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Decision Support

Technology selection and capacity investment under uncertainty

Tiago Pascoal Filomena [a,*], Enrique Campos-Náñez [b], Michael Robert Duffey [b]

[a] Management School, Federal University of Rio Grande do Sul, Washington Luiz Street, 855, 90010-460 Porto Alegre, Brazil
[b] Dep. Eng. Mgmt. and Systems Engineering, The George Washington University, Washington, DC, United States

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ABSTRACT

We analyze the problem of technology selection and capacity investment for electricity generation in a competitive environment under uncertainty. Adopting a Nash-Cournot competition model, we consider the marginal cost as the uncertain parameter, although the results can be easily generalized to other sources of uncertainty such as a load curve. In the model, firms make three different decisions: (i) the portfolio of technologies, (ii) each technology's capacity and (iii) the technology's production level for every scenario. The decisions related to the portfolio and capacity are ex-ante and the production level is ex-post to the realization of uncertainty. We discuss open and closed-loop models, with the aim to understand the relationship between different technologies' cost structures and the portfolio of generation technologies adopted by firms in equilibrium. For a competitive setting, to the best of our knowledge, this paper is the first not only to explicitly discuss the relation between costs and generation portfolio but also to allow firms to choose a portfolio of technologies. We show that portfolio diversification arises even with risk-neutral firms and technologies with different cost expectations. We also investigate conditions on the probability and cost under which different equilibria of the game arise.

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1. Introduction

The restructuring of the electricity sector into a competitive market requires changes in generators' investment policies. In a non-competitive environment in which companies had fewer interactions with respect to technology portfolio and capacity decisions, traditional optimization techniques were enough to address typical power investment problems. However, in a competitive setting, one company's decision has a significant impact on its competitors; for instance a capacity expansion decision can directly affect market prices. Consequently, game theoretical techniques in which strategic interaction between agents are taken into consideration are more suited to analyze generation investment policies for restructured electricity markets. Moreover, perfect competition may not be the most appropriate way to model the power sector given market concentration. An oligopolistic environment in which firms can exercise some market power is more suitable. Thus, the design of electricity generation investment policies needs to accommodate the characteristics of this restructured environment.

However, competition is just one issue which impacts the complexity of electricity investments. Cost uncertainty is a major component of investment problems and many factors can contribute to that. The uncertain status of greenhouse gases emission abatement programs is certainly one of them. These programs have been discussed around the world and have uncertain global implementation. Among the mechanisms available, emissions tax and cap-and-trade are the most common. Independent of which mechanism is implemented, these programs have significant impact on marginal production costs. The high volatility of fuel prices is another major cost factor, as evidenced by recent natural gas prices. Furthermore, the different demands that firms face during different seasons of the year, days of the week and even periods of the day are inherent features of electricity markets. Thus, it is difficult to argue for a model of investment in electricity markets without considering cost and demand uncertainty.

Recently, Banal-Estañol and Micola (2009) investigated the relationship between diversification in electricity portfolios and electricity prices. If we assume that there is some relation between the portfolio of generation technologies and market prices, then it becomes worthwhile to explore the relation between technologies' cost and the generation portfolio in equilibrium. Power generation corporations, in general, have multiple technologies in their portfolios; for instance coal, gas, nuclear and others. Thus, there is no reason to constrain the firm's choice to one or the other technology when electricity generation investment policies are evaluated. An electricity competition model should allow firms to have more than one technology in their portfolio.

Considering these features of the electricity sector, we address technology and capacity investment problems faced by electricity

* Corresponding author. Tel.: +55 51 3308 3694.
E-mail addresses: tpfilomena@ea.ufrgs.br (T.P. Filomena), ecamposn@gwu.edu (E. Campos-Náñez), duffey@gwu.edu (M.R. Duffey).

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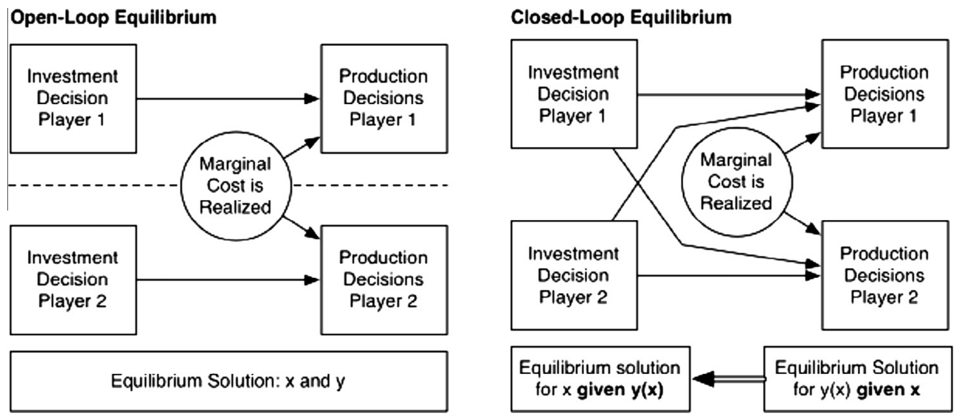

