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Cross-border effects of capacity mechanisms in interconnected power systems

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ABSTRACT

The cross-border effects of a capacity market and a strategic reserve in interconnected electricity markets are modeled using an agent-based modeling methodology. Both capacity mechanisms improve the security of supply and reduce consumer costs. Our results indicate that interconnections do not affect the effectiveness of a capacity market, while a strategic reserve is affected negatively. The neighboring zone may free ride on the security of supply provided by the zone implementing a capacity mechanism. However, a capacity market causes crowding out of generators in the energy-only zone. A strategic reserve implemented by this region could aid in mitigating this risk.

1. Overview

The growing penetration of intermittent renewable resources is leading to concerns regarding the security of supply and generation adequacy in the European Union (EU). These concerns revive and add to the existing debate about the security of supply of electricity markets (Borenstein and Bushnell, 2000; Brown, 2001; De Vries, 2007; De Vries and Hakvoort, 2003; Hesmondhalgh et al., 2010; Hreinsson, 2006; Joskow and Tirole, 2007; Pérez-Arriaga, 2001; Stoft, 2002; Woo et al., 2003). Consequently, the debate is reopened in the remaining energy-only markets in Europe whether to implement a capacity mechanism. Capacity mechanisms are policy instruments for ensuring adequate investment in generation capacity; in Europe, they are also called capacity remuneration mechanisms. The arguments for and against implementing capacity mechanisms have been described extensively in the literature (Chao and Lawrence, 2009; Cramton et al., 2013; De Vries, 2004; Hobbs et al., 2001; Joskow, 2008a; Stoft, 2002), but variable renewable energy resources add a new dimension to it.

In the EU, the decision whether to implement a capacity mechanism and its design and implementation are left to the discretion of the member states. The UK has recently implemented a capacity market (DECC, 2014) while France will do so in the near future (RTE, 2014). Belgium, Sweden, and Finland make use of strategic reserves. Germany may implement a capacity reserve but decided against a full-scale capacity market for the near future (BMWi, 2014). In a highly interconnected system, such as the continental European electricity system, an apparent risk is that the uncoordinated implementation of capacity mechanisms could reduce economic efficiency and even negatively affect the security of supply in neighboring systems (Pérez-Arriaga, 2001; Elberg, 2014; Tennbakk, 2014; Finon, 2015; Gore, 2015; Mastropietro et al., 2015; Meyer and Gore, 2015; Bhagwat et al., 2016a; Bhagwat, 2016). We utilize an agent-based model to analyze the effectiveness of capacity mechanisms in interconnected systems. We also study the cross-border effects on prices, investment and security of supply that they may cause. We expand EMLAb-Generation, an existing agent-based model of electricity markets, by modeling a strategic reserve and a capacity market.

2. Model description

2.1. EMLab-generation

The EMLab-Generation agent-based model (ABM) was developed to model questions that arise from the heterogeneity of the European electricity sector and the interactions among different

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policy instruments (De Vries et al., 2013; Richstein et al., 2015a, 2015b, 2014). The model provides insight into the simultaneous long-term impacts of different renewable energy, carbon emissions reduction, and resource adequacy policies, and their interactions, on the electricity market.

Power generation companies are the central agents in this model. The behavior of the agents is based on the principle of bounded rationality (as described by Simon (1986)); that is, the decisions made by the agents are limited by their current knowledge and their limited understanding of the future. The agents interact with each other and other agents via the electricity market and thereby bring about change in the state of the system. Consequently, the results from the model do not adhere to an optimal pathway and the model is typically not in a long-term equilibrium. The model thus allows us to study the evolution of the electricity market under conditions of uncertainty, imperfect information, and non-equilibrium.

In the short term, the power generation companies make decisions about bidding in the power market. Their long-term decisions concern investments in new capacity and decommissioning of power plants. The model resembles a cost-minimizing model in which investments are based on expected costs, as we did not program behavioral differences in the agents' algorithms. The only difference among the agents develops in the state of their finances during the simulation: agents that made bad investment decisions have less money to invest in later years. By having multiple agents with different financial resources, the effects of negative returns due to over investment develop more gradually than if it had been a cost-minimization model with a single investment decision.

