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Valuing modular nuclear power plants in finite time decision horizon

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ABSTRACT

Small and medium sized reactors, SMRs, (according to IAEA, 'small' refers to reactors with power less than 300 MWe, and 'medium' with power less than 700 MWe) are considered as an attractive option for investment in nuclear power plants. SMRs may benefit from flexibility of investment, reduced upfront expenditure, enhanced safety, and easy integration with small sized grids. Large reactors on the other hand have been an attractive option due to the economy of scale. In this paper we focus on the economic impact of flexibility due to modular construction of SMRs. We demonstrate, using real option analysis, the value of sequential modular SMRs. Numerical results under different considerations of decision time, uncertainty in electricity prices, and constraints on the construction of units, are reported for a single large unit and for modular SMRs.

1. Introduction

Deregulation of the electricity market has been driven by the belief in increased cost-efficiency of competitive markets. There is a need for valuation methods to make economic decisions for investment in power plants in these uncertain environments. Kessides (2010) emphasizes the use of real options analysis (ROA) to estimate the option value that arises from the flexibility to wait and choose between further investment in the nuclear plant and other generating technologies as new information emerges about energy market conditions.

There is an increased interest in SMRs as an alternative to large Gen III type nuclear reactors (Boarin et al., 2012). This is primarily because the former has, amongst other benefits, comparatively low upfront costs and flexibility of ordering due to its modular nature (Carelli et al., 2010). When comparing economy of large reactors and SMRs, it's necessary to take into account the value of flexibility arising due to modular construction, which traditional valuation methods like NPV cannot. As the decisions to order new reactors would be planned for finite time horizons, there is a need to adapt the real option valuation for modular construction, as proposed by Gollier et al. (2005), to a finite time horizon. The case studies presented here are not only important for the construction of power plants but they are also relevant for a larger class of decision questions in which flexibility due to modularity and economy of scale plays an important role.

The real options approach for making investment decisions in projects with uncertainties, pioneered by Arrow and Fischer (1974), Henry (1974), Brennan and Schwartz (1985) and McDonald and Siegel (1986) became accepted in the past decade. Dixit and Pindyck (1991) and Trigeorgis (1996) comprehensively describe the real options approach for investment in projects with uncertain future cash flows. Using real options it's possible to value the option to delay, expand or abandon a project with uncertainties, when such decisions are made following an optimal policy.

ROA has been applied to value real assets like mines (Brennan and Schwartz (1985)), oil leases (Paddock, et. al (1988)), patents and R&D (Lucia and Schwartz (2002)). Pindyck (1993) uses real options to analyze the decisions to start, continue or abandon the construction of nuclear power plants in the 1980's. He considers uncertain costs of a reactor rather than expected cash flows for making the optimal decisions. Rothwell (2006) uses ROA to compute the critical electricity price at which a new advanced boiling water reactor should be ordered in Texas.

In this paper we focus on the value of flexibility that arises from the modular construction of SMRs. Our approach is similar to Gollier et al. (2005), where the firm needs to make a choice between a single high capacity reactor (1200 MWe) or a flexible sequence of modular SMRs (4×300 MWe). We, however, consider *finite time horizon* before which the investment decision should be made. In a competitive market the

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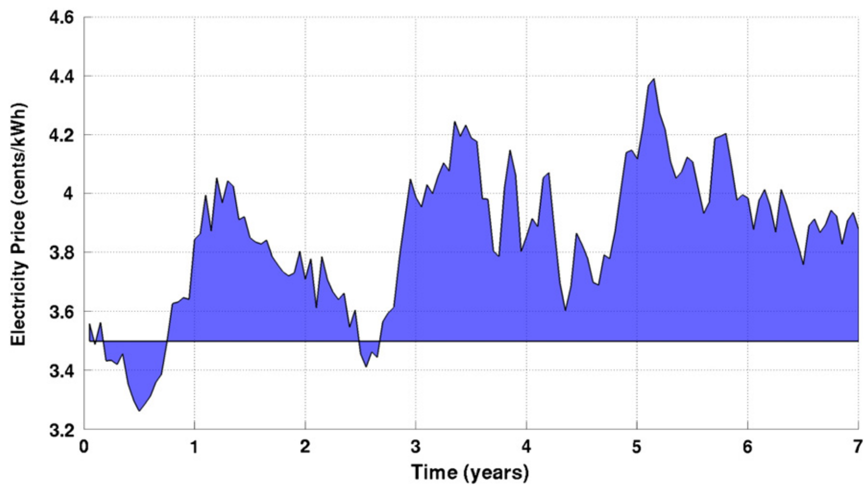

Fig. 1. The area between the electricity path (starting at 3.5 cents/kWh) and cost of operation = 3.5 cents/kWh, gives cash flow for the reactor.

firms cannot delay an investment decision for ever and need to decide before the anticipated entry of a competitor, or before a technology becomes obsolete. Also utilities need to meet the electricity demand with some minimum reliability, which restricts their decision horizon to finite time. The investment rules, such as the optimal time to start construction and the real option value of the investment, can differ significantly with changing decision horizons.

