RECLAMATION
Managing Water in the West

Hydro Model Data Project

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center

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Hydro Model Data Project

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SUMMARY REPORT

Hydro Model Data Project

U.S. Bureau of Reclamation
October 19, 2013

EXECUTIVE SUMMARY

This report summarizes progress and accomplishments of the Reclamation 2012 – 2013 effort to "gather information necessary to improve the hydro models used for wind and solar integration studies."[1] This project was undertaken because of concern that integration models do not accurately reflect hydro's actual capabilities to compensate for renewable variability, in light of hydro's operating constraints. A better definition of those constraints, and what data are required to quantify them, is needed.

A generic, preliminary set of powerplant operating constraints was defined and linked to potential data elements. These data elements were mapped to likely sources in Reclamation databases and other locations.

Reclamation initiated a cooperative effort with the National Renewable Energy Laboratory (NREL) in Golden, Colorado, to apply the constraints and data elements to their renewable energy models. Data on Reclamation's 53 powerplants were collected and made available. A method was developed and shared that provides more accurate estimates of available power at specific powerplants, taking into account actual horsepower at various hydraulic heads.

A parallel Reclamation project is forthcoming[2] whereby key power facilities will be quantitatively assessed for flexibility; e.g., ability to deliver more ancillary services (AS). This will incorporate many of the same constraints and data elements as hydro modeling. The two projects will complement each other.

The results of the hydro model data project provide a good starting point in working with other hydropower producers, power marketing administrations (PMA), and renewable-energy integration model builders in creating more accurate models. An initiative for collaboration has been initiated by Reclamation.

Full-fledged data collection for improving integration models (planning and / or real-time dispatching[3]) will require significant improvement in Reclamation's data collection and

[1] Scope section of Performance Work Statement (PWS), Hydro Model Data Project, 14 June 2012.
[2] Federal MOU for Hydropower – Two Year Action Plan – Quantification of Hydropower System Flexibility (2013)
[3] Per the June 2012 FERC Final Rule on Integration of Variable Energy Resources, the generation / transmission system must accommodate renewable integration. Eventually, real-time (e.g, 15-minute, 5-minute, continuous) forecasting will require transmission providers provide "intra-hourly" scheduling.

reporting systems. This improvement can be coordinated with another initiative,[4] involving establishment of standard operations reporting data throughout the hydro industry.

BACKGROUND

Renewable energy – wind and solar – is being integrated into the nation's electric power system, especially in the western U.S., where Reclamation's 53 powerplants reside. Renewable energy supplies fluctuate due to wind and solar variability. To compensate for this fluctuation a source of reliable, flexible power is required.

Power system models have been developed to facilitate renewable integration. These models account for renewable variability by counting on traditional powerplants to compensate for fluctuations. Such providers have always been relied on to supply power for load variations and to make up for generation inadvertently lost. However, with the increasing penetration of renewables, the capability of traditional providers to compensate must be reevaluated.

Hydro generation has unique characteristics that make it attractive as a source of variable power. Hydro can be started, stopped, and load-changed more easily and economically than steam generation. In fact, many hydro generators are operated in just this way – as a variable supplement to base-loaded powerplants.

However, there are limits to hydro's capabilities to meet fluctuating supplies / demands. First, there are basic engineering limitations on the size of the generating units. Second, hydraulic conditions dictate how much power and energy is possible, and these conditions vary by season and year. Finally, there are many non-power operational constraints on hydro, stemming from higher priorities than power generation.

Limitations in the third category are often overlooked when making assumptions about hydro's capability to mitigate renewable fluctuations. But, a better definition of limitations in all three categories is needed. This would benefit both hydro producers and those planning for renewable integration.

Renewable-integration model builders themselves generally admit they are not cognizant of hydro's unique constraints and that their models could be improved with better data. This is true of models used to plan for future integration, where nameplate data and historical operations records form the basis of their analysis. While the generalized nature, longer time scales, and breadth of data involved in planning models may lessen the need for quantifying plant-specific constraints, there is still concern because future operation may not mimic past operation.

As energy markets move toward near real-time dispatching, it becomes more important to know specific plant constraints and capabilities. These should be clearly understood and quantified.

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[4] Federal MOU for Hydropower – Two Year Action Plan – Hydropower Operational Data Analysis Guidelines (2013)

Unfortunately, most existing data collection systems do not support real-time quantification because not all data elements are tracked and not tracked on the shortened time steps required.

The time has come to better define what constraints affect hydro's ability to compensate for renewable fluctuation. It is incumbent on hydropower producers to identify and quantify these constraints and communicate them to integration model builders. While much can be done individually by producers, much is to be gained by a coordinated effort among all stakeholders: hydro producers, power marketing administrations (PMA), and renewable-integration model builders. The hydro model data project begins this process.

METHODOLOGY

This project followed these steps:

1. Understand the issue and Reclamation's concern.
2. Develop a generic, preliminary list of constraints.
3. Identify data elements, linked to the constraints, that could be used for quantification.
4. Research potential sources of data in Reclamation reference documents and data systems.
5. Map the data elements to potential sources.
6. Collect data, to the degree possible.
7. Identify gaps in the data and possible improvements.
8. Partner with a model builder to share knowledge, issues, and data.
9. Develop a plan to cooperate and communicate with other stakeholders to improve models.

Issues / Concerns

Reclamation staff in the Power Resources Office (PRO) and the Technical Service Center (TSC) have become increasingly concerned that renewable-integration models do not accurately reflect Reclamation's hydro capabilities and operating constraints. This concern stems from reading technical papers, attending meetings and conferences, networking with colleagues, etc. This is of particular concern to Reclamation whose powerplants supply much of the western U.S. hydropower.

The chief concern is that there appears to be a common belief that hydropower facilities are capable of supplying large amounts of ancillary services (AS) to support renewable energy development. Primarily, the AS of regulation / load following and spinning / non-spinning reserve are affected since these define what plant capability is available to meet fluctuating demand or loss in generation, e.g., renewable source fluctuation. Although hydro plants do have some capability to facilitate renewable variability, it is likely this ability is much smaller than assumed.

Model builders are not hydro producers and "don't know what they don't know" about hydro operation and its unique constraints. It is incumbent on hydropower producers to help model builders understand the issues. Making long-range decisions about renewable integration based on faulty assumptions and incomplete data serves no one.

Also, from time to time, model builders request data from Reclamation. It has become clear that these data are either not currently collected, are incomplete, or are on such long time steps that the data are not useful. Improvements should be made to data collection processes and systems.

These issues need to be addressed systematically within Reclamation and cooperation should begin with other stakeholders.

Constraints

It is not always possible to get maximum, rated power and energy from Reclamation powerplants. Several constraints apply.

- Most Reclamation hydro plants conduct maintenance and perform major uprates and replacements during the dry season. Even if water is available, these activities limit available plant capacity. Unit and plant outages must be taken into account when calculating capacity.

- From an engineering and environmental standpoint, hydro plants are not 100% flexible. Even hydro units cannot be loaded and unloaded instantaneously as equipment limitations and downstream flow control must be observed. Certain loading levels (rough and cavitation zones) must be avoided. These limit plant output.

- Hydro is seasonal in nature because of variability in the "fuel" supply: water. Unfortunately, in some locations, dearth of water coincides with higher variability in renewable supplies e.g., in the winter. Also, hydrologic conditions vary year by year and decade by decade, through wet and dry cycles. This variability in water supply greatly affects the available power and energy, especially since water for generation may be curtailed to meet other needs.

- Related to variable water supply is the sometimes-overlooked relationship between hydraulic head and electrical power output of the generating units. This relationship must be recognized and quantified.

- Power generation at Reclamation facilities is a byproduct of the projects' main purpose which is primarily to supply water for irrigation and municipal / industrial use. Also, reservoirs and rivers are controlled by Reclamation plants for recreation, environmental, and flood control purposes. While power generation is important, it is secondary to these other priorities, whose precedence is established by law and contracts. Thus, flexibility in meeting additional variable power and energy demands may be limited.

- Most power, energy, and ancillary services delivered by Reclamation plants are already contracted. Additional unit and plant capacity may not be available or may be minimal.

- Pumping schedules affect the availability of power to meet fluctuations. At some projects, irrigation pumping loads consume a significant amount of generated power / energy. This takes precedence over making electricity available for the commercial power system. Also, at pump-generating plants, units in pumping mode are not immediately available for generation.

The accompanying document, ***Table 1. – Renewable Integration Constraint Factors***, summarizes what constrains Reclamation's ability to meet additional, variable loads.

Data Elements, Sources, Mapping

Table 1 also links constraint factors to data elements which are needed to quantify the constraints. These data elements are fleshed out in accompanying ***Table 2. – Renewable Integration Data Elements***.

A third accompanying document, ***Table 3. – Data Mapping – Renewable Integration***, maps the data elements to data sources in Reclamation.

Data Collection / Gaps

Collecting powerplant-specific data is challenging for several reasons:

1. Operating constraints are not uniform across Reclamation because of the wide variety of facility types, purposes, operating criteria, and hydrologic conditions.

2. Data are not stored in a single system or centralized location. Some data are available from the Denver Office, while others are available only at the facilities.

3. There is little uniformity in collecting and reporting some data.

4. Some data are currently available on long time intervals (steps) that may not be useful for quantification.

5. Data needs differ depending on whether they are to be used for renewable planning purposes or real-time dispatching.

POMTS - Reclamation's POMTS (Power Operation and Maintenance Tracking System) is the most significant source of centrally-located operations data available. Although imperfect, POMTS data go back approximately 60 years and provide a good overview of each plant's operating history. However, POMTS does not capture all the data needed for quantifying limitations and capabilities of the powerplants. Also, POMTS captures the data monthly. This interval may adequate for integration planning purposes, but is likely not frequent enough for dispatching.