The main external drivers for change in the model are fuel prices, electricity demand growth scenarios, and policy instruments such as capacity mechanisms. The main outputs are investment behavior and its impact on electricity prices, generator cost recovery, fuel consumption, the evolution of the supply mix, and system reliability.

The model provides the functionality for conducting an analysis of an isolated electricity market as well as an interconnected electricity system. The representation of an interconnected system is limited to two zones with an interconnector. As the objective of this paper is to understand the evolution of the electricity market over the long-term, all scenarios consist of 40-time steps, each of which represents one year.

The overview of the model activities during a time step is presented in a flowchart in Fig. 1. At the start of each time step the power generation companies make annual loan repayments (if any) for their set power plants. In the next step, power generation companies submit price-volume bids to the electricity market for all available power plants. This is followed by electricity market clearing. Once the market is cleared, the power generation companies purchase fuel for their power plants, pay for the operation and maintenance costs of all their power plants and receive payment for the energy sold on the electricity market. In the last step, power generation companies make decisions regarding investment in new capacity and dismantling of existing power plants.

A detailed description of EMLab-Generation has been presented in various reports (De Vries et al., 2013), scientific literature (Bhagwat, 2016; Bhagwat et al., 2016b; Richstein et al., 2015a, 2015b, 2014) and also in an earlier doctoral thesis (Richstein, 2015). In the next section, the structure of the model is described in detail followed by the input assumptions, model outcomes, and model limitations.

2.2. Model structure

2.2.1. Demand

In this model, a single agent procures electricity on the behalf of all consumers. Electricity demand is represented in the form of a step-wise abstraction of a load-duration curve. In this approach, empirical load data is approximated by a step function consisting of segments with variable length in hours (see Fig. 2). Thus each segment of the load duration curve has an assigned load value and a time duration, which is set as part of the initial input scenario. In each time step of the simulation, the load value for all segments is updated based on the exogenous demand growth rate. These segments have also been called "load blocks" or "load levels" in literature (Wogrin et al., 2014).

This approach for representing demand in electricity market models has been utilized for power system modeling since the 1950s, especially for medium and long-term models (Wogrin et al., 2014). The most important advantage of using this approach is that it allows for a shorter run time, enabling a larger number of simulations within a practical time frame (Richstein et al., 2014). However, due to the loss of temporal relationship between load hours, short-term dynamics such as ramping constraints and unplanned shutdowns cannot be modeled (Wogrin et al., 2014).

2.2.2. Electricity market clearing

The electricity market is modeled as an abstraction of an hourly power system (Richstein et al., 2014). Within a one-year time step, the electricity market is cleared for each segment of the load-duration curve. Therefore the segment-clearing price is considered as the electricity price for the corresponding hours of the particular segment. The load-duration curve is divided into 20 segments. When the model is run in a two-zone configuration, each zone has its own separate load-duration curve.

The power generation companies create price-volume bid pairs for their controllable (thermal) power plants for each segment of the load-duration curve. (Variable renewable energy generation is treated differently, as described in Section 2.2.5.) The power generation companies bid their power plants into the market at their marginal cost of generation, which is determined solely by the fuel costs. The volume component of the bid is based on the capacity of the available power plants. Power plant outages are not modeled, availability is assumed to be 100%. The supply curve for each segment is constructed by sorting the bids in ascending order by price (merit order). The electricity market is cleared at the point where demand and supply intersect. The highest accepted bid sets the electricity market-clearing price for that segment of the market. If demand exceeds supply, the clearing price is set at the value of lost load (*VOLL*).

In the two-zone configuration, the market clearing algorithm that is described above is run together for both zones assuming that there is no congestion between the zones. This results in a single price for both zones. If the interconnector is congested (that is, the flow over the interconnector exceeds the interconnector capacity) the two markets are cleared separately (market splitting). In the zone that exports electricity, the demand is increased up to the level where the interconnector is completely utilized. The demand in the importing zone is reduced by the same amount. As a result, the market-clearing prices for the given segment in the two zones are based on the modified demand values.

2.2.3. Investment algorithm

The investment behavior of the power generation companies is based on the assumption that investors continue to invest up to the point that it is no longer profitable. In this model, power generation companies invest only in their own electricity markets thus entry