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Investment decisions in imperfect power markets with hydrogen storage and large share of intermittent electricity

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ABSTRACT

This paper analyzes the impact of hydrogen as energy storage on production and investment decisions in an electricity market when individual participants behave strategically. We develop a game-theoretic model on investment and generation game à la Cournot under the open-loop information structure. This framework is implemented as a mixed complementarity problem and applied to the German case assuming the phase-out of the German nuclear power plants, rising renewable energy supply and increasing energy demand for electric vehicles. The numerical results of our analysis indicate that utilization of energy storage has a positive effect on energy systems with large amount of intermittent electricity and inelastic demand. We find that additional hydrogen storage capacities improve system reliability, increase overall welfare and decrease GHG emissions. Adding demand for hydrogen as a fuel for FCEVs allows for a synergetic use of the technology and changes the investment incentives for energy storage. Although the power-to-gas technology has a price-smoothing effect the overall generation capacity is higher with energy storage providing additional supply security in markets with a large amount of intermittent energy production.

Introduction

The power system in Germany is undergoing substantial change and is therefore challenged in many ways. This is due to a number of crucial developments, ranging from market liberalization to increasing renewable electricity generation. On the one hand, competitive market structures could give rise to an exertion of the market power of large suppliers and not necessarily provide sufficient investment incentives for new generation capacities. According to many studies, e.g. Refs. [1] or [2], typical features of electricity markets such as concentration of production capacities on only a few market participants, also inelastic demand, expensive storability, and grid constraints are recognized as potential sources for the abuse of market power. Although the research on current exploitation of market power in Germany provides ambiguous results the impact of oligopolistic market structure on the investment behavior under future boundary conditions is an interesting research area.

On the other hand, intermittent electricity generation from renewable sources such as wind and solar power poses new challenges to the electricity system stability due to the limited predictability and seasonality of the weather-related feed-in, as well as to transmission congestion. This is further exacerbated by efforts to promote sustainable mobility and the

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corresponding additional energy demand of electric vehicles. These challenges can potentially be addressed by taking advantages of different flexibility options such as electrolytic production and storage of hydrogen as a universal energy carrier in the mobility and power sectors.

However, one important drawback of many studies on the economics of hydrogen production and storage is represented by the assumption of a sufficiently small firm which has no influence on the underlying electricity price. In reality, from the perspective of the power system, storage technology typically has a price-smoothing effect, as it increases low electricity prices through additional demand in off-peak periods and decreases high electricity prices through supply in peak-load periods (see e.g. Ref. [3]). In addition, due to the limited number of market participants, single firms might exercise market power and behave strategically when making investment and production decisions.

In this paper, we analyze the role of energy storage, in particular hydrogen storage, and peak-load power plants in an electricity system where market participants behave strategically. We develop a game-theoretic market model for capacity investment and electricity generation under an oligopolistic market structure á la Cournot, and apply it in the context of the German power market. We assume phase-out of nuclear power plants and a large amount of intermittent electricity feed-in according to the plan of the German Federal Government [4]. In peak-load hours when renewable supply is not sufficient to meet the demand, electricity is provided either by the peak-load power plants or by discharging energy from the storage plants. In this context, we are interested in optimal sizing and operation of different peak-load and storage technologies by the various market participants and the corresponding effects on market prices, social welfare, and GHG emissions. As argued by Sioshansi [5], comparing the results for different market and ownership constellations might help to develop important guidelines for policy decision in regard to the role of energy storage in the future energy system. Hence, the analysis is conducted for different market (perfect and imperfect competition) and storage ownership structures (storage owned by one player versus by all players). Moreover, we study the impact of additional demand from the mobility sector on the overall market results. In the next chapter we provide a literature review on storage utilization and capacity expansion in imperfect power markets. In the third section we formulate a game-theoretic market model, which is then applied in the fourth section in a case study in the context of the German market in a long-term perspective. In the fifth section we discuss the results whereas the sixth section concludes our study.

Literature on storage sizing and operation under a game-theoretic framework

The literature related to strategic utilization of electricity storage in the context of optimal sizing and operation can be subdivided into two major streams. On the one hand, the literature on storage operation typically analyzes optimal production decisions and their impact on market results under imperfect competition from the short-term perspective, such as a single week or month assuming given storage capacities. On the other hand, the capacity expansion literature focuses on investment games between strategic firms, from the long-term perspective (e.g. several years) and neglecting short-term intertemporal production constraints such as storage charging and discharging.

The analysis conducted in Ref. [5] belongs to the first stream of literature. The author proposes a stylized two-period model á la Cournot in order to investigate welfare effects of electricity storage under different market and ownership structures. He finds that stand-alone storage increases social welfare under perfect competition between all other generators, but might have a negative welfare effect when other market participants behave strategically. Moreover, storage operated by market participants with other production capacities might also decrease social welfare, however, this effect depends on the overall storage capacity installed, in comparison to the market size.

The study in Ref. [6] calculates the value of storage and welfare changes when storage is utilized by a wind generator to mitigate price-suppressing effects of intermittent feed-in. The proposed approach is defined as a Stackelberg type supply function equilibrium model with two stages including wind storage optimization and generation response of all other market participants. The author reports positive storage value, which, however, diminishes with rising wind capacity. In comparison to a case without storage, profits from wind generation increase on the one hand but the welfare of conventional generators and consumers decreases on the other. Since the latter effect is stronger than the former, the overall welfare is also lower when storage is in operation. The results are sensitive in respect to storage efficiency, level of market competition and storage ownership structure.

In Ref. [7] the authors develop a detailed model for storage operation under the Cournot oligopoly market structure. It is formulated as a mixed complementarity problem (MCP), which takes into account exact intertemporal relationship between storage input and output decisions as well as ramping constraints of conventional power plants. The model is applied to the German power market for two representative weeks assuming various ownership structures of given storage capacities. According to the analysis, pumped-hydro storage (PHS) operation has a price-smoothing effect and increases overall social welfare. The authors find that strategic behavior leads to underutilization of storage capacities and lower welfare in comparison to the non-strategic case. Both effects are further exacerbated by an uneven distribution of storage capacities among different players. The analysis also shows that under the assumptions of the case study, consumers' rent increases but producers suffer from welfare losses for all market and ownership structures due to storage utilization. It is worth mentioning that on the one hand the producer rent of the firm operating the storage increases due to additional arbitrage profits, but on the other hand all other conventional generation units are worse off due to the price-smoothing effect of the storage. Since the latter effect is stronger than the former, the overall producer rent decreases when storage is introduced to the market.

A similar methodology is also proposed by Bushnell [8], who applies a Cournot oligopoly model to the electricity market in the western United States. However, the

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