EUROPEAN TRANSACTIONS ON ELECTRICAL POWER
Euro. Trans. Electr. Power 2011; **21**:1015–1027
Published online 6 September 2010 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/etep.493

Optimal timing for generation investment with uncertain emission mitigation policy

Guozhong Liu[1], Fushuan Wen[2*,†] and Iain MacGill[3]

[1]*School of Electrical Engineering, South China University of Technology, Guangzhou 510640, China*
[2]*School of Electrical Engineering, Zhejiang University, Hangzhou 310027, China*
[3]*The Centre for Energy and Environmental Markets (CEEM) and School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney 2052, Australia*

SUMMARY

In view of the fact that different mechanisms for mitigating the CO_2 emission have been employed or proposed in different countries or regions, and those already implemented are still in an evolutionary procedure, the future CO_2 emission prices would be highly uncertain. Given this background, an effort is made for investigating the problem of generation investment decision-making in electricity market environment with uncertainties from the climate change policy for limiting the CO_2 emission. According to the changing characteristics of the uncertain factors, the models of the fuel prices, electricity prices, and CO_2 emission prices are respectively presented first. Next, under the existing real option approach (ROA) based methodological framework for the generation investment decision-making problem, a mathematical model accommodating multiple kinds of uncertainties and an efficient solving method are developed. Finally, the proposed model and method are illustrated by a numerical example with different scenarios.

KEY WORDS: generation investment decision-making; electricity market; climate change policy; CO_2 emission mitigation; real options; uncertainty

1. INTRODUCTION

The power industry worldwide is suffering or going to encounter three major challenges: significantly fluctuating fuel prices, power industry restructuring for introducing competition, and Greenhouse Gas (GHG) mitigation. These three factors could bring significant uncertainties for generation investment decision-making. Investment risks caused by the fluctuating fuel prices and power industry restructuring have been investigated in a few publications[1–5], mainly based on the well-established real options approach (ROA). For instance, in Reference [1] the impact of various uncertainties (i.e., the electricity price, load demand, natural gas price) on the net-present value of two power plant investments is investigated by using ROA. In References [2,3], in the ROA based framework, a two-branch model and a four-branch lattice model are developed to find the values of generation investment options. In Reference [4], the ROA is extended to consider the situation of a large generation company and it is shown that the uncertainty of the electricity price has to be considered in the investment analysis if the company is not able to hedge the price effect in the financial markets and if there is no competition on the investment opportunity. In Reference [5], the ROA is employed to determine the optimal investment strategies for capacity expansion where the investment can be carried out or delayed under market uncertainties.

*Correspondence to: Professor Fushuan Wen, School of Electrical Engineering, Zhejiang University, Hangzhou 310027, China.
†E-mail: fushuan.wen@gmail.com

GHG emissions have resulted in the global warming of 1.3°C since the age of industrialization. It is estimated that if the global climate increases 2°C further, dangerous consequences could be happened [6,7]. Hence, the well-known Kyoto Protocol that aims to limit global GHG emissions was agreed on in October 1997 and took effect on February 16, 2005[8]. Up to now, more than 140 countries have joined the Kyoto Protocol and the GHG emissions of the member countries in the Protocol have exceeded 55% of the global total volume. According to the Kyoto Protocol, by 2012, the reduced emission amount by industrialized countries should reach at least 5% compared to the baseline in 1990. In addition, in view that the first commitment period would be due in 2012 and the following reduction plan is still not confirmed, some countries or regions have already established mid- and long-term emission reduction plans. For instance, the Europe Union (EU) has planned to reduce the emissions by 20% at least and up to 30% through collaboration with other countries by 2020; at the same time, the long-term target by 2050 has also been set with the emission reduction to 60–80% as compared to the baseline in 1990 [9].