Fig. 1. Open-loop versus closed-loop game.

generators in a competitive environment and under uncertainty. We allow firms to exercise market power in an oligopoly à la Cournot. Our results are general to problems with uncertain marginal costs and different inverted demand curves (load curve), but we focus the discussion on marginal cost uncertainties. Our aim is to understand the relationship between different technologies' cost structures and the generation portfolio of technologies adopted by firms in equilibrium. For a competitive setting, to the best of our knowledge, our paper is the first not only to explicitly discuss the relation between costs and generation portfolio but also to allow firms to choose a portfolio of technologies. We assume that firms have similar efficiency levels, then they will also experience similar investment and marginal costs for the same technology.

In our model, firms make three different decisions: (i) the portfolio of technologies, (ii) each technology's capacity and (iii) each technology's production level for every scenario. The decisions related to the portfolio and capacity are ex-ante and the production level is ex-post to the realization of uncertainty. We consider the marginal cost as the uncertain parameter, although our results can be generalized easily to other sources of uncertainty such as a load curve. We start our discussion using a stochastic open-loop game in which firms adapt to the realization of uncertain parameters, also called S-adapted open-loop strategies by Haurie, Zaccour, and Smeers (1990). Despite being half way between a deterministic open-loop game and a dynamic closed-loop, this stochastic open-loop game[1] with these three decisions has the mathematical structure of a one stage game. However, we overcome this limitation by providing a closed-loop model. In this case, we focus on the symmetric subgame perfect equilibrium (SSPE). The equilibrium assumes symmetric levels of investment, but provides a recourse in case firms deviate from this strategy. The closed-loop model is a dynamic game in which, in the first stage, firms decide on the portfolio of technologies and their capacities and, in the second stage, after the uncertainty is revealed, they decide the production in a Cournot game. In this case, we have an equilibrium problem in the first stage (portfolio and capacity) subject to equilibrium constraints in the second stage (production).

Open-loop and closed-loop games have different information structures, as presented in Fig. 1. In closed-loop games all the firms' past plays are known in the beginning of each stage. As a consequence, a firm will have to consider the best response not only to equilibrium actions of prior stages, but also to any potential deviations. In contrast, in open-loop games firms do not observe the opponents' play considering the opponents do not deviate from equilibrium (Fudenberg & Levine, 1988). This difference in information structure makes open-loop much more tractable than closed-loop games (Basar & Olsder, 1999; Fudenberg & Levine, 1988; Fudenberg & Tirole, 1991). In practice, the open-loop model would be more appropriate for an electricity market organized with Power Purchase Agreement, while the closed-loop model is more applicable to a spot market structure (Murphy & Smeers, 2005). During the paper, we connect the open-loop and closed-loop models by showing that the SSPE is also the equilibrium for the open-loop game.

Our main result is that portfolio diversification arises even with risk-neutral firms and technologies with different cost expectations. Furthermore, we characterize the production level of each firm for each possible scenario realization, in other words each combination of cost and demand realization. Conditions that yield to diversification (or not) are discussed in the paper. For the open-loop model, under our assumptions, in aggregate terms firms always invest and produce the same quantities. Asymmetry on the use of technologies between firms can occur, but it only happens when technologies have the same cost expectation.

The paper is organized as follows. In the next section, we provide a literature review which is followed by a background on the model. Section 4 is an open-loop model in which we discuss properties of the problem and a duopoly with two scenarios. In Section 5, we present an analysis of the case with an arbitrary number of firms and scenarios based on a closed-loop model. The relationship of the open vs. closed-loop models and a discussion about socially optimal investment are respectively in Sections 6.1 and 6.2. Finally, we conclude the paper with also some future research directions. To enable an easier reading, we do not provide any mathematical proof in the main text. All the proofs are in the paper's E-Appendix.

2. Literature review

Game theory has received considerable attention in electricity markets (Kahn, 1998; Kleindorfer, Wu, & Fernando, 2001; Ventosa, Baíllo, Ramos, & River, 2005), and, it has become increasingly relevant to electricity investment decisions. We separated the literature on electricity investment in a competitive environment into two parts: one relying more on computational results and the other on highly stylized models whose purpose is to understand the strategic interaction of firms in markets that are highly concentrated. We also notice that, in one stream of highly stylized models, different firms use just one technology (symmetric firms) and, in another stream, different firms use different technologies but are constrained to use just one of them (asymmetric firms).

We start with computationally oriented models. Chuang, Wu, and Varaiya (2001) present a Cournot model for generation expansion, incorporating operational considerations such as capacity

[1] To simplify we will keep referring during the paper to this stochastic open-loop game just as open-loop.

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