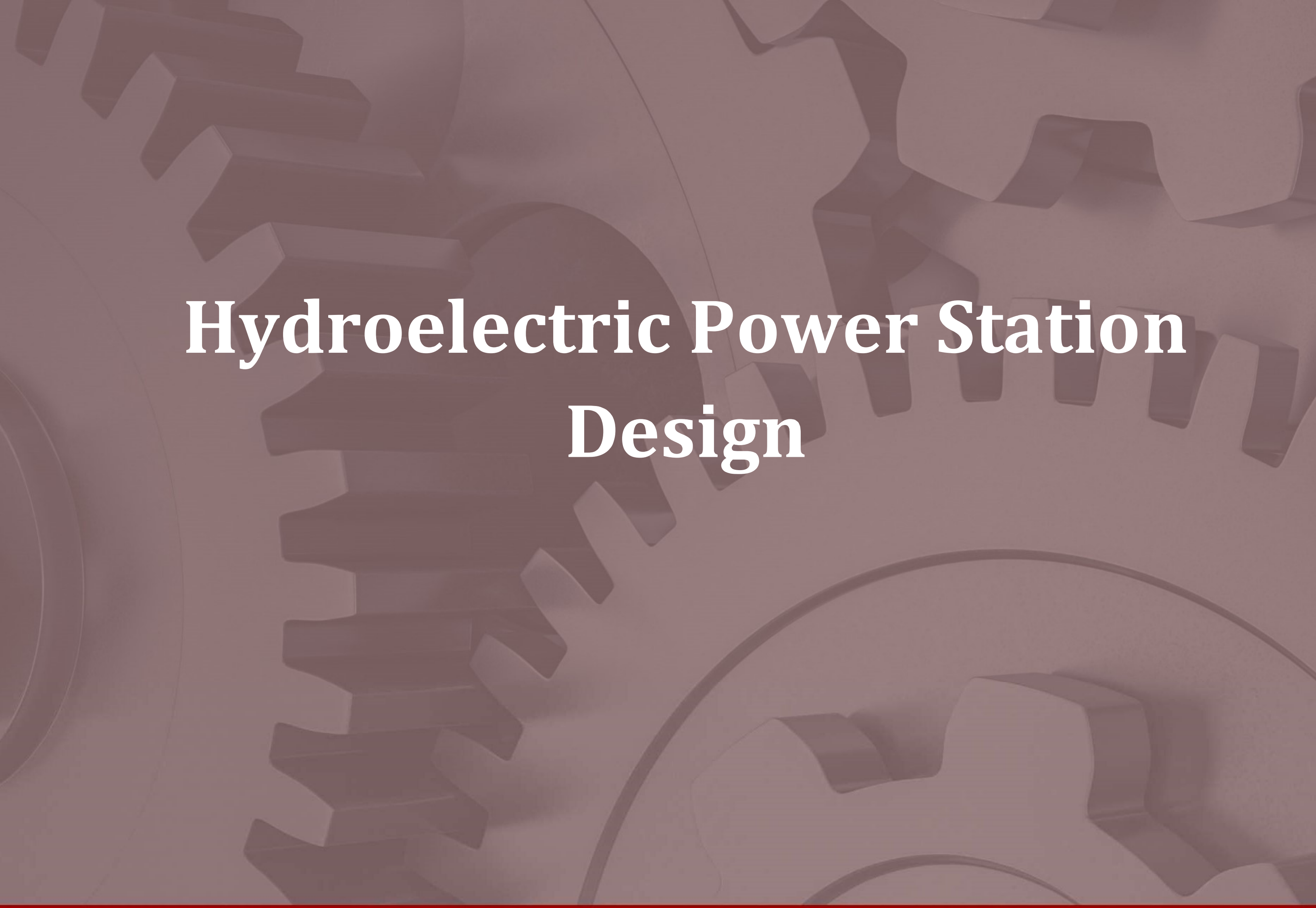

Hydroelectric Power Station Design

An Online Continuing Education Course for Engineers

Course Number: R-6005

Credit: 6 Hours / 6 PDH / 6 CPD

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Introduction:

According to a recent 2023 report from the International Energy Agency, “Hydropower is the largest source of worldwide renewable energy, producing 16% of the electricity from over 1,200 Gigawatts of installed capacity”. The International Renewable Energy Agency states that commissioned hydroelectric generation projects over the last ten years had an average levelized cost of electricity of US $0.05/kilowatt-hour. The capacity of hydroelectric generation in the United States is approximately 81 gigawatts, comprising 2,252 stations that will produce 6.2% of all electricity and 30% of all renewable generation by 2022. Hydroelectric power generation continues to be a low-cost electricity source globally. At the same time, the design and operation of hydroelectric power stations must be handled carefully to prevent issues such as spillway problems at the Oroville Dam in the city of Oroville, California, located in the Sierra Nevada foothills east of the Sacramento Valley. A long-awaited Independent Forensic Team report reveals the causes behind the spillway failure, indicating that it “was caused by a long-term systemic failure of the California Department of Water Resources (DWR), regulatory, and general industry practices to recognize and address inherent spillway design and construction weaknesses, poor bedrock quality and deteriorated service spillway chute conditions.”