In order to fulfill the commitments, several instruments were developed in Kyoto Protocol such as Carbon Emission Right Trading Scheme, Joint Implementation and Clean Development Mechanism. Some counties have implemented one or more of these schemes. For instance, the overall reduction obligation was distributed within the EU following a Burden Sharing Agreement (BSA). EU member states would face a cap on annual emissions, namely the quantity of allowances that are allocated to each country. Henceforth each member state developed its own National Allocation Plan (NAP). First, this allocates the country's total BSA target between the trading sectors and the non-trading sectors. Secondly, it specifies how the permits in the trading sector will be distributed among the individual sources [10,11].

Considering that the impact of GHG emissions on the global climate warming is becoming a focus of extensive concern from the public around the world, it is anticipated that more and more climate change policies or protocols will be gradually introduced in different countries to limit the GHG (mainly CO_2) emissions [8]. Allowances for the CO_2 emissions would be introduced into the Carbon Emissions Trading Market and become a new market product with market values and prices. As far as the power industry is concerned, coal is still the most popular energy source in most countries. It is well known that coal firing produces a great deal of CO_2. As a result, when CO_2 emissions are strictly restricted, the power industry would inevitably be significantly affected. Hence, in making future generation investment decisions for generation companies or potential investors, the uncertainty of CO_2 emission prices and the related investment risks caused by climate change policies should be taken into account. Up to now, research work in this area is still very preliminary.

It is found in Reference [12] that returns on investment in a nuclear plant will be higher in a scenario with uncertain carbon prices than in a world with certain prices. In References [13–15], the influences of future uncertain emissions trading and CO_2 penalties are investigated within a ROA setup. In these models, the design of emissions trading schemes and the number of allowances that are freely distributed are their main features. It is shown in Reference [16] that the uptake of various generation technologies varies significantly depending on the investors' views on the carbon price uncertainty. However, in these papers, only the carbon price uncertainty is considered. While in actual situations, more uncertainties will be encountered by investors in making generation investment decisions in the electricity market environment.

The major purpose of this paper is to illustrate explicitly how the market uncertainties, which results in the fluctuations of fuel prices and electricity prices, and the climate change policy uncertainty, which can lead to the CO_2 price fluctuation more significantly, influence the investment decision-making of generation companies. The mathematical model developed can accommodate multiple kinds of uncertainties and the impacts arising from these different uncertainties are contrasted in a relatively simple and transparent framework. The findings show that the uncertainties, which have generally been deemed to lead to the delay of investment, may result in higher probability to exercise an investment option under some conditions.

This paper is organized as follows. First, the real options theory for investments under uncertainty is briefly introduced in Section 2. In Section 3, the stochastic motion models are presented for the uncertain fuel price, electricity price and CO_2 emission price. In Section 4, the ROA is employed to compute the value of the investment option and a Monte Carlo based solving approach presented for finding the optimal investment strategy. A method for computing the annual profit of a generation company is developed in Section 5. An illustrative example and test results for different scenarios are served for demonstrating the essential features of the developed model and method in Section 6. Finally, the concluding remarks are given in Section 7.

2. THE REAL OPTIONS APPROACH

The real option approach (ROA), as comprehensively described in Reference [17], has been developed over the last two decades specifically for evaluating investments under uncertainty. According to ROA, if an investment is irreversible and the timing of the investment is flexible, the opportunity to invest can be considered as a real option. The ROA claims that the optimal timing of an investment does not occur until the value of the project itself exceeds the value of the option to invest in the future. In mathematical terms, the real options valuation is based on a stochastic dynamic optimization. Compared to a traditional static Net Present Value (NPV) evaluation of expected future cash flows from an investment project, the real options paradigm adds two important analytical dimensions to the problem. First, a dynamic representation of the timing of the investment decision is used. Secondly, important uncertain factors are represented as stochastic processes. The ROA usually gives a more restrictive investment strategy since the value of waiting for information about uncertain future trends is taken into account. The ROA also suggests the use of contingent claims analysis or risk-neutral valuation to bypass the problem of determining an appropriate risk-adjusted discount rate. The advantage is that a risk-free interest rate can be used for discounting. These methods are based on the assumption that a portfolio can be constructed in the financial markets, which exactly replicate the uncertainties in the investment project. This is a strong assumption, since investment projects can involve a number of uncertainties that are not necessarily traded or replicated in any financial market.

