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The Investment Evaluation of Third-Generation Nuclear Power - From the Perspective of Real Options

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1. Introduction

The continued growth of world's population and gradual increase of people's living standards in developing countries have sped up the exhaustion of fossil fuels and caused large amount of greenhouse gas emissions. Although renewable energy sources (e.g. wind energy, solar energy, hydro energy and biomass energy) have developed rapidly in recent years, limitations existing in these energy sources (e.g. non-continuous electricity supply of wind and solar power generation, resource constraints for hydro power and biomass energy etc.) still set barriers to launching application in large scale and fulfilling world's energy demand in near future.

Currently, great attention has been paid to nuclear technology. It has been widely accepted around the world that nuclear power is a clean energy option which causes zero-emissions of SO₂, NO_x, smoke dust and carbon. A safely-operating nuclear power plant with strict radiation monitoring and risk management system will have little impacts on its surroundings, and the effects of radiation dose on citizens near the plant will be lower than 1% of underground natural radiation. The development of nuclear energy can broaden the energy sources in energy industry, ease the limitations of fossil fuel supply, and reduce the environmental pollution caused by fossil fuel combustion. The development of nuclear technology will also have significant impacts on greenhouse gas emission reduction.

Asia has become the largest market for nuclear power after remarkable growth has emerged to its economies in the last decade, especially in China and India. The enjoyment of rapid economic development in Asian countries also brings the booming of energy consumption. On one hand, considering large fluctuation of international fossil energy prices (e.g. oil prices) in recent years and lack of effective energy supply, Asian countries have to face more serious energy security situations; On the other hand, the consumption of fossil energy has caused severe environmental pollutions and large amount of greenhouse gas emissions, in the case of renewable energy development barriers, Asian countries need to find other new, clean, stable and extensive energy resource to meet their domestic energy demand. Nuclear power is regarded as a trustworthy way to enhance Asian countries' energy security and becomes a preferred-choice in their energy options.

As the world's largest developing country which is struggling with limited energy resources, growing energy demand, increasing dependence on imported oil, deteriorating

environment, and enormous greenhouse gas emission, China has taken nuclear power as one of main directions in future energy development to cope with serious threats on domestic energy security. China's power generation portfolio aims to gradually reduce the proportion of coal-fired power in the total power-generation mix and to promote the diversification of electrical energy sources, the power industry's 'Eleventh Five-Year Plan' (NDRC, 2007) has been proposed to optimize the development of nuclear power. Furthermore, the objective of 'Mid and Long-term Nuclear Power Development Plan' (NDRC, 2007) is to achieve a new capacity of 40 GW Nuclear Power in the year 2020, which will account for 4% of total generating capacity. At the end of 2009, China has owned the largest scale of nuclear power plants under construction over the world, and the plants in progress have reached 21.92 GW with a total of 20 units.

After the development of first two generations of nuclear power, China proposed to pioneer the demonstration and deployment of third-generation nuclear power with advanced reactors (Generation III nuclear reactor) in order to further enhance the level of self-developed nuclear power technology. The third-generation reactors have: 1) a standardized, simpler and more rugged design for each type to expedite licensing; 2) higher availability and longer operating life expectancy; 3) comparatively lower possibility of core melt accidents; 4) resistance to serious damages; 5) higher burning temperature to reduce fuel use and the amount of waste and burnable absorbers to extend fuel life. In 2007, as one of the Generation III nuclear reactor technologies on basis of a comprehensive technology transfer, Westinghouse AP1000 has been selected by China National Nuclear Cooperation to build four nuclear reactors in two demonstration projects in Zhejiang Sanmen and Shandong Haiyang. Currently, nuclear reactors built in Zhejiang Sanmen are the only third-generation nuclear power units in the world.

2. Uncertainties of China's third-generation nuclear power technology investment

Some scholars have already studied the third-generation nuclear power from different perspectives. Yim (2006) has discussed the relationship between the future expansion of nuclear power and the prospect for world nuclear nonproliferation, he concludes that the development of nuclear power and expansion of advanced nuclear technology will not result in nuclear proliferation. Popa-Simil (2008) has proposed that the micro-bead heterogeneous fuel mesh gives the fission products the possibility to acquire stable conditions outside the hot zones without spilling and the high temperature fission products free fuel with near perfect burning, which is important to the future of nuclear power development. Marcus (2008) has studied the characteristics of advanced nuclear reactor in order to extensive demands worldwide, including the role of nuclear power in the world power generation, introduction of innovative nuclear technologies, nuclear path forward and international initiatives of advanced nuclear technologies. Tronea (2011) has discussed the European quest for standardisation of nuclear power reactors, including nuclear power design, new reactors standard and nuclear safety. Yan et.al (2011) has introduced the development of nuclear power and third-generation nuclear power demonstration projects in China, and they also have forecasted the future demand of uranium fuel in China.

In the study of the economics of nuclear power, Kessides (2010) has discussed nuclear power investment from the perspective of economic risks and uncertainties. He points out that several elements should be considered in nuclear power valuation, including

environmental benefits of nuclear power investments (the contribution of greenhouse gas emissions), fuel costs, costs of radioactive waste disposal, risks associated with radio activity release from all fuel cycle activity, with the capital or nuclear power construction costs with the greatest importance. However, as a technology that is currently in the research and development stage, China is facing numerous uncertainties in demonstration and deployment of third-generation nuclear power, including:

1. The uncertainty from the technology itself. As a large-scale and capital-intensive technology, third-generation nuclear power is still in the development and demonstration stage which exhibiting unsolved technology uncertainties. During the technology deployment process, uncertainties around the technology mainly come from the plant design and construction, reactor installation, and equipment commissioning. And this corresponds to the uncertainties of investment cost and construction period which are in need for technology deployment.
2. It is claimed in the design that the operating costs of third-generation nuclear power will be equal or even lower than that of second-generation. It should be noted that nuclear fuel cost has accounted for a large proportion in nuclear power operating costs. Currently, the price of nuclear fuel is relatively stable because uranium resources in each country are under government control, as more nuclear power plants will be put into use in the coming future, increasing demand of uranium resources worldwide may result in price increasing and fluctuation. This will add more price risk to generating cost.
3. Although the design of third-generation nuclear power is much safer than first two generations, because the lack of actual operational experiments, the potential risk of radiation can not be completely under control. China's National Nuclear Security Regulations require the Probabilistic Safety Assessment (PSA) must be carried out by all nuclear power plants. Nuclear accidents are unexpected events with small probability, and previous studies in nuclear power valuation have not considered the impacts of nuclear accidents and losses (or damage) caused by nuclear plants operation.
4. The uncertainty in electricity price mechanism. Currently, China's electricity price of nuclear power is set by the government, which is a cost-benefit pricing mechanism and each nuclear power plant has its own constant electricity price. So the electricity prices vary a lot among different nuclear plants. With the continuous electricity market reform, the electricity price will be gradually pushed forward to market-oriented. One important feature of electricity price marketization is "price bidding" among different kinds of power plants. Liberalized electricity price will be affected by seasonal demand for electricity, fuel price changes, and other factors. And thus it is uncertain. Electricity price mechanism and price level will directly affect the valuation of third-generation nuclear power investment.
5. Regarding climate policy, nuclear power can be viewed as an emission reduction option. Compared to thermal power with identical installed capacity, the operation of nuclear power does not produce greenhouse gas emissions, but this part of emission reduction can not be verified in current Clean Development Mechanism (CDM). So the application of nuclear power can not have Certification Emission Reduction (CER) and trade in CDM. In fact, the nuclear industry is promoting nuclear power CDM credits. If nuclear power can be included in Clean Development Mechanism, the uncertainties in climate policy and trading mechanism of CDM (Bilateral or Unilateral) will also affects the investment of third-generation nuclear power.

As NPV based evaluation method can not fully catch the impacts of these uncertainties on nuclear power investment, it is necessary to develop a proper method to handle such kinds of uncertainties to evaluate the demonstration and deployment of third-generation nuclear power plants in China.

Real options approach is suitable for evaluation of large-scale investment projects with great uncertainties. Brennan and Schwartz (1985) first introduced a real options approach to natural-resource investment decisions. After that, real options approach has been applied more frequently in the evaluation of energy investment (Paddock et. al, 1988, Smith and Nau, 1995, Smith and McCardle, 1998, 1999, Fan and Zhu, 2010). For power investment projects, real options approach can consider the uncertainties of the market environment, generating fuel prices, environmental factors, electricity demand and supply and so on (Venetsanos et.al, 2002, Davis and Owens, 2003, Siddiqui et. al, 2007, Abadie and Chamorro, 2008a, 2008b, Fuss et.al, 2008, Fleten and Näsäkkälä, 2009). Therefore, the real options approach would be useful for evaluation of advanced generating technologies. In the valuation of nuclear investment, Gollier et. al (2005) apply real options approach with the consideration of electricity price uncertainty to compare the critical value between flexible sequence of small nuclear power plants and a nuclear power plant of large capacity. They show that the option value of modularity has a sizeable effect on the optimal dynamic strategy of the producer, particularly in terms of the optimal timing of the decision to invest in the first module.