This course will present an efficient approach to designing an example hydroelectric power station. This course presents a type of design in which two horizontal bulb turbines, each rated at approximately 17 megawatts gross capacity, are installed at a lock and dam structure under the auspices of the Corps of Engineers. The dam is assumed to have a medium head risk level, equating to approximately a 20 to 50-foot headwater-to-tailwater height difference. The lock structure in this navigable waterway, run of the river project, is located on the opposite side of the dam structure from the gross capacity 34-megawatt (“MW”) hydroelectric power station. The course is intended to be highly practical by addressing various on-site construction issues (as well as critical design topics for negotiating the turnkey construction agreement with liquidated damages for deficient asset performance) to construct successfully, commission, and operate the asset for 50-plus years of useful life.

Proper plant design must provide safe operations, minimal environmental impact, regulatory compliance, and economic viability. Hydroelectric projects represent clean, renewable energy, but these generating stations have impacts on the environment that must be accommodated in the site plan, engineering, and equipment selection. Hydroelectric projects do not incur a fuel cost, but indirect revenue penalties exist for experiencing mechanical or electrical forced outages during optimal seasonal water flows. During forced outages and high flow water rates, the valuable potential energy of the water is wasted due to the power station being bypassed through diversion structure(s). Water potential energy and the corresponding revenue dollars are wasted in this case. In some cases, long-term sale agreements can be placed at risk of default for not meeting minimum availability or minimum production (kilowatt-hours “kWh”) requirements. Hydroelectric generating assets lacking headwater storage and facing volatile seasonal runoff, such as from spring snow melts, will suffer financial distress if not designed adequately with redundancy and a sizeable spare parts inventory to maximize availability and minimize forced outages.

While the operation of a hydroelectric facility results in clean electricity generation with no carbon emissions and can usually assist with local flood control, there are other water quality, recreational, safety, and habitat impacts of which the design engineer must be aware. These include examples as follows:

- Fish passage both downstream and upstream
- Dissolved oxygen content of downstream water discharges from the draft tube
- Inclement weather impacts, such as icing
- Trash management and removal
- Penstock water hammer
- Single and/or double-regulated turbine controls
- Suitable oil seals designed to prevent accidental discharges into the waterway
- Fail-safe shutdown design

This course provides a step-by-step process for compiling key design parameter data to successfully engineer a safe, compliant, and economically viable hydroelectric powerhouse at a lock and dam structure, essentially a run of river project (i.e., no significant upstream storage or pondage capacity). Optimal engineering of any power generating station requires an understanding of the site location, permitting, regulatory and environmental constraints, which are then compiled and translated by the engineer into a workable design serving a useful purpose by harnessing the renewable energy encapsulated in the potential energy difference between two separate water levels and a rate of flow between the headwater (upstream) and the tailwater (downstream).

The 34-megawatt (“MW”) plant that is the course's subject was built and is currently in operation. The author served as the on-site asset developer representative during the successful construction financing, long-term leveraged lease financing, design, construction, commissioning, performance testing, punch-list negotiations, and establishment of operations. He also coordinated the various agency relationships with the U.S. Army Corps of Engineers (“COE”) regional office and local fish and wildlife authorities. Different design aspects to be discussed will include the following facility design and operational decisions:

- Electrical Interconnection Agreement
- Turbine Selection and Configuration
- Performance Guarantees
- Index Testing
- Spare Parts Inventory to Optimize Reliability
- Operating Topics and Constraints
    - Weather (Rainfall & Icing)
    - Water Quality

    - Fish Impingement
    - Cavitation
    - Dissolved Oxygen
    - Water Hammer
    - Trash Removal
    - Fish Passage
    - Minimizing Pondage Elevation Volatility
    - Permitted Use of Flash Boards
    - Observance of Recreational Water Usage (Boating & Fishing)
    - Minimum Required Water Flow
- Ancillary Services – i.e., Black Start Capability, Power Factor support, etc.
- Asset Physical Options – i.e., flashboards, low flow units, headwater level management

The subject facility was not required to implement either upstream or downstream fish passage. However, given the importance of proper fish passage design for most hydroelectric power stations, this theme will be presented in Section I.(iii).