3. THE FRAMEWORK FOR GENERATION INVESTMENT DECISION-MAKING UNDER UNCERTAINTY

Suppose that generation company X possesses a relatively inefficient coal-fired power plant with C_X MW installed capacity. During the operation process, the generation company has been suffering an ever-increasing amount of burdens, such as the increasing environmental pressure, rapidly rising coal prices and the restriction of CO_2 emissions. On the other hand, for a Combined Cycle Gas Turbine (CCGT) plant, the natural gas has been regarded as clean energy and advocated to be utilized for generating electricity in a lot of countries. The emitted CO_2 amount for per MWh generation by a CCGT power plant only accounts for 33% of that by a coal-fired power plant; while for nitrogen oxides, the number is only 0.5%. In addition, a CCGT power plant basically does not produce SO_2. Compared with a coal-fired power plant, it is obvious that the CCGT power plant is much more environment-friendly.

The transition from a coal-fired power plant to a CCGT one does not generally require complicated inspection and approval procedures and basically new space is not required; most devices of the coal-fired power plant can continue to be utilized. Compared to the construction of a new power plant, the cost for the transition is also relatively low. Given these considerations, it is assumed that the generation company X would consider investing to transform the coal-fired plant to a CCGT one. In fact, some transitions have already been made in China because of the above-mentioned reasons. Hence, the corresponding decision-making process would be analyzed by simulation methods in this work. Suppose that this project investment may take place in a specific year t in $[t_0, T_{\exp}]$ and the capital investment is a constant I_X (\$). Here, t_0 refers to the current year and usually set to zero. During any year of $[t_0, T_{\exp}]$, the generation company X can choose to invest immediately, wait for better investment opportunities or abandon investment opportunities forever. In view of the fact that the investment plan can be exercised in any year, thus the investment opportunity can be viewed as an American-style call option. The value of the investment plan is identical to the value of the underlying

DOI: 10.1002/etep

asset; the investment capital is identical to the exercising price of the call option. The year T_{exp} is the last time to invest and can be identical to the maturity date of the call option.

For the generation company X, the investment profit would be dominated by three factors as follows: (1) the future fuel price; (2) the future electricity price under the electricity market environment; and (3) the future climate policies for GHG emissions. Hence, the three uncertain factors will be modeled below using the stochastic process.

3.1. Modeling fuel price uncertainties

Generally speaking, the variance of the fuel price in the future is a stochastic process, and this means that the price would rise or decline stochastically based on the present price. Based on the uncertain price model formulated by Dixit and Pindyck in Reference [17], the fuel price is modeled here by using the well-established Geometric Brownian Motion (GBM), as detailed below:

$$\mathrm{d}p_{\mathrm{fuel},t} = \mu_f p_{\mathrm{fuel},t}\mathrm{d}t + \sigma_f p_{\mathrm{fuel},t}\mathrm{d}w_t \tag{1}$$

$$\mathrm{d}w_t = \varepsilon_t\sqrt{\mathrm{d}t} \tag{2}$$

where $p_{\mathrm{fuel},t}$ is the fuel price in the tth year; μ_f is the expected growth rate of $p_{\mathrm{fuel},t}$; σ_f is the expected volatility rate of $p_{\mathrm{fuel},t}$ and expressed as a percentage change; $\mathrm{d}w_t$ is the increment of a wiener process which is used to simulate the shock of the stochastic market change on the fuel price; ε_t obeys the standard normal distribution, namely $\varepsilon_t \sim N(0,1)$; $\mathrm{d}t$ is the time step and set to 1 year in this work.