This paper applies real options theory with Monte Carlo method to establish a nuclear power investment evaluation model, incorporating the world's first third-generation nuclear power project-Sanmen nuclear power plant in Zhejiang province, to evaluate the value of third-generation nuclear power plant from the perspective of power generation enterprises. Several technical and economic uncertainty factors (deployment cost, generating cost and nuclear accident), and two price mechanisms (electricity price and CDM) have been considered in the model and it is solved by Least Squares Monte Carlo (LSM) method. As the model can be used as a policy analysis tool, under a given period of nuclear power operation, first we have evaluated the value of Sanmen third-generation nuclear power plant in current constant electricity price set by the government to see whether it is worth investing or not. Then the impacts of different electricity and CDM mechanisms on the valuation of third-generation nuclear power have been discussed. And we have also analyzed the acceptable level of investment cost for third-generation nuclear power in China.

3. Model description and parameter settings

As stated above, Sanmen third-generation nuclear power project has been chosen for evaluation object, the model established here is based on real options theory with Monte Carlo method and solved by Least Squares Monte Carlo (LSM) simulation. The valuation includes nuclear power plant construction period and operation period. As a large-scaled investment project, it will take time to complete nuclear power investment. And the power generation enterprise has the right to exercise the abandon option to terminate the nuclear project in the investment stage. So at each step of the investment stage, the enterprise can re-evaluate the nuclear project to decide whether to continue or abandon the investment. Assuming the total period for nuclear power construction and operation is T years, for the purpose of valuation we divide the T years into N periods, each with a length of

$\Delta t = T / N$, and define $t_n = n\Delta t$, $n = 0, 1, \dots, N$. All the units for the parameters described below is displayed in table 1.

3.1 Modeling third-generation nuclear power operation

At nuclear power plant operation period, first it is in need to calculate the cash flow during nuclear power operation. Assuming at any period t_n , the generating capacity of third-generation nuclear power is $Q_{Elec}(t_n)$, and all the electricity generated by nuclear power can be sold to grid. Considering the possibility of nuclear accident, after nuclear power investment has been completed, the cash flow $CF(t_i)$ earned by the power enterprise through electricity selling from nuclear power at t_i period should be:

$$CF_{Nu}(t_i) = [P_{Nu}(t_i) + P_C(t_i) - C_{Nu}(t_i) - R_w] \cdot Q_{Elec}(t_i) \cdot (1 - Tax) - \Delta q$$

Where $P_{Nu}(t_i)$ is the electricity price; $P_C(t_i)$ is the carbon price under CDM, and if nuclear power can not be included in CDM, this term will be 0; $C_{Nu}(t_i)$ is the nuclear generating cost; Tax denotes the income tax for power generation enterprise; R_w represents the cost for nuclear waste disposal; and Δq is the impact of nuclear accident.

At any period t_i after accomplishment of nuclear power investment, the value $V_{Nu}(t_i)$ for enterprise operating the nuclear power plant is:

$$V_{Nu}(t_i) = \sum_{n=i}^N e^{-r(t_n - t_i)} CF_{Nu}(t_n)$$

And r is the risk free rate.

During nuclear power plant operation period, we have considered the impact of three electricity price mechanism, two CDM price mechanism, generating cost (uranium fuel price) uncertainty, and unexpected events with small possibility on the nuclear power plant operating cash flow and value.

First, we can assume nuclear generating cost following a geometric Brownian motion:

$$C_{Nu}(t_{i+1}) = C_{Nu}(t_i) \exp(\alpha_C \Delta t + \sigma_C (\Delta t)^{1/2} \varepsilon_C)$$

Where ε_C is a normally distributed random variable with mean of 0 and standard deviation equivalent to 1; and α_C and σ_C represent the drift and variance parameters of the nuclear generating cost, respectively.

Nuclear accidents are unexpected events with small possibility. Here we apply a Poission process to describe the unexpected events (nuclear accidents) during nuclear power plant operation period. Let q be a Poission process, then we have:

$$\Delta q = \begin{cases} 0, & \text{Probability: } 1 - \lambda \Delta t \\ u = \begin{cases} u_S, \text{Probability: } \eta_S \\ u_M, \text{Probability: } \eta_M \\ u_L, \text{Probability: } \eta_L \end{cases}, & \text{Probability: } \lambda \Delta t \end{cases}$$

Where λ is the average probability for the unexpected events (nuclear accidents), and at any time horizon Δt , the probability of nuclear accidents happen will be $\lambda \Delta t$ and the

probability of nuclear accidents do not happen will be $1 - \lambda\Delta t$; u represents the damage or loss caused by nuclear accidents during nuclear operation, and $\eta_S + \eta_M + \eta_L = 1$.

Considering different level of nuclear accidents will cause different damage or loss, we define three levels of nuclear accidents which correspond to different probability:

1. Minor accident, the probability is η_S , there is a small loss u_S for nuclear power plant and it will not affect plant operation.
2. Moderate accident, the probability is η_M , there is a moderate loss u_M for nuclear power plant. And the plant will pause power generation in next two years in order to have necessary reactor security maintenance and monitoring nuclear leak, which $Q_{Elec}(t_{x+1}) = Q_{Elec}(t_{x+2}) = 0$.
3. Serious accident, the probability is η_L , there is a severe loss of u_L for nuclear power plant. And the plant will be shut down permanently, which $Q_{Elec}(t_{x+1}) = Q_{Elec}(t_{x+2}) = \dots = Q_{Elec}(t_N) = 0$.

For electricity price, three forms of price mechanism have been taken in to account in this paper, which are shown as follows:

1. The electricity price follows cost-benefit pricing mechanism and is set by the government, it is a constant price mechanism in which $P_{Nu}(t_{i+1}) = P_{Nu}(t_i)$.
2. The electricity price is still under government control but has a constant growth rate at each period, it is a constant growth price mechanism in which $P_{Nu}(t_{i+1}) = P_{Nu}(t_i)\exp(\alpha_p\Delta t)$.
3. The electricity price is liberalized as electricity marketization. Assuming the liberalized electricity price follows a geometric Brownian motion

$$P_{Nu}(t_{i+1}) = P_{Nu}(t_i)\exp(\alpha_p\Delta t + \sigma_p(\Delta t)^{1/2}\varepsilon_p)$$

Where ε_p is a normally distributed random variable with mean of 0 and standard deviation equivalent to 1; and α_p and σ_p represent the drift and variance parameters of the electricity price, respectively.

For CDM, two following forms of CDM have been modelled in this paper:

1. In bilateral CDM, the carbon price is constant, of which $P_C(t_{i+1}) = P_C(t_i)$.
2. In unilateral CDM, referring to previous research related carbon price modeling (Abadie and Chamorro, 2008, Heydari et.al, 2010), assuming the carbon price in unilateral CDM follows a geometric Brownian motion:

$$P_C(t_{i+1}) = P_C(t_i)\exp(\alpha_{Pc}\Delta t + \sigma_{Pc}(\Delta t)^{1/2}\varepsilon_{Pc})$$

Where ε_{Pc} is a normally distributed random variable with mean of 0 and standard deviation equivalent to 1; and α_{Pc} and σ_{Pc} represent the drift and variance parameters of the carbon price, respectively.

3.2 Modeling third-generation nuclear power investment

At nuclear power plant construction period, we apply a controlled diffusion process to describe the uncertainty of third-generation nuclear power investment. K_{Nu} is the expected total investment cost for power generation enterprises to deploy third-generation nuclear

power technology and the total deployment investment remaining at period t_i is $K_{Nu}(t_i)$. Assume that K_{Nu} follows the controlled diffusion process:

$$K_{Nu}(t_{i+1}) = K_{Nu}(t_i) - I_{Nu}(t_i)\Delta t + \beta[I_{Nu}(t_i)K_{Nu}(t_i)]^{1/2}(\Delta t)^{1/2}\varepsilon_x$$

Where β is a scale parameter representing the uncertainty around K_{Nu} ; ε_x is a normally distributed random variable with mean of 0 and standard deviation equivalent to 1. The variance of K_{Nu} is $Var(K_{Nu}) = \left(\frac{\beta^2}{2-\beta^2}\right)K_{Nu}^2$, whereby uncertainty of third-generation nuclear power technology reduces as K_{Nu} decreases.

