Generation Capacity Expansion in Electricity Markets under Rivalry and Uncertainty

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Introduction

Due to exposure to uncertainty created by the deregulation of electricity industries worldwide and the need to respond to climate change via investment in more sustainable technologies, the challenges and opportunities facing power companies have increased over the past decade. Consequently, the electric power sector requires decision support that is more responsive to market conditions, while policymakers seek insights about the consequences of uncertainty on investment outcomes. We propose to extend the traditional real options approach to electricity capacity expansion by investigating game-theoretic issues emerging from the competition between agents, each with a portfolio of electricity production technologies. Such a framework will take into account not only the feedback effect of capacity expansion on the price of electricity and the dependence of the value of a generation unit on the presence of others (Gahungu and Smeers, 2011) but also the strategic aspects of capacity expansion in a quasi-analytical framework.

Traditional real options theory (Dixit and Pindyck, 1994) assumes an exogenous price process, thereby implicitly excluding the impact of capacity expansion on the price process as well as the strategic interactions among firms. Although it may be plausible to assume that interactions between investment decisions may be irrelevant for infinitesimal energy generators, it is unrealistic to consider a price process independent of the total generation capacity. Adding new capacity creates a feedback effect on the price, and, as a result, asset independence (in the sense that cash flows accruing to one asset are independent of the capacities of other assets) is not an accurate assumption. Furthermore, real options capacity expansion models (Pindyck, 1988 and Baldursson and Karatzas, 1997) usually consider a single technology or, at best, several technologies with identical investment costs in order to ensure mathematical tractability. Yet, technologies may differ in both operation and investment costs.

Furthermore, investment decisions of a firm competing in an oligopolistic market depend not only on the value of the underlying economic variables but also on the actions undertaken by its competitors. The oligopolistic structure of a large number of sectors resulting from the extensive process of deregulation in combination with the ongoing process of mergers and acquisitions, implies that there is a strong need to incorporate a multiple decision maker framework into the real options theory. Although canonical real options theory finds particular application in sectors such as energy, manufacturing, and telecommunications, treatment of decision-making problems via canonical real options theory has mainly been in a monopoly or a perfect competition setting.

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Indeed, in most of the real options literature, the perspective taken is of a single decision maker that has an exclusive right to invest and faces no strategic competition (McDonald and Siegel, 1985 and 1986).

Gahungu and Smeers (2011) develop a real options capacity expansion model for power generation in a competitive market with several technologies taking into account that investing in a given technology actually depreciates the option value of investing in others. Assuming several technologies with asymmetric investment and variable costs, they use optimal plant dispatch to compute the instantaneous welfare of the social planner by maximising the consumer and producer surplus net of operation costs and operation and maintenance cost. Then, using the vector of Lagrange multipliers of capacity constraints, they evaluate the profit flow of each type of plant and, subsequently, assume myopia in order to compute the value of marginal units through Monte Carlo simulations. Finally, the marginal values of the units are regressed by polynomial functions of the state variables driving the uncertainty, while optimal stopping problems on these fitted value functions are solved analytically. Results indicate that the investment trigger for each technology increases with the volatility, which is in line with the view of investment as an option exercise. Furthermore, allowing for the capacities of the different technologies to increase, the investment trigger of a technology increases with its own capital stock as well as with the capital stock of other technologies. Hence, their model reflects the dependency of cash flows among a portfolio of technologies.

Ehrenmann and Smeers (2010) present different adaptations of former optimisation capacity expansion models to the competitive environment, thereby extending these models to stochastic equilibrium. They begin with a standard two-stage version of a stochastic optimisation capacity expansion model and then reformulate it into a complementarity representation of the investment problem. Thus, they develop an equilibrium formulation that may encompass more general models that cannot be derived through an optimisation problem. In order to account for risk aversion, they invoke stochastic discount factors that are directly embedded in the equilibrium models, thus overcoming the limitations of the capital asset pricing model. Indeed, by resorting to risk functions it is possible to account for idiosyncratic risk, and, hence, extend project valuation based on the market price of risk.

