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Benefits of coordinating congestion management in electricity transmission networks: Theory and application to Germany

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ABSTRACT

This article analyzes the coordination of congestion management in the electricity grid and identifies the benefits from closer cooperation among Transmission System Operators. Mimicking the German situation with four Transmission System Operators in charge of relieving grid congestion, in particular by redispatch of power plants, we set up a model with shared transmission network constraints. Through different valuations of these constraints we consider cases of coordination. Based on a Generalized Nash Equilibrium model, we suggest an intuitive approach to introducing coordination. An application to German data provides evidence that more coordination is beneficial, providing channels through which redispatch volumes and specific costs are influenced. We discuss implications of our results for security of supply and network expansion.

1. Introduction

Incorporating increasing shares of renewable energy in the electricity generation portfolios of many countries requires adjustments across the entire electricity system. For instance, markets and their underlying procedures must be redesigned to allow for the integration of intermittent or variable generation. Furthermore, transmission of electricity to load centers becomes more important in two aspects. First, the geographical location of renewable resources (in particular wind and solar) and thus their spatial generation pattern depend on natural conditions. Second, renewable capacities are installed in a more decentralized fashion than conventional thermal generation units. Both aspects result in new requirements on the transmission network to transport electrical energy from generation to load centers. In the long term, the transmission infrastructure[1] can be reshaped in order to meet changing requirements and eventually yield an efficient integration of renewable energy generation. In the short term, however, the transmission network is determined by the existing infrastructure. Hence, the capacity of the existing transmission network may not always be sufficient to transport the demanded amount of electrical energy. Congestion occurs when the requested transmission capacity exceeds the available capacity of the existing network.

One method to alleviate line overflows is the redispatch of power plants. To this end, a transmission system operator (TSO), or any other entity in charge of managing the network, alters nodal generation or demand to achieve a feasible flow pattern in the given electricity network. Put abstractly, if a particular line is congested from north to south, lowering generation in the north and increasing generation in the south can reduce the flow on that line until it is below the capacity limit. At the same time, overall load must stay constant; thus other plants might have to alter output as well until all adjustments level out.

In this article we analyze how the coordination of redispatch among different TSOs can be beneficial. To this end, we set up a model in which different TSOs have the objective of providing a cost-minimal redispatch to eliminate line overflows. In meshed alternating current (AC) transmission grids, electricity flows cannot be distinctly directed through specific lines. These so-called loop flows are not constrained by administrative borders and thus influence neighboring transmission networks. At the same time, TSOs draw on different resources but may be responsible for feasible

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[1] Throughout this article, we analyze high-voltage infrastructure for inter-regional transport of electricity; for Germany covering voltage levels above 220 kV.

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flows on identical lines. We introduce different degrees of coordination by varying these responsibilities for parts of the grid. Formally, this is achieved by a multiplicative decomposition of shadow variables in the arising Generalized Nash Equilibrium (GNE) framework.

Our approach is motivated by the situation in Germany where four TSOs are in charge of network management in four different geographical areas. The framework and model could, however, be also applied to other congestion management settings requiring coordination. Our central result is in line with expectations. More coordination entails higher efficiency. A higher degree of coordination allows access to cheaper units, thus lowering specific costs. At the same time, maintaining zonal balances influences redispatching volumes. We discuss the implications of our results for supply security and network expansion.

The contribution of this article is twofold: first, building on an equilibrium model developed in Oggioni et al. (2012), we suggest an intuitive approach to solving the formal class of problems arising in this application. The approach is based on multiplicatively decomposing the multipliers of shared constraints, while at the same time introducing degrees of coordination. Second, in our application we illustrate the benefits of coordinating congestion management in Germany using a detailed representation of the German transmission grid and generation portfolio, as well as discussing channels through which coordination results in more efficient outcomes.

The remainder of this article is structured as follows. Section 2 gives an overview of the academic literature on congestion management and coordination issues. Section 3 introduces the economic redispatch model that captures the issue of coordinating congestion management among multiple TSOs. Section 4 describes the application of the model to a dataset covering the German electricity system. We present our results in Section 5 and discuss them in Section 6. Finally, Section 7 concludes.

