CAI QIANG
WANG TAO
and
LI LE

Renewable energy power generation R&D investment under incomplete information

The incomplete information of the future prospects of new renewable energy power generation technology, which is contained in external random events regarding policy, technology and market, together with the technical uncertainty of R&D success will affect the investment decision of renewable electric power enterprises. The critical beliefs, which are necessary for single enterprise and duopoly renewable energy power enterprises for their investment in new power generation technologies, are obtained respectively by taking into consideration the incomplete information, technical uncertainty and competitiveness and construction of decision-making model based on real options, and the equilibrium type that may generate in market competition of the two symmetric enterprises and the generation conditions are further analyzed in this paper. The result indicated that the winner-take-all privilege granted to the leading innovator and the technical uncertainty to innovative technology by policy will make the following enterprises react in two ways, investment delay or investment advancing. The faster signal arrives, the higher the signal quality is and the higher is the investment belief of the following investor. Moreover, the R&D competition equilibrium among enterprises can result in preemptive equilibrium and simultaneous investment equilibrium.

Keywords: *Incomplete information, renewable energy power, R&D, option game, game equilibrium.*

1. Introduction

Power generation technology is the focal point of commercial development and utilization of renewable energy under the current technical conditions. Based on the international experience of renewable energy power generation development, feed-in-tariff, the scientific design and formulation of which depend on how much people have mastered its functional rule and even formation mechanism, is an important method to promote renewable energy power generation development. Therefore, the microscopic process and decision behaviours of renewable energy power investment must be studied starting out from "microscope" and based on the evolution characteristics and investment decision environment of renewable energy power technology. Since the cost formation characteristics of renewable electricity depend on its technical characteristics, while the cost reduction relies on its technical innovation, and at the same time, continuous cost reduction becomes the inevitable choice for renewable electricity to compete in electricity market and to replace traditional fossil fuels, renewable energy power enterprises, grid companies, governments and academic circles are paying more and more attention to the new power generation technology and equipment and R&D regarding renewable energies.

The same as investments under other uncertain conditions, the investment on renewable energy power generation R&D, which may involve in competitive investment in different market structures, is also under an uncertain environment in terms of technology and market. However, renewable energy power generation technologies are diversified and differ in terms of commercialization, cost formation characteristics and development phases, enterprise R&D is on different objects and is far away from grid connection and generation of actual earnings; therefore, the prospect of R&D investment seems myopic. On the other hand, the inherent intermittent and instability of renewable electricity and the negative external factors, it may bring to grid and society will "overshadow" the actual earnings of R&D investment further.

Hence, in addition to technical uncertainty, future earning uncertainty and competition of potential rivals, investment decisions on renewable energy power generation R&D may be affected by different randomly arrived events that can imply the future prospects of projects. Sometimes, the future prospect information is clear and understandable, while in some cases the information implied is indistinct. On the latter, decision makers need to keep observing random events and analyzing the information implied and then making approximate inferences. Yet decision makers cannot be 100% sure about information authenticity due to their own limited cognitive competence. Therefore, the information implied by random events is incomplete for decision makers, and the

Messrs. Cai Qiang, Wang Tao and Ms. Li Le, Macro economic and financial research center, Sichuan Radio TV University; School of Management and Economics, University of Electronic Science and Technology of China.

information incompleteness may interfere with the investment decisions made on renewable energy power generation R&D. Enterprises will face huge challenges brought to them by the constantly rising signals which are hard for them to predict and judge. For that reason, this paper studies on the competitive investment behaviours of renewable energy power enterprises with incomplete information conditions by constructing decision model based on real options with consideration of incomplete information, technical uncertainty and competition included.

