Technical Session 1B (11:10 - 12:40)	**Energy Markets**	**Chair: Alexandre Street, PUC**	
	Two-Phase Optimization Approach for Profile Block Bidding in Short-Term Hydropower Scheduling	Stein-Erik Fleten	NTNU
	Virtual reservoir bids: A solution for the externalities in the operation of hydro cascades	Gabriel Rocha Cunha	PSR
	Impact of high-price taxes on power systems with hydropower	Viviane Aubin	NTNU
	The IARA Model: A Market Design Simulator for Short-Term Electricity Price Formation	Gabriel Vidigal	PSR

A Two-Phase Optimization Approach for Profile Block Bidding in Short-Term Hydropower Scheduling

M. Jafari Aminabadi,[1,2] S. Séguin,[1,2] S.-E. Fleten,[3] E.K. Aasgård[4]

[1] Department of Computer Science and Mathematics, Université du Québec à Chicoutimi, Saguenay (QC), Canada
[2] Group for Research in Decision Analysis (GERAD), Montréal (QC), Canada
[3] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway
[4] Aneo AS, Trondheim, Norway

Introduction

Hydropower is one of the most significant renewable energy sources, providing clean, reliable, and cost-effective electricity generation. Hydropower optimization is a complex nonlinear and nonconvex problem, further complicated by the large scale of systems and uncertainties in key input parameters such as electricity prices. The deregulation of electricity markets and the dominance of the day-ahead market, which holds the largest share of trading, have intensified the need for effective decision-making tools to maximize profits and balance short-term and long-term objectives under uncertainty [1]. Block bids allow producers in electricity markets to consolidate multiple hours into a single offer, making them particularly effective in hydropower systems with intertemporal dependencies and market uncertainties. These bids help address operational challenges such as aligning production schedules with market prices and ensuring stable energy delivery over longer periods. Regular block bids provide constant power, while profile block bids enable variable energy delivery to better match price fluctuations by adjusting output during periods of high demand [2]. This approach enhances operational flexibility and supports profit optimization in competitive day-ahead markets under uncertain conditions [3]. Studies in the existing literature have primarily focused on regular block bids, while research on profile block bids remains limited. This study aims to address this gap by focusing on profile block bids to enhance operational flexibility and better align with uncertain market conditions.

Objectives

The main objective of this research is to develop an optimization framework focused on profile block bids for short-term hydropower optimization in the day-ahead electricity market. Considering the complexity of this problem, the study aims to propose a method that not only captures the nonlinear nature of hydropower systems but also provides efficient solutions within a reasonable time frame. Specifically, the objective of this project is to develop a two phase optimization approach to select the profile bids. In Phase 1, a mixed-integer nonlinear model is developed, accounting for startup costs, opportunity costs, and other operational constraints such as reservoir limits and water discharge bounds. The model aims to generate feasible profile block bids, enabling the maximization of profitability in short-term hydropower optimization. Phase 2 is developed to select the optimal combination of profile block bids under market price uncertainties. The model evaluates various market scenarios to identify the most profitable combination of profile block bids, maximizing revenue while avoiding unnecessary or suboptimal selections. In this phase, a two-stage stochastic mixed-integer linear model is proposed.

Methodology

The methodology is based on two phases:

1. **Phase 1: Profiled Block Generation.** In the first phase, a nonlinear mixed-integer model is developed to generate a comprehensive set of feasible production profiles. This model incorporates critical operational constraints, including reservoir bounds, water discharge limits, startup costs, and opportunity costs. The objective of this phase is to maximize potential revenue by carefully coordinating water discharge schedules. By solving this model deterministically, a set of robust profiles is created to use as inputs for the second phase.

2. **Phase 2: Two-Stage Stochastic Profile Selection Optimization.** The second phase utilizes a two-stage stochastic mixed-integer linear model to determine the optimal combination of profile block bids while accounting for market price uncertainties. The model analyzes multiple market scenarios to identify the most profitable set of blocks, ensuring unnecessary or suboptimal selections are minimized. A maximum of 15 block combinations is allowed for market participation. The objective of this phase is to maximize expected revenue and minimize regret associated with varying scenario prices. The methodology ensures that the total unimodularity conditions are satisfied in both phases, enabling the relaxation of binary variables and solving the problem as a continuous optimization model. This approach significantly reduces computational complexity.