According to Equations (1) and (2), the fuel price in the studied time horizon T can be represented as follows:

$$p_{\mathrm{fuel},t} = p_{\mathrm{fuel},t-1}\exp\{(\mu_f - 0.5\sigma_f{}^2)\mathrm{d}t + \sigma_f\varepsilon_t\sqrt{\mathrm{d}t}\} \tag{3}$$

Note that whether or not GBM is appropriate to model the uncertainties in risk management and option pricing has been discussed in some books and papers [17,18]. In fact, some motion models such as the Geometric Brownian Motion, mean-reverting motion, and Poisson motion are suitable for modeling some uncertainties according to the statistic characteristics of the problem studied. By analyzing historical data, we found that GBM is a good candidate for modeling the fuel price. Besides, up to now, it is still an open question that if there exists one motion model which would be absolutely accurate for modeling the change of uncertainties.

3.2. Modeling the future electricity price

In the electricity market environment, the load level is one of the main factors having impacts on the electricity price. Hence, it is supposed here that the uncertainties of the electricity price mainly come from the load growth, and again the GBM is employed to simulate the load motion as formulated below:

$$\mathrm{d}L_{\mathrm{max},t} = \mu_L L_{\mathrm{max},t}\mathrm{d}t + \sigma_L L_{\mathrm{max},t}\mathrm{d}w_t \tag{4}$$

$$\mathrm{d}w_t = \varepsilon_t\sqrt{\mathrm{d}t} \tag{5}$$

where $L_{\mathrm{max},t}$ is the maximum load in the tth year; μ_L is the expected growth rate of $L_{\mathrm{max},t}$; σ_L is the expected volatility rate of $L_{\mathrm{max},t}$; μ_L and σ_L can be estimated by using historical data; the meanings of $\mathrm{d}w_t$, ε_t, and $\mathrm{d}t$ are the same as those defined before.

According to Equations (4) and (5), the maximum load in the tth year can be represented as

$$L_{\mathrm{max},t} = L_{\mathrm{max},t-1}\exp\{(\mu_L - 0.5\sigma_L{}^2)\mathrm{d}t + \sigma_L\varepsilon_t\sqrt{\mathrm{d}t}\} \tag{6}$$

It is obvious that the investment strategies employed by the other generation companies or investors will have significant impacts on the optimal investment decision-making of the generation company X.

DOI: 10.1002/etep

While in the electricity market environment, investment strategies are surely private issues and could not be broadcasted to the public before the investment is implemented. Thus, it will be necessary for the generation company X to estimate the investment strategies of rivals based on available information, for instance, the generation planning established by the regulators or system operators, the historical investment strategies of the rivals and other related market information. For the convenience of presentation, the other generation companies are aggregated as a large company and named as the generation company A. Suppose that the current installed capacity $C_{A,0}$ of the company A is public information and the installed capacity increasing rate $\tilde{k}_A$ obeys a normal distribution, namely $\tilde{k}_A \sim N(\mu_A, \sigma_A)$, thus the installed capacity of the company A in the tth year can be represented as,

$$C_{A,t} = (1 + \tilde{k}_A) C_{A,t-1} \tag{7}$$

Based on the weekly weighted average electricity price and the weekly average system capacity adequacy of the PJM day-ahead energy market in 2001 (detailed data can be found in Reference [19]), it is discovered that a cubic equation is suitable for describing the relationship between the electricity price and the capacity adequacy as detailed below,

$$\begin{aligned} & p_{e,t,w} = ar_{t,w}^3 + br_{t,w}^2 + cr_{t,w} + d \\ \text{s.t.} \quad & 0 \le p_{e,t,w} \le \bar{p}_e \end{aligned} \tag{8}$$

where a, b, c, and d are constant coefficients and in the following analysis their estimated values from historical data in the PJM electricity market are employed: $a = -18\,632$, $b = 31\,728$, $c = -17\,912$, $d = 3414$. $p_{e,t,w}$ and $r_{t,w} = (C_{t,w} - L_{t,w})/C_{t,w}$ respectively represent the average electricity price and the average capacity adequacy in the wth week of the tth year; $\bar{p}_e$ is the price cap set by the market regulator to prevent the market power from being abused; $L_{t,w}$ is the average load in the wth week, and can be calculated by employing the typical historical load curve and a sampled value of the maximum load; $C_{t,w}$ is the average installed capacity in the wth week of the tth year, and is represented as

