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Decision Support

Impact of storage competition on energy markets

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ABSTRACT

We study how storage, operating as a price maker within a market environment, may be optimally operated over an extended period of time. The optimality criterion may be the maximisation of the profit of the storage itself, where this profit results from the exploitation of the differences in market clearing prices at different times. Alternatively it may be the minimisation of the cost of generation, or the maximisation of consumer surplus or social welfare. In all cases there is calculated for each successive time-step the cost function measuring the total impact of whatever action is taken by the storage. The succession of such cost functions provides the information for the storage to determine how to behave over time, forming the basis of the appropriate optimisation problem.

We study particularly competition between multiple stores, where the objective of each store is to maximise its own income given the activities of the remainder. We show that, at the Cournot Nash equilibrium, multiple stores which between them have market impact collectively erode their own abilities to make profits: essentially each store attempts to increase its own profit over time by overcompeting at the expense of the remainder. We quantify this for linear price functions.

We give examples throughout based on electricity storage and Great Britain electricity spot-price market data.

1. Introduction

There has been much discussion in recent years on the role of storage in future energy networks. It can be used to buffer the highly variable output of renewable generation such as wind and solar power, and it further has the potential to smooth fluctuations in demand, thereby reducing the need for expensive and carbon-emitting peaking plants. For a discussion of the use of storage in providing multiple buffering and smoothing capabilities, including the ability to integrate renewable generation into energy networks see, for example, the fairly recent review by Denholm, Ela, Kirby, and Milligan (2010), and the many references therein. Within an economic framework much of the value of energy storage may be realised by allowing it to operate in a market environment, provided that the latter is structured in such a way as to allow this to happen. Thus the smoothing of variations in demand between, for example, nighttime when demand is low and daytime when demand is high may be achieved by allowing a store to buy energy at night when the low demand typically means that it is relatively cheap, and to sell it again in the day when it is expensive. Similarly, the use of storage for buffering against shortfalls in renewable generation may – at least in part – be effected by allowing storage to operate in a responsive spot-price market when prices will rise at the times of such shortfall. We remark though that if it is intended that the use of storage should facilitate, for example, a reduction in carbon emissions, then there is of course no guarantee that a market environment will in itself permit this to happen – for some recent insights into the possible unexpected side effects of storage operating in a market, see Virasjoki, Rocha, Siddiqui, and Salo (2015).

It is also the case that price arbitrage as above is not the only way in which storage may compete in the marketplace. In particular much energy storage has the ability to provide power – sometimes in large quantities, as in the case of some pumped storage facilities – at very short notice, i.e. within time scales of the order of seconds or less (see, for example, the recent GB National Grid enhanced frequency response (EFR) auctions National Grid plc (2017)). Thus energy storage typically provides a variety of services, and even those which are concerned with smoothing imbalances in supply and demand on time scales longer than those above may be paid for other than through arbitrage opportunities, for example through fixed “capacity” contracts which cover substantial periods of time and in which stores are paid fees fixed in advance simply to be available to provide energy as needed. Nevertheless the

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use of storage for arbitrage is significant and may become more so in future systems, for example, in the presence of either more nuclear generation or of increased renewable generation, neither of these being easily controllable so as to smooth fluctuations in the supply-demand balance. (Whether the benefits which storage can bring in such situations is paid for through providing arbitrage opportunities to the storage will depend very much on how markets are organised.) A storage facility may well reserve some of its energy capacity and power capabilities for the provision of services such as EFR, and then seek to use the remainder of its resource so as to make money through arbitrage. For some work on the simultaneous use of storage for both arbitrage and buffering against the effects of sudden events see Cruise and Zachary (2015), while for work on a whole systems assessment of the value of energy storage see Pudjianto, Aunedi, Djapic, and Strbac (2014).

When stores buy and sell in the market, it is important to understand the effect on the market itself of the activities of the stores, and to understand also the effect of competition between stores on the profitability of their activities. A small store may be expected to function as a price-taker, buying and selling so as, for example, to maximise its own profit over time. However, a larger store, or a sufficient number of smaller stores, will act as price-makers, perhaps significantly affecting the market in which they operate, and thus also affecting quantities such as generator costs, consumer surplus and social welfare. Further a number of stores which between them possess market impact, by competing with each other, may smooth prices to the point where they are unable to make sufficient profits as to be economically viable – at least via their arbitrage activities, as we demonstrate in the simple example below.

