Technical Session 4A (14:00 - 15:10)	**Modeling of System Components**	**Chair: Stein-Erik Flaten, NTNU**	
	Optimizing the operation of cascade reservoirs to reduce environmental impacts	Rodrigo Tomaz	UFPR
	Representation of Maximum Turbine Discharge Capacity as a Function of Net Head in Hydroelectric Plants	Douglas Maciel	CEPEL
	Modelling Complex Tunnel Networks for Short-term Hydropower Scheduling	Christian Øyn Naversen	SINTEF

Optimizing the operation of cascade reservoirs to reduce environmental impacts

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Objectives

Brazil has significant hydroelectric potential and is one of the leaders in producing this type of energy. Hydroelectric energy is considered clean and renewable. However, installing and operating hydroelectric plants can damage the ecosystem, especially the fauna and flora that inhabit the reservoirs formed by the dams.

In the current literature, most studies on hydroelectric plants arranged in cascades do not address the significant environmental impacts these operations cause on the ecosystems in which the reservoirs are located.

This study aims to optimize the maintenance and equalization of water volumes in cascade reservoirs by developing a mathematical model. The idea is to refine the optimal solution for reservoir operations by adding environmental variables and constraints not considered in the original problem.

Methodology

As a case study, we use the reservoirs of 5 hydroelectric plants, arranged in series, belonging to the Iguaçu river cascade, located in the state of Paraná, Brazil. The developed model considers ecological flow constraints (minimum flow), respecting the minimum flow limits for water to continue flowing in the river. It also incorporates storage volume ramp configurations. These ramps are strategies to minimize the abrupt changes in water level caused by the repletion and depletion processes occurring in the reservoirs of the hydroelectric plants.

The aim is to optimize the synchronous operation of all hydroelectric plants by minimizing the volumetric variations in their reservoirs and maintaining parity between generation and electricity demand in each stage included in the study horizon.

So far, this work has implemented a simplified cascade operation model, including environmental constraints. The model was implemented using the AMPL integrated development environment, and tests were carried out using the SCIP solver. The model's objective function encompasses meeting demand, spilling, and varying reservoir volumes. Each component of the objective function has its weight to act as a penalty in the minimization function. The constraints included each plant's hydraulic limits and the cascade generation sum per stage. However, for simplification, the variation in the productivity of the hydroelectric plants as a function of the height of fall was implemented linearly by considering constant fall heights in its calculations.

The model's input data includes the historical data of the hydroelectric plants and the actual data used by the plants studied. The test case included 52 stages and a weekly discretization, with 168 hours (7 days) in each stage, resulting in a 1-year horizon. In this horizon, the process of depleting and refilling reservoirs due to operations is observed.

Results

The model developed in this work optimizes the cascade's operation, containing adjusted values for electrical generation, water volumes (spilled, turbinated, and stored), and inflow and outflow flow for each plant at each stage. The results showed attenuation in the volumetric variations of the reservoirs studied, where the average variation in total volume was 10.72% lower than the actual variation practiced without altering the amount of electrical generation in the cascade at each stage.

The optimization process includes adjustments to variations in reservoir water volumes, which can result in more sustainable cascade operation alternatives, as shown by the results obtained so far. In addition, it could be coupled with the current optimization models for Brazilian energy programming, refining the weekly volumetric optimization of cascades.

To obtain more accurate results, the mathematical model must be evolved, incorporating the non-linear complexities inherent in solving the problem. In addition, tools from the field of computational intelligence must be applied to solve the proposed model.

This study demonstrates the feasibility of incorporating environmental variables into the operational planning of hydroelectric plants arranged in cascades. The proposed approach preserves the efficiency of electricity generation while helping to reduce the environmental impacts on the ecosystem.

KEY WORDS. Renewable Energy, Sustainability, Hydropower, Modeling, Optimization, Environment, Ecosystem

Representation of Maximum Turbine Discharge Capacity as a Function of Net Head in Hydroelectric Plants

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I. Introduction and Objectives

The energy planning of predominantly hydroelectric systems in Brazil, Norway, and Chile requires an accurate representation of the turbines' maximum water intake. This parameter, which depends on the net head, is often treated, as constant (see [1], for instance). However, this approach disregards operational variations, leading to inconsistencies and compromising decision-making accuracy. This work proposes a methodology that:

- Integrates the variation of the maximum water intake with the net head in the optimization process;
- Enables a more accurate representation of generation capacity;
- Aligns operational decisions with real operating conditions;
- Optimizes the use of power reserves in critical scenarios.

Therefore, this approach aims to improve the accuracy of operational planning without compromising computational performance.

II. Main Concepts

The maximum water intake ($q_{\max}$) is the upper limit of the turbine flow (q), determining the maximum amount of water that can pass through the turbines to generate energy. This value represents the flow required for the set of turbines to reach their maximum power, considering the available net head.