$$C_{t,w} = C_t (1 - \tilde{k}_d) \tag{9}$$

Where: $\tilde{k}_d$ is the escaping rate of the generation capacity from the studied electricity market, and is supposed to obey the normal distribution, namely $\tilde{k}_d \sim N(\mu_d, \sigma_d)$; C_t is the total installed capacity including $C_{X,t}$ MW from the generation company X and $C_{A,t}$ MW from the generation company A.

3.3. Modeling the CO_2 price jumping

In the future, the uncertainties of the CO_2 emission price come from three major aspects: (1) The price fluctuation in the short term; (2) the price drifting in the long term; and (3) the price jumping caused by the change of emission mitigation policies.

In a competitive market environment, the price fluctuation in the short term does not have much impact on the long-term investment decision-making, and hence needs to be considered.

The long-term price drifting process could still be modeled by the GBM. New emission mitigation policies or the change of GHG emission mechanisms could lead to the CO_2 price jumping. Up to now, the post-2012 carbon agreements are still under debate. The 2009 United Nations Climate Change Conference, commonly known as the Copenhagen Summit, was held in Copenhagen, Denmark, between 7 December and 18 December. The conference included the 15th Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change and the 5th Meeting of the Parties (MOP 5) to the Kyoto Protocol. According to the Bali Road Map, a framework for climate change mitigation beyond 2012 was to be agreed there. However, only a "meaningful agreement," the Copenhagen Accord, had been reached. The agreement only recognized that climate change is one of the greatest challenges of the present day and that actions should be taken to keep any temperature increases to below 2°C. The document is not legally binding and does not contain any legally binding commitments for reducing CO_2 emissions, but many countries and non-governmental organizations were still opposed to this agreement.

DOI: 10.1002/etep

The post-2012 carbon agreements may or may not result in commitments with stricter levels of the emission reduction and higher CO_2 prices. Given such considerations, it is assumed that a new mitigation mechanism for CO_2 emissions would be implemented in a particular year τ so as to investigate the potential impacts of such a policy change. Thus, before the τ th year, the CO_2 price fluctuation could still be modeled by the GBM; while at the τ th year, in addition to the GBM, there should be an extra stochastic process to model the price jump; after the τ th year, the price will follow the GBM again, but at a new level. The models are detailed below:

$$\mathrm{d}p_{\mathrm{co}_2,t} = \begin{cases} \mu_{\mathrm{co}_2} p_{\mathrm{co}_2,t}\mathrm{d}t + \sigma_{\mathrm{co}_2} p_{\mathrm{co}_2,t}\mathrm{d}w_t + \eta p_{\mathrm{co}_2,t}(2\mathrm{d}y-1) & t=\tau \\ \mu_{\mathrm{co}_2} p_{\mathrm{co}_2,t}\mathrm{d}t + \sigma_{\mathrm{co}_2} p_{\mathrm{co}_2,t}\mathrm{d}w_t & t\neq\tau \end{cases} \tag{10}$$

$$\mathrm{d}w_t = \varepsilon_t \sqrt{\mathrm{d}t} \tag{11}$$

where $p_{\mathrm{co}_2,t}$ is the CO_2 emission price in the tth year; μ_{co_2} is the expected growth rate of $p_{\mathrm{co}_2,t}$; σ_{co_2} is the expected volatility rate of $p_{\mathrm{co}_2,t}$ expressed as a percentage change; the meanings of $\mathrm{d}w_t$, ε_t and $\mathrm{d}t$ are already defined before; $\mathrm{d}y$ is an uniformly distributed random number between 0 and 1; and η is a scale factor.

