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Investment incentives for flexible demand options under different market designs☆

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ABSTRACT

This paper analyzes investment incentives for flexible manufacturing facilities under different market designs. We propose a multi-stage equilibrium model incorporating endogenous determination of generation capacity investment, network expansion and redispatch based on the model introduced by Grimm et al. (2016), including flexibilization of industrial electricity consumption. The model allows to investigate incentives for flexibilization and the impact of flexible industrial electricity consumers on the system. An application to the German electricity market reveals that flexible industrial electricity consumption can be profitable for firms. If the share of flexible electricity consumers is high, price fluctuations are mitigated, which lowers the individual cost savings from demand flexibility. Comparing different market designs, positive impacts of flexible electricity demand on the system are observed in both the system optimum and the market equilibrium. In scenarios with flexible industrial electricity consumption, welfare is considerably higher than in those without. This is due to lower electricity costs of industrial consumers, but more importantly due to less investment in conventional power generation as well as a reduced transmission network expansion. However, a comparison of nodal and uniform pricing underlines the importance of regional price signals with respect to an efficient allocation of flexible industrial demand.

1. Introduction

Due to the growing share of renewable energy, the German electricity market is changing from a demand-side driven market to a supply-side driven system. In this context, a transition to a flexible electricity demand in order to benefit from price fluctuations could be attractive. This does not only concern demand side management (DSM) for private households but also industrial electricity consumers that account for a share of 44% of Germany's gross electricity consumption (cf. Grave et al., 2015). Several contributions exist that analyze the DSM potential of different industries. They point out that especially the aluminium and chlorine electrolysis, electric steel, paper and cement industry and refineries have a high potential for integrating flexibility in their production process (cf. e.g. Langrock et al., 2015 and Paulus and Borggrefe, 2011). Additionally to lower electricity costs for flexible consumers, an adequate demand response in the industrial sector could also enhance network stability, increase the efficiency of electricity production and even reduce the need for further transmission line expansions (cf. Strbac, 2008).

It is important to notice that if flexible industrial electricity consumption (IEC) is carried out on a large scale, price fluctuations might be mitigated. This can in turn lead to a reduction of profitability of flexible IEC for the industry sector. Therefore, it is important to not only analyze short-term incentives for flexible IEC, but also to examine the long-term effects of a large scale IEC flexibility on the electricity market as a whole. For a long-term analysis of market interaction, our goal is to develop a model that answers the following questions: What is the impact of flexible IEC on price fluctuations? How should the current transmission network be expanded taking into consideration a large scale demand response? What is the effect of flexible IEC on investment in generation capacity? Which market design is most favorable in order to create incentives for flexible IEC?

In the paper at hand, we provide answers to these questions using a model that allows us to assess the long-run impact of flexible IEC on liberalized electricity markets. In a first step, we analyze a setup where we focus on the profitability of investing in a flexible production process. Our results reveal that flexible IEC leads to considerably lower electricity costs compared to a scenario without flexible IEC. Further, we analyze the impact of flexible IEC for different industry sizes. We obtain the result that flexible electricity consumption of a relatively

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small industry has a negligible impact on wholesale electricity prices, while flexible IEC of a relatively large industry does lead to a smoothing of the distribution of electricity spot prices. This, however, leads to decreasing incentives for flexibilization with a growing share of flexible IEC units. Furthermore, average electricity prices increase with a growing share of flexible IEC units, which leads to higher electricity expenses for inflexible IEC units. When evaluating investments in flexible production processes, one should thus not only consider the lower electricity costs that occur due to flexible IEC, but also the additional electricity expenses for inflexible IEC units.

In a second step, we analyze the effect of flexible IEC units on the electricity market. We consider a market equilibrium in an electricity market with a single price zone. In our model, a transmission system operator decides on network expansion and private firms decide on generation investment. Hourly spot market trading is carried out thereafter without taking into account network restrictions. In case the quantities traded at the spotmarket are not technically feasible, any congestion is resolved by the TSO via cost-based redispatch. We compare this case to a first best benchmark, where an integrated planner decides about transmission expansion, investment in generation capacity, and spot market trading simultaneously. For both settings, we find that if the share of flexible IEC units is large enough, this has large positive effects on the overall system. Welfare is generally higher in scenarios with flexible IEC due to lower electricity expenses of flexible IEC units, as well as less investment in conventional generation expansion, as there is less consumption in peak-load periods with high prices.