In terms of investment with incomplete information, Thijssen et al. (2001a, 2001b) [1, 2] discussed the investment strategies of absolute monopoly enterprises and duopoly enterprises under incomplete information on the foundation laid by Dixit and Pindyck (1994) [3]. Lambrecht and Perraudin (2003) [4] established another duopoly option-game model relating to information arrival. Decamps et al. (2005) [5] used filtering and Martingale technology to solve the optimal stopping problem of bivariate Markov process to study investment timing selection under incomplete information. By supposing that an enterprise does not know the critical value of preemptive investment but does know the probability distribution of its rival, Wu Jianzu and Xuan Huiyu (2006) [6] introduced incomplete information and studied the optimal R&D investment timing of enterprises under uncertain competition environment with incomplete information. Cai Qiang, Zeng Yong and Deng Guangjun (2007) [7] studied the patent competitive purchasing decisions under incomplete information condition. Cai Qiang, Deng Guangjun and Zengyong (2009) [8] analyzed the influence of randomly arriving incomplete information on patent competition. Furthermore, lots of research achievements conducted based on real options on investment decisions under uncertain conditions have been made, and will not be repeated here due to space limitations.

In terms of renewable energy investment decisions, Wang Xiaotian and Xue Huifeng (2012) [9] qualitatively described the causality between the factors that affect renewable energy investment behaviours by constructing the conceptual model for analysis of renewable energy investment decision-making behaviour based on behaviour decision theory, and demonstrated that the transcendental belief, policy preference and attitude towards technical risks of investors will affect investment decisions significantly. Wang Wenping and Yang Hongping (2008) [10] established wind power investment decision-making model based on delayed real options and wind power project investment decision-making model based on composite real options respectively. Liu Jun et al. (2013) [11] brought up photovoltaic power generation investment decision-making model based on real option theory. Huang Wenjie and Huang Yi (2010) [12] studied and constructed a generation option-game investment decision-making model based on different risk preferences of investors.

Taken together, it is still rare cases to introduce incomplete information into renewable electricity investment decision-making environment and use game-option theory and method for study in the existing researches. Therefore, the paper innovatively introduced three uncertainties at the same time: uncertainty of arrival time of information about the future market prospects of new power generation technology, the uncertainty of the reduction of renewable energy power generation cost and negative externality by new technology, and the technical uncertainty of successful R&D in the model, and thus simulated the renewable energy power generation R&D investment decision-making environment under incomplete information conditions in a better way.

Through the investment decision making model based on real options established in the paper, the critical beliefs, which are necessary for single enterprises and duopoly renewable energy power enterprises for their investment in new power generation technologies, is obtained respectively, and the equilibrium type that may generate in market competition of the two symmetric enterprises and the generation conditions are further analyzed.

2. Absolute monopoly investment decision-making model

Suppose there is only one enterprise that has obtained the opportunity to research and develop a certain new renewable energy power generation technology in the market, the R&D cost is denoted by I, and the successful obedience parameters of new technology R&D is λ and is independent to the Poisson process of random events. In the mind of this enterprise, the new renewable energy power generation technology can only be either “effective” or “ineffective”, i.e. when this new technology can reduce the cost and negative externality of renewable energy power generation effectively, it will get more proportion in grid connection, and its value, denoted by R^H, will thus be high, the technology is called “effective technology”; conversely, the technology will be “ineffective technology” and its value will be denoted by R^L. Without loss of generality, it is supposed that R^L=0. Before R&D, the enterprise will have an initial transcendental concept towards the new power generation technology, namely the prior probability that deems this new technology as “effective technology”, which is: $P(H)=p_0$.

R&D investment decisions of renewable energy power generation enterprises are affected by random arrival events, which are the signal to test the effectiveness of innovation technologies on renewable energy power generation cost and negative externality reduction. If the signal shows that the innovation technology is effective, it will be called a good signal in this paper and denoted by h; conversely, it will be called a bad signal and denoted by l. No matter what kind of signal it is, it partly contains real market information, i.e. H (it can reduce renewable energy power generation cost and negative externality actually) and L (it cannot reduce renewable energy power generation cost and negative externality for certain). Due to limited cognitive abilities of humans, the probability of an innovation technology turns out to be an actual "effective technology" when people think the arrival signal is a good signal h is α, but in fact, the "effective technology" probability is $1-\alpha$ m, where $\alpha > \frac{1}{2}$. Of course, if it is supposed that $\alpha < \frac{1}{2}$, the analysis result will not be affected. But if $\alpha \neq \frac{1}{2}$, the signal will be ineffective, which means the signal cannot have the enterprise to learn more about the effectiveness of the innovation technology, and the value of waiting arisen thus will disappear. Suppose the arrival obedience process of the signal that reflects if the signal is effective is the Poisson process with $\mu > 0$, and the quantity of incoming signal is denoted as n, then:

$$\text{then: } dn(t) = \begin{cases} 1 & \text{Probability } \mu dt \\ 0 & \text{Probability } 1\text{-}\mu dt \end{cases}, \text{ and } n(0) = 0$$