Example 1. Consider a model with two time periods and n perfectly efficient stores. Suppose that each store k buys x_k in time period 1 which it then sells in time period 2, and that this results in a unit price differential (the price at time 2 less that at time 1) of $p - p' \sum_{k=1}^{n} x_k$ where $p > 0$, $p' > 0$. (This will be the case when, for example, the stores face appropriate linear residual supply functions in each time period – see Section 2.) In what is a model of simple Cournot competition, we suppose that each store k seeks to maximise its profit $\left(p - p' \sum_{j=1}^{n} x_j\right) x_k$ given the quantities x_j, $j \neq k$, traded by the remaining $n-1$ stores. If the stores are unrestricted in the quantities x_k they may trade, it is easily checked that at the Nash equilibrium we have $x_k = p/(p'(n+1))$ for all k, and that the price differential between the two time periods is $p/(n+1)$. Thus in particular each store makes a profit proportional to $1/(n+1)^2$, and the *total* profit made by all the stores declines as approximately $1/n$ as n becomes large. Consider also, for reference, the case in which the stores instead cooperate and each trade a fraction $1/n$ of that which a single store would have traded in the case $n = 1$, so that here $x_k = p/(2p'n)$ for all k. Here the *total* profit made by all the stores remains constant as n increases, a result which would also hold in the competitive case if the capacities of the individual stores were appropriately constrained.

The above example is concerned with the effects of competition between stores themselves, something which we explore in more detail in Section 4, where in particular we study competition over extended periods of time. There are, however, also many more general issues surrounding the effects of storage considered collectively on the market in which it operates. Aspects of many of these issues have been explored in the literature. Recent work on the use of storage in a specifically market environment is given by Gast, Tomozei, and Le Boudec (2012), Gast, Le Boudec, Proutiere, and Tomozei (2013), Graves, Jenkin, and Murphy (1999), Hu, Chen, and Bak-Jensen (2010) and Secomandi (2010). Sioshansi, Denholm, Jenkin, and Weiss (2009) study the effects of storage on producer and consumer surplus and on social welfare. Sioshansi (2014) gives an example where storage may reduce social welfare. Gast et al. (2013) show how in appropriate circumstances storage may be used to minimise generation costs and thus maximise consumer welfare.

There is also a considerable literature on the economics of hydroelectric power, which may be regarded as storage in which in general only the output process is controllable. Within this literature input flows are given and often modelled as stochastic; then the problem is that of the optimal control of the outflows, something which is frequently approached via stochastic dynamic programming – for recent work see in particular Löhndorf, Wozabal, and Minner (2013) and Zéphyr, Lang, Lamond, and Côté (2017) and the references therein. Other work is more applied, focusing on hydroelectric power as it exists today in particular places – see Fleten and Kristoffersen (2007), Borenstein and Bushnell (1999), Bushnell (2003), and the survey by Rangel (2008). The latter three papers are concerned with the market impact of hydroelectric storage in a competitive environment and stores are therefore treated as price makers. The present paper is concerned with competition between more general forms of storage which is sufficiently large as to have market impact, in which both input and output may be controlled, and in which it is necessary to explicitly account for both rate and capacity constraints in the optimisation of the behaviour of each individual store. We make use of a Lagrangian approach (Proposition 1 below) to yield prices for the rate and capacity constraints. The resulting optimality conditions for each agent given the actions of its competitors provide a complementarity problem defining a Nash equilibrium.

In the present paper we therefore aim to develop a more comprehensive mathematical theory of the way in which storage, buying and selling over a possibly extended period of time in such a way as to maximise its overall profit from these activities, interacts with the time-varying market in which it finds itself. Our motivation is to understand both this interaction and also the way in which competing stores, through this interaction, affect each others abilities to make profits. We study the former in Section 3, looking in particular at the impact of storage on prices and consumer surplus, and providing examples with conclusions which are in some cases counter-intuitive; these results complement those of other authors. Our principal concern, however, is to study the effect of competition between stores. While this is illustrated in Example 1 above, in that example the activity of each store is determined by its decision at a single point in time – since what is bought at time 1 must be sold at time 2. We show in Section 4 that conclusions similar to those of Example 1 continue to hold when stores, unconstrained in their capacities and rates, operate over extended periods of time under a similar model of Cournot competition: within this model each store optimises its own total profit over time given the profiles of quantities traded by the remainder. Notably we show that again a large number of stores severely reduce each other's profitability in a manner which (precisely) quantitatively mirrors that of the earlier example. However, the imposition of capacity and/or rate constraints on the stores reduces their ability to affect each other in this way, to the benefit of all the stores. We discuss also in Section 4 the extent to which other models of competition between stores are possible.

Our fundamental assumption is therefore that each individual store operates over a given period of time in such a way as to optimise its "profit" – or equivalently minimise its costs – with respect to time-varying cost functions presented to it. These may represent either the prevailing costs within a free market, as may be natural when the store is independently owned, or adjusted costs which take into account the wider impact of the store's activities, as would be appropriate when the store was owned, for example, by the generators or by society – see Section 5. Thus if it is desirable that a store should function in a particular way – for example

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