Under the real option analysis framework, the power generation enterprise owns the abandon option during nuclear power plant construction period. At any time period t_i in construction period, the value of the nuclear power investment opportunity owned by the enterprise is denoted by $F_{Nu}(t_i)$. At the time period which nuclear power investment is completed (construction finished), the value of abandon option is equal to nuclear power project value:

$$F_{Nu}(\tau) = V_{Nu}(\tau)$$

At the time period t_i before investment is completed, the value of the nuclear power investment opportunity that the enterprise owns is equal to:

$$F_{Nu}(t_i) = \max\left\{0, E_{t_i}\left[e^{-r(t_{i+1}-t_i)}F_{Nu}(t_{i+1})\right] - I_{Nu}(t_i)\right\}$$

Where $E_{t_i}[*]$ is the expected value which the enterprise chooses to hold abandon option and continue to invest in nuclear power plant at the time period t_i .

3.3 LSM Solution to the model

The abandon option $F_{Nu}(t_i)$ of third-generation nuclear power investment is computed by the Least Squares Monte Carlo (LSM) method. The LSM method was developed for valuing American options and is based on Monte Carlo simulation and least squares regression (Longstaff and Schwartz, 2001; Schwartz, 2004). The model also computes the related greenhouse gas emission reduction which is avoided by applying nuclear power to take place of thermal power. Take τ_g to represent the time that the third-generation nuclear power investment is completed in path g . Thus, the greenhouse gas emission reduction from the adoption of nuclear power during the given observation period can be computed as:

$$ER(g) = e \cdot Q_{Elec} \cdot (T - \tau_g)$$

Where $ER(g)$ is the emission reduction amount during path g ; e is the emission factor for existing thermal power. Taking the average over all the paths, the total emission reduction amount through investing in third-generation nuclear power technology can be obtained. LSM method described has been implemented in Matrix Laboratory (MATLAB), and all solution procedure is vividly described in figure 1.

3.4 Model parameters

Table 1 shows the parameter values of the model. The project data related to Sanmen third-generation nuclear power plant mainly derive from public reports. Liberalized electricity price mechanism refers to European electricity market, and the data of uranium price comes from EIA. Some parameter values are estimated in this research due to data lack.

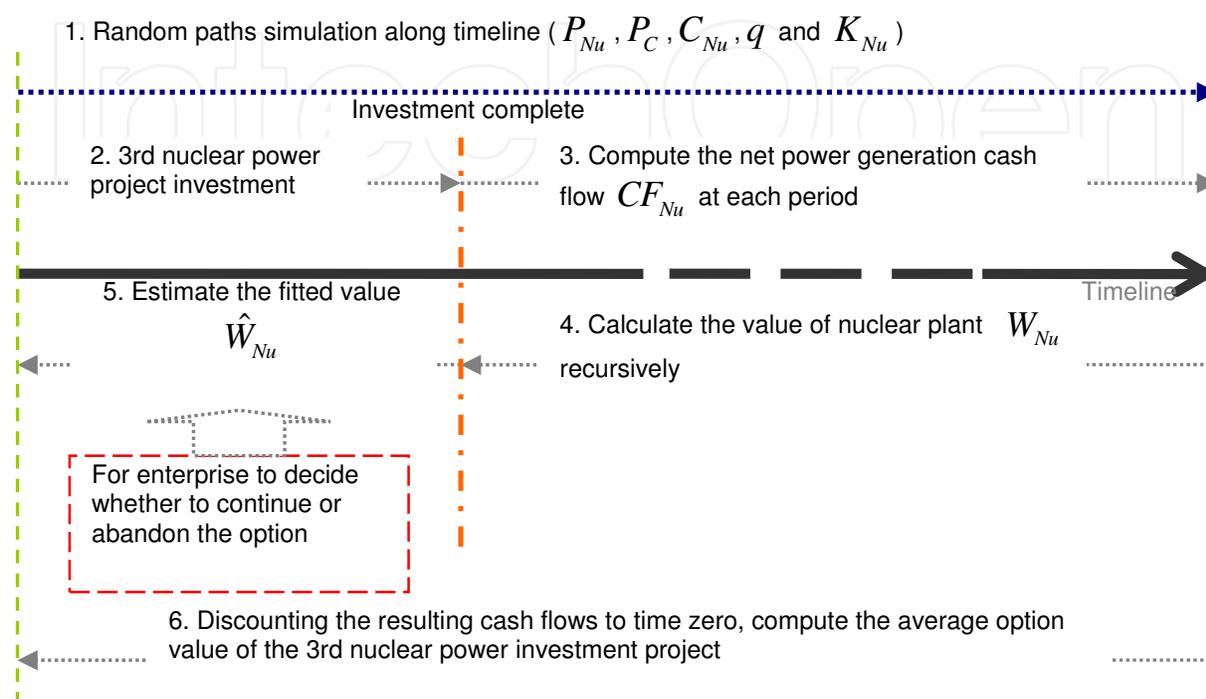


Fig. 1. LSM based Model Solution Procedure

Parameter	Model symbol	Value	Notes
generation capacity	Q_{Elec}	$15000 \cdot 10^6$ kwh	After Sanmen Nuclear Power project phase I has been completed, it will provide the power installed capacity of 2.5 million kilowatts, with a electricity supply of annual 17.5 billion kwh. It is designed to meet new electricity demand in Zhejiang province.
Total investment cost of third-generation nuclear power plant	K_{Nu}	$40000 \cdot 10^6$ yuan	Sanmen Nuclear Power Project will build 2 units with each installed capacity of 1.25 million kilowatts, and the total investment cost is 40 billion.
Initial annual investment cost	I_{Nu}	$8000 \cdot 10^6$ yuan	The time needed for nuclear power construction is generally 5 years. Sanmen Nuclear Power Project has started construction in 2009, and it is expected to be put into in operation in 2014. So the initial investment cost can be set as five years annual investment cost.
Nuclear technology uncertainty	β	0.5	Here refers to the settings in the research of Schwartz (2003), Dixit and Pindyck (1994).

Parameter	Model symbol	Value	Notes
Nuclear power generating cost	C_{Nu}	0.25 yuan/kwh	The data refers to the estimation of uranium generating cost from Zhu and Fan (2010). Set by this study.
Nuclear power generating cost drift rate	α_C	0.01/year	
Nuclear power generating cost standard deviation rate	σ_C	6.24%/year	The data refers to the estimation of uranium generating fuel risk from Zhu and Fan (2010).
Electricity price	P_{Nu}	0.45 yuan/kwh	The price level refers to the electricity price set for Tianwan nuclear power plant which is newly put into operation, and this is also the baseline electricity price in our model.
Electricity price drift rate	α_P	0.01/year	Set by this study.
Electricity price standard deviation rate	σ_P	5.00%/year	Set by this study. Considering future economic development in China, the demand for electricity is to some extent rigid, so here we set a low level of price volatility.
Correlation between Electricity price and generating cost	ρ_{PCNu}	0.3	Set by this study.
Carbon price	P_C	0.12 yuan/kwh	The data refers to the estimation of carbon emission cost from Zhu and Fan (2010). And this is also the baseline carbon price in our model.
Carbon price drift rate	α_{Pc}	0.02/year	Set by this study.
Carbon price standard deviation rate	σ_{Pc}	11.50%/year	The data refers to the estimation of carbon price risk from Zhu and Fan (2009).
Probability of nuclear accident	λ	0.01%/year	Set by this study.
Probability of minor accident	η_S	98.90%	Here assume most of the nuclear accident are minor accident
Probability of moderate accident	η_M	1.00%	Assuming there will be 1.00% the probability to be moderate accident after nuclear accident happened.
Probability of serious accident	η_L	0.10%	Assuming there will be 0.10% the probability to be serious accident after nuclear accident happened.
Damage or loss of minor accident	u_S	50×10^6 yuan	The loss for minor accident and it will not affect plant operation.
Damage or loss of moderate accident	u_M	500×10^6 yuan	The loss for moderate accident, And the plant will pause power generation in next two years in order to have necessary reactor security maintenance

Parameter	Model symbol	Value	Notes
Damage or loss of serious accident	u_L	5000×10^6 yuan	and monitoring nuclear leak. The loss for serious accident, And the plant will be shut down permanently.
Nuclear waste disposal cost	Rw	0.02 yuan/kwh	The cost of nuclear waste disposal is generally account for 10% of total nuclear generating cost.
Riskfree rate	r	0.05%	China's long-term deposit interest rate is used as a risk-free rate to represent the discount rate.
Tax rate	Tax	25%	Refers to the level of current domestic income tax.
Observation time	T	30 year, year 2010-2040	Here we consider the first 30 years of nuclear power plant life, this period is main investment accounting period for nuclear power investment.
Time Step Size in Simulations	Δt	1 year	
Number of Simulations	G	5000	In general, the simulation results will start to convergence when paths more than 1000, so the number of paths simulated in different scenarios are set as 5000.
Emission Factor	e	893g CO ₂ /kwh	Emission factor of coal-fired generation comes from IEA (2009). In 2007, CO ₂ emission per kwh from electricity and heat generation using coal/peat in China is 893g CO ₂ /kwh.