Given signal quantity and good signal quantity (where), the probability of the innovation technology obtained by quoting the result achieved by Thijssen et al. (2001a) [3], i.e. by adopting Bayes update, turns out to be an actual "effective technology" is:

$$p(H \mid n, g) = \frac{\alpha^k}{\alpha^k + (1-\alpha)^k \xi} = p(k) \qquad \text{... (1)}$$

Where, $k = 2g - n$, $\xi = \frac{1-p_0}{p_0}$. k represents the number by which good signals are more than bad signals, and it is the only variable of belief.

When the enterprise implements investment on new power generation technology R&D at any $p(k)$, the probability of unsuccessful R&D within the time interval is $(0, \tau)$ is $e^{-\lambda\tau}$, while the probability of first event R&D succeeds within the next smaller time interval is $(\tau, \tau + d\tau)$ is $e^{-\lambda\tau}\lambda d\tau$, and the enterprise earning after successful R&D is $R = \{R^H, R^L\}$. The risk-free interest rate is denoted by r, and once R&D starts, the present value of earning expected by the enterprise is:

$$E = \int_0^{+\infty} e^{-r\tau} e^{-\lambda\tau} \lambda R d\tau = \frac{\lambda R}{r+\lambda} = \frac{\lambda}{r+\lambda}$$
$$\left[p(k)R^H + (1-p(k))R^L\right] = p(k)\frac{\lambda}{r+\lambda}R^H \qquad \text{... (2)}$$

The sunk cost of new power generation technology R&D investment is I. At given n and g or k(as $k = 2g-n$), the net present value $NPV(k)$ of R&D investment is:

$$NPV(k) = p(k)\frac{\lambda}{r+\lambda}R^H - I \qquad \text{... (3)}$$

In Formula (3), the "opinion" of renewable energy power enterprises on the innovation technology, i.e. the probability of or the belief on "effective technology", changes dynamically and affects the evaluation on expected returns. As the evaluation of the enterprise on the innovation technology is corrected constantly according to the signals received, belief of the enterprise on different time points varies, and $NPV(k)$ thus varies as well. The critical point of the final investment decision implemented on innovation technology R&D of the enterprise depends on its belief. With NPV as the evaluation criteria, the critical belief of break-even is:

$$p_{NPV} = \frac{r+\lambda}{\lambda R^H} I \qquad \text{... (4)}$$

Due to the uncertain prospect of innovation technology on reducing the cost and negative externality of renewable energy power generation and irreversibility of investment, waiting for more arriving signals can reduce the influence of uncertainty based on real option thought and thus increase investment value. Therefore, it is necessary to take option value into consideration.

As for the value of k of the innovation technology at a certain time point, it may be in three possible intervals that divide option value function into corresponding three parts, which is similar to the inference of Thijssen et al. (2001a) [1]. The following value function $V(k)$ is obtained :

$$V(k) = \begin{cases} \dfrac{A_1\beta_1^k + A_2\beta_2^k}{\alpha^k + \xi(1-\alpha)^k} & k < k^* - 1 \\ \dfrac{\mu}{r+\mu}[\alpha\dfrac{\lambda}{r+\lambda}R^H p(k) - (\alpha p(k) + (1-\alpha)(1-p(k))) & \\ \qquad \times I + \alpha(1-\alpha)\dfrac{A_1\beta_1^{k-1} + A_2\beta_2^{k-1}}{\alpha^k + \xi(1-\alpha)^k}] & k^* - 1 \le k < k^* \\ \dfrac{\lambda}{r+\lambda}R^H p(k) - I & k \ge k^* \end{cases}$$

... (5)

