilities," HydroVision 2008, July 2008.

Spicher, T., *Hydro Wheels: A Guide to Maintaining and Improving Hydro Units*, Kansas City, Missouri: HCI Publications Inc., 2004.

Wolff, P. J., P. A. March, R. K. Jones, and D. B. Hansen, "Structuring a Hydroturbine Testing Program to Measure and Maximize Its Benefits," *Proceedings of Waterpower XIV*, Kansas City, Missouri: HCI Publications, Inc., July 2005.

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