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Economic impact of pumped storage power plant on social welfare of electricity market

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ABSTRACT

Pumped storage hydroelectric plants are attractive in competitive electricity markets because of their operational flexibility and ability to provide rapid response to change in spot price of electricity. Operating pumped storage plant affects the consumer and producer surplus of the individual market and hence leads to significant changes in energy prices. This paper investigates the impact of pumped storage energy trading on the social welfare of electricity market. A theoretical analysis and intuitive explanation are presented and numerical case study is also illustrated to validate the analytical results developed. Energy trading by pumped storage increases the overall social welfare of the market, when both storing and releasing energy. Further, the implications of pumped storage energy trade are producers benefit more during storage and consumers benefit more during release of stored energy.

1. Introduction

Pumped storage hydroelectric plant is the oldest kind of large-scale energy storage technology [1–3]. Since 1904, they are in active operation and new ones are still being built because of their operational flexibility and ability to provide rapid response to changes in system demand or spot price of electricity. In a vertically integrated market, hydrothermal coordination [4,5] is used to reduce the fuel cost by letting the pumped-storage generators serve the peak load and then pumping the water back into the upper reservoir at light-load periods. In recent years, as restructuring has gained momentum, both new generation investments and efficient power plant operation have taken greater strategic significance [6]. In a competitive electricity market, pumped-storage plant owner can now buy and sell electricity either on the day-ahead and real-time markets or with the bilateral contracts.

The efficient market solution generated by a competitive market maximizes the social welfare that is the sum of consumer and producer surplus. Operating pumped storage plant can lead to significant changes in the consumer and producer surplus of an individual power market since pumped storage energy trading can significantly alter energy prices and market efficiency. Deb [7] presented a case study of the operation of a hypothetical hydro and pumped storage units in a multiple-product electricity market, and compared the revenues earned by these units to their counterpart earnings through conventional operation in an energy-only market. The impacts of spinning reserve on energy prices has been studied in [8] and the role and value of pumped storage units in ancillary service markets has been analyzed in [9].

From the earlier literatures discussing energy storage interactions with electricity market, in [10] operation strategies for pumped hydroelectric energy storage utilizing electricity price arbitrage is discussed and in [11], the authors analyze the arbitrage value of a price-taking storage device in PJM during a specific period, to understand the impact of fuel prices, transmission constraints, efficiency and storage capacity. In [12] operational and economic benefits of battery energy storage plants is discussed and in [13] incentives for the merchant storage operators, consumers, and generators and show that under most reasonable market structures a combination of merchant and consumer ownership of storage maximizes potential welfare gains from storage use were examined. Ref. [14] give a study on strategic utilization of storage in imperfect electricity markets. In [17], the authors propose a new mode of storage operation by coupling electricity storage with electricity markets and a welfare analysis in the French market is carried out to evaluate public way as well as the private way of storage operation. Other possible storage options were also discussed in [15,16].

Energy trading by pumped storage plant increases the overall social welfare of markets, may have different economic implications for the consumers and generators of an individual power market, depending on whether pumped storage plant is importing or exporting energy from the market. This paper investigates how the integration of pumped storage hydro power plant's energy trade affects the social welfare of individual power market. In particular, this paper attempts to analyze the changes in the consumer and producer surplus of a market as the volume of energy trading by the pumped storage continues to increase.

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This paper is organized as follows. Section 2 depicts a model used to clear the electricity market with multiple buyers and sellers. The residual demand/supply curve faced by the pumped storage power plant is developed in order to select its market bids and offers. The general impacts upon prices, consumer welfare, producer welfare and the social welfare of the market are discussed in Section 3 and a case study is presented in Section 4, for a typical competitive electricity market to validate the analytical results developed. Finally Section 5 gives the conclusion.

2. Electricity market model

Electricity market operator receive offers from generating companies to produce energy and bids from consumers for willingness to consume energy. The market operator then performs a simple merit-order dispatch in order to clear the market. The supplier bid model is a linear increasing function that consists of MW outputs along with associated prices. Similarly, the consumer bid model is a decreasing function. For the market simulation, these bids are treated as the marginal cost or benefit of the bidder. With these bids and the agreed bilateral trades along with the DC power flow model, market optimization problem can be formulated to maximize the social welfare and determine the supplies, demands and prices based on uniform pricing equal to last accepted offer (LAO). The electricity market model developed in [18,19] and [20] are used to clear the electricity market and determine the Locational Marginal Prices (LMPs) or spot prices.

Consider a competitive electricity market with n market participants having perfect competition, connected to a common transmission utility as shown in Fig. 1. To analyze the change in the social welfare of an individual market due to pumped storage energy trade, it is assumed that in the market, a pumped storage power plant is considered as one participant and the rest of $n-1$ participants include other generators or loads.