A. Maximum Power and Maximum Water Intake

The maximum power of a generating unit corresponds to the highest active power that can be produced while respecting the limitations of the turbine and the generator. When the net head is lower than the effective head, the turbine does not provide sufficient mechanical energy, restricting power generation. For heads higher than the effective value, the generator becomes the limiting factor, reducing the maximum water intake to prevent overloading. In this context, the maximum water intake can be constrained by factors such as:

- **Turbine capacity:** generation is limited when the turbine cannot intake the required water flow due to low net head. In this condition, the generator operates with available capacity, but the hydraulic pressure is insufficient to reach the turbine's nominal flow rate, restricting power generation.
- **Generator capacity:** if the generator's maximum power is reached, the plant cannot convert additional mechanical energy into electrical energy.

This behavior explains the variation in maximum water intake as a function of the net head, as illustrated in Figure 1.

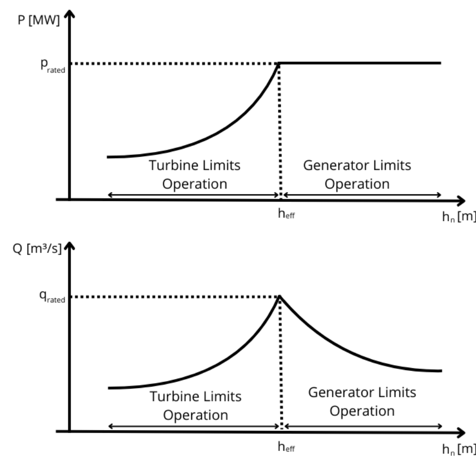

Fig. 1. Power and flow curves as a function of the net head (h_n). The turbine and generator limitations are highlighted in the graphs.

B. Modeling and Calculation of Maximum Water Intake

In the official mid-term model used in Brazil (DECOMP), the calculation of the maximum water intake should take into account the limitations of both the generator and the turbine, with the final value determined as the minimum of the two calculated values:

$$q_{\max} = \min\left(q^G_{\max}, q^T_{\max}\right) \tag{1}$$

The generator-based maximum water intake can be represented by the installed power and the plant's specific productivity, as given by:

$$q^G_{\max} = \frac{p_{\text{inst}}}{\phi_{\text{avg}}} \tag{2}$$

where:

- p_{inst}: installed power of the plant
- ϕ_{avg}: average productivity

On the other hand, the turbine-based maximum water intake takes into account the theoretical maximum water intake curve of the turbine, which we consider as:

$$q_{\max}^{T} = \left(\frac{h_{\text{n}}}{h_{\text{eff}}}\right)^{\alpha} \cdot q_{\text{rated}} \tag{3}$$

where:

- h_{n}: net head at the time of operation
- h_{eff}: effective head
- q_{rated}: registered effective flow
- α: factor dependent on the turbine type

Currently, in Brazilian energy planning models: NEWAVE, DECOMP and DESSEM [2], the modeling of maximum water intake incorporates the limitations od turbines and generators. In DECOMP, an iterative pre-processing step is applied only to the turbine, in which the downstream water level is adjusted according to the maximum turbine flows, considering a reference reservoir level. The generator's maximum water intake is calculated directly based on the average productivity.

III. Methodology

Although the estimated constant value of the maximum water intake may be a satisfactory approximation, in the optimization process, decision-making does not account for the variation in maximum water intake as a function of the operating point, which can lead to inconsistencies when the operating condition changes.

Given this context, this study proposes a modeling approach that integrates the variation of maximum water intake as a function of the net head—determined by the reservoir volume and the plant's outflow—directly within the optimization process.

After analyzing the behavior of maximum turbine flow curves, considering the limitations imposed by both the turbine and the generator, we proceed with a piecewise linear approximation of those curves with two segments as a function of the reservoir volume. Figure 2 illustrates, for the Furnas Hydroelectric Power Plant, the behavior of the nonlinear exact curves and their approximation by the linear model in Eq. 4.

Since the reservoir volume usually is the decision variable the energy planning models, the maximum turbine flow lines were expressed as a function of usable volume.

$$\begin{aligned} q_{\max}^{T} &= a_{k_T} \cdot v + b_{k_T}, \quad a_{k_T} \geq 0, b_{k_T} \geq 0 \\ q_{\max}^{G} &= a_{k_G} \cdot v + b_{k_G}, \quad a_{k_G} \leq 0, b_{k_G} \geq 0 \end{aligned} \tag{4}$$

In Fig. 2 we observe that the maximum water intake may vary from 1400 m³/s to 1500 m³/s, meaning that if the operation changes, the maximum water intake adjusts accordingly. This approach aims to reduce the deviation between the maximum water intake estimated by optimization process and the theoretical maximum turbine flow (Eq. 1), making the modeling more accurate.

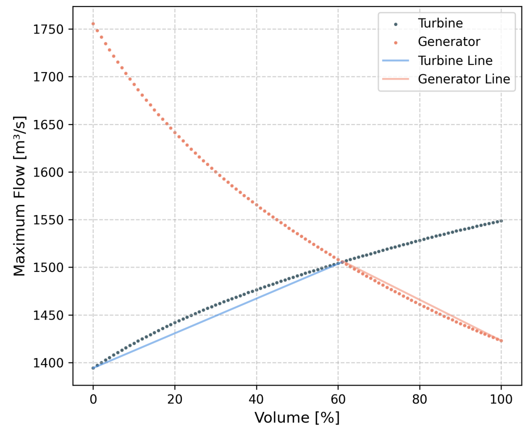

Fig. 2. Relationship between reservoir volume and maximum turbine flow at the Furnas power plant. The curves represent the turbine and generator limitations on turbine flow, as well as their respective linear approximations.