Reclamation is studying how to expand POMTS capability to capture more data and do so on shorter time steps. It is desired to automate as much of this data collection as possible. The Power Resources Office would like to redesign POMTS around a set of hydropower operations data elements developed by consensus with other hydro producers. This would facilitate exchange of data and automated analyses. The Federal MOU for Hydropower – Two Year Action Plan – Hydropower Operational Data Analysis Guidelines (2013) is the vehicle for developing the consensus set of operational data elements with other entities. The subset of renewable-integration data elements should be compatible with the broader operations data element set.

Data from Facilities – As Table 3 shows, much data needs to be acquired at the facilities. These data have evolved over the years, as plant operation has been adjusted to meet site-specific criteria. These data are not compiled in a centralized location. Site visits will be needed to acquire the data once it has been decided which data elements are critical to actual modeling.

Other Sources – Table 3 lists several sources of data initially investigated within Reclamation. A brief description of each source is included in Appendix A. There are probably other sources of data that will be discovered during more extensive data collection.

Available Power / Energy

Integration models should include algorithms or data reflecting that electrical power output of hydro generating units is directly related to hydraulic head. Not taking this into account will result in inaccurate estimates of available power. Generator nameplate ratings reflect ideal conditions often not encountered in plant operation, so a more realistic estimate is needed.

Turbine mechanical energy in horsepower (HP) varies with head, and electrical power in kilowatts (kW) varies in proportion to HP. Turbine capability curves and test data quantify the head vs. HP relationship, which is approximately linear. Knowing the specific head vs. HP relationship at a plant and the historical or actual hydraulic head yields an approximate value for available power.

This calculation does not take into account all other operating constraints, which must be factored in afterwards. However, the calculation is a good starting point.

Under the Hydro Model Data project, an algorithm was developed relating available kW to head and data was collected on Reclamation's largest units for use in this algorithm. A full description of this method and its associated data are in an accompanying document. This method and data have been shared with the NREL model teams.

Although available power in kW is a most important calculation, available energy in kWH is important as well. Makeup power delivered over an extended period could deplete available water resource at facilities with small storage. Available-energy calculations require knowing the volume of water available for generation (a fraction of total water in the forebay). This volume data will need to be acquired from each facility and may be difficult to get. An algorithm for available energy has not yet been developed but will rely heavily on the available power algorithm.

Partnering with Model Builder NREL

From the beginning of the project, it was recognized that developing constraints and data elements internally would be insufficient. Collaboration with one or more renewable integration model builders would be necessary. Reclamation initiated a working relationship with NREL in Golden, Colorado, to explore applicable constraints and data elements, as well as furnishing detailed data. NREL is developing two models: ReEDS (for long-term integration planning) and PLEXOS (for operational dispatching to compensate for real-time renewable fluctuation).

Reclamation provided its preliminary lists of constraints and data elements to the ReEDS and PLEXOS teams, who responded with their prioritized lists.

ReEDS. - See accompanying Table 4. – NREL ReEDS Prioritization of Constraints/Data Elements.

The ReEDS team identified the following powerplants as being of most interest at one time: Grand Coulee, Yellowtail, Parker, Canyon Ferry, Anderson Ranch, Fremont Canyon, Kortes, Seminoe, Alcova, Glendo, Guernsey.

Reclamation began furnishing data to the ReEDS team, including a complete set of POMTS data on all powerplants. The ReEDS team continues to integrate these data and work with Reclamation, clarifying and commenting.

PLEXOS. – See accompanying Table 5. – PLEXOS Prioritization of Constraints / Data Elements. This table illustrates that data elements for real-time models have different priorities than elements for planning models.

The PLEXOS team furnished information outlining a recent project which modeled the Columbia River system by interfacing PLEXOS to RiverWare.[5] RiverWare models a complete, interconnected river system with multiple facilities and incorporates power and non-power constraints. The purpose of this project was to arrive at a better representation of hydro in renewable integration models. Reclamation continues to work with the PLEXOS team to better understand how the PLEXOS / RiverWare effort can help with the hydro model data project.

Optimization

The data elements and process for acquiring the data for this hydro model data project overlap with those used in the Reclamation powerplant optimization program. The optimization program

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[5] An customizable river basin modeling system available through CADSWES – Center for Adnvanced Decision Support for Water and Environmental Systems at the University of Colorado, Boulder.

(developed in the TSC) intends to create and implement automated methods for optimizing the operation of a subset of Reclamation powerplants.[6] Many of the data elements required for optimization also are required for hydro modeling. The optimization team has encountered challenges similar to hydro modeling in getting the needed data.

An important piece of the optimization program is an automated method for acquiring data in real time. This could dovetail nicely with the enhanced data needs of POMTS and the modeling data project.

Parallel Initiative

Under the Federal MOU for Hydropower – Two Year Action Plan – Quantification of Hydropower System Flexibility, Reclamation will issue in FY2014 a Request for Proposal (RFP) to Department of Energy (DOE) laboratories, soliciting proposals to "rigorously quantify the capability of a subset of Reclamation powerplants to provide ancillary services, on at least a monthly basis but preferably at finer time scales, for a specified range of hydrologic conditions." This will include the ancillary services of regulation / load following and spinning / non-spinning reserve and will incorporate operating constraints.

This initiative will advance the goals of the hydro model data project for this set of plants. The work already done under the hydro model data project will set the stage for the Quantification initiative and identify key considerations and data sources.

Cooperation and Communication Plan

The issue of accurate modeling of hydro plants in renewable energy integration models transcends Reclamation. Other hydro producers also are affected. And, the issue should be of prime importance to power marketing administrations. A cooperative effort among stakeholders would establish a common set of definitions and tools to define the problem and its solutions.

Integration model builders should be apprised of hydro's constraints and capabilities via proactive communication from the hydro-producer and PMA community.

A draft issue paper was prepared and delivered to the Power Resources Office outlining the need and strategy for the cooperative effort.

RELATED STUDIES

Reclamation Sponsored. - Some Reclamation plants have been or are being studied in depth for capacity improvements. As part of these studies, detailed analysis has been made of the existing

[6] The current optimization project will eventually be applied at most of Reclamation's powerplants, except for those which already have optimization tools: Grand Coulee, Yellowtail, Hoover. Currently, testing is taking place at Black Canyon.

plant's ability to produce more power/energy, given the operating constraints. Data from these studies could be useful in creating a Reclamation database for renewable energy integration.

Appendix B summarizes these studies.

CHEERS. - Argonne National Laboratory recently developed and demonstrated a river-optimization toolset, Conventional Hydropower Energy and Environmental Systems. CHEERS assists operators in day-ahead scheduling and real-time operation to increase efficiency and maximize the value of power and ancillary services, in compliance with multiple operating constraints.

One CHEERS demonstration project was Reclamation's Aspinall Cascade powerplants in the Curecanti Project. The constraints included, and data collected, for this demonstration could be very useful for renewable hydro-modeling.

CONCLUSIONS AND RECOMMENDATIONS

Reclamation and other hydropower producers should proactively ensure that renewable energy integration model builders are apprised of the factors that limit hydro's ability to compensate for renewable variability. This includes identifying operating constraints and data elements, as well as collecting, organizing, and furnishing data for specific powerplants. The goal is to quantify hydro's actual power and energy capabilities as they relate to renewables.

Data currently available are incomplete and on longer time steps than are required for accurate quantification of plant capabilities. Data are not uniformly collected or centrally stored, making it difficult to assemble a set of data for all Reclamation plants. In the short term, data can be collected on a plant-by-plant basis, using what data are available in the Denver Office and extracted during site visits. This is time-consuming and may result in data that quickly become stale.

In the long run, a more systematic method for collecting data on an ongoing basis is desirable. Data would be refreshed regularly (particularly if automated) and could be accessed from various locations. However, this will take time to establish and manual data-collection efforts may need to continue in the meantime.

NREL's experience combining PLEXOS and RiverWare sounds very promising, especially since it is designed to observe multiple operating constraints: power and non-power. Work is needed to ensure that all constraints important to Reclamation are included in such a model.

Reclamation can follow these action steps:

1. Actively pursue the Quantification of Hydropower System Flexibility project. This will advance Reclamation's understanding of actual capabilities at certain plants and that knowledge can be applied to other facilities. The constraints and data elements

investigated for Quantification can be compared to those collected in this hydro data project.

2. Promote a cooperative effort with other hydropower producers and PMAs to establish a unified position on hydro capabilities and limitations. This includes developing consensus constraint and data element definitions and time steps. It also includes implementation of an action plan for communicating with model builders.

3. Continue working with NREL and other model builders to better understand how the models represent hydro and clarify their data needs. Pursue in more depth NREL's use of RiverWare and Argonne's CHEERS as tools for representing hydro's operating constraints.

4. Refine the Reclamation data elements list based on the above actions and further assess internal processes and systems for their ability to support data collection.

5. Develop and execute a plan to renovate Reclamation's processes and systems to collect the data, coordinating with efforts to enhance POMTS and with the optimization program.

APPENDICES

A. Description of Data Sources
B. Related Studies

ACCOMPANYING DOCUMENTS

1. Table 1. – Renewable Integration Constraint Factors
2. Table 2. – Renewable Integration Data Elements
3. Table 3. – Data Mapping – Renewable Integration
4. Table 4. – NREL ReEDS Prioritization of Constraints / Data Elements
5. Table 5. – NREL PLEXOS Prioritization of Constraints / Data Elements
6. Calculating Available Power

APPENDIX A

DESCRIPTION OF DATA SOURCES

From Facilities - Data available only at the powerplant, area / project office, or regional office. Not centrally compiled in the Denver Office.