Table 1. Parameters used in the model

Figure 2a and 2b shows the changes of nuclear power generating cost C_{Nu} and remaining investment cost of third-generation nuclear power plant K_{Nu} in 250 of 5000 simulation paths. Figure 2c-2e shows once nuclear accident happen, the impact of three levels of nuclear accident on the nuclear power plant operation and cash flow in a single path. A large sample of random routing Monte Carlo simulation can simulate every possible result of cost change, and can better quantify the impact of nuclear accident on the value of third-generation nuclear power plant.

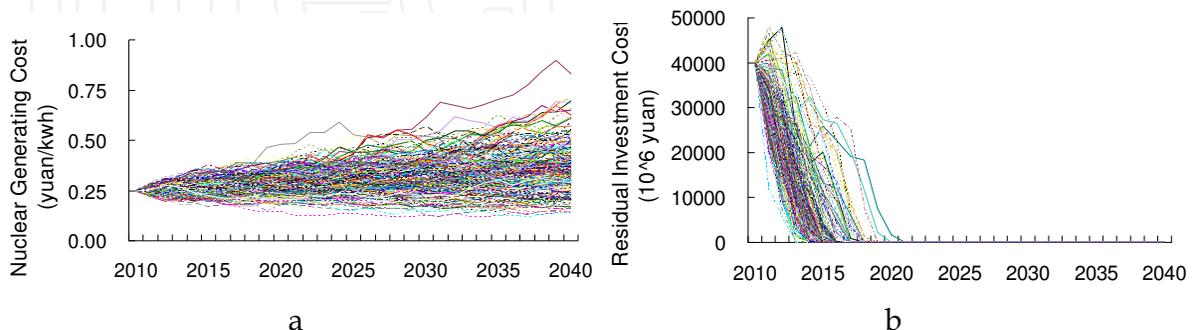


Fig. 2a. Generating cost simulation (Paths:250 of 5000)

Fig. 2b. Residual investment cost simulation (Paths:250 of 5000)

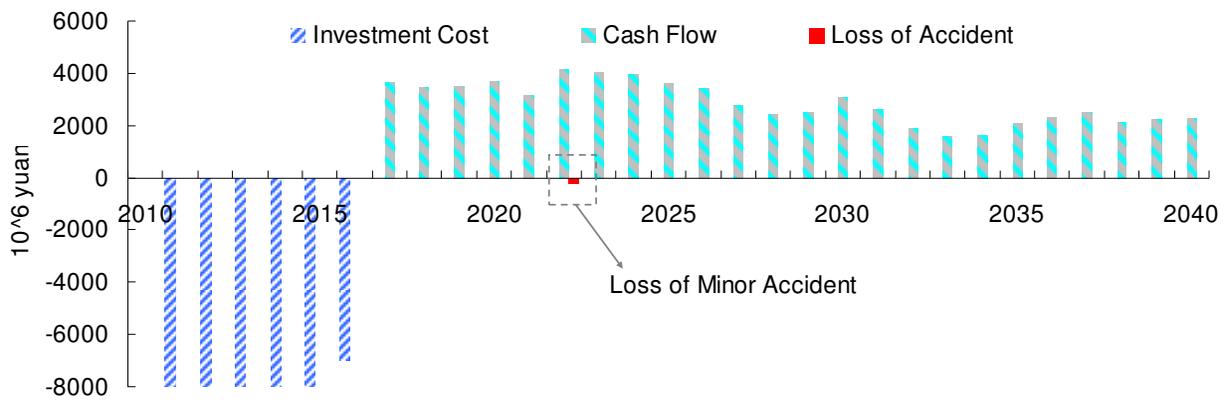


Fig. 2c. Single simulated path of minor nuclear accident

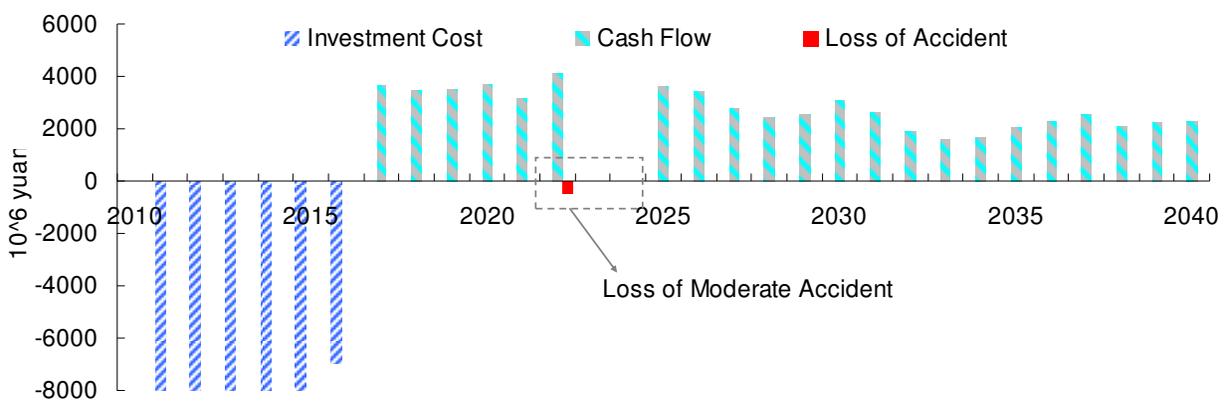


Fig. 2d. Single simulated path of moderate nuclear accident

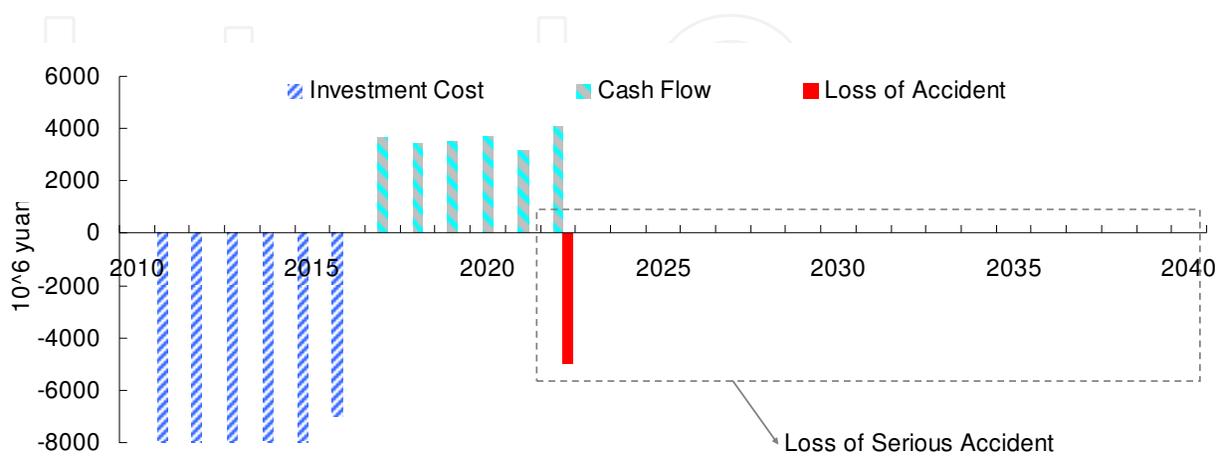


Fig. 2e. Single simulated path of serious nuclear accident

4. Evaluation of third-generation nuclear power investment in China

Take the value of parameters into the model, and simulate the future changes of uncertainty factors according to their initial settings, then we can calculate the nuclear power plant value with abandon option by LSM method. Considering the Randomness of Monte Carlo simulation and in order to have a more accurate result, we have calculated five seeds for each result. And each seed has a result based on 5000 paths simulation with the application of LSM solution. Taking the average of the results in five seeds then we can get the value of third-generation nuclear power plant with abandon option.

For comparisons, we have presented two cases. Case 1 is based on current situation in China that the electricity price of nuclear power is set by the government and nuclear power can not be included in CDM. The constant electricity price set in our model is 0.45yuan/kwh which refers to the electricity price set for Tianwan nuclear power plant, and carbon price is 0. Case 2 sets the electricity price that is liberalized and nuclear power can be included in CDM (unilateral CDM with uncertain carbon price). The initial electricity price is set as 0.45yuan/kwh, and carbon price is 0.12yuan/kwh. See results in table 2.

It can be seen from table 2 that, in Sanmen third-generation nuclear power investment, if the electricity price is set by the government and nuclear power can not join CDM, the value of nuclear power plant is 0 and the investment has been abandoned in all paths. This means, because of high investment cost and uncertainty, under current level of constant electricity price for nuclear power, third-generation nuclear power is not worth investing in China. And if we consider the liberalized electricity price and CDM, the value of nuclear power plant lies between 17979.49 and 18582.92 million yuan, with a mean of 18322.38 million yuan. The percentage of paths abandoned is 0.74%, which is really small. And the CO₂ emission reduction amount is 325.78 million tons CO₂e. This means under case 2, the investment of third-generation nuclear power is very attractive and with a very small investment risk.