Regardless of the source of generation, whether renewable, fossil fuel, or nuclear, the electric power industry is comprised of four components to (a.) originate electrical energy and (b.) deliver power to retail, commercial, and industrial consumers:

1. Generation (or from temporary battery storage),
2. Transmission (i.e., long distances, high voltage, interstate, etc.),
3. Distribution (local area power lines to deliver from high voltage lines to customers) and
4. Consumption (industrial, commercial, and residential).

This course will focus on generation and a specific form of electrical generation – Hydroelectric ("Hydro"). Electricity is the flow of electrons through a conductor. The qualities of electricity as a commodity are unique because, unlike every other commodity (natural resources, metals, currencies, etc.), electricity markets require constant monitoring of supply (generation) and demand (customers). Lack of real-time, constant 24-hour oversight can result in an imbalance that almost immediately affects the transmission and distribution systems. An imbalance means an over- or under-frequency condition in the distribution system that will cause potentially severe grid service interruptions such as brownouts and blackouts. System interruptions are disturbances that are propagated throughout the distribution system in a matter of seconds. Uniform voltages and frequency must be maintained to avoid impaired service that can damage property. Voltage spikes can damage sensitive computer equipment and high frequency levels can also damage generation equipment.

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1. Hydroelectric Power Generation

1. Overview – the “Generation Stack”

The current United States power market has been dramatically affected by low natural gas prices and environmental attacks on coal plant emissions. Consequently, the generation mix in the United States is shifting away from coal towards natural gas units and renewables such as wind and solar. With help from low natural gas prices, the gas-fired units provide fast-start peaking service to the grid and operate more in the base-loaded generation band as coal plants are retired and financial institutions seek more stable cash flows rather than risky, volatile merchant plant revenue. Nevertheless, the advantages of hydroelectric power generation indicate this form of power generation will remain a stable component of the generation stack to serve load and for generation companies to achieve their sustainability targets for shareholders and investors.

Hydroelectric power benefits are both clean, renewable energy and some flexibility compared to wind and solar generation, both intermittent power sources. Water for hydroelectric generation can be managed within limits to mitigate intermittent dispatching of other renewable power sources. The design and operation of hydroelectric facilities are now keenly focused on maximizing availability and efficiently using water resources to match power demand needs while flattening volatility in water flows as much as possible. Minimizing water losses over spillway structures is a priority, as water represents lost kilowatt hours. Technology improvements in equipment, materials science, and operations & maintenance programming are also constantly improving reliability efficiency and lowering costs. New turbine runners and redesigned bearings are improving efficiency and reliability.