POMTS (Power O&M Tracking System) – Database (currently populated with data supplied by an electronic version of the POM 59 forms) contains historical generation data for each powerplant. It is accessible only by the Reclamation intranet. (Power Resources Office)

PLEESM - Planning Level Energy and Economics Study Model. Part of Reclamation's Hydropower Modernization Initiative. Developed for Reclamation and the Corps of Engineers to simulate energy production at powerplants, with the goal of evaluating the value of adding capacity. (Power Resources Office)

Hydraulic Turbine Data Sheets – Comprehensive data for each turbine family by plant. The first section lists manufacturer's data for all design and construction aspects. The remaining two sections show predicted characteristic curves based on the manufacturer's data. One set of predictive curves relates efficiency, discharge (cfs), and output power (hp) for the design head. The second set of curves relates horsepower, and discharge (cfs) to net head (ft) over the expected range from minimum to maximum head. (TSC Hydraulic Equipment Group)

Flow Tables / Curves – Relate capacity (MW) to head (ft) and relate capacity (MW) to flow (cfs) at various heads. (TSC Hydraulic Equipment Group and area / project offices)

Head / Flow Duration Curves / Data – Forebay elevation and active storage volume are related. Knowing the elevation / volume, inflow, and the discharge rate, the time that the flow can be sustained can be calculated. This is a measure of available energy. Curves for each reservoir showing the relationship may exist but have not yet been located. However, data to perform the calculations are available in ACE (area, capacity, elevation) tables (available from area offices). Total flows are available from the Reclamation water operations website and turbine discharge is available from the hydraulic turbine data sheets.

500+ MW PP Data – (Currently compiled for FY1997 - 2007). This database contains parameter and historical generation data for Reclamation's powerplants with capacity over 500 MW (Grand Coulee, Shasta, Glen Canyon, & Hoover). Data include: Installed capacity, present capacity, gross and net generation, maximum hourly generation, plant factor, several performance factors, ancillary services delivered, and some water operations constraints. (Power Resources Office)

Hydropower Reports and Data Website – (Data currently available through FY2007). This website provides a wide variety of parameter and power performance data for each Reclamation powerplant for the date range. The site could be updated by the Power Resources Office for later years. These data are available at the Reclamation website www.usbr.gov/power/data (Power Resources Office)

Optimization Program Data – These data are collected to support the development of plant optimization systems for most efficient allocation of generating units, based on current hydrological conditions and unit performance characteristics. (TSC Hydropower Diagnostics and SCADA Group)

Project Data Book – (Published 1961, updated 1981, 1983). Provides basic data on every Reclamation project constructed. The hardcover version of the book includes general descriptive information, history, authorizations, benefits, project and engineering data, and structural data. Data include structural information such as construction elevations that may be useful. Also, a "tailwater curve", relating elevation to discharge, is included. The hardcover book is available in many libraries, including the Reclamation Denver Office library, Denver, CO (but access is limited due to security concerns). Much of the book's narrative and data are available on the web (http://www.usbr.gov/projects/) but the drawings are not included, for security reasons.

Water Operations Website – This website provides a wide range of historical and current data on water operations at Reclamation facilities. It includes narratives, graphs, and tables showing data such as snowpack and reservoir levels, river flows, current power generation, dam and powerplant histories and specifications, reservoir allocations (active capacity, etc.), and hard maximum/minimum reservoir elevation limits. Data plots are available using daily archive data on a wide variety of quantities, such as current flow in CFS per MW, current powerplant efficiency, daily mean power turbine discharge, etc. This site includes an annual operating plan for each power facility that describes historical operation and planned water and power operations, taking into account operating constraints. These data are available via the Reclamation website www.usbr.gov/main/water .

Regional Web Pages – These webpages provide access to current and historic water and power data for power facilities in each region. In the PN and GP regions, much of the data is supplied by Hydromet; other regions supply the data in other ways. Regional web pages access much of the same data as the water operations website, described above. Regional web pages can be accessed via www.usbr.gov/ with the regional abbreviation (PN, MP, LC, UC, GP) added to the end of the address.

USGS Water Data Website – This website provides current and historical water flow, levels, and quality measurements in streams and lakes throughout the United States (over 1.5 million sites). This includes all reservoirs and rivers associated with Reclamation power facilities. These data are available through the USGS website www.usgs.gov/nwis .

Standing Operating Procedures (SOP) and Operations Staff – SOPs, maintained at each powerplant, describe authorized procedures for operating the facility, including constraints that must be observed. These documents are available (subject to security limitations) at each powerplant and are assumed to be complete and current for purposes of the Data Collection table. Powerplant and control center operations staff knowledge supplements the SOPs.

Generator Characteristics Data – Data exist for every known parameter for each Reclamation generator, including calculated and test efficiencies. These data are in several formats, including drawings (104-D-689, 1177, 690, 1178), an Excel spreadsheet, and a data book. (TSC Electrical Design Group)

Generator Capability Curves – Generator output is constrained by the thermal limits of the stator and rotor and KVA capacity. These are defined on generator capability curves which quantify the tradeoff between real and reactive power. Generators supplying reactive power to the system cannot use all their capacity for MW generation. These curves are available for all Reclamation units. (TSC Power System Analysis and Control Group)

APPENDIX B

RELATED STUDIES

Hydropower Advancement Project (HAP) Report (Final Report 06/18/2012) – This report summarizes a detailed study of Flaming Gorge powerplant by Oakridge National Laboratory in early 2012 for DOE. Included in this report is a thorough hydrological analysis that compares the stream potential power to actual power output to determine the potential for increased generation. Spreadsheets, tables, and charts show data such as plant flow vs. efficiency, unit flow vs. power at various heads, net head efficiency vs. unit power, optimized plant efficiency vs. power, and actual annual generation. This report is available from the Power Resources Office, Denver, CO. (Appendix 2: Workbook for Performance Analyses is not complete / available at this time).

Study of Pump Storage Capability and Potential Enhancement for Wind Power Integration - John W. Keys III Pump Generating Plant (October 2009) – This study specifically assesses the Coulee PG plant ability to compensate for renewable energy variability. The study includes specific information on water constraints and guidelines for FDR Lake (forebay for the Left, Right, and Third powerplants) and the Columbia River (tailrace for these 3 plants). Also included are FDR Lake historical elevations in dry, normal, and wet years. This report is available from the Pacific Northwest regional office, Boise, ID.

Pumped Storage Analysis Study (In progress, a by HDR/CDM) – This study assesses several Reclamation power facilities for feasibility of adding pump generation, within the existing operating constraints. Four powerplants (Seminoe, Fremont Canyon, Yellowtail, Trinity) for technical feasibility and two will be chosen for additional economic evaluation. The screening process includes analysis of the plants' current capacity to provide additional generation. This study is ongoing; when completed, this report will be available from the Power Resources Office, Denver, CO.

TABLE 1
Renewable Integration Constraint Factors
Bureau of Reclamation
October 10, 2013

FACTOR NAME	DESCRIPTION	IMPACT ON INTEGRATION	HARD OR SOFT	FLEXIBILITY POTENTIAL	DATA REQUIRED
WATER MANAGEMENT					
Contracted Water Delivery, Minimum / Maximum Stream Flow, and River Regulation	Delivering minimum / maximum downstream water flow for: Irrigation Municipal and industrial (M&I) use Support animals and vegetation Regulation of downstream rivers and reservoirs for recreation, irrigation, navigation, and power generation by others.	Water may not be available for generation. Takes precedence over power generation.	Soft	Additional generation possible between upper and lower flow limits. Limits are rigid, being dictated by contracts, law, court rulings, environmental statements, etc.	Upper limit downstream flow. Actual generation. Present plant capacity.
Forebay Elevation Control	Maintaining forebay elevation within acceptable range, e.g., for recreation, irrigation, riparian support, etc.	Water may not be available for generation Takes precedence over power generation	Hard	None, with existing limits. Additional generation not available when forebay elevation is at or below minimum allowed. Is forebay active storage increase possible?	Lower limit on forebay elevation. Actual forebay elevation.
Dissolved Oxygen / Water Quality & Temperature Control	Regulation of water release to tailrace to control: Amount of dissolved oxygen (DO) Water temperature Other water quality variables	Water may not be available for generation Takes precedence over power generation	Soft	Additional generation possible between upper and lower limits on DO, temperature, and other water quality indicators. Limits are rigid, being dictated by lw, court rulings, environmental statements, etc.	Upper and lower limits on DO. Actual DO. Upper and lower limits on temperature. Actual temperature. Other upper and lower water quality indicator limits. Actual water quality.