Expected Results

The proposed two-phase optimization framework is evaluated on a case study involving a hydropower system located in Norway, consisting of six reservoirs and five hydropower plants. This system features interconnected reservoirs with upstream and downstream dependencies, reflecting the operational complexities typically observed in real-world hydropower networks. Phase 1 focuses on generating a comprehensive set of profile block bids for a 24-hour horizon. By relaxing binary variables and solving the model as a continuous optimization problem, the computational complexity is significantly reduced. This allows for the generation of a large number of feasible profiles within a short timeframe. For example, the model can generate over 1,000 profile blocks in just a few minutes while considering operational constraints such as reservoir volume limits, water discharge bounds, startup costs, and opportunity costs. Phase 2 optimizes the selection of profile block bids under market price uncertainties. From the profiles generated in Phase 1, the model selects up to 15 optimal blocks by analyzing multiple market price scenarios. The stochastic approach minimizes regret and maximizes expected revenue. Phase 2 is also highly efficient, capable of solving problems with 1,000 profiles and 25 price scenarios in just a few seconds. To further evaluate the proposed model, the results for 24-hour profile block bidding strategy will be compared with those of hourly bidding to assess its performance under different market conditions.

References

[1] E. K. Aasgård, G. S. Andersen, S.-E. Fleten, and D. Haugstvedt, "Evaluating a Stochastic-Programming-Based Bidding Model for a Multireservoir System," *IEEE Transactions on Power Systems*, vol. 29, no. 4, pp. 1748–1757, 2014.

[2] Makedon Karasavvidis, Dimitrios Papadaskalopoulos, and Goran Strbac, "Optimal offering of a power producer in electricity markets with profile and linked block orders," *IEEE Transactions on Power Systems*, vol. 37, no. 4, pp. 2704–2719, 2021.

[3] Stein-Erik Fleten and Trine Krogh Kristoffersen, "Stochastic programming for optimizing bidding strategies of a Nordic hydropower producer," *European Journal of Operational Research*, vol. 181, no. 2, pp. 916–928, 2007.

Virtual reservoir bids: A solution for the externalities in the operation of hydro cascades

- **Overview**

As it is widely known from the economic literature, markets can be an effective way of aggregating information and incentivizing actions from different agents in order to achieve the most socially desirable final outcome – as opposed to relying on a central planner to aggregate information and orient and supervise individual agents' actions. Particularly in the context of the energy sector, liberalized electricity markets have been successful in promoting a more efficient operation and planning of electricity sectors worldwide.

However, a key underlying assumption necessary for decentralized markets to be truly efficient is the absence of externalities – said in another way, the impacts of each agent's choices should be fully "internalized" into the price signals they receive. One type of situation in which this assumption is clearly violated is where cascaded hydro power plants in the same river have different owners. If agents only receive revenue proportional to their electricity production (as is the case in "classic" implementations of electricity markets), they will not be financially impacted by the fact that their operational choices will change the amount of water available for other hydro power plants downstream – thus creating an externality.

Having a single owner (or consortium) responsible for the entire cascade could eliminate this externality, but this could lead to a situation in which this single owner has exacerbated market power. Therefore, the exploration of alternative mechanisms is warranted, and the main goal of this paper is to explore a potential bid-based solution constructed around "virtual reservoirs".

- **Methods**

The virtual reservoir mechanism will be introduced step by step, along with their mathematical formulation as implemented in the optimization software. In particular, key elements that will be presented include:

- Parameterization of the underlying physical reality. This includes the topology of the hydro cascades present in the system, operational parameters of each individual physical hydro plant (such as their production factor, installed capacity, and useful volume), and the probability distribution of arriving inflows. This parameterization also includes information about other generation units (e.g. thermal and renewable units) as well as demands present in the system.

