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Dual technology energy storage system applied to two complementary electricity markets using a weekly differentiated approach

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ABSTRACT

This paper deals with integration of energy storage systems into electricity markets. We explain why the energy storage systems increase flexibility of both power systems and energy markets and why such flexibility is desirable, particularly when variable renewable energy sources are being used in existing power systems. As opposed to the existing literature, our model includes a dual technology energy storage system, acting in two different markets. We introduce a mathematical formulation for this model applied to two Dutch electricity markets. Adopting optimal control approach with the goal to maximize the yearly benefit, we show that the dual energy storage system can be profitable already when the same buying/selling strategies are adopted for the working days and weekends. We show that the profitability (slightly) increases with different buying/selling strategies for the weekdays and weekends. Finally, we demonstrate how the yearly benefit varies with size and efficiency of the devices chosen and market prices.

1. Introduction

1.1. Motivation, background and literature review

The worldwide energy policy goals include further integration of the renewable generation technologies into the energy markets. For example, the European Union is striving to achieve 20% of energy generated from renewable energy sources (RES) by 2020 and to reach a minimum of 27% of renewable generated energy by 2030, while reducing greenhouse gas emissions by at least 40% by 2030 compared to their level in 1990 [1]. Objectives for 2050 are even more challenging, with a reduction of the carbon emissions by 80–95% [2]. All around the world (e.g. in China [3], Japan [4], New Zealand [5], United States of America [6,7] and Turkey [8]) the power systems are being prepared for an increasing level of deployment of renewable generation technologies.

In conjunction with RES, the integration of other recent technologies, such as electric vehicles (EV), but also the unbundling and modification in the regulation of the power sector, influence the paradigm and structure of the power sector. As electricity has to be dealt with when generated, either by being consumed or stored, matching the levels of generation and load at all times is fundamental. The fact that most RES are weather-dependent will cause the generation output to vary more likely with the climate conditions than with the market needs. The increasing integration of electric vehicles also increases the likelihood of high load variations during the day. The novel technologies are expected to be applied to an extent which will certainly amplify the effect of these variations.

The above mentioned technological and regulatory developments call for adjustment of planning and operation of the power systems – they need to be more flexible. This flexibility can be achieved through several technologies and techniques (e.g. energy storage systems (ESSs'), cross-border interconnection capacity, RES management, more flexibility from conventional generation, active demand side management and vehicle-to-grid) and their combinations [9]. Among these, ESS is seen as one of the long term most feasible options to achieve that goal [10].

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ESSs can provide up to twice their rating (sum of charge and discharge capacities) to balance the electricity grid. This is accomplished by switching between the two modes of charging and discharging, in either direction (from charging to discharging or from discharging to charging). Therefore, ESSs help to balance the electricity system when there is a generation surplus or a deficit. ESSs can provide various services, most important of which belong to one of the two major categories:

- power market arbitrage
- ancillary services and balancing

Power market arbitrage is an energy service provided via charging an energy storage device when the electricity prices are low and discharging it when the prices are high [11]. The price variations are caused by daily, weekly or seasonal cycles. Lately, also variations in renewable power generation, e.g. wind and solar energy, are affecting the energy markets to a degree depending on their level of market penetration and the flexibility of the underlying conventional generation fleet. The most adequate markets exercising arbitrage are day-ahead and intra-day markets [12].

In unbundled markets, the system operators are not allowed to own energy generation assets. Therefore, they need to procure several ancillary services. Examples of these ancillary services are balancing support and congestion management.

Other services can be supplied by ESSs [6,7,11], depending on the characteristics of the specific energy storage technologies. The problem of energy storage integration into existing electricity markets was studied in [13–15]. The literature implies that in most markets, with current price differences, arbitrage provision is not sufficient to make energy storage profitable. Hybrid energy storage systems using two energy storage devices are present in the literature. However, these are associated with electric vehicle power system or variable renewable energy generation site integration into the grid [16]. Nonetheless, to the best of our knowledge, no models including two electricity markets and two ESS technologies operating in parallel have been developed so far.