Flood Control	Control of flood water to protect downstream life and property. Water may be retained in reservoir or water may be spilled (not generating) or maximum generation may take place to utilize water.	Water may not be available for generation. Emergency situation that takes precedence over power generation and other considerations.	Soft	Additional generation possible when plant output is maximized with high water flows.	NA

POWER					
Power Delivery Obligations	Real power (MW) delivered for: 1. Project use (See Pumping Schedules, below) 2. Preference power customers 3. Retail customers	Reduces amount of generation available.	Soft	Additional generation possible between present plant capacity and generation commitments.	Present plant capacity based on present net head. Generation commitments (scheduled).
Plant Capacity Limits	Unit Capability Limits Physical limitation on generator output based on unit capability.	Limits amount of generation available.	Hard	None. Limits cannot be exceeded.	Unit and plant nameplate capacities. Turbine capacity data (HP vs Head). Actual hydraulic head. Generator capability curves which identify rotor and stator thermal limits on capacity. Generator and GSU transformer efficiencies. Actual plant MW output.
	Unit Unavailability Unavailability of generating units resulting from forced and scheduled outages.	Limits amount of generation available.	Hard	None. Unavailable units cannot generate.	Present plant capacity, including unavailable units. Unit availability status.
	Ancillary Service Obligations Delivery of contractually-required services: 1. Reactive power for system voltage management 2. Spinning reserve 3. Non-Spinning reserve (10 minute) 4. Replacement reserve (1 hour) 5. Regulation (load following) and frequency control	Reduces amount of generation available.	Soft	Additional generation possible between plant capacity and ancillary service commitments.	Present plant capacity. Generator capability curves which identify rotor and stator thermal limits for real and reactive power. Actual plant output of reactive power. Plant capacity committed to reserves.

	P/G Unavailability Unavailability of pump-generating units to generate while in pumping status.	Limits amount of generation available.	Hard	None. Cannot use a unit that is pumping to generate.	P/G unit present capacity in MW. Pumping or generating status of units.
Ramp Rate Limits	Restrictions on how quickly a generator can be loaded to prevent thermal damage. Generally limited to 10% nameplate rating per minute. Restrictions on how quickly a unit can be loaded or unloaded to prevent unacceptable downstream water fluctuations.	Limits amount of generation available.	Hard	None. Limits cannot be exceeded.	Generator ramp rate limits. Actual plant MW output. Present capacity of units in spinning, non-spinning, and replacement reserve status not already committed to other system needs. Downstream ramp rate limits. Present downstream flow.
Unit Rough Running Zone Limitations	Restrictions on levels of possible generator output as limited by turbine rough running zones where vibration can be damaging to the unit.	May limit amount of generation available.	Hard	None. Operation in rough-running zones not allowed (except in emergencies)	Individual unit rough running zone MW output ranges at present capacity. Present capacity of each online unit. Present unit MW output.
Pumping Schedules	Restrictions on amount of power available due to need to pump water for project purposes.	Limits amount of generation available.	Soft	Pumping schedules may be modified to make more generation available during volatile periods.	Pumping schedules.
P/G Unit Transition Time	Restriction on how fast a P/G unit can deliver power because of transition from pumping to generating mode.	Limits amount of generation available.	Soft	Generation delay time during transition could be minimized with expedited procedures.	Pumping schedules. Current transition times. Operational evaluation of transition process.

TABLE 2
Renewable Integration Data Elements
Bureau of Reclamation
October 10, 2013

NOTES:
1. Period Hour = Total Hours in Fiscal Year.
2. For POMTS data details, see FIST Vol. 1-2, Conduct of Power Operations
3. Data for several elements vary seasonally and yearly with water availability.
4, Time steps for data are different for predicitve models and for real-time dispatching.

DATA ELEMENT	DESCRIPTION	NOTES
PLANT DESCRIPTION	Powerplant name, location, region, area/project office, river, forebay name, project purpose, NERC region/area, PMA/region, remote operation, control center, power use, production mode (base, peaking, intermediate), etc.	Data from various sources.
NO. of UNITS, RATED / NAMEPLATE CAPACITY	Number of main generating units. Unit & powerplant capacities.	Based on generator & turbine nameplate ratings, power factor. Use uprated / downrated values.
PLANT FACTOR %	(Gross Generation / (Installed Plant Capacity*Period Hours))*100	Monthly from POMTS
AVAILABILITY FACTOR % (Plant or Unit)	(Available Hours / Period Hours)*100	Monthly from POMTS
WEIGHTED AVAILABILITY FACTOR (Plant)	(∑ (Available Hours* Unit Capacity) / ∑ (Period Hours*Unit Capacity))*100	Monthly from POMTS
UTILIZATION FACTOR %	(Maximum Hourly Generation / Installed Plant Capacity)*100	Monthly from POMTS

FORCED OUTAGE FACTOR %	(Forced Outage Hours / Period Hours)*100	Monthly from POMTS
WEIGHTED FORCED OUTAGE FACTOR %	(∑ (Forced Outage Hours*Unit Capacity) / ∑ (Period Hours* Unit Capacity))*100	Monthly from POMTS
SCHEDULED OUTAGE FACTOR % (Plant or Unit)	(Scheduled Outage Hours / Period Hours)*100	Monthly from POMTS
WEIGHTED SCHEDULED OUTAGE FACTOR	(∑ (Scheduled Outage Hours* Unit Capacity) / ∑ (Period Hours * Unit Capacity))*100	Monthly from POMTS
WATER FACTOR %	(Water for Generation / (Water Used for Generation + Other Water Releases))*100	Monthly from POMTS
AVERAGE EFFICIENCY %	(Gross Generation / Water Used for Generation * Head * 0.0010242)	Monthly from POMTS
AVAILABLE POWER (KW) (Regulation / Load Following, Spinning / Non-Spinning Reserve)	Unit / Plant Capacity at Current or Historical Average Head	Reclamation available power algorithm relating MW to Head
	Current or Histoical Average MW Loading	From facilities.
	Current or Histoical Average MVAR Loading	From facilities.
	Unit Availability vs. Maintenance Outages, Commitment to Non-Spinning Reserve, etc.	From facilities.
GROSS GENERATION (kWH)	Plant Total Energy Generation	Monthly from POMTS

PLANT AUXILIARY USE (kWH)	Energy Used fIn Plant	Monthly from POMTS
NET GENERATION (kWH)	Gross Generation - Plant Auxiliary Use	Monthly from POMTS
MAXIMUM HOURLY GENERATION (KWH)	Monthly Maximum Generation in One Hour	Monthly from POMTS
CONDENSER OPERATION ENERGY (kWH)	Energy Used to Motor the Unit in Synchronous Condenser Operation	Monthly from POMTS
WATER USED FOR GENERATION (AF)	Water Volume Used for Generation	Monthly from POMTS
OTHER WATER RELEASED DOWNSTREAM (AF)	Water Volume Used for Purposes Other than Generation	Monthly from POMTS
KWH GENERATION / AF	Energy per Acre Foot of Water	Monthly from POMTS
RESERVOIR ELEVATION (FT)	Forebay Elevation	End of Month Snapshot from POMTS
TOTAL FLOW (CFS)	Total Plant Water Flow	End of Month Snapshot from POMTS
UNIT OUTAGE (HRS)	Individual Unit Scheduled or Forced Outage Time	Monthly from POMTS
MAINTENANCE FACTOR %	Total Actual Maintenance Time in Month / Total Hours in Month	Monthly from POMTS

MAX / MIN FOREBAY ELEVATION LIMITS (FT)	Maximum / Minimum Permitted Forebay Elevation	From facilities.
FOREBAY CAPACITY FOR GENERATION (AF)	Volume of Water Available for Generation	From facilities.
TAILRACE ELEVATION LIMITS (FT)	Maximum / Minimum Tairace Elevation Permitted	From facilities.
TAILRACE ELEVATION (FT)	Tailrace Elevation	From facilities.
RATED HEAD (FT)	Hydraulic Head for Rated Output	Engineering Data
HEAD LOSS (FT)	Penstock Losses at Maximum Flow	Engineering Data
MAX / MIN ALLOWABLE HEAD (FT)	Maximum / Minimum Hydraulic Head Allowed for Turbine Operation.	Engineering Data
TURBINE EFFICIENCY %	Efficiency at Various Gate Openings and Heads	Engineering Data
GENERATOR EFFICIENCY %	Generator Tested Efficiency	Engineering Data
GSU TRANSFORMER EFFICIENCY %	Step Up Transformer Efficiency	Engineering Data
DOWNSTREAM FLOW LIMITS (CFS)	Maximum / Minimum Flow of Water Permitted to Flow in the Tailrace	From facilities.
MAX / MIN POWERHOUSE FLOW (CFS)	Maximum / Minimum Allowable Powerhouse Flow	From facilities.
NON-POWER REQUIRED RELEASES (CFS)	Required Flows for Water Contracts, Fish & Riparian, Water Quality, etc.	From facilities.

INFLOWS (CFS)	Flows Into the Forebay Reservoir	From facilities.
GENERATOR RAMP RATE LIMITS (MW/MIN)	Heating Limit on How Fast a Generator May be Loaded.	Engineering Data. Often 10% of Nameplate Rating per Minute
TAILRACE RAMP RATE LIMITS (CFS or FT)	Tailwater Flow / Elevation Limits	From facilities.
ROUGH ZONE BOUNDARIES (MW)	Generation Levels Above and Below Which Unit Should Not Operate Due to Excessive Vibration	From facilities.
CAVITATION ZONE BOUNDARIES (MW)	Generation Levels Above and Below Which Unit Should Not Operate Due to Turbine Runner Cavitation	From facilities.
PUMPING SCHEDULES	Pumping Schedules for P/G Units and for Pumps Using Project Power	From facilities.
P/G TRANSITION TIME (MIN)	Time to Reverse Operation from Pump to Generate	From facilities.
WATER QUALITY LIMITS (Units depend on parameter)	Liimits on Water Quality Quantities	From facilities.

Table 3. - Data Mapping - Renewable Integration
Bureau of Reclamation
October 18, 2013

NOTES:
1. Period Hour = Total Hours in Fiscal Year.
2. For POMTS data details, see FIST Vol. 1-2, Conduct of Power Operations
3. Data for several elements vary seasonally and yearly with water availability.
4. Time steps for data are different for predicitve models and for real-time dispatching.

