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# The value of arbitrage for energy storage: Evidence from European electricity markets

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## HIGHLIGHTS

- We determine the value of arbitrage for energy storage across European markets.
- Price-taker pumped hydro and compressed air energy storage are employed.
- We apply different energy trade strategies and time intervals for a 5-year period.
- We also associate market characteristics with the value of arbitrage.
- Strategy selection and sizing directions are given for different-features markets.

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ABSTRACT

We use a portfolio of energy trade strategies to determine the value of arbitrage for pumped hydro and compressed air energy storage across European markets. Our results demonstrate that arbitrage opportunities exist in less integrated markets, characterized by significant reliance on energy imports and lower level of market competitiveness. We show that, among all strategies tested, arbitrage value maximizes for the weekly back to back energy trade strategy. Moreover we estimate the optimum size of energy storage systems in terms of arbitrage value for each different electricity market and evaluate the potential of arbitrage to support investment in the sector. Finally, it is argued that energy storage can take over multiple roles as a necessary positioning to facilitate financial profitability.



## 1. Introduction

The debate on what roles can energy storage support in the power sector and contemporary electricity markets has been prominent for more than a decade [1]. Despite the fact that such systems can provide a bundle of services [1,2], including avoidance of costly interconnecting infrastructure and emission reduction [3], investment remains limited due the absence of a concrete valuation framework and the high capital costs of most energy storage systems. Nevertheless, research on energy storage and its role in supporting increased integration of renewable energy sources (RES) has been intensive [4–14]. In this context, novel operation strategies that consider collaboration with RES challenge State support for energy storage through the production of social welfare effects [15–17]. Arguing that energy storage can take over multiple roles, our notion is that a portfolio of value-adding services [18–22] can produce further revenue streams; thus facilitate investment in the sector more effectively. Given that, the main scope of the specific paper is to determine what is the value of one such revenue stream, i.e. arbitrage, for grid-scale energy storage across European markets.

In economics and finance, arbitrage is the practice of taking advantage of a price difference between two or more markets: striking a combination of matching deals that capitalize upon the imbalance, the profit being the difference between the market prices. Arbitrage practiced by energy storage on the other hand refers to the application of energy trading strategies within an electricity market environment, aiming to buy energy from the

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grid at low price and sell it back to the grid at a meaningfully higher price; i.e. take advantage of spot market price spreads (between off-peak and peak demand hours) that can produce value, considering also energy conversion losses during the storage system operation. Similar research has been conducted in the past [20,23–26], yielding that arbitrage is not in itself adequate to support energy storage investments; thus welfare gains of energy storage services need to be identified in order to elicit State support [27–29]. Nevertheless, in most of these studies, comparison between the system operational cost and the arbitrage value is used as a measure of economic performance, disregarding capital costs and the system capacity factor. Furthermore, a serious limitation of this body of literature relates to study of exemplary cases which look at fixed system sizes (i.e. main system components are not allowed to vary in size), normally corresponding also to price-taker units,[1] along with one type of energy storage technology, e.g. pumped hydro storage (PHS), and a single power market examined, hindering in this way the generalization of conclusions.

To capture broader market and technology effects, examination of the arbitrage value across different European electricity markets is undertaken for PHS and compressed air energy storage (CAES), taking also into account variation of the system size. For this purpose, we use historical, hourly spot price data for the period 2007–2011, for the electricity markets of Nord Pool, EEX, UK, Spain and Greece. The selection of the specific markets aims to reflect differences in the value of arbitrage in association with market characteristics such as fuel mix and market competition. In terms of arbitrage strategies, we apply both time and price based signals on a daily and weekly time step. To this end, we estimate the arbitrage value and its net difference with the system electricity production cost. Moreover, in the case of price signals we also study variable system sizes and provide optimum size results concerning both the value of arbitrage and its net difference with the system production cost. Thus, innovation of the specific paper lies on the simultaneous study of four different arbitrage dimensions for energy storage, these referring to the different European power markets investigated, the different energy storage technologies examined, the variable size of energy storage system components considered and finally, the different energy trading strategies applied.