Incorporating strategic interactions in a real options setting typically mitigates a firm's incentive to delay investment. Smets (1993) first combined real options valuation techniques with game theory, thus developing a continuous-time model of strategic real options exercise under product market competition, assuming that entry is irreversible, demand is stochastic, and simultaneous investment occurs only when the role of the leader is defined exogenously. Huisman and Kort (1999) reconcile real options with game theory to illustrate how the decision-analytic incentive to postpone investment is counteracted by the strategic motivation to pre-empt one's rival in order to enjoy first-mover advantage. Extensions to this line of research include two sources of uncertainty (Paxson and Pinto, 2005) and uncertain technology innovation (Weeds, 2002). Paxson and Pinto (2005) extend the traditional real options approach that treats the number of units sold and the price per unit as an aggregate variable by presenting a rivalry model in which the profits per unit and the number of units sold are both stochastic variables. They examine a pre-emptive setting (where both firms fight for the leader's position) as well as a non-pre-emptive one (where the role of the leader is defined exogenously). Their results indicate that the triggers of both the leader and the follower increase as the correlation between the profits per unit and the quantity of units increases since then the aggregate volatility increases. Furthermore, they illustrate how a marginal increase in the number of units sold while the active leader is alone in the market increases the value of the active project by more than the extra benefit from delaying investment. Thus, the non-pre-emptive leader's incentive to invest increases, thereby reducing the discrepancy between the pre-emptive leader's and non-pre-emptive leader's entry thresholds. Weeds (2002) considers irreversible investment in competing research projects with uncertain returns under a winner-takes-all patent system. The technological success of the project is probabilistic, while the economic value of the patent to be won evolves stochastically over time. Results indicate that in a pre-emptive leader-follower equilibrium, firms invest sequentially and option values are reduced by competition.

Methodology

We explore the application potential of real options theory in this new context of capacity expansion in the electricity sector by accounting not only for dependency between the cash flows of competing technologies but also for competition from a rival. Thus, we seek to extend Gahungu and Smeers (2011) by developing a mixed-complementary model, which should provide insights for the electricity sector. Although market equilibrium can be determined analytically in stylised real options models, in a more general setting with asymmetric costs, multiple supply and demand nodes, and pipeline capacity restrictions, analytical solution of a system of equations is not possible. For example, unlike in the perfectly competitive market structure where the objective is to maximise social welfare and minimise supply costs, in a Cournot oligopoly setting, competitors maximise their own objective functions, which cannot be aggregated in a single optimisation objective. Therefore, a convex programming approach cannot be adopted to find the market equilibrium, while complementarity problems provide a viable modelling approach.

In order to extend the framework of Gahungu and Smeers (2011) to account for competition, we need to cast this problem as a mixed complementarity one. Therefore, we begin by considering two agents, each holding a portfolio of electricity generation units. Following the approach of Gahungu and Smeers (2011), we solve the optimal dispatch problem for each agent, thereby obtaining the Lagrange multipliers of the capacity constraints, with which we evaluate the profit flow of each type of plant and compute the value of marginal units through Monte Carlo simulations. Simultaneously, the objective functions of the duopolists are linked through the Karush-Kuhn-Tacker (KKT) conditions. This can be implemented in various software platforms, such as Matlab and GAMS, which offer a convenient environment for exploration and visualisation and facilitate the solution of linear and nonlinear complementarity problems combined with Monte Carlo simulations. Subsequently, by regressing the marginal values of the units using the Lagrange multipliers from the complementarity problem on polynomial functions of the state variables, we obtain closed-form expressions for the fitted value functions on which real options analysis may be performed using standard methods.

Insights

While a monopolist typically defers entry into an industry as price uncertainty increases, it has been shown that the presence of a rival may hasten investment. Consequently, the optimal entry decision requires a trade-off of both opposing effects. Real options models investigating this trade-off rely mostly on the assumption that each player holds a single asset, and, as a result, the strategic implications are neglected. Here, we propose to examine this trade-off in a setting of duopolistic competition, where each agent holds a portfolio of electricity production technologies and plans to expand the generation capacity. While Gahungu and Smeers (2011) indicate that the incentive to delay investment increases both with greater uncertainty and capital stock, whether a strategic context would promote a greater herding tendency or erode the option value of waiting is an important open research question, which becomes of even greater interest when considering the particular nature of the portfolios and allows for the ability to diversify them.

Future Work

The framework developed here may be used to investigate particular game-theoretic aspects of the electricity sector, such as the impact of increasing investments in renewable energy technologies, e.g., offshore wind, on market power, and market structure. In the long run, this work may facilitate policy-oriented research that aims at capturing market risk stemming from deregulation and other policy dispensations. Indeed, capturing the risk embedded in structural transformations, such as the decarbonisation of the UK electricity sector, will provide policymakers with a coherent decision-support process that integrates the value of diversity and timing of mitigation options under various evolving uncertainties.

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