		Data Sources														
DATA ELEMENT	DESCRIPTION	FROM FACILITIES	POMTS	PLEESM	HYDRAULIC TURBINE DATA SHEETS	FLOW TABLES AND CURVES	HEAD/FLOW DURATION CURVES	500+ MW PP DATA	HYDROPOWER REPORTS/DATA WEBSITE	OPTIMIZATION DATA	PROJECT DATA BOOK	WATER OPERATIONS WEBSITE/REGIONAL WEB PAGES	USGS WATER DATA WEBSITE	SOPs	GENERATOR CHARACTERISTICS DATA	GENERATOR CAPABILITY CURVES
PLANT DESCRIPTION	Powerplant name, location, region, area/project office, river, forebay name, project purpose, NERC region/area, PMA/region, remote operation, control center, power use, production mode (base, peaking, intermediate), etc.	YES	SOME	SOME	SOME	SOME	SOME	YES	YES	YES	YES	Some	NO. Identification is by reservoir, river.	SOME	SOME	SOME
NO. of UNITS, RATED / NAMEPLATE CAPACITY	Number of main generating units. Unit & powerplant capacities.	YES	YES	YES	YES	SOME	SOME	YES	YES	YES	YES, but out of date	NO	NO	YES	YES	YES
PLANT FACTOR %	(Gross Generation / (Installed Plant Capacity*Period Hours))*100	YES	Monthly	Calculates Annual Capacity Factor, unclear if this is Plant Factor.	NO	NO	NO	YES	YES	YES	NO	NO	NO	NO	NO	NO
AVAILABILITY FACTOR % (Plant or Unit)	(Available Hours / Period Hours)*100	YES	Monthly	NO	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
WEIGHTED AVAILABILITY FACTOR (Plant)	(∑ (Available Hours* Unit Capacity) / ∑ (Period Hours*Uni	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
UTILIZATION FACTOR %	(Maximum Hourly Generation / Installed Plant Capacity)*	YES	Monthly	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
FORCED OUTAGE FACTOR %	(Forced Outage Hours / Period Hours)*100	YES	Monthly	Simulates outage time.	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
WEIGHTED FORCED OUTAGE FACTOR %	(∑ (Forced Outage Hours*Unit Capacity) / ∑ (Period Hours* Unit Capacity))*100	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

SCHEDULED OUTAGE FACTOR % (Plant or Unit)	(Scheduled Outage Hours / Period Hours)*100	YES	Monthly	Simulates outage time and calculates energy value for optimal outage scheduling.	NO	NO	NO	YES	YES	NO	NO	NO	NO	NO	NO	NO
WEIGHTED SCHEDULED OUTAGE FACTOR	(∑ (Scheduled Outage Hours* Unit Capacity) / ∑ (Period Hours * Unit Capacity))*100	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
WATER FACTOR %	(Water for Generation / (Water Used for Generation + Other Water Releases))*100	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
AVERAGE PLANT EFFICIENCY %	(Gross Generation / Water Used for Generation * Head * 0.0010242)	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
AVAILABLE POWER (KW) (Regulation / Load Following, Spinning / Non-Spinning Reserve)	Unit / Plant Capacity at Current or Historical Average Head	Use available power algorithm relating MW to Head	HISTORICAL	SOME	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	Current or Historical Average MW Loading	YES	HISTORICAL	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
	Current or Historical Average MVAR Loading	YES	HISTORICAL	NO	NO	NO	NO	N	NO	NO	NO	NO	NO	NO	NO	NO
	Unit Availability vs. Maintenance Outages, Commitment to Non-Spinning Reserve, etc.	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
GROSS GENERATION (kWH)	Plant Total Energy Generation	YES	Monthly	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
PLANT AUXILIARY USE (kWH)	Energy Used fin Plant	YES	Monthly	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
NET GENERATION (kWH)	Gross Generation - Plant Auxiliary Use	YES	Monthly	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
MAXIMUM HOURLY GENERATION (KWH)	Monthly Maximum Generation in One Hour	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
CONDENSER OPERATION ENERGY (kWH)	Energy Used to Motor the Unit in Synchronous Condenser Operation	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
WATER USED FOR GENERATION (AF)	Water Volume Used for Generation	YES	Monthly	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
OTHER WATER RELEASED DOWNSTREAM (AF)	Water Volume Used for Purposes Other than Generation	YES	Monthly	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

KWH GENERATION / AF	Energy per Acre Foot of Water	YES	Monthly	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
RESERVOIR ELEVATION (FT)	Forebay Elevation	YES	EOM SNAPSHOT	YES, if head not available directly.	NO	NO	YES	NO	Water Supply Chart	YES	Total and Active Capacities available	YES	YES	NO. Varies as head varies.	NO	NO
TOTAL FLOW (CFS)	Total Plant Water Flow	YES	EOM SNAPSHOT	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
UNIT OUTAGE (HRS)	Individual Unit Scheduled or Forced Outage Time	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
MAINTENANCE FACTOR %	Total Actual Maintenance Time in Month / Total Hours in Month	YES	Monthly	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
MAX / MIN FOREBAY ELEVATION LIMITS (FT)	Maximum / Minimum Permitted Forebay Elevation	YES	NO	Indirectly by assuming historic operation complies with limits	NO	NO	NO	NO	NO	YES	NO	NO	NO	YES	NO	NO
FOREBAY CAPACITY FOR GENERATION (AF)	Volume of Water Available for Generation	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
TAILRACE ELEVATION LIMITS (FT)	Maximum / Minimum Tairace Elevation Permitted	YES	NO	Indirectly by assuming historic operation complies with limits	NO	NO	NO	NO	NO	YES	NO	NO	NO	YES	NO	NO
TAILRACE ELEVATION (FT)	Tailrace Elevation	YES	NO	NO, uses head.	NO	NO	NO	NO	NO	YES	Strutural info and elevation vs flow diagram on	YES	YES	NO. Varies with flow.	NO	NO
RATED HEAD (FT)	Hydraulic Head for Rated Output	YES	NO	Input parameter data	YES	NO	NO	YES	NO	YES	YES	NO	NO	YES	NO	NO
HEAD LOSS (FT)	Penstock Losses at Maximum Flow	YES	NO	Input parameter data.	NO	NO	NO	NO	NO	When available	NO	NO	NO	NO	NO	NO
MAX / MIN ALLOWABLE HEAD (FT)	Maximum / Minimum Hydraulic Head Allowed for Turbine Operation.	YES	NO	Input parameter data.	YES	NO	NO	NO	NO	YES	NO	NO	NO	YES	NO	NO
TURBINE EFFICIENCY %	Efficiency at Various Gate Openings and Heads	YES	NO	Input parameter: At maximum flow for max gen output. Input parameter data: In tabular format, % efficiency at 10 different heads. Claims to be turbine-generator efficiency, but it may be turbine efficiency only.	Efficiency curve over HP/discharge range at rated head. Best efficiency curves over a range of heads at various heads.	NO	NO	NO	NO	YES	NO	NO	NO	NO	NO	NO

GENERATOR EFFICIENCY %	Generator Tested Efficiency	YES	NO	See Turbine Efficiency	NO	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES	NO
GSU TRANSFORMER EFFICIENCY %	Step Up Transformer Efficiency	YES	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
DOWNSTREAM FLOW LIMITS (CFS)	Maximum / Minimum Flow of Water Permitted to Flow in the Tailrace	YES	NO	Indirectly by assuming historic operation complies with limits	NO	NO	NO	NO for Coulee, Shasta, Hoover. YES for Glen Canyon	NO	YES	NO	NO	NO	YES	NO	NO
MAX / MIN POWERHOUSE FLOW (CFS)	Maximum / Minimum Allowable Powerhouse Flow	YES	NO	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO
NON-POWER REQUIRED RELEASES (CFS)	Required Flows for Water Contracts, Fish & Riparian, Water Quality, etc.	YES	NO	Input time-series total daily required flow. Calculated average, maximum, minumum.	NO	NO	NO	NO for Coulee, Shasta, Hoover. YES for Glen Canyon	NO	YES	NO	NO	NO	YES	NO	NO
INFLOWS (CFS)	Flows Into the Forebay Reservoir	YES	NO	Apparently not included.	NO	NO	NO	NO	NO	NO	YES, but out of date	YES	YES	NO. Varies	NO	NO
GENERATOR RAMP RATE LIMITS (MW/MIN)	Heating Limit on How Fast a Generator May be Loaded.	YES	NO	NO	NO	NO	NO	NO for Coulee, Shasta, Hoover. YES for Glen	NO	YES	NO	NO	NO	YES	NO	NO
TAILRACE RAMP RATE LIMITS (CFS or FT)	Tailwater Flow / Elevation Limits	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
ROUGH ZONE BOUNDARIES (MW)	Generation Levels Above and Below Which Unit Should Not Operate Due to Excessive Vibration	YES	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	YES	NO	NO
CAVITATION ZONE BOUNDARIES (MW)	Generation Levels Above and Below Which Unit Should Not Operate Due to Turbine Runner Cavitation	YES	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	YES	NO	NO
PUMPING SCHEDULES	Pumping Schedules for P/G Units and for Pumps Using Project Power	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
P/G TRANSITION TIME (MIN)	Time to Reverse Operation from Pump to Generate	YES	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
WATER QUALITY LIMITS (Units depend on parameter)	Liimits on Water Quality Quantities	YES	NO	NO	NO	NO	NO	General environmental constraints listed	NO	NO	NO	NO	NO	YES?	NO	NO