2.1. Aggregation of demand/supply curves

The approach to clear a market with multiple buyers and sellers, each with individual linear demand/supply curves, under non-discriminatory pricing, is to aggregate the demand and the supply curves separately, and then reduce the problem to the single seller, single buyer case. The single seller is the aggregate of all sellers, and the single buyer is the aggregate of all buyers [21]. The key idea here is that since all buyers are cleared at the same price, one can infer quantities sold to each individual buyer by evaluating their curves at their respective bid. The same holds for the sellers.

The aggregation of buyer and seller curves is arrived as follows. Consider a set of linear or piecewise linear demand curves $d_1; d_2; \ldots ; d_n$, when there are n participants in the system. The demand curve of participant i is defined as

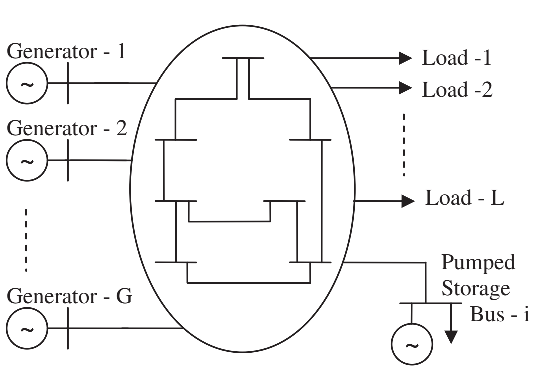

Fig. 1. Electricity market with pumped storage hydro-power plant.

$$d_i(\rho) = a_i\rho + b_i \tag{1}$$

Their aggregate curve is a piecewise linear function D such that $D(\rho)$ is the total demand at unit price ρ. That is,

$$D(\rho) = d_1(\rho) + d_2(\rho) + \ldots + d_n(\rho) \tag{2}$$

where $d_i(\rho)$ is the demand by curve i at unit price ρ. Seller curves are also handled in the same way.

$$S(\rho) = s_1(\rho) + s_2(\rho) + \ldots + s_n(\rho) \tag{3}$$

The aggregation of linear functions leads to a linear function. Thus, if a price interval $[\rho_1; \rho_2]$ does not contain the breakpoints of any of the demand curves, then the aggregate curve in the interval $[\rho_1; \rho_2]$ has the form

$$D(\rho) = \left(\sum a_i\right)\rho + \sum b_i \tag{4}$$

where a_i and b_i are the coefficients of the component linear curves. The aggregate demand and supply curves are shown in Fig. 2a.

2.2. Residual demand/supply curve

The residual demand/supply curve [22] faced by the pumped storage power plant during generating/pumping mode respectively is applied to analyze the change in the social welfare of the market due to its energy trade. The demand curve that an individual firm (generator-i) faces is called the residual demand curve: the market demand that is not met by other sellers at all price levels. The residual demand function equals the aggregate market demand function $D(\rho)$, minus the supply of all other firms except i, i.e. $S_{-i}(\rho)$.

$$D_{Ri}(\rho) = D(\rho) - S_{-i}(\rho) = D(\rho) - \sum_{j\neq i} S_j(\rho)\ \forall \rho \in [\rho_{min}, \rho_{max}] \tag{5}$$

where $[\rho_{min}, \rho_{max}]$ is the range of possible energy market prices.

In a typical electricity market, different generation firms are located at different buses. Transmission constraints will generally lead to different nodal prices for different buses [23]. So instead of having uniform market price ρ, consider a vector of nodal prices,

$$B = [\rho_1\ \rho_2\ \ldots\ \rho_n]^T \tag{6}$$

The demand at each bus depends on only its local price, because it is unlikely that a market participant could shift loads between buses according to real-time nodal prices. Accordingly, a generation firm's residual demand will be a function of its local nodal price. Neglecting network losses for simplicity, the market energy balance condition is

$$\sum_{j=1}^{n} (D_j(\rho_j) - S_j(\rho_j)) = 0 \tag{7}$$

Moving specific $S_i(\rho_i) - D_i(\rho_i)$ on the left-hand side and all other terms to the right-hand side,

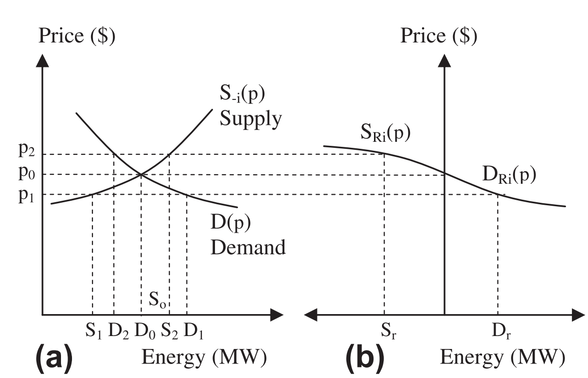

Fig. 2. (a) Aggregate demand and supply curves, (b) Residual demand/supply curve.