Externalities in the joint operation of hydro cascades: an assessment of the performance of different market-based solutions

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Overview

As it is widely known from the economic literature, markets can be a very efficient 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 direct actions from each of these agents one by one. Particularly in the context of the energy sector, liberalized electricity markets have been extremely 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 – or, said in another way, each agent should fully internalize the financial impacts of the choices they make. One practical type of situation in which this assumption is clearly violated is the case of cascaded hydro power plants in the same river (and different owners): if the hydro plant located higher up in the river chooses to use most of the incoming water to produce electricity (or, conversely, to keep more water stored in its reservoir and only turbine a smaller share of inflows), this will certainly influence the amount of water available for other hydro power plants downstream. However, in "classic" unmodified implementations of electricity markets, the upstream plant's owner's remuneration only depends on the amount of electricity produced by the upstream plant, such that its influence on the operation of the downstream plants is an externality.

There are several solutions to this problem, such as the possibility of bilateral case-by-case negotiations and/or the creation of various types of cooperation and risk-sharing agreements (which have been common in practice between hydro producers in the same cascade in several countries, such as in Norway, Brazil, and the Columbia river in Northwestern USA). However, with the possibility of climate change altering the underlying conditions of existing agreements and a desire to manage conflicts even in contentious cases (including examples in which the cascade is split into two by a border crossing), it becomes increasingly important to look more closely into possible systematic schemes for handling hydro cascade externalities.

Methods

For the analyses of this paper, we first introduce a "parameterized" version of a cascaded hydro system describing the key features of an electricity market, along with an indication of how a real-world system can be tuned to such a parameterized version. Among the key parameters of this idealized representation are the target net demand to be served, the cost of supplying this demand with non-hydro generation assets (typically representing thermal plants' fuel and operating costs), the cost of curtailing demand if needed, the probability distribution of hydro inflows, and the conversion curve for the hydro plants. Note that the conversion curve is a nonlinear function, showing diminishing returns (i.e. a lower efficiency in the conversion of water resources into electricity). In addition, this model also allows for increasing the number of firms in the market in order to assess how the equilibrium is affected by market power. It is possible to show that, in the presence of externalities, the market equilibrium will not converge to the social optimum even in the competitive limit as the number of agents approaches infinity.

This parameterized hydro system is then calibrated using a Brazilian cascade as a case study, and tested against three main mechanisms, taken from the literature: (i) a shared ownership model, in which agents in practice share ownership of all plants in the same cascade; (ii) a wholesale water market in which agents downstream must pay upstream agents in accordance with the amount of water that is sent downstream; and (iii) a virtual reservoir model in which the management of the upstream reservoir is driven by bids submitted by the agents (these bids can be handled completely in parallel with the "standard" electricity market bids). The virtual reservoir model in particular, even though it has been first proposed in Brazil in 2002, has had limited presence in the academic literature, for which this paper brings an important contribution.

Note that, if transaction costs for agents to communicate and negotiate with one another are negligible, one can expect that even in the absence of any explicit mechanism for handling externalities the agents would voluntarily coalesce into an agreement (that would likely essentially emulate one of the three solutions above). This is in line with the classic economic result of Coase's theorem.

Results

This article computes the market equilibrium under three mechanisms for handling externalities (shared ownership, wholesale water market, and virtual reservoir), using a Brazilian river as a case study. As a result, the total dispatch cost, marginal energy prices, plant owners' profits, and the amount of water used for generation are obtained, among other variables. These are compared with the social optimum – the operation that would be achieved by a centralized operator with perfect knowledge.

The paper demonstrates that, as expected, the distance between the social optimum and the market equilibrium decreases as the number of firms increases. This result is quite robust even to changes in the cascade's key defining parameters.

By changing the cascade parameters, one can find conditions in which the magnitude of this "cost of anarchy" is smaller or greater. The "cost of anarchy" represents the difference between the socially optimal result and the market equilibrium result in a condition of maximum externality (that is, when transaction costs are too high and thus no bilateral agreements between the agents in the cascade can be reached).

Conclusions

This paper explores various types of agreement between hydro power plants belonging to the same cascade that could be implemented, either as bilateral agreements negotiated directly between the agents or as "facilitator mechanisms" introduced and encouraged by a central entity.

These analyses allow for making qualitative recommendations regarding each of the strategies evaluated. The shared ownership model is perhaps the simplest and most intuitive, but it has the downside of increasing market power (as the number of bidding entities decreases if both companies in the same cascade bid as one) – which also could create an incentive for agents negotiating bilaterally to prefer this scheme. The wholesale water market has good theoretical properties, although a practical downside is relying on an "oracle" that both agents must agree to in order to determine water prices in real time. The virtual reservoir model could be an effective conceptual approach for handling externalities, with Brazilian cascades a promising case.

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