Where, A_1 is the undetermined coefficient,

$$k^* = \frac{\ln(\frac{p^*}{1-p^*}) + \ln(\xi)}{\ln(\frac{\alpha}{1-\alpha})}, \beta_{1,2} = \frac{r+\mu}{2\mu} \pm \frac{1}{2}\sqrt{(\frac{r}{\mu}+1)^2 - 4\alpha(1-\alpha)},$$

$$p^* = p(k^*) = \frac{1}{\rho(\lambda R^H / I(r+\lambda) - 1) + 1},$$

$$\rho = \frac{\beta_1(r+\mu)(r+\mu(1-\alpha)) - \mu\alpha(1-\alpha)(r+\mu(1+\beta_1-\alpha))}{\beta_1(r+\mu)(r+\mu\alpha) - \mu\alpha(1-\alpha)(r+\mu(\beta_1+\alpha))}.$$

Since $0 < \rho < 1$ [1], then

$$p^* = \frac{1}{\rho(\lambda R^H / I(r+\lambda) - 1) + 1} > \frac{1}{(\lambda R^H / I(r+\lambda) - 1) + 1}$$
$$= \frac{I(r+\lambda)}{\lambda R^H} = p_{NPV}.$$

Thus it can be seen that the critical investment belief obtained with real option method is higher than the critical belief obtained with traditional net present value. The internal cause is that p^* has the factor ρ while p_{NPV} not, which demonstrates that waiting option value makes an enterprise more willing to wait for more good signals.

3. Investment decision on new power generation technology R&D under competitive conditions

Suppose two symmetric renewable energy power enterprises compete for the same certain power generation technology, and the enterprise that successfully researches and develops the technology first can obtain all potential returns on the new technology, while the other one will obtain nothing (the purpose to make an assumption like this is to simplify analysis and to deviate from the fact to some extent; for example, the cost reduction brought by the new technology is a kind of returns for the enterprise.). Symmetry means that the R&D cost of both enterprises I is, and the successful R&D of new technology is conforming to the poisson process with λ as the parameter. The two investors can only invest in succession or invest at the same time for sure; in the former case, one of them will be the leader and the other will be the follower. The value of gaming participants in the sequence of follower, leader and simultaneous investment is analyzed with backstepping method and then equilibrium was analyzed.

3.1 Investment decision of the follower

When k reaches the critical belief k_F after the leader invests, the follower starts to invest. According to the value of k at a certain time point, value function of the follower is divided into the following three parts:

First, when $k \geq k_F$, the optimal strategy for the follower is to invest immediately, and its value will be the net present value $NPV_F(k)$ while both of them have invested:

$$NPV_F(k) = \int_0^{+\infty} e^{-r\tau} e^{-\lambda\tau} e^{-\lambda\tau} \lambda R d\tau - I = \frac{\lambda R}{r+2\lambda} - I$$
$$= p(k)\frac{\lambda}{r+2\lambda}R^H - I \qquad \text{... (6)}$$

Second, when $k_F-1 \leq k < k_F$ i.e. the follower would invest when the value of k is increased by 1, its function value $V_1(k)$ satisfies the following Bellman equation:

$$rV_1(k)dt = E[dV_1(k)] \qquad \text{... (7)}$$

At last, when $k<k_F-1$, i.e. the follower would not invest even if the value of k is increased by 1, its value function $V_0(k)$ satisfies the following Bellman equation:

$$rV_0(k)dt = E[dV_0(k)] \qquad \text{... (8)}$$

By solving the equation (7) and (8), it can be obtained that the value function $V_F(k)$ of the follower is:

$$V_F(k) = \begin{cases} \dfrac{\bar{A}_1\bar{\beta}_1^k + \bar{A}_2\bar{\beta}_2^k}{\alpha^k + \xi(1-\alpha)^k} & k < k_F - 1 \\ \dfrac{\mu}{r+\mu+\lambda}\left(\alpha\dfrac{\lambda}{r+2\lambda}R^H p(k) - (\alpha p(k) + (1-\alpha)(1-p(k)))I \right. & \\ \left. \quad + \alpha(1-\alpha)\dfrac{\bar{A}_1\bar{\beta}_1^{k-1} + \bar{A}_2\bar{\beta}_2^{k-1}}{\alpha^k + \xi(1-\alpha)^k}\right) & k_F - 1 \leq k < k_F \\ p(k)\dfrac{\lambda}{r+2\lambda}R^H - I & k \geq k_F \end{cases} \qquad \text{...(9)}$$