Case 1: Electricity Price Fixed + Without CDM	Seed 1	Seed 2	Seed 3	Seed 4	Seed 5	Average
Nuclear Power Plant Value (Millions RMB)	0	0	0	0	0	0
Percentage of Paths Abandoned	100%	100%	100%	100%	100%	100%
Emission Reduction Amount (Millions tonnes CO ₂ e)	0	0	0	0	0	0
Case 2: Electricity Price Uncertain + Unilateral CDM	Seed 1	Seed 2	Seed 3	Seed 4	Seed 5	Average
Nuclear Power Plant Value (Millions RMB)	18297.62	18447.95	18582.92	18303.94	17979.49	18322.38
Percentage of Paths Abandoned	0.72%	0.74%	0.72%	0.52%	1.00%	0.74%
Emission Reduction Amount (Millions tonnes CO ₂ e)	325.84	325.91	325.81	326.48	324.85	325.78

Table 2. Nuclear Power Plant Values Results for Different Seeds

In the next, we will further discuss the impacts of three electricity price mechanism, two CDM, and different levels of investment cost on the valuation of third-generation nuclear power investment.

4.1 The impact of three electricity price mechanism

Nuclear power electricity price level is a significant factor in nuclear investment. Our model has introduced three electricity price mechanisms: constant electricity price set by the government, electricity price with constant growth rate, and liberalized electricity price as market-oriented (the price follows stochastic process). This part aims to investigate, under these three electricity price mechanisms, the impact of different level of electricity price on the value of third-generation nuclear power. In constant electricity price mechanism, the price level will increase from 0.45yuan/kwh gradually up to 0.575yuan/kwh. And in constant growth rate and liberalized electricity price mechanism, the initial price level will increase from 0.45yuan/kwh gradually up to 0.575yuan/kwh. See results in figure 3a-3c.

Figure 3a is the trend for the value of third-generation nuclear power changes as electricity price changes. In constant electricity price mechanism, the value of third-generation nuclear power can exceed 0 only when electricity price is 0.575yuan/kwh, and the value is 88.74 million yuan. Compares to 40000 million yuan investment cost for third-generation nuclear power plant, it has very low investment returns. And the electricity price of 0.575yuan/kwh has increased 27.78% than that of Tianwan nuclear power plant, the price level is high. This mean if we wish to make the investment value of third-generation nuclear power exceed 0, the electricity price need to at least increase 30% than that of current price level in Tianwan nuclear power plant.

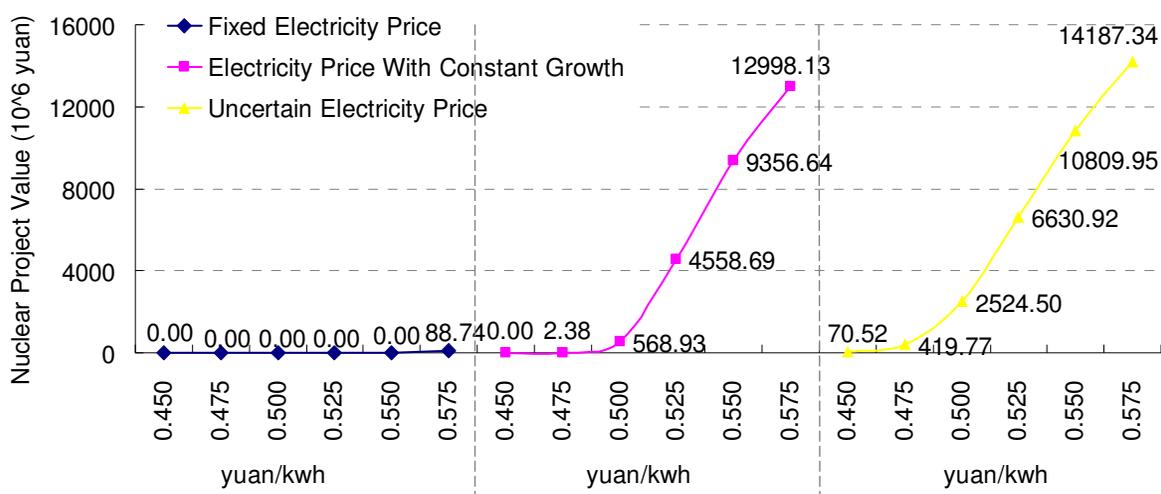


Fig. 3a. Nuclear plant value under 3 electricity price mechanisms

In constant growth rate and liberalized electricity price mechanisms, the value of third-generation nuclear power increases as the initial electricity price level increases. And given the same initial price level, the value in liberalized electricity price mechanism is always higher than that of constant growth rate price mechanism (given the initial electricity price as 0.45yuan/kwh and 0.575yuan/kwh, the value in liberalized electricity price mechanism are 70.52 million yuan and 14187.34 million yuan, which are all larger than 0 and 12998.13 million yuan in that of constant growth rate price mechanism). So in liberalized electricity

price mechanism, future uncertainty in electricity price can indeed increase the value of third-generation nuclear power and make the investment much more attractive.

Figure 3b is the paths abandoned among three electricity price mechanisms. In constant electricity price mechanism, all the paths are abandoned when electricity price level is lower than 0.55yuan/kwh, and the percentage of paths abandoned is 98.80% when the electricity price is 0.55yuan/kwh, which indicates that the investment risk is very high. In constant growth rate and liberalized electricity price mechanisms, the percentage of paths abandoned decreases as the initial electricity price level increases. Take the initial electricity price as 0.45yuan/kwh, the percentage of paths abandoned in constant growth rate and liberalized electricity price mechanisms are 100% and 99.05%. And take the initial electricity price as 0.45yuan/kwh, the percentage of paths abandoned in the two price mechanisms are 0.28% and 2.30%, respectively.

When the initial electricity price is low, the investment risk in constant growth rate mechanism is higher than that of liberalized electricity price mechanism (Take the initial electricity price as 0.475yuan/kwh, the percentage of paths abandoned in constant growth rate price mechanism is 99.93%, which is higher than that of 94.74% in liberalized electricity price mechanism). And when the initial electricity price is high, the investment risk in constant growth rate mechanism is smaller than that of liberalized electricity price mechanism (Take the initial electricity price as 0.55yuan/kwh, the percentage of paths abandoned in constant growth rate price mechanism is 6.55%, which is lower than that of 9.75% in liberalized electricity price mechanism). Though at the same initial price level, the value in liberalized electricity price mechanism is always higher than that of constant growth rate price mechanism, given a higher initial electricity price, the investment risk can be well hedged in constant growth rate price mechanism. This can not happen in liberalized electricity price mechanism because a higher initial electricity price can not fully hedge the uncertainty in future electricity prices. Therefore, the investment risk always exists in liberalized electricity price mechanism.

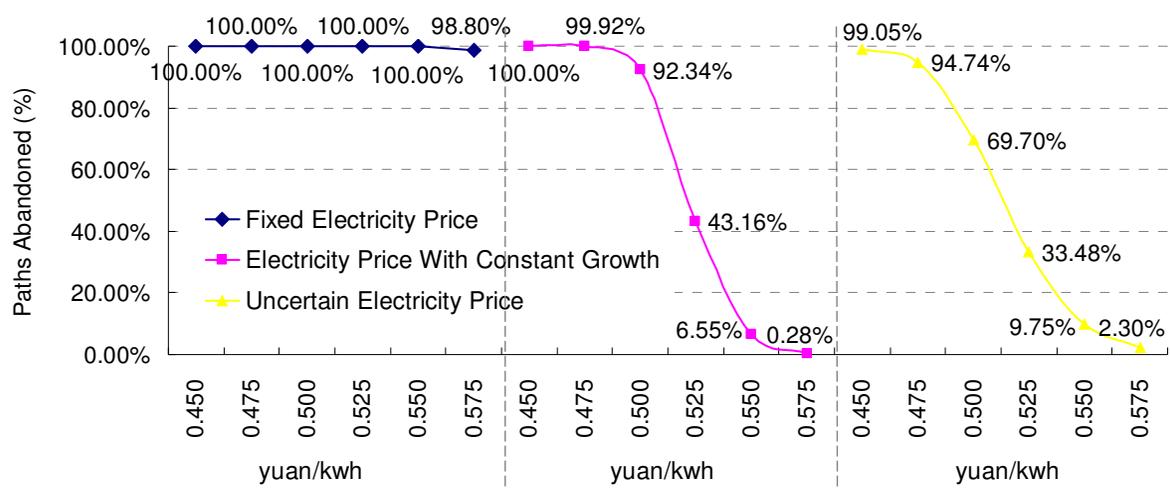


Fig. 3b. Paths abandoned under 3 electricity price mechanisms

Figure 3c is the CO₂ emission reduction amount among three electricity price mechanisms. CO₂ emission reduction amount is negatively correlated to the percentage of paths abandoned. Higher nuclear investment risk will result in lower emission reduction amount. In constant electricity price mechanism, when electricity price level is lower than

