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Capacity expansion games with application to competition in power generation investments

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ABSTRACT

We consider competitive capacity investment for a duopoly of two distinct producers. The producers are exposed to stochastically fluctuating costs and interact through aggregate supply. Capacity expansion is irreversible and modeled in terms of timing strategies characterized through threshold rules. Because the impact of changing costs on the producers is asymmetric, we are led to a nonzero-sum timing game describing the transitions among the discrete investment stages. Working in a continuous-time diffusion framework, we characterize and analyze the resulting Nash equilibrium and game values. Our analysis quantifies the dynamic competition effects and yields insight into dynamic preemption and over-investment in a general asymmetric setting. A case-study considering the impact of fluctuating emission costs on power producers investing in nuclear and coal-fired plants is also presented.

1. Introduction

The need to reduce carbon emission to achieve the 2 Celsius degree target puts under pressure power systems of many countries. Lowering the carbon content of electricity requires the development of competitive non-emissive energies for base-load generation. The most immediately viable alternative to provide dispatchable base-load power would be nuclear power plants. But, as shown in the 2005 and 2010 editions of the Projected Cost of Electricity Generation by the International Energy Agency, the relative competitiveness of nuclear power compared to coal-fired generation strongly depends on the existence of a material price for carbon emission. Indeed, a carbon price of 30 USD/tCO2 would definitively make nuclear power plants much more economical than coal-fired plants for electricity base-load generation. Unfortunately for the nuclear industry, as Fig. 1 shows, the carbon price of the European Union Emission Trading System (EU-ETS) has fallen to a low of 5 € /tCO2 since mid-2012, and has not recovered since then to a value high enough to sustain emission reduction based on economic efficiency. Nevertheless, ongoing political developments, market design changes and technological

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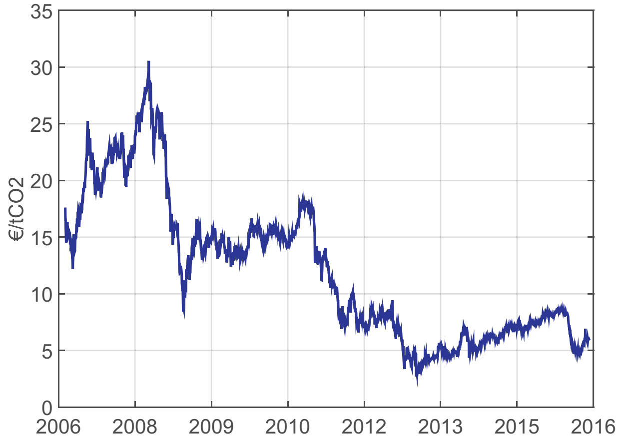

Fig. 1. Price (in euros per ton of CO_2) of the one year-ahead emission allowance on the EU-ETS. Source: TheIce.

advances might change this situation and benefit the nuclear producers. A crucial dilemma thus arises for the nuclear industry: either wait for a significant rise in the carbon price at the risk of base-load generation being preemptively taken by coal-fired plants, or intervene now at the cost of enduring short-term losses.

Motivated by this context, we build a model to analyze a capacity expansion game in a competitive market. The game takes place between two players, representing sectors of electricity generators. Producer 1 invests in nuclear power plants with unit expansion cost K^1, while producer 2 invests in coal-fired plants with expansion cost K^2. We consider that those costs include the Operation & Maintenance costs since once the decision is made to invest, they become sunk costs. These investment costs are so massive that projects can be considered as a one-shot decision. To give an order of magnitude, the Hinkley Point Project of two nuclear power plants being built in the UK carries a cost of approximate 15 billion USD, and the cost of a 1 GW-capacity supercritical coal-fired plant is approximately 1 billion USD. Moreover, given the enormous sunk costs and plant lifetime of 40+ years, investments are viewed as irreversible. The aim of the article is then to analyze the resulting competitive investment to determine who and when will build new generating capacity.

In line with the above narrative, we focus on the carbon price X_t as the main state variable. Higher X_t benefits nuclear producers, while lower X_t benefits coal-fired plants. To reflect the significant uncertainties associated with the carbon price (see again Fig. 1 which can be viewed as a historical trajectory of X_t), we work in a continuous-time stochastic setting. Thus, firms' investment strategies correspond to stopping times related to X_t. The game aspect of the model arises from the negative externality of capacity expansion. Namely, the competitive price is driven by the aggregate capacity of the producers, so that when one of the firms expands, electricity prices decline, hurting her competitor. This creates a preemptive motive for the investors and converts our framework into a non-zero-sum duopolistic game of timing. We assume that the firms make decisions to maximize their expected net present value of total future profits (NPV) in terms of the stochastic (X_t). Relying on the mechanism of a Nash equilibrium, we then characterize the competitive equilibrium by solving optimal stopping problems for one firm's best-response to her rival's actions. Importantly, depending on the competition strength, we find that both *threshold-type* and *preemptive* equilibria might arise.

Beyond the two profit-maximizing investors, we also aim to understand the role of the third-party regulator, or government in the game outcome. Carbon emission markets remain highly politicized, with a fluid market design. For instance, we can mention initiatives to prevent carbon price collapse, such as the Stability Reserve Mechanism in the ETS, and the United Kingdom carbon price floor of approximately 18 GBP/tCO2 institutionalized since 2016. France is following the same path. Thus, the establishment of a high and steady value for carbon strongly depends on the political will and ability of each state. Our purpose is thus to analyze the effect of such commitment on the market equilibrium. In particular, we are interested in the deviation of this equilibrium compared to the decision a benevolent planner would do.

As we discuss below, our setting yields a non-trivial extension of existing literature on stochastic timing games. Thus, our analysis is driven by methodological innovation and is relevant for other economic settings. In particular, it reflects a long-term research programme by the first and third authors on dynamic (i.e. with multi-stage strategies) non-zero-sum games.

1.1. Existing literature

The general problem of capacity expansion under uncertainty has been extensively studied as a stochastic optimal control problem since the late 1950s (Luss, 1982) and offers a natural link to the theory of real options. Existing research has considered a variety of approaches to the choices faced by the firm, including singular control (Steg, 2012); impulse control (Aïd et al., 2016); timing control (Grenadier, 2000), and two-sided optimal switching control (Hamadène and Jeanblanc, 2007). Single-agent models for multi-stage capacity expansion were initiated in Dixit (1995) and Bar-Ilan et al. (2002).