According to Equations (10) and (11), the CO_2 price in the studied time horizon T can be formulated as

$$p_{\mathrm{co}_2,t} = \begin{cases} p_{\mathrm{co}_2,t-1}\exp\{(\mu_{\mathrm{co}_2} - 0.5\sigma_{\mathrm{co}_2}{}^2)\mathrm{d}t + \sigma_{\mathrm{co}_2}\varepsilon_t\sqrt{\mathrm{d}t} + \eta(2\mathrm{d}y-1)\} & t=\tau \\ p_{\mathrm{co}_2,t-1}\exp\{(\mu_{\mathrm{co}_2} - 0.5\sigma_{\mathrm{co}_2}{}^2)\mathrm{d}t + \sigma_{\mathrm{co}_2}\varepsilon_t\sqrt{\mathrm{d}t}\} & t\neq\tau \end{cases} \tag{12}$$

From Equation (12), given $\tau = 9$, three typical motion processes for the CO_2 price in the years from 0 to 19 are illustrated in Figure 1.

4. A GENERATION INVESTMENT DECISION-MAKING METHOD

The uncertainties of the fuel price, electricity price and CO_2 emission price could cause the generation company X to defer an investment so that it can get more information for reducing the investment risk. Hence, for the generation company X, choosing the optimal investment time or evaluating the value of deferring investment, i.e., the value of an investment option, has emerged as a crucial problem in the decision-making.

In this work, a Monte Carlo based approach is employed to evaluate the value of an investment option and obtain the optimal investment strategies. The main steps are as follows:

Step 1: Input the required parameters including the specified sampling times N, and stochastic motion parameters such as μ_f, σ_f, μ_L, σ_L, μ_d, σ_d, μ_A, σ_A, μ_{co_2}, σ_{co_2}, $L_{\max,0}$, $p_{\mathrm{co}_2,0}$, $p_{\mathrm{fuel},0}$, τ.

Step 2: Set counter $k = 1$.

Step 3: Sample the random values of $L_{\max,t}$, $p_{\mathrm{fuel},t}$, and p_{co_2} ($t = t_0, \ldots, T_{\exp}$) according to their respective motion models.

Step 4: Sample the random values of $C_{A,t}$ and $C_{t,w}$ according to Equations (7) and (9).

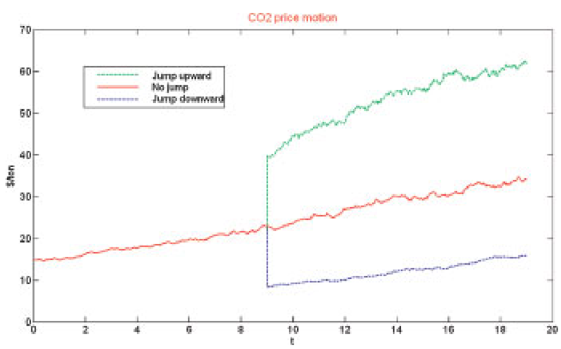

Figure 1. Modeling of the uncertain CO_2 prices.

DOI: 10.1002/etep

Step 5: Compute $r_{t,w}$ and then obtain the value of $p_{e,t,w}$ through Equation (8).

Step 6: Compute the investment profit V_t^{inv}. Define A_t and B_t as the profits of the coal-fired plant and the CCGT plant in the tth year, respectively. The transition from the coal-fired plant to the CCGT plant is supposed to be completed at the year T_{ld}, and during the transition process the profit of the generation company X is supposed to be A_t. Then should the generation company X invest in the tth year, the expected profit will be

$$Vt^{\text{inv}} = \sum_{n=t}^{t+T_{ld-1}} e^{-(n-t)r\text{d}t} A_n + \sum_{n=t+T_{ld}}^{T_{lf}} e^{-(n-t)r\text{d}t} B_n - I_x$$

where r is the risk-free interest rate and T_{lf} is the lifetime of the power plant.