2. Plant Design

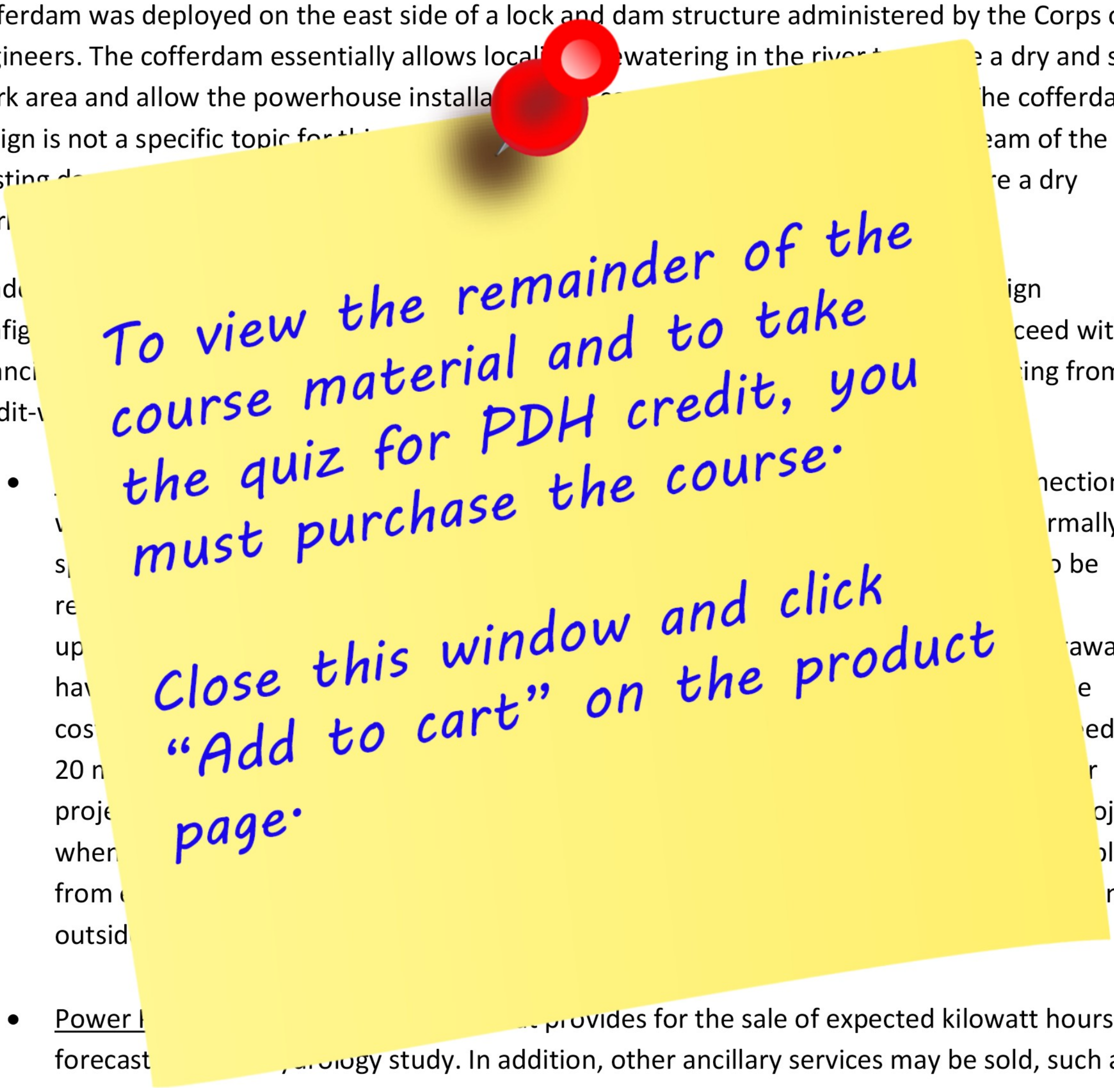
i. Initial Feasibility – begins with a hydrology study, which, depending on the site's local topography and watershed, can be relatively simple or highly problematic. The subject plant hydrology study was relatively simple because historical headwater levels, tailwater levels, and river flow rates were directly (not requiring theoretical extrapolation from adjacent watersheds) available from various credible sources on this popular navigable waterway. Other sites lacking direct river data (gauges and flow data from the specific river being dammed) will require extrapolation, introducing estimation error factors and less precise results. That extrapolation creates hydrology risk, which equals energy (kWh) volumetric forecast risk, making debt financing more problematic and eventually more costly for asset equity owners. Also, sites that experience extremely volatile flow rates, such as mountainous regions with potential sudden, abrupt spring run-off from winter snow melting, are potentially riskier in preparing a reliable hydrological energy production forecast. Highly volatile flow rates are undesirable, and averaging such data can result in erroneous production data. In other words, the actual extreme flow rates and existing water levels will not reflect the ability of the installed hydroelectric turbines to capture averaged flows. Hydrology reporting is best contracted to independent third-party entities for accuracy and credibility with lending institutions.

While the Subject Plant had no storage available, the site had consistent flow rates up and down the river system, given that the overall navigable waterway management was led by the Corps of Engineers. Relatively higher volatile river flows will result in flow rates and net head levels (i.e., headwater minus tailwater elevation) outside the rated design operating constraints of the turbine(s). The hydrology study is the most important feasibility document as it calculates the site's energy production capability and provides the design parameters to select and size the number of turbines to maximize energy capture from flowing water to convert into kilowatt-hours. In addition, the hydrology study is used by investors to develop underwriting and base case proforma models for financing feasibility work. Typically, at least 20 years of minimum data is used to determine KWhr production. If local river metering data is unavailable, then data is extrapolated from other estuaries and rainfall data. Project lenders may use the worst three years in operating years 1,2 and 3 and then use the average of all 20 years in operating year 4 and beyond.

The turbine output (kilowatts or horsepower) at the shaft is a function of four major variables. This excludes the losses and generator conversion efficiency to eventually move electricity to the substation and out to the grid, where the economic proforma would calculate the net capacity and net kilowatt-hours sales under the Power Purchase Agreement. The four variables are:

- Head
- Flow Rate
- Specific Weight of Water
- Turbine Efficiency (losses due to friction, bearings, seals, leaks, etc.)

The capital costs are heavily influenced by whether a new dam structure and/or tunneling work is required. The Subject Project required neither a dam nor any tunneling. Instead, a temporary cofferdam was deployed on the east side of a lock and dam structure administered by the Corps of Engineers. The cofferdam essentially allows local watering in the river e a dry and safe work area and allow the powerhouse installa he cofferdam design is not a specific topic f eam of the existing e a dry wor



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- Power provides for the sale of expected kilowatt hours as forecast ology study. In addition, other ancillary services may be sold, such as power factor support, capacity support, and black start capability, which hydroelectric plants have the unique ability to assist the local utility in re-energizing the transmission line after a regional blackout event. The PPA document is critical to demonstrate the revenue potential of the facility by multiplying kWh's forecasted from the hydrology times the PPA rate (cents/kWh). In addition, any economic benefits from key ancillary services such as