Table 4. - NREL ReEDS Prioritization of Constraints / Data Elements
April 11, 2013

DATA ELEMENT	DESCRIPTION	Priority for ReEDS	SMC Notes
PLANT DESCRIPTION	Powerplant name, location, region, area/project office, river, forebay name, project purpose, NERC region/area, PMA/region, remotely operation, control center, power use, production mode (base, peaking, intermediate), etc [Not all data available from every source].	High	project purpose and production mode could be useful to identify dispatchable vs. non-dispatchable. Data for some dams are better than none.
NO. of UNITS, RATED / NAMEPLATE CAPACITY	Number of main generating units. Unit & powerplant capacities based on generator & turbine nameplate ratings	High	I have nameplate capacity, but variation in capacity over time would be useful.
ANCILLARY SERVICES	Ancillary services provided by the plant: spinning reserve, non-spinning reserve, replacement reserve, regulation/load following, voltage support, black start.	High	This information would be very useful to determine the fraction of capacity I should make available for spinning reserves and/or quick start capability.
PRESENT PLANT CAPACITY	Powerplant generation capacity available with present head (MW)	High	It would be great to get capacity over time, but if not, a non-nameplate average would be better than assuming nameplate.
PLANT FACTOR %	100 X Ratio of average power to rated capacity	High	How is "plant factor" defined? Currently I use capacity factors calculated from EIA-reported nameplate capacity and energy to dictate the quantity of energy available each season. New/better capacity factor data must relate correctly to assumed capacity so energy availability is correct.
UTILIZATION FACTOR %	100 X Ratio of maximum load to rated capacity	High	How exactly do you define this quantity, and how is it related to Plant Factor?
NON-POWER REQUIRED RELEASES	Actual required flows required for water contracts, fish & riparian, water quality, etc. (CFS)	High	It would be good to have this information so we can better characterize dispatchability of facilities and operating constraints.
FLOWS AVAILABLE FOR GENERATION	Flows available for generation, after other commitments. (CFS)	High	Definitely useful if we can translate into energy/power available over time.
NET GENERATION	Energy generated by the plant minus energy used inside the plant(MWH)	High	Generation data could be useful for identifying operating patterns that we could represent in ReEDS.
ENERGY VALUE ADJUSTMENT FACTORS	Multiplier for calculation of actual available energy from average available energy.	High	This information sounds very useful. We would want to fully understand the calculation procedure at minimum. If the underlying data could be shared, that would be preferred.

RAMP RATE LIMITS	Limit on how fast a generator may be loaded. Electrical limits usually 10% of nameplate rating per minute (MW / min). Tailwater flow/elevation limits may also limit ramp rate (CFS / min).	High	ReEDS does not explicitly represent ramp rate constraints, but we do have the framework to incur ramping costs (as a proxy for inefficiencies during ramping). However, the more information we have about ramping costs and constraints, the better.
AVAILABILITY FACTOR %	100 X Ratio of the time the unit / plant is able to produce power in a period of time to the amount of the time in the period	Med	This information would be useful to better define forced and planned outage rates.
FORCED OUTAGE FACTOR %	100 X Ratio of the time the unit / plant is unavailable to produce power (due to failure) in a period of time to the amount of time in the period	Med	It would be great if these could be supplied. A fleet avg number is all that's necessary, but regional differences could be included.
SCHEDULED OUTAGE FACTOR %	100 X Ratio of the time the unit / plant is unavailable to produce power (due to planned / scheduled maintenance or rehabilitation) in a period of time to the amount of time in the period	Med	It would be great if these could be supplied. A fleet avg number is all that's necessary, but regional differences could be included.
MAX / MIN FOREBAY ELEVATION LIMITS	Maximum / minimum forebay elevation permitted (FT)	Med	I do not think this information is directly useful to ReEDS, but it would be if translated into min/max capacity.
FOREBAY ELEVATION	Historical forebay elevation (FT)	Med	I do not think this information is directly useful to ReEDS, but it would be if translated into capacity/energy over time.
HEAD	Historical hydraulic head available with current forebay & tailrace elevations (FT)	Med	Current information could help define initial conditions, but long-term average or seasonal profiles would be more useful.
MAX / MIN ALLOWABLE NET HEAD	Maximum / minimum powerhouse net head (FT)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize energy availability.
DOWNSTREAM FLOW LIMITS	Maximum / minimum flow of water permitted to flow in the tailrace (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help characterize capacity availability over time.
TOTAL OUTFLOW	Actual flow in the tailrace from all sources (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize cpacity and energy availability.
TURBINE FLOW	Actual total turbine flow/discharge. (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize cpacity and energy availability.
MAX / MIN POWERHOUSE FLOW	Maximum / minimum powerhouse flow (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize cpacity and energy availability.

PERCENT PEAK / NON-PEAK	Percentage of the time the plant is generating in peak and off-peak periods	Med	Only useful if it reveals an underlying operating constraint or strategy that should be incorporated into ReEDS. Another possible use would be identifying dispatchable vs. non-dispatchable capacity.
PEAK / OFF-PEAK ENERGY	Energy generated during peak and off-peak periods (MWH)	Med	Only useful if it reveals an underlying operating constraint or strategy that should be incorporated into ReEDS. Another possible use would be identifying dispatchable vs. non-dispatchable capacity.
CURRENT GENERATION	Actual current plant generation (MWH)	Med	Current real-time information probably isn't necessary for ReEDS as long as we have enough generation data to characterize operating constraints.
POWERHOUSE OUTPUT AT MAXIMUM FLOW	Powerhouse output at maximum flow (MW)	Med	How would this quantity differ from nameplate capacity?
GENERATOR REAL vs REACTIVE POWER	Limitation on MW output of generators which may use capacity to provide reactive power MVAR.	Med	ReEDS does not model reactive power, but resulting limits on real power could be important.
WATER QUALITY LIMITS	Limits on water quality quantities (Units vary depending on parameter)	Med	How exactly are these limits imposed? I doubt the information is directly useful to ReEDS, but I want to better understand it first.
WATER QUALITY	Actual water quality quantities (Units vary depending on parameter)	Med	Could you please clarify the definition of this quantity?
FOREBAY CAPACITY	Total and/or active capacity of forebay reservoir (AF)	Low	I do not think this information is directly useful to ReEDS. Long-term characteristics are more important than current conditions.
TAILRACE ELEVATION LIMITS	Maximum / minimum tairace elevation permitted (FT)	Low	I do not think this information is directly useful to ReEDS.
TAILRACE ELEVATION	Historical current tailrace elevation (FT)	Low	I do not think this information is directly useful to ReEDS.
RATED HEAD	Difference between forebay elevation and tailrace elevations for which the turbine/generator is designed (FT)	Low	I do not think this information is directly useful to ReEDS.
HEAD LOSS	Head loss at maximum powerhouse flow.(FT)	Low	I do not think this information is directly useful to ReEDS.

HEAD AT MAXIMUM POWERHOUSE FLOW	Hydraulic head at maximum powerhouse flow (FT)	Low	I do not think this information is directly useful to ReEDS.
TURBINE EFFICIENCY	Percent efficiency in converting hydraulic energy to mechanical energy	Low	I do not think this information is directly useful to ReEDS.
GENERATOR EFFICIENCY	Percent efficiency in converting mechanical energy to electrical energy	Low	I do not think this information is directly useful to ReEDS.
NON-REQUIRED, NON-POWER RELEASES	Actual required flows for spillage or other. (CFS)	Low	I don't think non-power information is useful to ReEDS unless it reveals the complementary energy available.
INFLOWS	Flows into the forebay reservoir (CFS)	Low	While useful for determining energy availability, I do not think this information is directly useful to ReEDS.
GROSS GENERATION	Energy generated by the plant (MWH)	Low	Not important if we have net generation data.
TRANSFORMER EFFICIENCY	Genertor step-up transformer efficiency (%)	Low	I do not think this information is directly useful to ReEDS.
ROUGH ZONE BOUNDARIES	Generation levels above and below which unit should not operate due to excessive vibration (MW)	Low	I do not think this information is directly useful to ReEDS.
CAVITATION ZONE BOUNDARIES	Generation levels above and below which unit should not operate due to turbine runner cavitation (MW)	Low	I do not think this information is directly useful to ReEDS.

