Optimal Time Choice Game for Energy Infrastructure Investment with Spillover Effect

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Overview

The purpose of this study is to analyze the consequence of optimal time choice game for energy infrastructure investment when spillover effect among investments exists. We consider a situation where firms can increase their subsequent revenue stream by investing at a period of time. The investment opportunity is assumed to be one-time opportunity and once it is made, it cannot be redone, i.e., the investment is irreversible. This indicates that the choice of optimal time of investment is formulated as a so-called "optimal stopping problem" in mathematics. Moreover, we assume that the investment has a spillover effect to other firms. Namely, once a firm makes an expensive investment, all other firms can obtain the same result from the next time period by the same investment with no cost. This positive externality allows firms to enter the game of identifying their own optimal investment time vis-à-vis their opponent's choice of time.

This setting is realistic in that substantial change or transition in the energy and environmental sector sometimes requires investment for infrastructure that includes not only physical but also intellectual bases, i.e., development of intellectual properties, R&D, etc. Such investment for infrastructure is typically associated with spillover effect because the infrastructure can be utilized as public goods. For example, once transmission network is established by some firm and is made available later to all new entrant firms in accordance with some liberalization policy, it definitely benefits these new entrants.

It is noted, however, that existence of spillover effect does not always mean benefits to the public. If the transmission network is set freely open to all firms, it results in a free lunch that dampens motivation for further investment of any firm. On the contrary, if the network is only possessed by the builder, the investment competition by firms may be described by the typical story of the theory of natural monopoly: In this well-known theory, firms are supposed to compete to each other to establish a monopolistic position in the market by investing more than others. In the process of establishing the monopolistic position by one firm, there will be double, triple, or multiple capital investment by those competing firms, resulting in the accumulation of excessive capital. That situation with excessive capital is not socially efficient. In any way, whether or not existence of positive externality benefits the economy is thus dependent upon a prediction of which and how many firms are willing to launch investment activity.

In this paper, we develop game models in which multiple firms compete for investment for infrastructure. Analyzing these models provide policy implications for energy policy formulations.

Methodological approach

We first develop a basic model that describes a gaming situation with two firms. Then, we extend it to a multi-firm setting. The basic model is as follows. Consider two identical firms. Each firm earns a net revenue of X_t dollars in time t (t = 0 to infinity). The present time is represented by t = 0. Further, assume that the firm's net revenue grows at a rate of g, i.e., the following equation holds true:

$X_t = X_0 (1+g)^t$, where X_0 is the initial value of the net revenue.

Suppose that the firm reserves an investment opportunity. Once the decision to take it is made, it allows the firm to raise a net revenue in each year (time) to aX_t ($a > 1$) from the next year to forever at the cost of I dollars.

We introduce a key assumption that if one of the two firms invests first, the other firm can enjoy the same effect of net revenue increase from the next time period with zero-cost for investment of their own. More specifically, let τ denote the time when one of these firms invests while σ denotes the time at which the opponent invests. Both τ and σ are integer and non-negative. If $\tau \leq \sigma$ holds true, the firm needs to make the investment with a positive cost, I. However, if $\sigma < \tau$ holds true otherwise, the cost of the investment for the firm is null (i.e. I=0) because the same effect has already become available to the firm.

Each firm's net present value of income stream is denoted by $g(\tau, \sigma)$. Thanks to the assumption of identical firms, any concept of equilibrium in the game of these two firms is defined in a symmetric manner. A definition of Nash equilibrium (NE) in this game is formally introduced as follows:
Definition. NE is (τ^N, σ^N) *such that* $g(\tau^N, \sigma^N) \geq g(\tau, \sigma^N)\ \forall \tau$ *and* $g(\sigma^N, \tau^N) \geq g(\sigma, \tau^N)\ \forall \sigma$.

The above model is then extended to a multiple firm setting. The definition of Nash equilibrium is accordingly extended to the following:
Definition. NE is $(\tau_1^N, \tau_2^N, \ldots, \tau_k^N, \ldots, \tau_K^N)$ *such that*
$h_k(\tau_1^N, \tau_2^N, \ldots, \tau_k^N, \ldots, \tau_K^N) \geq h_k(\tau_1^N, \tau_2^N, \ldots, \tau_{k-1}^N, \tau_k, \tau_{k+1}^N, \ldots, \tau_K^N)\ \forall k, \forall \tau_k$,
where $h_k(\tau_1, \tau_2, \ldots, \tau_k, \ldots, \tau_K) = g(\tau_k, \sigma)$ and $\sigma = \min\{\tau_1, \tau_2, \ldots, \tau_{k-1}, \tau_{k+1}, \ldots, \tau_K\}$.

Results

A question is whether such redundant investment is possible in our analytical framework. The following proposition for the case of two-firm setting is insightful in this regard.

Propostion. If $\left\{1 - \left(\frac{1+g}{1+r}\right)\right\} \frac{(1+g)(a-1)}{r-g} X_0 \geq I$ *holds true, then two firms immediately make the investment simultaneously. Otherwise, simultaneous investment never constitutes an NE.*

This proposition indicates that there is a possibility of double investment only when the investment cost is very low and below a certain level. The result makes sense in that if the cost for the investment is sufficiently low, the benefit from taking the action as soon as possible overwhelms any other strategies. Otherwise, double investment never occurs. It is shown that a similar result is obained in the multiple firm setting: excess simultaneous investment by these two or more firms would be unlikely to occur.

Discussion and conclusions

The above result is remarkable when we contrast it to the theory of natural monopoly. As was mentioned in the Overview, the theory of natural monopoly leads to a conclusion that completion among firms investing for monopolistic position may result in the accumulation of excessive capital, which is not socially efficient. In contrast, the above proposition declines such possibility, implying that the competition leads to social efficiency. Only one firm will make investment that is necessary and sufficient for the society to enjoy the outcome. This result thus supports policy formulations that promote competition rather than intervene between firms in a market with externality.