2. Literature on congestion management and coordination

Generally, congestion management comprises all methods of dealing with limited transmission capacities from an operational perspective. Methods have been developed to ease line overflows either using technical or economic procedures. Kumar et al. (2005) provide a literature survey on congestion management methods in deregulated electricity systems, finding that technical measures increase capacity by adjusting load flows in the transmission network through specific devices[2], thus avoiding changes in demand and generation. On the other hand, economic methods rely on adjusting nodal feed-ins or extractions to reduce line overload.

Those latter methods can be divided into preventive and curative methods based on their timing within the market-clearing process. Preventive measures are applied before or during the clearing of the daily electricity markets, while curative methods are applied after final market clearing. Explicit and implicit auctions are exemplary preventive congestion management methods. They are applied, for instance, in central Western Europe for allocating cross-border transmission capacity in the market coupling scheme and in the US regional market of PJM (Pennsylvania–New Jersey–Maryland) using a nodal pricing approach. Curative congestion management includes the redispatch of power plants based on the final market commitments, and counter-trading. These methods are applied within many national electricity markets in Europe to manage internal congestion.

Regarding the economic evaluation of these methods, de Vries and Hakvoort (2002) show that both preventive and curative congestion management are equally efficient in the short term. Ding and Fuller (2005) analyze the economic effects of different pricing and congestion management regimes on the Italian electricity system, finding that generation costs are identical among the investigated regimes, but the distribution of benefits and costs among market participants differs.

On a European scale, the issue of a coordinated congestion management approach among zones or markets is discussed in Ehrenmann and Smeers (2005) and Perez-Arriaga and Olmos (2005). Comparable analyses are performed in Kunz (2012) and in Neuhoff et al. (2013) for the German and European electricity systems, respectively. These latter studies identify cost savings from adjusting congestion management regimes from national curative redispatch to a perfectly coordinated nodal pricing regime.

In a similar fashion, Chaves-Avila et al. (2014) find that congestion across network areas may cause the current German imbalance pricing scheme to give flawed incentives toward increasing system imbalances and create undue arbitrage opportunities. Greater coordination, taking account of the peculiarities of cross-zonal balances, entails efficiency gains in this respect. More generally, Brunekreeft (2015) underlines the importance of coordination among market players on or across different levels of the value chain in the electricity sector. Lessons from vertical unbundling and optimal network charging point to substantial efficiency gains from less fragmentation, be it through long-term or short-term incentive structures.

The issue of coordination in congestion management among different transmission system operators is formally investigated in Oggioni et al. (2012). The authors develop a GNE model that reflects different degrees of coordination among regional TSOs. Applications in Oggioni and Smeers (2012, 2013) to stylized electricity systems show that the degree of coordination in congestion management affects redispatch costs. In this study, we build on the equilibrium model developed in Oggioni et al. (2012), while addressing the implications of the Generalized Nash property of the model, and apply it to a large-scale dataset for Germany.

3. The model

Our model consists of two stages: first, in the pre-stage, the electricity spot market is cleared by equalizing supply and demand in a cost-minimizing fashion without taking network limitations into account. Thereafter, in the main stage, plants and load are redispatched to correct for network infeasibilities that potentially may have emerged. Our focus lies on this congestion management stage.

Here, the network is divided into several non-overlapping geographic zones. For each zone, there is a TSO in charge of relieving congestion. Within this basic framework, we analyze three cases of coordination. First an *unrestricted case* provides a benchmark in which one single TSO is responsible for congestion management in an integrated network across all zones. Second, a *restricted coordinated* case involves one TSO for each zone, restricted to resources within its own zone, but responsible for feasible flows on all lines in the system. Third, a *restricted uncoordinated* case involves one TSO for each zone, restricted to resources within its own zone and responsible only for feasible flows within its own zone.

Beyond the benchmark case, we thus separate the ability to conduct congestion management from the responsibility to do so; restricted to resources within their own zone, TSOs must

[2] For example FACTS, phase-shifting transformers, and switching of transmission lines.