- Definition of the boundaries for the virtual reservoir mechanism. Each "virtual reservoir" is defined exogenously (for example, in the Brazilian system we would have one virtual reservoir each for the North, Northeast, Southeast, and South) and can include any combination of hydro units. Even though it is generally expected that hydro plants in the same zone and/or in the same cascade would be part of the same virtual reservoirs (or at least "neighboring" virtual reservoirs), this is not a strict requirement.
- Definition of the ownership structure of the virtual reservoirs. This component includes three key pieces of information: (i) which agent is responsible for physically operating a hydro unit (requiring remuneration of administrative costs and operations and maintenance costs), (ii) how many "inflow shares" an agent has (as a percentage of new inflows arriving at each stage of the multi-stage simulation), (iii) how many "virtual reservoir shares" an agent has as a starting condition (represented as a percentage of the starting volume of the simulation).
- Structure of the virtual reservoir bids. Each agent participating in the mechanism must present daily a "price-quantity bid" representing their preference – that is, how many of their current "virtual reservoir shares" they wish to sell and at what price.
- Definition of the optimization problem structure. This is analogous to a "classic" cost minimization problem for the electricity system, with zonal representations of the electricity balance equations and dispatch decisions for thermal and renewable plants (and eventually demand deficit). Physical hydro plants are represented in detail, and the choice of end volume each period is guided by the agents' virtual reservoir bids and a "physical-virtual correspondence constraint". Even though there is no explicit representation of the opportunity costs of hydro storage, implicitly each agent does consider opportunity costs (as future expected profits) when deciding their virtual reservoir bids.
- Definition of the financial remuneration equations. This represents the final financial incentive to bidders based on how many virtual reservoir shares they choose to sell. This remuneration depends chiefly on the "virtual reservoir marginal price" (analogous to the electricity marginal price) but also foresees components for O&M payments, a financial surplus component, and a spillage penalty component.

- **Results**

A simplified version of the Brazilian system is presented as a case study of the virtual reservoir mechanism, which is fully implemented in specialized open-source software. We analyze four different scenarios of bidding strategies (for a given underlying physical reality and ownership structure) and assess how agents' expected profit changes based on these strategies. We discuss the implications of these results in terms of expected market equilibria, agents' final profits, and physical storage volumes decided from the combination of agents' strategies.

Finally, we discuss the pros and cons of the proposed virtual reservoir model, in comparison to other known strategies for solving the externality issues of hydro cascades in an electricity market context.

- **References**

1. P. Lino, L.A. Barroso, M.V.F.Pereira, R.Kelman, M.H.C.Fampa. "Bid-Based Dispatch of Hydrothermal Systems in Competitive Markets". Annals of Operations Research 120, 81–97 (2003).
2. K.J. Ketchum, L.A.Barroso. "The Columbia River Treaty - an example of effective cross-border river regulation". X Symposium of Specialists in Electric Operational and Expansion Planning - SEPOPE (2006).
3. M.M.Resende, G. Cunha. "Alternativas para a Implementação de Mercados Baseados em Ofertas e suas Consequências para Hidrelétricas em Cascata". XXVI SNPTEE (2021).
4. L.A. Barroso, S. Granville, P. Jackson, M. V. Pereira, E.G. Read. "Overview of Virtual Models for Reservoir Management in Competitive Markets". Proceedings of the 3rd conference on Hydroscheduling in Competitive Markets (2012)
5. F.A. Calabria. "Enhancing Flexibility and Ensuring Efficiency and Security Improving the Electricity Market in Brazil Using a Virtual Reservoir Model". PhD thesis, University of Porto (2015).
6. R.H. Coase. "The Nature of the Firm". Economica 4, n. 16 (1937): 386–405. doi:10.1111/j.1468-0335.1937.tb00002.

Authors' names and institutions:

Viviane Aubin – Department of Electric Energy, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Arild Helseth – SINTEF Energy Research, 7465 Trondheim, Norway

Magnus Korpås – Department of Electric Energy, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Email corresponding author:

viviane.aubin@ntnu.no

Impact of high-price taxes on power systems with hydropower

Many power systems are experiencing a transformation of their resource mix. Variable renewable energy (VRE) sources are rising while thermal power plants are being decommissioned. In addition, the changing climate is increasingly affecting both the supply and demand sides of the power system. These new dynamics raise concerns about the adequacy of the current power market design, which the recent European energy crisis intensified. However, out-of-market interventions that are discussed and implemented may have unexpected consequences that reach further than their initial purpose.

Reservoir hydropower can play a major role in highly renewable systems as a flexibility and energy security provider. Meanwhile, its operations are especially sensitive to changes in power market design given their interdependency over long time horizons. For example, a policy that targets a few critical hours may influence hydropower scheduling decisions over long periods. An efficient use of its resources requires a thorough understanding of the interactions between policy, market design, and hydropower operations.