This paper focuses on a combination of energy market arbitrage and provision of balancing support by the same dual energy storage system. The model that we introduce in this paper differs from the models analysed in the literature in two major aspects. Firstly, we consider a system combining arbitrage and ancillary services. With this combination we expect higher yearly benefits than using arbitrage only. Secondly, the energy storage system that we propose uses two energy storage technologies simultaneously. The dual technology system was chosen in order to profit from characteristics of both devices and market price variations. This paper extends our research presented in [17].

In order to see how profitable the ESS could be, in this paper we seek optimal strategy in terms of price thresholds for buying and selling electricity at the Dutch day-ahead and balancing electricity markets. Mathematically, we formulate the problem as an optimal control problem with the goal to maximize the yearly benefit. Firstly, we consider the situation when buying and selling thresholds may vary between working days and weekends. Secondly, we consider a situation when the working days and weekend thresholds are the same. We use pattern search to find the optimal strategy and motivate the choice of this method.

The remainder of this paper is composed as follows. Section 2 introduces electricity markets in The Netherlands. Section 3 explains the background of the model we put forward. The problem dealt within this paper is defined mathematically in Section 4. Implementation of the model and a solution method are described in Section 5. Section 6 presents and discusses the results of the case studies. Section 7 finalizes the paper with the conclusions and directions for future research.

1.2. Notation

Tables 1 and 2 describe the main symbols used in this paper.

2. Electricity markets in The Netherlands

In The Netherlands most of the electricity is still traded in the bilateral market, where the generation companies sell the electricity directly to large consumers, traders and supply companies. The remaining electricity generated is traded in one of the two spot markets: the day-ahead and intra-day markets. For balancing purposes also a dedicated market exists, managed by the Dutch transmission system operator (TSO) TenneT. The day-ahead and intra-day markets have distinct dimensions. For 2011, about 40 TWh of electricity were traded in the day-ahead market and less than 1% of that value, 278 GWh, were traded in the intra-day market [19]. The Netherlands has been identified as “the most promising [electricity market] for mass storage” [18].

2.1. Day-ahead market

The Dutch day-ahead market is active every day prior to the day of operation and closes at noon. This market has an hourly time unit. Unless stated differently, in this paper we use price data from 2014. For this year, we calculated the mean price of energy per MWh for the Dutch day-ahead market: 41.18 €/MWh. Fig. 1 depicts the average prices for 2014 and both day-ahead and balancing market. It is possible to observe the weekend variation in the day-ahead market in the last two days, where prices tend to be lower than during the weekdays.

2.2. Balancing market

Balancing markets are volatile, and are used to balance the unattended mismatch between generation and load. In The Netherlands, the balancing market, also called imbalance market, works with a time unit of 15 min. This unit is also called program time unit (PTU). This market is managed by TenneT, the national transmission system operator (TSO). The TSO tries to avoid the mismatch mentioned as much as possible by sharing balancing responsibilities with balancing responsible parties (BRPs). Each BRP aggregates a part of the consumers and generators in the network. The BRPs submit their daily zero-sum consumption and generation plans ex-ante. Each of these plans include their expected net energy exchange with the other BRPs to the TSO. Afterwards, in real time, the TSO verifies if there is any imbalance in the system.

There are two types of BRPs, those specifically asked to provide balancing capacity by active contributions (Balancing Service Providers – BSPs) and those either using the imbalance settlement system for their own imbalance or being active without being selected [20]. By bidding on the imbalance market, each BRP gives the TSO the right (but not the obligation) to buy balancing energy.

Load forecasting is not exact and energy generation forecasting with increasing integration of variable renewable-based generation is harder to achieve. Thus, the balancing market is used to solve these unexpected variations, by trading flexibility. Traditionally, this was achieved by increasing or decreasing generation [21]. Recently, whenever available, also demand side response and energy storage may be used [21], as long as the technologies used can cope with the response time required by the system operator.

The Dutch imbalance market has 4 possible modes: downwards, upwards, upwards/downwards and no contribution, which