Step 7: Compute the profit of waiting to invest V_t^{wait}. If the generation company X continues to wait for a better investment opportunity, then the expected profit of waiting would be

$$Vt^{\text{wait}} = A_t + e^{-r\text{d}t} V^*_{(t+1)}$$

where $V^*{}_{(t+1)}$ represents the maximum profit when the generation company X has chosen an optimal investment time during the time period $[t+1,\ T_{\text{exp}}]$

Step 8: Obtain the optimal investment strategy. In the year T_{exp}, if the expected profit of investing would exceed that of waiting, then the generation company X should implement the investment plan; otherwise, it would abandon the investment opportunity forever. Hence, the value of the investment option in the year T_{exp} would be

$$\max\left\{ \sum_{n=T_{\text{exp}}}^{T_{\text{exp}}+T_{\text{ld}-1}} e^{-(n-T_{\text{exp}})r\text{d}t} A_n + \sum_{n=T_{\text{exp}}+T_{\text{ld}}}^{T_{\text{lf}}} e^{-(n-T_{\text{exp}})r\text{d}t} B_n - I_x,\ \sum_{n=T_{\text{exp}}}^{T_{lf}} e^{-(n-T_{\text{exp}})r\text{d}t} A_n \right\}$$

In any year t ($t = t_0, \ldots, T_{\text{exp}} - 1$), the investment option value F_t can be obtained by comparing the expected value of exercising the option versus that of waiting for a better investment opportunity through the backward recursive method as detailed below:

$$F_t = \begin{cases} \max\left\{ \sum\limits_{n=T_{\text{exp}}}^{T_{\text{exp}}+T_{\text{ld}-1}} e^{-(n-t)r\text{d}t} A_n + \sum\limits_{n=T_{\text{exp}}+T_{\text{ld}}}^{T_{lf}} e^{-(n-T_{\text{exp}})r\text{d}t} B_n \right. \\ \left. \quad -I_x,\ \sum\limits_{n=T_{\text{exp}}}^{T_{\text{lf}}} e^{-(n-T_{\text{exp}})r\text{d}t} A_n \right\} & t = T_{\text{exp}} \\ \max\left\{ Vt^{\text{inv}}, Vt^{\text{wait}} \right\} & 0 \le t < T_{\text{exp}} \end{cases} \tag{13}$$

Define $L_{T_{\text{exp}}}$ and L_t respectively as the criteria for identifying whether the option should be exercised in the year T_{exp}, and whether the option should be exercised in the year t ($t = t_0\ \ldots,\ T_{\text{exp}} - 1$):

$$L_{T_{\text{exp}}} = \begin{cases} 1 & V_{T_{\text{exp}}}{}^{\text{inv}} - V_{T_{\text{exp}}}{}^{\text{wait}} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

$$L_t = \begin{cases} 1 & Vt^{\text{inv}} - Vt^{\text{wait}} > 0 \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

In Equations (14) and (15), "1" represents that the investment option should be exercised and "0" the opposite.

In order to maximize the investment profit, the generation company X would choose to invest immediately when L_t equals to "1" for the first time, then the corresponding investment time is the optimal t^*. Before t^*, L_t would keep being "0," and this means that the optimal strategy for the generation company X is to hold the option and wait for a better investment opportunity; at t^*, L_t equals to "1," and this means that investing immediately can get higher profit than waiting further.

Step 9: Set $k = k+1$, if $k < \text{N}$, go back to Step 3; otherwise, go to the next step.

Step 10: Compute the distribution probability of the optimal timing and investment profit based on the simulated data in a statistical way.

DOI: 10.1002/etep

5. COMPUTATION OF THE ANNUAL PROFIT OF THE GENERATION COMPANY

Certainly, different electricity market patterns would have different impacts on the profit of the generation company and accordingly on the investment decision-making as well.

In an energy-only market, the cost recovery and profit making of the generation company depend on the amount of the electricity sale in the spot market as well as in the bilateral contract market.