Where, $\bar{\beta}_{1,2} = \dfrac{r+\mu+\lambda}{2\mu} \pm \dfrac{1}{2}\sqrt{(\dfrac{r+\lambda}{\mu}+1)^2 - 4\alpha(1-\alpha)}$,

$p_F = \dfrac{1}{\rho_F(\lambda R^H / I(r+2\lambda) - 1) + 1}$, $k_F = k(p_F)$,

$\bar{A}_1$ is the undetermined coefficient,

$$\rho_F = \frac{\bar{\beta}_1(r+\lambda+\mu)(r+\lambda+\mu(1-\alpha)) - \mu\alpha(1-\alpha)(r+\lambda+\mu(1+\bar{\beta}_1-\alpha))}{\bar{\beta}_1(r+\lambda+\mu)(r+\lambda+\mu\alpha) - \mu\alpha(1-\alpha)(r+\lambda+\mu(\bar{\beta}_1+\alpha))}$$

3.2 Investment decision of the leader

Affected by the potential investment of the follower, value of the leader is within the intervals $k<k_F-1$ and $k_F-1<k<k_F$, and consisting of the expected R&D returns and option value. Apparently, existence of the follower brings negative effects to the value of the leader, which demonstrates that the option value is a negative item. When $k \geq k_F$, the value function of the leader is the same as that of the follower. Therefore, the value function of the leader is:

$$V_L(k) = \begin{cases} p(k)\dfrac{\lambda}{r+\lambda}R^H - \dfrac{A_L\bar{\beta}_1^k}{\alpha^k + \xi(1-\alpha)^k} - I & k < k_F - 1 \\ p(k)\dfrac{\lambda}{r+\lambda}R^H - \dfrac{\mu}{r+\mu+\lambda}\left(\alpha\dfrac{\lambda}{r+2\lambda}R^H p(k) - (\alpha p(k) + \right. & \\ \left. (1-\alpha)(1-p(k)))I + \alpha(1-\alpha)\dfrac{B_L\bar{\beta}_1^{k-1}}{\alpha^k + \xi(1-\alpha)^k}\right) - I & k_F - 1 \leq k < k_F \\ p(k)\dfrac{\lambda}{r+2\lambda}R^H - I & k \geq k_F \end{cases}$$
$$\text{... (10)}$$

The undetermined coefficient A_L and B_L in the formula above can be calculated through continuity conditions and value matching conditions, which will not be repeated here.

3.3 Optimal Simultaneous Investment

Optimal simultaneous investment means that two enterprises "collude" to invest at the optimal timing simultaneously. In this case, the value of simultaneous investment of the two enterprises is higher than the leading value and following value respectively at competition. In the symmetric case, the two enterprises are regarded as one "integrated enterprise" and the success of either of them will be deemed as the success of the "integrated" enterprise. It can also be demonstrated that the risk ratio of the integrated" enterprise is 2λ, while the net present value of a single enterprise is half of the net present value of the "integrated" enterprise. Therefore, optimal simultaneous decision can be regarded as the optimization problem [9] of a single enterprise ("integrated" enterprise) when the investment cost is $2I$ and risk ratio is 2λ.

The investment cost $2I$ and risk ratio 2λ are substituted into the expression of p^* to obtain the critical belief of the optimal simultaneous investment:

$$p_S = p(k_S) = \frac{1}{\rho(2\lambda R^H / 2I(r+2\lambda) - 1) + 1}$$
$$= \frac{1}{\rho(\lambda R^H / I(r+2\lambda) - 1) + 1} \quad \text{... (11)}$$