The methodology can be applied in optimization energy planning models to improve the representation of the water intake. The linear model proposed became linear inequality constrains relating the water intake and the volume, which can be incorporated in any optimization scheme without compromise computational time.

IV. Results and Conclusions

To evaluate the proposed model, we used data from the Brazilian system. We adapted the mid-term model used by the Independent System Operator to define the centralized energy dispatch, in order to be able to compare the deviations of the maximum water intake considered nowadays with the proposed model.

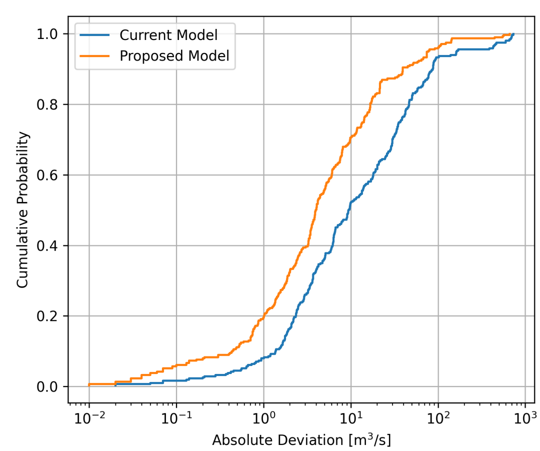

Fig. 3. Empirical Cumulative Distribution Function (ECDF) of the absolute deviations between the current and proposed models.

Figure 3 shows that the absolute deviation was generally reduced, indicating that the proposed model improves the representation of the turbines' maximum water intake and more accurately reflects the actual operation of hydroelectric plants.

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SINTEF

Energy Research

Modelling Complex Tunnel Networks for Short-term Hydropower Scheduling

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Objective

Hydropower reservoirs in cascaded topologies are either connected by pressurized tunnel systems or by open channels like rivers and canals. While open channel flow may cause long time delays and the dispersion of water down a long river stretch, pressurized tunnel systems are governed by rapid changes in flow and very tight time-couplings between connected reservoirs. Complex tunnel networks may include adjustable gates, creek intakes that introduce inflow directly into the tunnels, and the coupling of large and tiny reservoirs in the same system. Previous work has shown that it can be important for hydropower producers to model implicit time delay caused by open channel flow over weirs to time the electricity markets accurately [1]. An accurate physical model of the dynamics of pressurized systems is equally important for hydropower producers with power plants that draw water from complex tunnel networks. The amount of power that can be generated from such power plants will often be strongly dependent on the state of the tunnel network. If the dynamics of the flow and pressure above the power plant is estimated inaccurately, it could directly impact the hydropower producer's market performance.

The short-term hybrid optimization tool SHOP is used by many large hydropower producers in the Nordics for decision support, and is able to model both open channel flow and complex tunnel networks. In this work, the details of how the non-linear and state-dependent tunnel network equations are linearized and modelled in SHOP will be presented.

Methodology

The flow in a pressurized network of tunnels is essentially decided by the mass and pressure balance at every node in the system. The mass balance in a network node is a simple linear equation in the flow over incoming and outgoing tunnels to the node:

$$q_{\text{in}} = q_{\text{out}}.$$

However, friction losses over a tunnel segment can be approximated as quadratic in the tunnel flow, with the resulting head (or pressure) loss over a tunnel segment:

$$\Delta h = \alpha \cdot q|q|.$$

As reservoir levels set the pressure in the nodes where they are connected, the mass and pressure balance equations form a non-linear set of equations that couple the reservoir levels to the tunnel flow. These equations must be linearized before they can be implemented into a mixed-integer linear optimization tool like SHOP. Instead of a direct linearization of the quadratic losses over each tunnel segment, the flow in each tunnel is linearized around the current system state. A Newton–Raphson solution methodology is used to solve the non-linear tunnel network equations and calculate a differential for the tunnel flow in each tunnel based on changes in reservoir levels, plant discharge, and gate positions.

Results

The tunnel system above the Røldal power plant in western Norway is a good example of a complex tunnel network. Two reservoirs, three creek intakes, and the outlet of another power plant are directly coupled to the intake tunnel of Røldal. In addition, a controllable gate can be used to disconnect one of the two reservoirs to preserve water at a higher altitude when Røldal is not running. A case study of this tunnel system using the described tunnel modelling framework will be presented. Historical data for typical dry and wet periods will be used in the study, and the optimized flow results will be validated by performing a post-simulation of the system. The post-simulation will recalculate the reservoir levels and flow in the tunnels given the optimized production plan and gate position, which removes the need for any linearization.

References

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