1. *Objective*

This study evaluates how adjustments to the market clearing price influence the behaviour of power producers. Special attention is given to the impact of such out-of-market interventions on storage and hydropower reservoir management in particular. Repercussions are compared between cases with risk-neutral and risk-averse producers. A case study on high-price (windfall profit) taxes complements the analysis. This type of tax was introduced in Norway in the context of the recent energy crisis in 2022. If the market clears at a price higher than a certain threshold, producers must pay an additional tax on their revenues.

2. *Methodology*

Equilibrium modelling is used to provide a system-level perspective while capturing the difference between the market clearing price and the perceived price by producers. Nash equilibria are found where perfectly competitive producers optimize their revenues while considering the incentive distortion caused by price adjustments.

3. *Expected results*

For most technologies, while they probably would influence investments, price-adjusting interventions induce limited changes in production patterns. However, for technologies with storage, like hydropower, those interventions introduce variations in the opportunity costs, which steer the allocation of stored energy. For example, the high-price tax decreases the valuation of water, leading to lower reservoir levels. The impact is more prominent for hydropower producers with lower risk aversion. Given the reduced energy reserves, high-price periods occur more often, and energy security may be compromised in hydro-dominated systems. If we assume that the revenues from the high-price tax are redistributed among consumers, we observe that the net impact of the tax on the consumers depends on the redistribution policy and the consumption profile.

The IARA Model: A Market Design Simulator for Short-Term Electricity Price Formation

Price formation is a fundamental topic in electricity markets. The issue is relevant worldwide and has received special attention in Latin America, with countries such as Chile, Brazil, and Colombia conducting studies to explore different possibilities. Two main market designs dominate discussions. On one side, there is the cost-based design, currently used in Brazil and Chile, in which costs are audited, and then the system is operated using models that incorporate these costs to guide dispatch decisions. On the other side, there is the bid-based design, where market participants submit their own cost and capacity bids, as seen in Colombia, Europe, and the United States. Between these theoretical extremes, several hybrid models combine elements from both approaches, such as a cost-based system with elastic demand bids, among other variations.

Other market design elements have also been widely debated, either in conjunction with or independently of the cost-versus-offer discussion. There has been discussion on single versus dual settlements, which are crucial for improving forecasting of uncertainties associated with dispatch, such as demand and renewable generation. Another relevant topic is the representation of integer variables, which are essential for accurately modeling real-world systems but introduce nonlinearities that can impact price formation. Additionally, the format of price bids has been considered, with some systems following a multi-component structure, typical in the United States, while others use a generic profile structure, common in Europe.

The assessment and comparison of these highly relevant factors for price formation must be conducted carefully for specific systems to better understand market designs, their consequences, and the associated regulatory changes needed for effective market operation.

In this work, we introduce the IARA model, a tool designed to simulate various market designs. IARA is a fully open-source tool, with all code publicly available under a permissive license, and solver-agnostic. By default, it uses the open-source solver HiGHS, ensuring that any user, regardless of location, can access the tool. However, for simulating highly complex systems, commercial solvers such as Xpress, Gurobi, and CPLEX can also be used.

The IARA model was developed with two main pillars: ease of use and development, and computational efficiency. To achieve these goals, it was implemented in Julia, using the JuMP (Julia for Mathematical Programming) package. As a result, IARA is highly extensible, allowing new constraints and variables to be easily incorporated, and capable of solving large-scale problems efficiently.

The tool supports the modeling of multiple market designs, by solving four different market clearing problems. These can be ex-ante or ex-post problems regarding the uncertainties, as well as physical or commercial problems, which can differ in the level of complexity represented, such as linearizing integer variables to allow marginal cost calculations.

The model can solve problems ranging from a purely cost-based framework, where it can represent different asset's physical constraints, to a purely bid-based approach, where different bid types can represent different designs seen across the world's energy markets.

An open model like IARA enables fully transparent studies, ensuring that all model details can be publicly inspected and critically analyzed. This fosters an open science environment that facilitates concrete knowledge sharing.

To demonstrate the model's capabilities, case studies and usage examples will be presented. These examples will highlight contrasts between some of the market designs described earlier. Additionally, these studies will be available online in the form of tutorials.