Following this introduction, the selected electricity markets are described in Section 2, while in Section 3 we analyze the applied methodology and arbitrage strategies. Sections 4 and 5 present the application results and discuss the association of the arbitrage value with market characteristics, energy storage technology and trading strategy used. The paper concludes with Section 6, where the main findings are critically presented.

## 2. European electricity markets

In order to capture different market characteristics we examine both regionally integrated and isolated electricity markets of different competition level, fuel mix characteristics (see also Fig. 1) and cross-border transmission capacity. More precisely, the markets of Nord Pool, EEX (European Energy Exchange), UK (APX), Spain and Greece were selected as representative examples.

### *2.1. The market of Nord Pool*

Nord Pool is the first and largest market for power trading in the world [30]. It comprises of the former Nordic markets (i.e. the Danish, the Finish, the Swedish and the Norwegian) that were deregulated in the early 90s to engage into an integrated new market along with Estonia and Lithuania deregulated in the late 2000s. The participation of different countries in that case ensures a liquid market environment that can handle extreme price events effectively [31] and provides a relatively diverse fuel mix. Nevertheless, electricity generation in Nord Pool is mainly based on hydropower and nuclear, with sufficient power exchange potential playing an important role (Fig. 1). Nord Pool facilitates large-scale wind energy integration in Denmark [32,33] and is highly competitive; thus, in the context of this paper, Nord Pool is used as an integrated, mature and highly energy secure market, with sufficient regulating and balancing ability deriving from its hydro and power exchanging potential.

### *2.2. The European Energy Exchange (EEX) market*

The EEX [34] was founded in 2002 from the merger of the two German power exchanges in Frankfurt and Leipzig. Later, in 2008, EEX entered a close cooperation with Powernext, during which both partners integrated their power spot and derivatives markets. EEX now holds 50% of the shares in the joint venture EPEX SPOT which operates the spot market for Germany, France, Austria and Switzerland. As a result, EEX comprises a diverse electricity market that is dependent on fuel imports in order to support nuclear power and natural-gas based generation. At the same time, it is a market that despite its considerable power exchange potential, suffers relatively frequently from extreme price events.

### *2.3. The UK market (APX)*

APX Power UK was established in 2000 as Britain's first independent power exchange [35]. In 2011, coupling with Netherlands – through the BritNed electrical cable – brought increased liquidity to the local market from the very liquid Power NL spot market and beyond from Germany, Belgium, France and Norway that also affected electricity prices. In the meantime, UK is increasingly dependent on primary energy imports [36,37] while presenting – until 2010 – little activity in electricity trade (see also Fig. 1). As a result, APX can be seen as a less integrated, highly competitive and import-dependent market which is in a transitional stage of decarbonising its fuel mix [38] and enhancing its electricity trade.

### *2.4. The Spanish market*

In 1998, Spain and Portugal formed the integrated, pool-structured Iberian market, known as Mibel [39]. Integration between the two markets has intensified over the years [40,41], resulting to minimum price differential explained by greater convergence of the two countries' fuel mix and the effectiveness of the cross-border trading mechanism. However, Spain does not enjoy equal interaction with neighboring European regions, with its cross-border transmission capacity to France limited to less than 2.8 GW. Moreover, the Spanish market suggests an ideal example of high RES contribution [42] with almost 1/3 of its total electricity generation coming from hydro, wind and solar energy. To facilitate this large-scale RES integration (mainly wind), natural-gas power plants are employed to provide the required flexibility, similar to the UK. Thus, Spain is a market of high RES contribution that depends on fuel imports and enjoys a close synergy with Portugal but limited connectivity to the rest of Europe.

### *2.5. The Greek market*

Greece although liberalizing its market in 2001 [43], comprises a deregulated market only by euphemism and should thus be studied as a monopoly. The local Public Power Corporation holds almost 85–90% [44] of the market generating capacity. In this

[1] A price taker is an investor whose buying or selling transactions are assumed to have no effect on the market.

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