The same as the steps to calculate the value function of a single enterprise above, the value function of each enterprise at optimal simultaneous investment can be obtained:

$$V_S(k) = \begin{cases} \dfrac{C_S \beta_1^k}{\alpha^k + \xi(1-\alpha)^k} & k < k_S - 1 \\ \dfrac{\mu}{r+\mu}[\alpha \dfrac{\lambda}{r+2\lambda} R^H p(k) - (\alpha p(k) + (1-\alpha)(1-p(k))) \\ \qquad \times I + \alpha(1-\alpha)\dfrac{C_S \beta_1^{k-1}}{\alpha^k + \xi(1-\alpha)^k}] & k_S - 1 \le k < k_S \\ \dfrac{\lambda}{r+2\lambda} R^H p(k) - I & k \ge k_S \end{cases} \quad \text{... (12)}$$

Where, C_s can be calculated through continuity conditions and value matching conditions as with a single enterprise.

3.4 Equilibrium analysis

The paper aims at finding the real option value change rule of investment on the new power generation technology R&D of renewable energy power enterprises, analyzes the critical investment belief at maximum value of each enterprise and find out the optimal new technology R&D investment decision making plan for enterprises finally. For this reason, critical beliefs p^*, p_F and p_s (or k^*, k_F and k_s corresponding to them) need to be analyzed.

First, $p^* = \dfrac{1}{\rho(\lambda R^H / I(r+\lambda) - 1) + 1} < \dfrac{1}{\rho(\lambda R^H / I(r+2\lambda) - 1) + 1} = p_S$;

since $\dfrac{\partial \rho}{\partial r} > 0$, $\rho_F > \rho$. Hence:

$p_S = \dfrac{1}{\rho(\lambda R^H / I(r+2\lambda) - 1) + 1} > \dfrac{1}{\rho_F(\lambda R^H / I(r+2\lambda) - 1) + 1} = p_F$.

The relation between p^* and p_F is unclear, as compared to absolute monopoly, the value of follower is always based on the precondition that the leader has not reached and developed yet. On one hand, it is just like that the discount rate improves, the value of waiting thus "shrinks" and the investment tendency is advanced; on the other hand, the expectation of the follower decreases due to the existence of the leader, which will delay investment. It is obvious that these two influences are opposite to each other.

As the belief $p(k)$ leaps along with the change of discrete variable k, the belief above will not reach just right and the following definition is made: $\hat{p}^*=p[k^*]$, $k^* = k(p^*)$; $\hat{p}_F=p[k_F]$, $k_F=k(p_F)$; $\hat{p}_s=p[k^*]$, $k_s=k(p_s)$. Where, "[ ]" is the integral symbol. For example, $[k^*]$ is the minimum integer that is not smaller than k^*.

It is known that p^* is the critical belief at optimal investment of a single enterprise when there is no competition; when there is a competitive threat, the leading enterprise will not wait for p^* before they start to invest. If enterprise 1 starts to invest when $p=p^*$, then the other enterprise 2 will invest when $p=p^*-\varepsilon$, where ε is a positive infinitesimal. Enterprise 1 can forecast this condition, so it will invest when $p=p^*-2\varepsilon$. By continuous analogy like this, both of the gaming parties will compete at a certain limit value, which is called the first point of entry by Fudenberg and Tirole (1985) [13] and defined as below:

$$p_L = p\lceil k_L \rceil, k_L = \min_k \{k \mid V_L(k) = V_F(k)\} \quad \text{...(13)}$$

Different k values at the beginning of gaming will lead to different equilibrium results. When $k \in [0, k_L)$, no enterprise is willing to invest as the expected earning is too low, and they will wait for more good news to come; however, when $k=k_L$, $V_F(k)=V_L(k)$, the enterprises are willing to be either the leader or the follower without preference, which refers to the so called rent equalization [13], and the probability for both enterprises to be the leader is 0.5; when $k \in (k_L, k_F)$, both enterprises want to become the leader as $V_L(k)>V_F(k)$, and the game becomes a preemptive game; when $k \in [k_F, k_s)$, both of them invest immediately and the simultaneous investment equilibrium with non-Pareto optimality is generated; when $k \in [k_s, +\infty)$, the optimal strategy for both of the gaming parties is to invest immediately and to generate the simultaneous investment equilibrium with non-Pareto optimality. It should be noted that the above analysis is the result acquired based on simultaneous investment value $V_s(k)$ other than constant large value $V_L(k)$; otherwise, both enterprises will have no motive to forestall and will invest when k_s is reached in order to realize optimal simultaneous investment equilibrium like they have colluded in advance. However, as long as there is $V_L(k)>V_s(k)$ before k_s is reached, the collusion of both enterprises will be damaged by the motive to enter first, and the outlook of the players will make them understand that it is impossible to get $V_s(k)$, so they will compete to be the leader once they have the edge to forestall.

