## *Arbitrage Strategies for Energy Storage Units*

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## Overview

The increasing share of intermittent renewable sources in the generation mix is adding strains on the electricity system. Energy storage serves two main purposes; first as readily available power for supply and system security, and second as highly controllable and flexible source or sink to smooth variations in intermittent (and other) supplies. Energy storage in the second capacity serves a potentially important role by eliminating high price periods, or even avoiding curtailment periods, and thus being an important and integral part of the future energy system with a higher degree of intermittent penetration.

Assessing the value of energy storage units and the profitability of investment in such strategies is essentially an assessment of uncertain future revenue streams in a highly stochastic environment. A number of past studies of the value of energy storage relies on  perfect foresight thereby overestimating the arbitrage value of the storage unit. Other studies have relied on various rule-of-thumb strategies which most likely underestimates the arbitrage value and may give incorrect recommendations with respect to the relative merits of the various rules.

This paper describes the arbitrage strategy for an energy storage unit that participates in a dispatch auction. Most restructured energy markets are using auctions in the day-ahead markets and/or in any balancing markets before the operating hour of the electricity system. The optimal bidding for selling and buying electricity by the energy storage unit is model explicitly as a dynamic expected profit optimization problem where the decision maker does not know the electricity price. The analytical solution is characterized and also solved numerically for several day-ahead markets. The numerical solutions allow for the assessment of the potential arbitrage gains from operating a storage unit, and is an integral part of the investment analysis for such a unit.

## Methods

The energy storage unit is assumed to participate in a market auction where the storage manager submit a bid for buying or selling one unit of energy in the next period. The manager has an estimate (belief) of the market clearing price in the next period. The manager decision is modeled using stochastic dynamic programming where number of energy units in storage is the state variable and the buy and sell bids are the control variables. The analytical model is developed both for a single period auction and for a multi-period auction where the manager submits bids for several sequential market clearing periods at a time. The analytical solution is derived and used to characterize the no-arbitrage conditions.

This model is also solved numerically where the probability distributions are taken from the actual market clearing prices in three different markets: the British, the Danish and the German day-ahead markets. This markets are distinct with respect to market penetration of intermittent renewables and also with respect to peak/off-peak prices.

## Results

The explicit formulation of energy storage manager's bidding problem allows the explicit expression of the no-arbitrage conditions. Furthermore the numerical model first of all demonstrates the viability of this approach to valuing any energy storage units. The numerical analysis shows clear differences in the arbitrage value of an energy storage unit between these three markets. Even if the Danish energy system has the highest renewable energy source penetration, the Danish market represents the lowest arbitrage value. This is a direct result of the low peak/off-peak prices spread observed in Denmark where flexible energy production in interconnected neighboring countries is already absorbing much of the arbitrage value. The increase in solar production in Germany has reduced the peak/off-peak spread over time, and this is reflected in a decrease in arbitrage value for storage in Germany from 2012 to 2016.

## Conclusions

The increased penetration of intermittent renewable generation sources is placing electricity system under pressure with respect to price volatility and system security. Large scale storage may be needed in order to maintain system security, and could also represent profitable arbitrage opportunities. The analytical model proposed here is designed to represent the storage unit manager's decision problem when participating in a dispatch auction. The  model is also solved numerically, thus demonstrating the practical viability of this approach, and how this model can be used to assess the expected revenue stream from an energy storage unit.