0.55yuan/kwh, all the emission reduction amount are all 0 as all the paths are abandoned. When electricity price level is 0.575yuan/kwh, the emission reduction amount is 3.95 million tons CO₂e as percentage of paths abandoned is 98.8%. In constant growth rate and liberalized electricity price mechanisms, CO₂ emission reduction amount of investing in third-generation nuclear power increases as the initial electricity price level increases. When the initial electricity price is low, the CO₂ emission reduction amount in constant growth rate mechanism is smaller than that of liberalized electricity price mechanism (Take the initial electricity price as 0.475yuan/kwh, the CO₂ emission reduction amount in constant growth rate price mechanism is 0.26 million tons CO₂e, which is smaller than that of 17.26 million tons in liberalized electricity price mechanism). And when the initial electricity price is high, the CO₂ emission reduction amount in constant growth rate mechanism is smaller than that of liberalized electricity price mechanism (Take the initial electricity price as 0.55yuan/kwh, the CO₂ emission reduction amount in constant growth rate price mechanism is 306.60 million tons CO₂e, which is larger than that of 296.19 million tons in liberalized electricity price mechanism). This is mainly because of the changes of investment risks among the two electricity mechanisms.

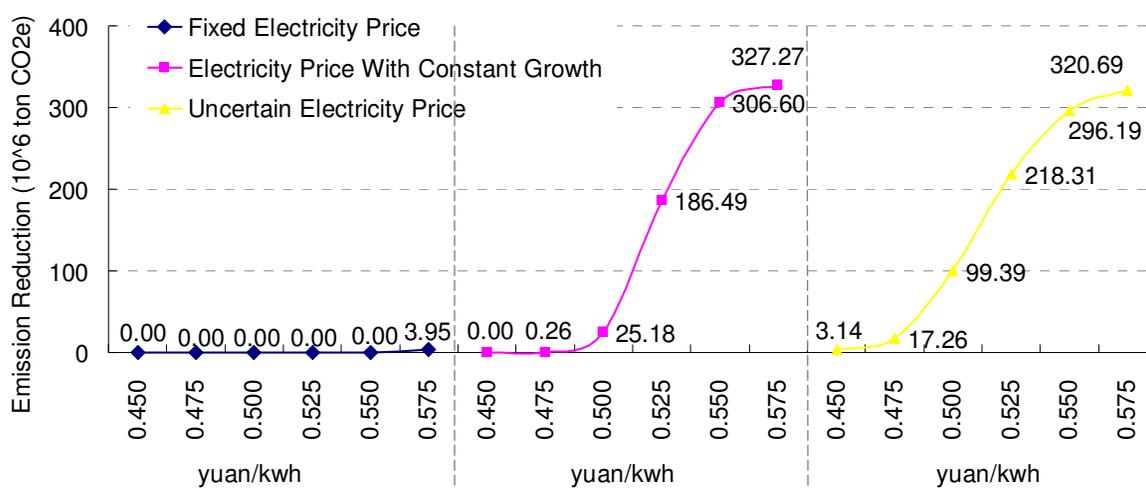


Fig. 3c. Emission reduction amount under 3 electricity price mechanisms

From the results we know that under current domestic constant electricity price level, nuclear power can not be included in CDM, third-generation nuclear power does not worth to invest. And the electricity price need to increase at least 30% than that of current price level in Tianwan nuclear power plant so as to make the investment value of third-generation nuclear power exceed 0. In constant growth rate and liberalized electricity price mechanisms, the value of third-generation nuclear power has increased a lot than that in constant electricity price mechanism. And in liberalized electricity price mechanism, as future uncertainty in electricity price can indeed increase the value of third-generation nuclear power, under this mechanism the value of third-generation nuclear power is the largest, and the investment is the most attractive.

4.2 The impact of two Clean Development Mechanism (CDM)

The nuclear industry is pushing hard to give nuclear power CDM credits. Our model has introduced two forms of CDM, bilateral CDM (constant carbon price) and unilateral CDM (uncertain carbon price). Here we set the electricity price as 0.45yuan/kwh and keep it

constant, the income of nuclear power generation is from two parts, selling electricity plus carbon credit. This part aims to investigate, under two forms of CDM, the impact of different level of carbon price on the value of third-generation nuclear power. In unilateral CDM, the carbon price level will increase from 0 gradually up to 0.125yuan/kwh. And in bilateral CDM, the initial carbon price level will increase from 0 gradually up to 0.125yuan/kwh. See results in figure 4a-4c.

Figure 4a is the trend for the value of third-generation nuclear power changes as carbon price changes. In unilateral CDM, although nuclear power can be included in CDM, the value of third-generation nuclear power still can not exceed 0 when carbon prices are lower than 0.10yuan/kwh. And at the baseline level of carbon price (0.12yuan/kwh) set in our model, the value is only 22.95 million yuan, which is relatively small. In bilateral CDM, at the baseline level of initial carbon price (0.12yuan/kwh), the value of third-generation nuclear power is 7147.07 million yuan, which makes nuclear power more attractive for investment. The value of third-generation nuclear power increases as the initial carbon price level increases, which is similar to that in liberalized electricity price mechanism. But given the same income level, the value in bilateral CDM is much smaller than that in liberalized electricity price mechanism (in bilateral CDM, when the initial income level is $0.45+0.10=0.55$ yuan/kwh, the value is 2444.34 million yuan, which is much smaller than that of 10809.95 million yuan in liberalized electricity price mechanism with initial electricity price is 0.55yuan/kwh).

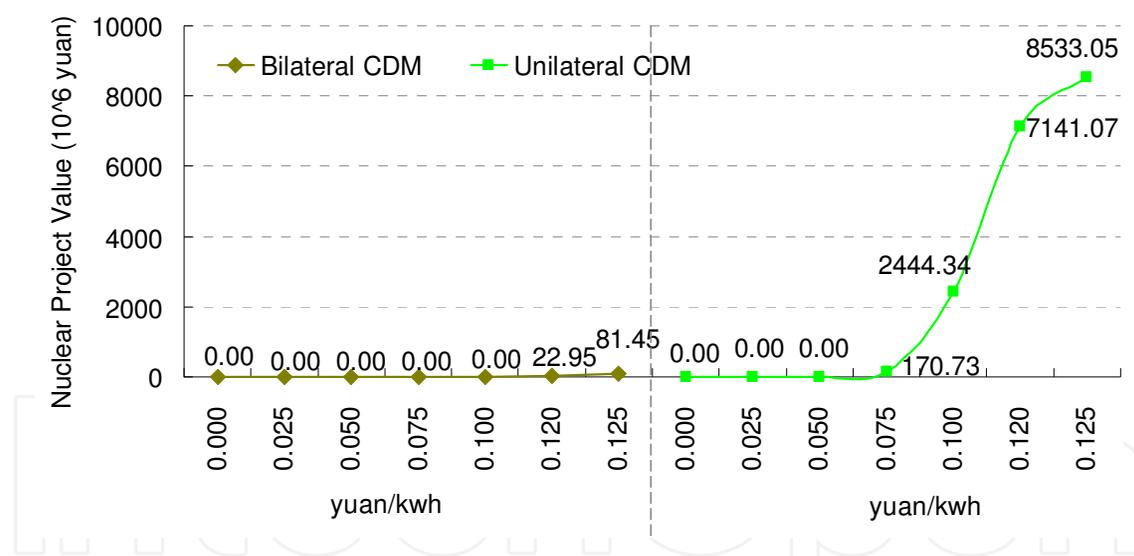


Fig. 4a. Nuclear plant value under 2 CDM mechanisms

Figure 4b presents the paths abandoned among two forms of CDM. In unilateral CDM, the investment risk of third-generation nuclear power is very large. In bilateral CDM, the percentage of paths abandoned decreases as the initial carbon price level increases, which is similar to that in liberalized electricity price mechanism. However, provided in given the same income level, the paths abandoned in bilateral CDM is much larger than that in liberalized electricity price mechanism (in bilateral CDM, when the initial income levels are $0.45+0.075=0.525$ yuan/kwh and $0.45+125=0.575$ yuan/kwh, the percentage of paths abandoned are 97.72% and 16.40%, which are much larger than that of 33.48% and 2.30% in liberalized electricity price mechanism with initial electricity prices are 0.525yuan/kwh and

0.575yuan/kwh, respectively). This means at the same initial income level, the investment risk in bilateral CDM is always larger than that in liberalized electricity price mechanism.