4. Application examples

Suppose the new power generation technology R&D project faced with two symmetric renewable energy power enterprises can satisfy the parameter:

$R^H=9$, $R^L=0$, $\lambda=0.1$, $\mu=2$, $\alpha=0.7$, $p_0=0.5$, $r=0.05$, $I=3$.

(1) At absolute monopoly

By substituting the parameters above, it can be calculated that: $p_{NPV} = \dfrac{r+\lambda}{\lambda R^H} I = 0.5$, $\beta_1 = \dfrac{r+\mu}{2\mu} + \dfrac{1}{2}\sqrt{(\dfrac{r}{\mu}+1)^2 - 4\alpha(1-\alpha)} = 0.7420$,

$$\rho = \frac{\beta_1(r+\mu)(r+\mu(1-\alpha)) - \mu\alpha(1-\alpha)(r+\mu(1+\beta_1-\alpha))}{\beta_1(r+\mu)(r+\mu\alpha) - \mu\alpha(1-\alpha)(r+\mu(\beta_1+\alpha))} = 0.0949,$$

then there is the critical patent R&D investment belief: $p^* = \dfrac{1}{\rho(\lambda R^H / I(r+\lambda) - 1) + 1} = 0.9133$, $k^* = k(p^*) = 2.7790$,

$\hat{p}^*=p[k^*] = 0.9270$.

From the above it can be concluded that due to optional value, absolute monopoly enterprise will invest only when the belief value is higher (0.9270). Enterprises may invest at the beginning if option value is not taken into consideration as $p_0 = p_{NPV} = 0.5$.

(2) At competition

$$\rho_F = \frac{\tilde{\beta}_1(r+\lambda+\mu)(r+\lambda+\mu(1-\alpha)) - \mu\alpha(1-\alpha)(r+\lambda+\mu(1+\tilde{\beta}_1-\alpha))}{\tilde{\beta}_1(r+\lambda+\mu)(r+\lambda+\mu\alpha) - \mu\alpha(1-\alpha)(r+\lambda+\mu(\tilde{\beta}_1+\alpha))} = 0.2284$$

where, $\tilde{\beta}_1 = 0.8184$,

$$p_F = \frac{1}{\rho_F(\lambda R^H / I(r+2\lambda)-1)+1} = 0.9563,$$

$$k_F = k(p_F) = 3.6418 \text{ and } \hat{p}_F = p\lceil k_F \rceil = 0.9674,$$

$$p_S = \frac{1}{\rho(\lambda R^H / I(r+2\lambda)-1)+1} = 0.9814,$$

$$k_S = k(p_S) = 4.6822 \text{ and } \hat{p}_S = p\lceil k_S \rceil = 0.9857.$$

With the value function $V_F(k)$ of the follower and the value function $V_L(k)$ of the leader, the following first entry point can be calculated: $[k_L] = 1$, $p_L = p[k_L] = p(1) = 0.7$. Values of $V_s(k)$ and $V_L(k)$ when $k = 0, 1, 2, 3, 4$ were calculated to judge if the simultaneous investment value before is reached is constantly larger than the value of the leader, which will not be repeated here due to space limitations. If the calculation result shows that $V_s(k)$ is constantly larger than $V_L(k)$, both parties have no motive to forestall and will invest until $k=[k_s]=5$, to generate optimal simultaneous investment equilibrium. Conversely, as long as there is $V_s(k)<V_L(k)$ before k_s is reached, preemptive game will be started, i.e. both parties would not invest and would wait for good news when k=0; when k=1, 2, 3, both parties will compete to be the leader, and the unfortunate "follower" will start to invest when $k=[k_F]=4$; when k=4, simultaneous investment equilibrium will be generated but the non-Pareto optimality is not obtained at this time. When k=5, both parties will invest immediately to generate optimal simultaneous investment equilibrium.