As flexible IEC units are able to absorb fluctuations in electricity generation, a large share of flexible IEC units could even be an alternative to further transmission line expansion, if located at the right spots. We therefore examine another scenario, where the location of flexible IEC units is determined optimally in the model. This, however, only makes sense for the first best benchmark, as in the original setting, network restrictions are not taken into account for spot market trading. Applying the resulting optimal locations determined in the first best benchmark to the market equilibrium, we also examine the case of optimal locations for flexible IEC units in this scenario. The results demonstrate that in a market with locational price signals, flexible consumers would be located in the north of Germany, where there is a concentration of wind power plants. In this case, flexible consumers could absorb fluctuations in electricity generation when they occur, meaning that less network is necessary to transport the produced electricity to demand centers. Welfare is thus highest in the scenarios with an optimal allocation of IEC units.

Our analysis demonstrates the large potential of flexible IEC for industries as well as the electricity market itself. It does not only lead to considerably lower electricity expenses for flexible consumers, but also to positive effects concerning investment in generation and transmission capacity. However, the right locational incentives are crucial in order to achieve these positive effects. Overall, our results underline the importance of an analysis of the long-term effects of flexible IEC on prices and investments when assessing its potential.

1.1. Literature

Different strands of literature are of interest with respect to the potential of flexible IEC.

First of all, there are empirical approaches that analyze the technical and socio-technical flexibility potential of different industries. Some of them point out the high potential of flexible IEC in industries with electricity intensive production processes (cf. e.g. Langrock et al., 2015; Shoreh et al., 2016). Moreover, various studies assess responsiveness of household consumers to fluctuating retail prices (cf. e.g. Filippini, 2011; Wolak, 2011; Thorsnes et al., 2012). Typically, those studies rely on observed consumption data and assess preferences of households based on an econometric analysis of observed consumption decisions under different pricing regimes.

Various contributions analyze flexibilization of electricity consumption in specific industries in a bottom up analysis for given market conditions. These studies consider flexibilization of specific processes and provide cost minimizing production plans, assuming that electricity prices are exogenous (cf. e.g. Lou et al., 1998; Ashok and Banerjee, 2001; Ashok, 2006). Conejo and Morales (2010) propose an optimization model to adjust the hourly load of a given consumer in response to hourly electricity prices. They also present a robust approach to account for price uncertainties. Feuerriegel and Neumann (2016) compare the benefit of load shifting, control reserve and balancing energy in the German market. They find that load shifting implies the highest benefits for both households and industrial consumers. Summerbell et al. (2017) develop a flexible production schedule reacting to fluctuating electricity costs. In a case study, they quantify the potential savings of a cement plant due to flexibility. All studies reveal a significant potential for cost reduction from flexibilization of IEC. However, the feedback of flexible IEC on overall market outcomes, such as equilibrium prices as well as investment in generation capacities and network expansion, are not considered in those models. As one consequence, predicted cost savings might be estimated too high.

Another large strand of the literature focuses on an overall system perspective by analyzing the ideal size, location and operation of IEC and their implications for the remaining energy system including production facilities and network. Several articles in this context focus on the short run perspective, e.g. Göransson et al. (2014) and Zerrahn and Schill (2015). Other contributions analyze the impacts of IEC on investment decisions in a system optimum. Paulus and Borggrefe (2011), for example, assess the long-term effects of demand-side management in energy intensive industries on market prices, dispatch and investments in electricity markets. Fehrenbach et al. (2014) analyze the economic potential for thermal load management within the residential sector.

Models focusing on the system optimum are useful, since they provide insights on the optimal investment and production decisions that would be taken by an integrated planner. However, in liberalized electricity markets, different agents decide on investment in generation capacity on the one hand, and transmission line expansion on the other hand. An analysis of this setup requires models that reflect this sequence of decisions in a market environment. Several contributions, such as Baringo and Conejo (2012) and Jenabi et al. (2013), explicitly analyze market interaction in liberalized electricity markets. To the best of our knowledge, however, there are no contributions, which explicitly consider the scope of flexible IEC. Grimm et al. (2016) and Grimm et al. (2017c) propose a trilevel market model that allows to analyze the long-run impact of electricity market design on both transmission line and generation capacity expansion.

The analysis in this paper is based on the model developed in Grimm et al. (2016). We extend it by the possibility to invest in flexibilization of IEC. This is important in order to investigate the long-run effects of demand flexibility on the electricity market. Further, it allows to quantify the trade-off between network expansion and flexibility of electricity demand, which can both be measures to reduce grid congestion.

1.2. Outline of the paper

The remainder of this paper is structured as follows. In Section 2 we explain our idea of flexibilization of the industrial production process and how we integrated this into the existing electricity market model developed in Grimm et al. (2016). We then present the scenarios we consider for our analysis of the German electricity market in Section 3, where we also refer to the data we use for calibrating the model. In Section 4, we first present results on the profitability of flexible IEC for individual firms, before we quantify general market impacts and locational effects. We conclude with a summary of our findings in Section 5,