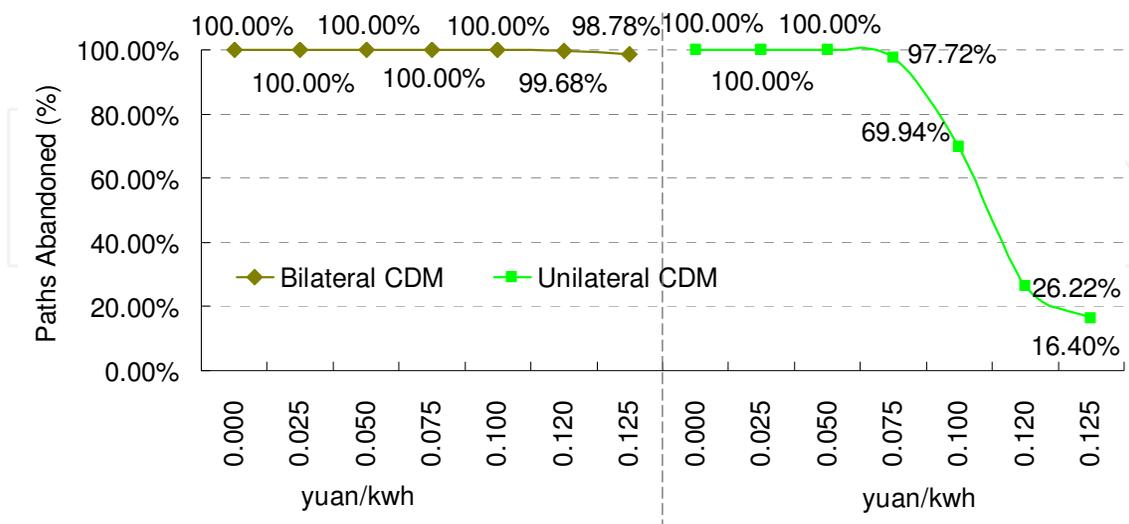


Fig. 4b. Paths abandoned under 2 CDM mechanisms

Figure 4c is the CO2 emission reduction amount among two forms of CDM. In unilateral CDM, the emission reduction amounts are 0 or relatively small because most of the paths are all abandoned. In bilateral CDM, the emission reduction amount increases as the initial carbon price level increases. As given the same initial income level, because the investment risk in bilateral CDM is always larger than that in liberalized electricity price mechanism, so the emission reduction amount in bilateral CDM is always smaller than that in liberalized electricity price mechanism (given the same initial income level as 0.55yuan/kwh, the emission reduction amount in bilateral CDM is 98.70 million tons CO₂e, which is smaller than that of 296.19 million tons CO₂e in liberalized electricity price mechanism).

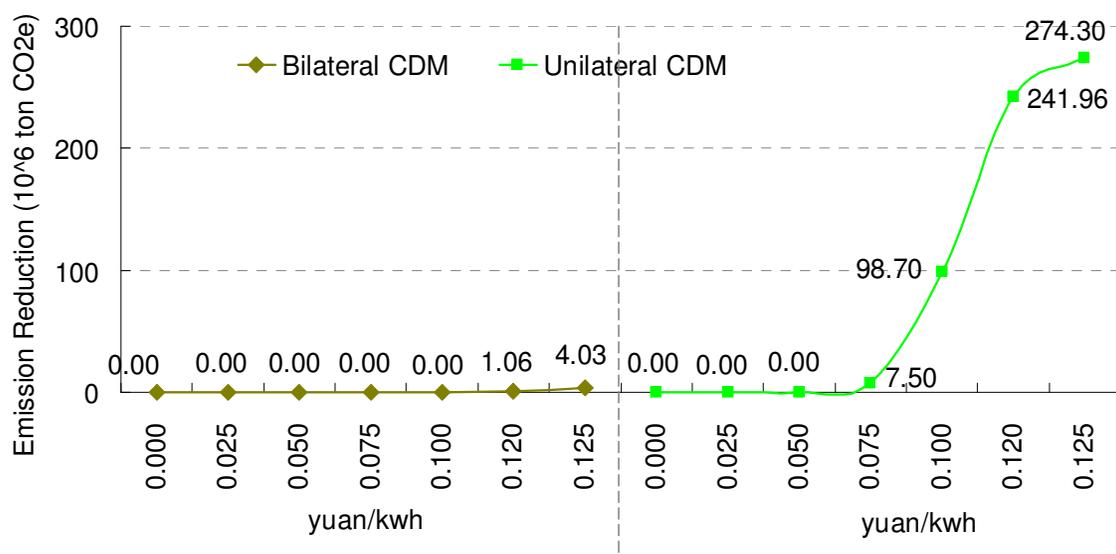


Fig. 4c. Emission reduction amount under 2 CDM mechanisms

From the results we can see that when the carbon price level is low, neither unilateral CDM nor bilateral CDM can increase the attraction of third-generation nuclear power investment. At the baseline carbon price level (0.12yuan/kwh), the carbon credit income in both unilateral CDM and bilateral CDM can increase the value of nuclear power on the basis of constant electricity price (0.45yuan/kwh). And the value will be higher in bilateral CDM. Therefore, if the nuclear power can be included in CDM, we would advise the power generation enterprise to take more efforts in bilateral CDM, but not conservative follow bilateral CDM which is more common for domestic carbon credit sellers. As a result, it can obtain more benefits from carbon credits.

4.3 The impact of different levels of nuclear investment cost

Based on the data from Sanmen third-generation nuclear power plant, the total investment cost is 40000 million yuan with installed capacity of 2500MW (2*1250MW). And the average unit investment cost is 16000yuan/kw, which is relatively high. High investment cost of third-generation nuclear power will result in great investment risk. This part aims to investigate the impact of investment cost reduction on the valuation of third-generation nuclear power. Here also set the electricity price as 0.45yuan/kwh and remain constant, and nuclear power can not be included in CDM. The investment cost will decrease from 40000 million yuan (16000yuan/kw) gradually down to 25000 million yuan (10000yuan/kw). And 10000yuan/kw is equal to the unit investment cost of domestic second-generation nuclear power plant. See results in figure 5a-5c.

Figure 5a is the trend for the value of third-generation nuclear power changes as investment cost changes. The impact of marginal investment cost reduction on the value of nuclear power shows 'increased first and then decreased' (as total investment cost decrease from 37500 million yuan to 35000 million yuan, the increment of nuclear power value is 2250.96 million yuan; as total investment cost decrease from 35000 million yuan to 32500 million yuan, the increment of nuclear power value is 2700.83 million yuan; as total investment cost decrease from 27500 million yuan to 25000 million yuan, the increment of nuclear power value is 1928.53 million yuan). Consequently, the contribution to nuclear power value from marginal investment cost reduction will decrease when the total investment cost is less than 32500 million yuan.

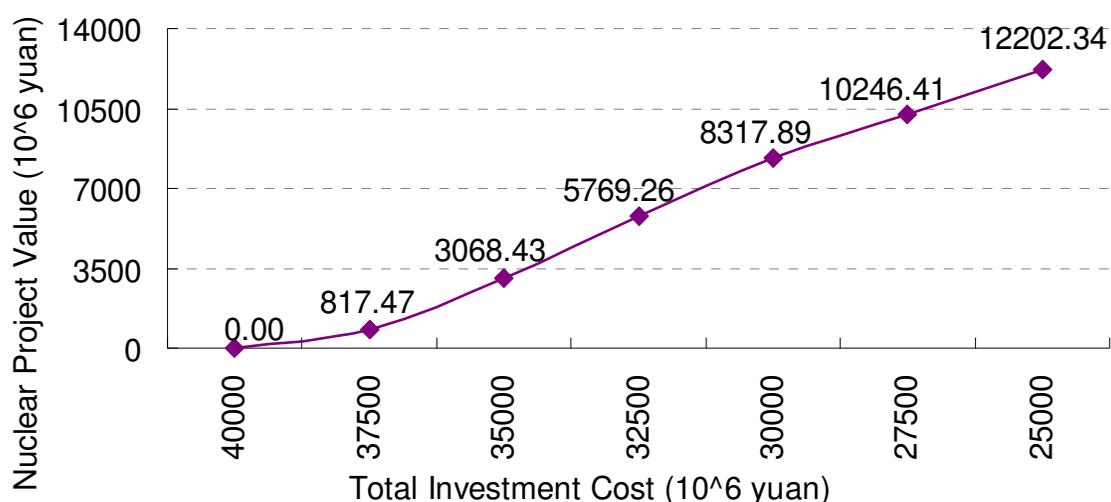


Fig. 5a. Nuclear plant value under different total investment cost

Figure 5b is the trend for the percentage of paths abandoned changes as investment cost changes. The percentage of paths abandoned decreases as third-generation nuclear power investment cost decreases and total investment cost reduction can reduce the investment risk effectively. The percentages of paths abandoned are all less than 5% when total investment cost falls below the level of 30000 million yuan. And as the total investment cost decreased to 25000 million yuan, the percentages of paths abandoned is only 0.26%, the investment risk is very small. The marginal investment risk reduction also shows 'increased first and then decreased' as investment cost decreases, and the contribution to nuclear power investment risk reduction from marginal investment cost reduction decreases when total investment cost falls below 32500 million yuan.