Table 5. - NREL PLEXOS Prioritization of Constraints / Data Elements
September 2013

DATA ELEMENT	DESCRIPTION	Priority for ReEDS	SMC Notes	Priority for PLEXOS
PLANT DESCRIPTION	Powerplant name, location, region, area/project office, river, forebay name, project purpose, NERC region/area, PMA/region, remotely operation, control center, power use, production mode (base, peaking, intermediate), etc [Not all data available from every source].	High	project purpose and production mode could be useful to identify dispatchable vs. non-dispatchable. Data for some dams are better than none.	High
NO. of UNITS, RATED / NAMEPLATE CAPACITY	Number of main generating units. Unit & powerplant capacities based on generator & turbine nameplate ratings	High	I have nameplate capacity, but variation in capacity over time would be useful.	High
ANCILLARY SERVICES	Ancillary services provided by the plant: spinning reserve, non-spinning reserve, replacement reserve, regulation/load following, voltage support, black start.	High	This information would be very useful to determine the fraction of capacity I should make available for spinning reserves and/or quick start capability.	High
PRESENT PLANT CAPACITY	Powerplant generation capacity available with present head (MW)	High	It would be great to get capacity over time, but if not, a non-nameplate average would be better than assuming nameplate.	High
PLANT FACTOR %	100 X Ratio of average power to rated capacity	High	How is "plant factor" defined? Currently I use capacity factors calculated from EIA-reported nameplate capacity and energy to dictate the quantity of energy available each season. New/better capacity factor data must relate correctly to assumed capacity so energy availability is correct.	Med
UTILIZATION FACTOR %	100 X Ratio of maximum load to rated capacity	High	How exactly do you define this quantity, and how is it related to Plant Factor?	Med
NON-POWER REQUIRED RELEASES	Actual required flows required for water contracts, fish & riparian, water quality, etc. (CFS)	High	It would be good to have this information so we can better characterize dispatchability of facilities and operating constraints.	High
FLOWS AVAILABLE FOR GENERATION	Flows available for generation, after other commitments. (CFS)	High	Definitely useful if we can translate into energy/power available over time.	High
NET GENERATION	Energy generated by the plant minus energy used inside the plant(MWH)	High	Generation data could be useful for identifying operating patterns that we could represent in ReEDS.	Med

ENERGY VALUE ADJUSTMENT FACTORS	Multiplier for calculation of actual available energy from average available energy.	High	This information sounds very useful. We would want to fully understand the calculation procedure at minimum. If the underlying data could be shared, that would be preferred.	High
RAMP RATE LIMITS	Limit on how fast a generator may be loaded. Electrical limits usually 10% of nameplate rating per minute (MW / min). Tailwater flow/elevation limits may also limit ramp rate (CFS / min).	High	ReEDS does not explicitly represent ramp rate constraints, but we do have the framework to incur ramping costs (as a proxy for inefficiencies during ramping). However, the more information we have about ramping costs and constraints, the better.	High
AVAILABILITY FACTOR %	100 X Ratio of the time the unit / plant is able to produce power in a period of time to the amount of the time in the period	Med	This information would be useful to better define forced and planned outage rates.	High
FORCED OUTAGE FACTOR %	100 X Ratio of the time the unit / plant is unavailable to produce power (due to failure) in a period of time to the amount of time in the period	Med	It would be great if these could be supplied. A fleet avg number is all that's necessary, but regional differences could be included.	High
SCHEDULED OUTAGE FACTOR %	100 X Ratio of the time the unit / plant is unavailable to produce power (due to planned / scheduled maintenance or rehabilitation) in a period of time to the amount of time in the period	Med	It would be great if these could be supplied. A fleet avg number is all that's necessary, but regional differences could be included.	High
MAX / MIN FOREBAY ELEVATION LIMITS	Maximum / minimum forebay elevation permitted (FT)	Med	I do not think this information is directly useful to ReEDS, but it would be if translated into min/max capacity.	High
FOREBAY ELEVATION	Historical forebay elevation (FT)	Med	I do not think this information is directly useful to ReEDS, but it would be if translated into capacity/energy over time.	High
HEAD	Historical hydraulic head available with current forebay & tailrace elevations (FT)	Med	Current information could help define initial conditions, but long-term average or seasonal profiles would be more useful.	High
MAX / MIN ALLOWABLE NET HEAD	Maximum / minimum powerhouse net head (FT)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize energy availability.	High
DOWNSTREAM FLOW LIMITS	Maximum / minimum flow of water permitted to flow in the tailrace (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help characterize capacity availability over time.	High
TOTAL OUTFLOW	Actual flow in the tailrace from all sources (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize cpacity and energy availability.	Mod
TURBINE FLOW	Actual total turbine flow/discharge. (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize cpacity and energy availability.	Mod

MAX / MIN POWERHOUSE FLOW	Maximum / minimum powerhouse flow (CFS)	Med	I do not think this information is directly useful to ReEDS, but it could help us better characterize cpacity and energy availability.	High
PERCENT PEAK / NON-PEAK	Percentage of the time the plant is generating in peak and off-peak periods	Med	Only useful if it reveals an underlying operating constraint or strategy that should be incorporated into ReEDS. Another possible use would be identifying dispatchable vs. non-dispatchable capacity.	Low
PEAK / OFF-PEAK ENERGY	Energy generated during peak and off-peak periods (MWH)	Med	Only useful if it reveals an underlying operating constraint or strategy that should be incorporated into ReEDS. Another possible use would be identifying dispatchable vs. non-dispatchable capacity.	Low
CURRENT GENERATION	Actual current plant generation (MWH)	Med	Current real-time information probably isn't necessary for ReEDS as long as we have enough generation data to characterize operating constraints.	Mod
POWERHOUSE OUTPUT AT MAXIMUM FLOW	Powerhouse output at maximum flow (MW)	Med	How would this quantity differ from nameplate capacity?	Low
GENERATOR REAL vs REACTIVE POWER	Limitation on MW output of generators which may use capacity to provide reactive power MVAR.	Med	ReEDS does not model reactive power, but resulting limits on real power could be important.	Low
WATER QUALITY LIMITS	Limits on water quality quantities (Units vary depending on parameter)	Med	How exactly are these limits imposed? I doubt the information is directly useful to ReEDS, but I want to better understand it first.	High
WATER QUALITY	Actual water quality quantities (Units vary depending on parameter)	Med	Could you please clarify the definition of this quantity?	High
FOREBAY CAPACITY	Total and/or active capacity of forebay reservoir (AF)	Low	I do not think this information is directly useful to ReEDS. Long-term characteristics are more important than current conditions.	High
TAILRACE ELEVATION LIMITS	Maximum / minimum tairace elevation permitted (FT)	Low	I do not think this information is directly useful to ReEDS.	High
TAILRACE ELEVATION	Historical current tailrace elevation (FT)	Low	I do not think this information is directly useful to ReEDS.	High
RATED HEAD	Difference between forebay elevation and tailrace elevations for which the turbine/generator is designed (FT)	Low	I do not think this information is directly useful to ReEDS.	High
HEAD LOSS	Head loss at maximum powerhouse flow.(FT)	Low	I do not think this information is directly useful to ReEDS.	High

HEAD AT MAXIMUM POWERHOUSE FLOW	Hydraulic head at maximum powerhouse flow (FT)	Low	I do not think this information is directly useful to ReEDS.	High
TURBINE EFFICIENCY	Percent efficiency in converting hydraulic energy to mechanical energy	Low	I do not think this information is directly useful to ReEDS.	High
GENERATOR EFFICIENCY	Percent efficiency in converting mechanical energy to electrical energy	Low	I do not think this information is directly useful to ReEDS.	High
NON-REQUIRED, NON-POWER RELEASES	Actual required flows for spillage or other. (CFS)	Low	I don't think non-power information is useful to ReEDS unless it reveals the complementary energy available.	High
INFLOWS	Flows into the forebay reservoir (CFS)	Low	While useful for determining energy availability, I do not think this information is directly useful to ReEDS.	Mod
GROSS GENERATION	Energy generated by the plant (MWH)	Low	Not important if we have net generation data.	Low
TRANSFORMER EFFICIENCY	Genertor step-up transformer efficiency (%)	Low	I do not think this information is directly useful to ReEDS.	Low
ROUGH ZONE BOUNDARIES	Generation levels above and below which unit should not operate due to excessive vibration (MW)	Low	I do not think this information is directly useful to ReEDS.	High
CAVITATION ZONE BOUNDARIES	Generation levels above and below which unit should not operate due to turbine runner cavitation (MW)	Low	I do not think this information is directly useful to ReEDS.	High

Calculating Available Power

July 25, 2013 (Revised 8/23/13 & 10/8/13)

The following is a method of estimating dispatchable power available from each Reclamation generator for the turbine operating range. The results may be used in renewable energy integration models to provide an instantaneous power value which is more accurate than using generator nameplate capacity (or rule of thumb percentages).

This more-accurate available power value can also be useful for calculating available energy, using reservoir capacity that is available for generation. This energy calculation method is not derived herein.

Method

The method uses the Net Head vs. Horsepower (HP) curves found on the hydraulic turbine data sheets and turbine test data which are maintained by the mechanical design office in Denver. The data quantify turbine characteristics for each turbine or family of turbines.

The method assumes that the Head vs. HP relationship is essentially linear and it derives an equation for that line which allows calculation of theoretical available kW at any operating head. The equation takes into account generator and step-up transformer efficiencies for a more accurate estimate of available power. The equation also takes into account the current kW loading of the generator, subtracting it from the power theoretically available. The resulting available kW is the power available (dispatchable) for use for new loads, such as renewable fluctuations.

The available kW calculated by the equation is limited by an algorithm which recognizes that the kW available cannot exceed the generator rating and that there is zero generation available when the head is too high or low for turbine operation.

The method does not account for whether the unit is currently available for service, rough-running zones, ramp rates, commitment to ancillary services, etc. It also does not account for maximum tailrace flow restrictions, efficient operating points, etc. These factors could be incorporated as refinements. However, it does provide an approximate value of power theoretically available and is an improvement over using nameplate values (or rule-of-thumb percentages thereof).

The calculation could be performed on a real-time basis, giving currently available, dispatchable power. Or, it could be performed using daily, weekly, or monthly averages where broader, less time-sensitive estimates of available power are sufficient.

Definitions

Static Values from Turbine Data Sheets or Turbine Test Data (See attached Chandler example)

HPrated: Turbine horsepower at which generator kW rating is achieved.

HEADrated: Head at which generator kW rating is achieved.

HPmin: Turbine horsepower at Headmin.

HEADmin: Head below which turbine cannot be operated.

HEADmax: Head above which turbine cannot be operated.

Other

HEADactual: Current hydraulic net head (time variable).

KWavail: Calculated power available for dispatch (above KWactual).

KWactual: Current power output of the generator (time variable).