It can be thus seen that introduction of competition will reduce the critical belief $\hat{p}^*$=0.9270 (the k value corresponded should be 3 at least) necessary for the R&D investment of a single enterprise to the first entry belief p_L=0.7 (the k value corresponded can be 1), part of the value of option of waiting will be lost and the probability of wrong R&D investment decision will increase [1] correspondingly to $P_1^{(0)} = \left(\frac{0.7}{1-0.7}\right)^{0-1} = 0.429$ from $P_3^{(0)} = \left(\frac{0.7}{1-0.7}\right)^{0-3} = 0.079$.

5. Conclusion

Incomplete information and uncertainty will affect the R&D investment decision of renewable electric power enterprises. Against the R&D competition between two symmetric enterprises, the investment strategies of two competitive enterprises are analyzed by taking into consideration the uncertainty of the arrival of random events, the uncertainty of good or bad news contained by random events that act as signals and the technical uncertainty of R&D success, and constructing real option investment model. The result indicates that the winner-take-all privilege granted to leading innovators and the technical uncertainty to innovative technology by policy will make following enterprises react in two ways, investment delay or investment advancing. The faster signal arrives, the higher is the signal quality higher will be the investment belief of following investors. Moreover, the R&D competition equilibrium among enterprises can result in preemptive equilibrium and simultaneous investment equilibrium.

For further study, this model can be expanded to non-symmetric enterprises or several enterprises, or consideration of different R&D objects and signal acquisition cost can be included.

References

[1] Thijssen J J J, van Damme E E C, Huisman K J M, Kort P M. Investment under Vanishing Uncertainty due to Information Arriving over Time[R]. Working Paper, No. 2001-14, Center, Tilburg University, 2001a.

[2] Thijssen J J J, Huisman K J M, Kort P M. Strategic Investment under Uncertainty and Information Spillovers[R]. Working Paper, No. 2001-91, Center, Tilburg University, 2001b.

[3] Dixit A K, Pindyck R S. (1994): Investment under Uncertainty [M]. Princeton, NJ: Princeton University Press.

[4] Lambrecht B, Perraudin W. (2003): Realoptions and Preemption under Incomplete Information[J]. Journal of Economic Dynamics & Control, 27(4): 619-643.

[5] Decamps J, Mariotti T, Villeneuve S. (2005): Investment Timing under Incomplete Information[J]. Mathematics of Operations Research, 30(2): 472–500.

[6] Wu Jianzu, Xuan Huiyu. (2006): Option-game analysis on optimal R&D investment timing of enterprises with incomplete information [J]. Systems Engineering —Theory & Practice, 26(4): 50-54.

[7] Cai Qiang, Zeng Yong, Deng Guangjun. (2008): Patent investment with incomplete information [J]. System Engineering, 26(9): 64-67.

[8] Cai Qiang, Deng Guangjun, Zeng Yong. (2009): Influence of randomly arriving incomplete information on patent competition [J]. Systems Engineering – Theory & Practice, 29(4): 81-91.

[9] 2012, 28(1): 115-120. Wang Xiaotian, Xue Huifeng. Positive analysis and policy implication on factors affecting renewable energy power generation investment decision- making behaviours [J]. Journal of Xi'an University of Technology, 28(1): 115-120.

[10] Wang Wenping, Yang Hongping. (2008): Application of real option theory on wind power generation project investment decision-making [J]. Power Grid and Clean Energy, 8:42-46.

[11] Liu Jun et al. (2013): Photovoltaic power generation investment decision - making model based on real-option theory. Energy Conservation Technology, 31(1): 75-78.

[12] Huang Wenjie, Huang Yi. (2010): Power generation option-game investment decision-making model based on risk preferences of investors [J]. *Journal of North China Electric Power University*, 37(2): 99-103.

[13] Fudenberg D, Tirole J. (1985): Preemption and Rent Equalization in the Adoption of New Technology[J]. Review of Economic Studies, 52(3): 383-401.