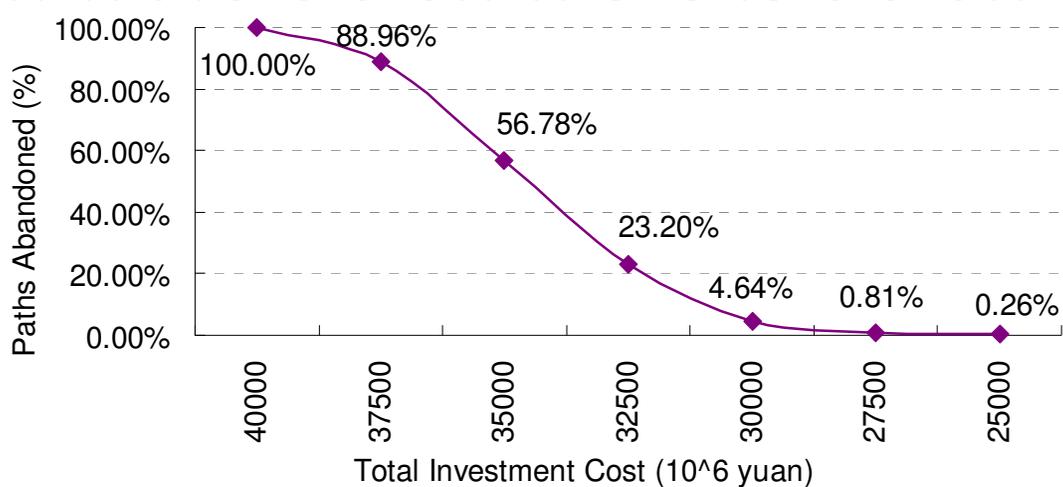


Fig. 5b. Paths abandoned under different total investment cost

Figure 5c is the trend for the CO₂ emission reduction amount as investment cost changes. The emission reduction amount increases and the marginal CO₂ emission reduction amount also shows 'increased first and then decreased' as third-generation nuclear power investment cost decreases. When the total investment cost falls below 30000 million yuan, the CO₂ emission reduction amounts are all larger than 310 million tons CO₂e, the changes in marginal CO₂ emission reduction amounts are very tiny.

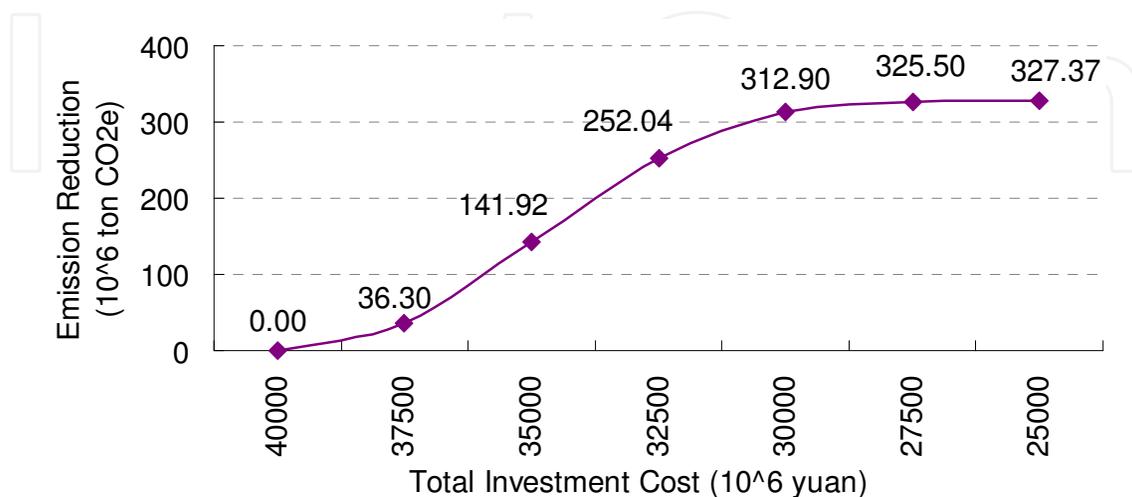


Fig. 5c. Emission reduction amount under different total investment cost

From the results we are informed that under baseline constant electricity price as 0.45yuan/kwh, changes in investment cost have significant impact on the value of third-generation nuclear power. If the total investment cost falls below 30000 million yuan which investment cost per unit is 12000yuan/kw, the investment risk is lower than 5%, implying that the investment is more viable. At this case the investment cost per unit is 1.2 times to that of average unit cost of domestic second-generation nuclear power plant.

5. Conclusions and further work

This paper applies real options theory with Monte Carlo method to establish a nuclear power investment evaluation model, incorporating the world's first third-generation nuclear power project-Sanmen nuclear power plant in Zhejiang province to evaluate the value of third-generation nuclear power plant in China. With several technical and economic uncertainty factors (deployment cost, generating cost and nuclear accident) considered in the model, we have investigated the impacts of three electricity price mechanisms, two forms of CDM, and investment cost reduction on the value of Sanmen third-generation nuclear power plant. Based on the result analysis, a couple of conclusions are drawn as follows:

1. Under constant electricity price mechanism, third-generation nuclear power is worth investment if the price refers to the electricity price in Tianwan nuclear power plant. And the electricity price need to at least increase 30% than current price level in Tianwan nuclear power plant so it can make third-generation nuclear power worth to invest. It should be noticed that in liberalized electricity price mechanism, the investment of third-generation nuclear power is more attractive than the other two price mechanisms among all electricity price levels. So the electricity price marketization will be a preferred option to promote the investment in third-generation nuclear power under current investment cost level.
2. Currently nuclear power can not be included in CDM. If the CDM can give nuclear power credit, the selling of carbon credit can increase the income of nuclear power plant, and this will also promote the investment in third-generation nuclear power. Considering the current electricity price is set by the government and remains constant, at baseline carbon price level, CDM has provided another option for power generation enterprise to compensate for the large investment cost of third-generation nuclear power. Based on the comparison between bilateral CDM and unilateral CDM, we would advise the power generation enterprise to take more efforts in bilateral CDM to obtain more benefits from carbon credits.
3. As the world's first third-generation nuclear power project, currently the investment cost of Sanmen nuclear power plant is relatively high. As the value of nuclear power is sensitive to investment cost, under current constant electricity price mechanism, the investment in third-generation nuclear power will be more viable if the total investment cost can be reduced to 1.2 times to that of domestic second-generation nuclear power plant.

Third-generation nuclear power is an advanced generating technology with large uncertainties. Our model still has limitations. Firstly, some data, especially nuclear accidents data in the model, are estimated in this research owing to shortage of actual data supporting. Secondly, the model does not consider any flexibility during the nuclear power operating period and we only consider the abandon option in Sanmen nuclear power plant

first phase project. Actually, the power generation enterprises can decide whether to invest in second phase project based on the judgment of electricity market of nuclear power operation status. As a consequence, taking compound option during nuclear power operational period into our model is one of the most important directions for model improvements. The forementioned issues require emphasizing in future work.

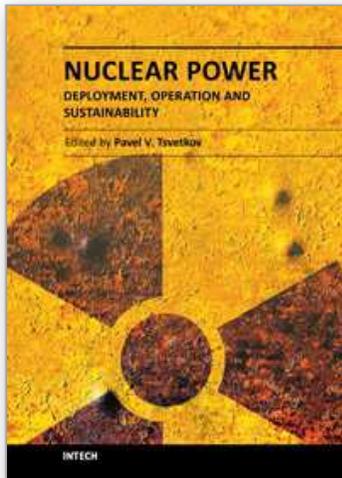
6. Acknowledgement

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We are fortunate to live in incredibly exciting and incredibly challenging time. Energy demands due to economic growth and increasing population must be satisfied in a sustainable manner assuring inherent safety, efficiency and no or minimized environmental impact. These considerations are among the reasons that lead to serious interest in deploying nuclear power as a sustainable energy source. At the same time, catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, design requirements and facilitated growing interests in advanced nuclear energy systems. This book is one in a series of books on nuclear power published by InTech. It consists of six major sections housing twenty chapters on topics from the key subject areas pertinent to successful development, deployment and operation of nuclear power systems worldwide. The book targets everyone as its potential readership groups - students, researchers and practitioners - who are interested to learn about nuclear power.

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