EFFgen: Generator Efficiency (static).

EFFtrans: Step-up Transformer Efficiency (static).

1 HP = 0.746 kW

Data Collection

The accompanying spreadsheet shows values for Reclamation's largest generating units. Note that for some Hoover units, ratings have decreased over time. This is the result of a reduced hydraulic head caused by a persistently lower reservoir elevation due to drought.

Caveats

1. Turbine data are from model tests. Actual in-plant values may be different and, if available, could be used to refine the calculations.

2. Turbine data are at full wicket gate opening, not at maximum turbine efficiency.

3. Data ignore head losses in the penstock. These are equivalent to only a few feet of head and are not accounted for in this derivation.

4. Generator and transformer efficiencies vary by unit / plant. Therefore, these are included in the equation as variables and site-specific values can be used. In absence of site data, it is reasonable to assume that values are relatively constant at EFFgen = 97% and EFFtrans = 95%, at full load. These proxy values are used in the example below.

Derivation

Straight Line HP Derivation (See attached Chandler example)

The HP vs. Head curve is essentially a straight line over most of the head range.[1] The general form of a straight-line equation is y = mx+b, where m is the slope of the line and b is the y-axis intercept. In this case, the y-axis is HP and the x-axis is head.[2]

For this derivation, the slope m = HPrated – HPmin / HEADrated – HEADmin and the y-axis intercept is HPmin.

The value for Head (the x variable) is always HEADactual – HEADmin. HEADactual varies with time and HEADmin is constant.

Thus, the straight line equation for available HP is:

{ [(HPrated – HPmin) / (HEADrated – HEADmin)] x (HEADactual – HEADmin) } + HPmin

KW Derivation

To calculate available kW:

- Horsepower is converted to theoretical kW by multiplying by 0.746.
- Theoretical kW is multiplied by the generator and transformer efficiencies, EFFgen and EFFtrans, to account for losses.
- To get available (dispatchable) kW, current generation KWactual must be subtracted.

KWavail = 0.746 [{ [(HPrated – HPmin) / (HEADrated – HEADmin)] x (HEADactual – HEADmin) } + HPmin] (EFFgen) (EFFtrans) - KWactual

[1] See the attached Shasta validation example; the straight line is within approximately 5% of test data points in HP values.
[2] Note that the way turbine data curves are drawn shows HP on the horizontal axis and Head on the vertical axis.

Remember, the only variables in this equation are the current head (HEADactual) and current generator output (KWactual). All other terms are static and pre-determined.

Limitations

As the turbine data curve shows, there are limits on the turbine HP output:

- For any value of head over HEADrated, machine HP and kW output is limited by the generator rating, KWrated.

- For any value of head over HEADmax or below HEADmin, the machine cannot be operated and the kW output is zero

Limitations Algorithm Definition

IF: HEADactual > HEADrated AND HEADactual < HEADmax
THEN KWavail = [0.746 x HPrated x EFFgen x EFFtrans] - KWactual

IF: HEADactual > HEADmax
THEN: KWavail = 0

IF: HEADactual < or = HEADmin
THEN: KWavail = 0

ELSE:
KWavail = 0.746 [{ [(HPrated – HPmin) / (HEADrated – HEADmin)] x (HEADactual – HEADmin) } + HPmin] (EFFgen) (EFFtrans) - KWactual

Example

Using the Chandler turbine data sheet, attached:

HPrated = 8500 hp

HEADrated = 117 ft

HPmin = 7400 hp

HEADminimum = 106 ft

HEADmax = 122 ft

EFFgen = 0.97 (proxy)

EFFtrans = 0.95 (proxy)

Generator Rating: 6000 kW

Assume a current head HEADactual = 112 ft and a current generator output KWactual of 3000 kW.

KWavail = 0.746 [{ [(8500 – 7400) / (117 – 106)] x (112 – 106) } + 7400] (0.97) (0.95) - 3000

KWavail = 2500 kW

This amount of dispatchable power is available from the generator for the sample head.

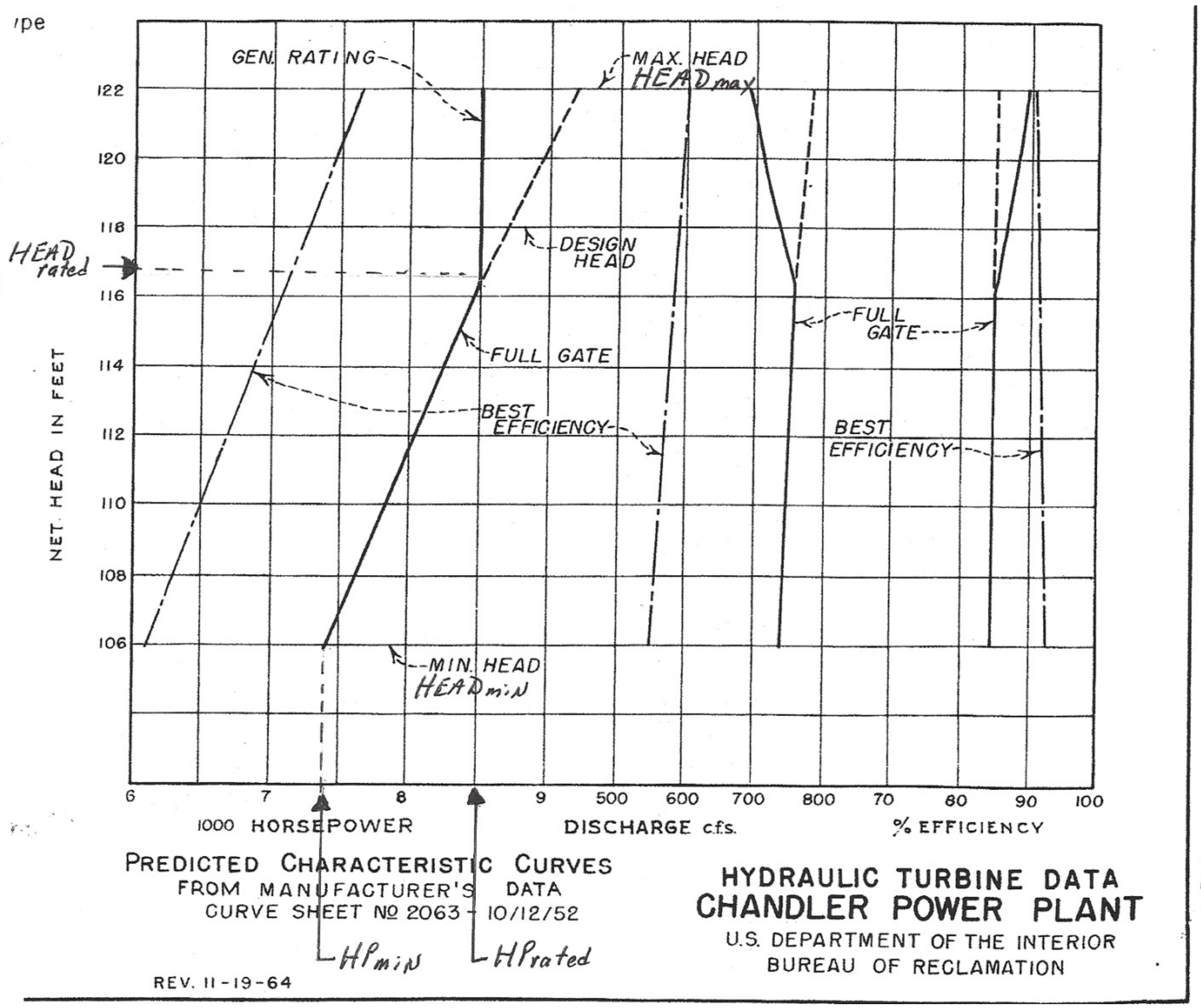
If the above analysis is not employed, and the generator rating of 6000 kW is used with a current loading of 3000 kW, it implies that 3000 kW of dispatchable capacity is available. If a rule-of-thumb estimate of 50% generator rating is used with a current loading of 3000 kW, it implies that 500 kW of dispatchable capacity is available. Neither of these estimates are as accurate as using the straight-line method.

Summary

The straight-line available-capacity strategy described above provides a relatively accurate estimate of available power at various heads and current loading. The method does not account for most constraints that may be encountered, but these could be added as refinements.

Once the unit data are known, the only variables are head and current kW loading. As a predictive tool using historical data, head could be a historical average of daily or monthly head values, perhaps by season or even by wet / dry years. Similarly, current loading could come from historical loading averages.

As a real-time scheduling tool, actual current head and kW loading acquitted from SCADA could be input into the calculations.


ype
GEN. RATING
MAX. HEAD
HEADmax
DESIGN HEAD
HEAD rated
FULL GATE
BEST EFFICIENCY
FULL GATE
BEST EFFICIENCY
MIN. HEAD
HEADmin
NET. HEAD IN FEET
122
120
118
116
114
112
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108
106
6
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8
9
500
600
700
800
70
80
90
100
1000 HORSEPOWER
DISCHARGE c.f.s.
% EFFICIENCY
PREDICTED CHARACTERISTIC CURVES
FROM MANUFACTURER'S DATA
CURVE SHEET № 2063 - 10/12/52
HPmin
HPrated
REV. 11-19-64
HYDRAULIC TURBINE DATA
CHANDLER POWER PLANT
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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Bureau of Reclamation

COMPUTATION SHEET

BY Osburn	DATE 8/23/13	PROJECT Hydro modeling	SHEET 1 OF 1
CHKD BY	DATE	FEATURE	
DETAILS Validation of Available Power Straight Line Method