Real options can be priced with methods used for pricing American- or Bermudan-style financial options. We use a simulation based algorithm, called the stochastic grid method (SGM) (Jain and Oosterlee, 2012), for computing the real option values of modular investment decisions. SGM has been used to price Bermudan options in (Jain and Oosterlee, 2012) with results comparable to those obtained using the well-known least squares method (LSM) of Longstaff and Schwartz (2001), but typically with tighter confidence intervals using fewer Monte Carlo paths. The option values are computed by generating stochastic paths for electricity prices, and thus with uncertain future cash flows. As an outcome of computing the real option price, we find the optimal electricity price at which a new module should be ordered.

In the sections to follow we state the problem of modular investment in nuclear power plants and compare it with its counterpart in the financial world. In Section 2 we describe the problem and its real option formulation. In Section 3 the mathematical formulation behind the problem is discussed. Section 4 gives the description of the stochastic grid method used to value the real option. Section 5 describes in detail the application of the method to the nuclear case. Finally, Section 6 gives some concluding remarks and possible future research questions that need to be addressed.

2. Problem context

We consider a competitive electricity market where the price of electricity follows a stochastic process. The utility faces the choice of either constructing a single large reactor of 1200 MWe, or sequentially constructing four modules of 300 MWe each. The total number of series units is denoted by n. Unit number i is characterized by discounted averaged cost per KWh equal to θ_i, its construction time is denoted by C_i and the lifetime of its operation by L_i. Both construction and lifetime are expressed in years. It is assumed that different modules are constructed in sequence, where,

1. similar to the case of Gollier et al. (2005), construction of module $i+1$ cannot be decided until construction of unit i is over, i.e. no overlap in construction of modules is allowed.
2. a more relaxed constraint where the construction of unit $i+1$ can be decided from any time subsequent to the start of construction of unit i.

We assume a constant discount rate denoted by r here.

The utility here needs to take a decision to start the construction of the modules within a finite time horizon, denoted by T_i for the ith module. In terms of financial options, T_i represents the expiration time for the 'option to start the construction of the ith module'. Unlike financial options, it's difficult to quantify the *expiration time* for real options, and it is usually taken as the expected time of arrival of a competitor in the market, or time before which the underlying technology becomes obsolete. In case of an electricity utility, it also represents the time before which the utility needs to set up a plant to meet the electricity demand with certain reliability.[2]

2.1. The real option formulation

The problem of modular construction can be formulated as a multiple exercise Bermudan option. In this case we consider the stochastic process, X_t, to be the process which models the electricity price. The payoff, $h_i(X_t=x)$, for the real option problem is the expected net cash flows per unit power of electricity sold through the lifetime of module i, when it gets operational at time t and state $X_t=x$.

Fig. 1 illustrates the profit from the sale of electricity for one realized electricity price path. The cost of operation, θ, in the illustration is 3.5 cents/kWh and the area between the electricity path and θ gives the profit from the sale of electricity. We are interested in the expected profit, i.e. the mean profit from all possible electricity paths in the future. This expected profit (or net cash flow) is the payoff, $h_i(X_t)$, for the real option.

The *revenue*, R_i, for the ith module, for every unit power of electricity sold through its lifetime L_i, starting construction at time t, when the electricity price is $X_t=x$, can be written as

$$R_i(X_t = x) = \mathbb{E}\left[\int_{t+C_i}^{t+C_i+L_i} e^{-ru} X_u du | X_t = x\right]. \tag{1}$$

R_i is the discounted expected gross revenue over all possible electricity price paths. The revenue starts flowing in once the construction is over, and therefore the range for the integral starts from $t+C_i$ and lasts as long as the plant is operational, i.e. until $t+C_i+L_i$. Similarly, the *cost* of operating the ith module, K_i, through its lifetime for every unit power of electricity generated, is:

$$K_i = \int_{t+C_i}^{t+C_i+L_i} e^{-ru} \theta_i du. \tag{2}$$

[2] Reliability is measured as the probability of the number of unplanned outages in a year with one of the reasons for such an outage being demand exceeding available generation.