While in an electricity market with the capacity payment, the generation company could get profits not only from the energy sale but also from its available generation capacity. Moreover, different capacity mechanisms could lead to different profiting pattern. In Reference [20], the profit differences under different market patters are compared, including the energy-only market, capacity payment, capacity obligation, and capacity subscription. Due to space limitation, only the profit of the generation company in the energy-only market is presented below.

After having calculated the value of $p_{e,t,w}$ through Equation (8), the profit of the generation company X in the tth year can be represented as

$$r_{e,t} = \sum_{w=1}^{52} 168 \max\{p_{e,t,w} - C_{\mathrm{var},X}, 0\} C_X \tag{16}$$

$$C_{\mathrm{var,X}} = C_{\mathrm{fuel}} + C_{\mathrm{fuel,co_2}} + C_{\mathrm{var,\,O\,\&\,M,\,fuel}} \tag{17}$$

where $C_{\mathrm{var},X}$, C_{fuel}, $C_{\mathrm{fuel,CO_2}}$, and $C_{\mathrm{var,O\&M,fuel}}$ are respectively the variable cost, the fuel cost, the CO_2 emission cost, and the operation and maintenance cost, for per MWh generation of the plant.

In Equation (16), it is assumed that the generation unit will be fully dispatched if $p_{e,t,w} > C_{\mathrm{var},X}$, or shutdown when $p_{e,t,w} \le C_{\mathrm{var},X}$. This assumption is only used to highlight the basic characteristic of the proposed method which is actually applicable to general situations.

The annual profit of the coal-fired plant and the CCGT plant, i.e., A_t and B_t, can be formulated as

$$A_t = \sum_{w=1}^{52} 168 \max\{p_{e,t,w} - C_{\mathrm{var},X,\mathrm{coal}}, 0\} C_X \tag{18}$$

$$B_t = \sum_{w=1}^{52} 168 \max\{p_{e,t,w} - C_{\mathrm{var},X,\mathrm{gas}}, 0\} C_X \tag{19}$$

where $C_{\mathrm{var},X,\mathrm{coal}}$ and $C_{\mathrm{var},X,\mathrm{gas}}$ are respectively the variable costs of the coal-fired plant and the CCGT plant for per MWh generation.

6. CASE STUDY

Suppose that the efficiencies of the coal-fired plant and the CCGT plant are 40 and 70%, and the CO_2 emission factors from the coal-fired plant and the CCGT plant are 1.15 and 0.35 ton/MWh, respectively. The investing planning period is 20 years between [0,19]. Other techno-economic data are shown in Table I. These data are based on the average value of the plant costs given in Reference [21], with minor modifications for coal-fired and CCGT plants based on discussions with people in generation companies.

Table I. Techno-economic data of the two different power plants.

Variables	Coal-fired plant	CCGT plant
Plant lifetime T_{lf} (Years)	20	25
Plant capacity C_x (MW)	600	600
Investment capital I_X ($)	0	2.5×10^8
Reconstruction time T_{ld} (Years)	2	0
Variable operation and maintenance cost $C_{\mathrm{var,O\&M,fuel}}$ ($/MWh)	3.3	1.5

DOI: 10.1002/etep

In order to quantify the impact of the uncertainties on the investment profit and investment decision-making, three scenarios have been analyzed, as detailed below.

In Scenario 1, the volatilities of the fuel price and the CO_2 emission price are assumed to be very low (approaching zero), thus their future prices can be considered to keep increasing stably. At the same time, assume that the electricity price fluctuates randomly. The specifications are detailed below:

(1) The risk-free interest rate r is 5%.
(2) The initial coal price $p_{\text{coal},0} = 2500$ \$/TJ with an annual growth rate $\mu_{\text{coal}} = 1.2\%$, and annual volatility rate $\sigma_{\text{coal}} = 0.1\%$.
(3) The initial gas price $p_{\text{gas},0} = 5500$ \$/TJ with an annual growth rate $\mu_{\text{gas}} = 1.2\%$, and annual volatility rate $\sigma_{\text{gas}} = 0.1\%$.
(4) The initial maximum load $L_{\max,0} = 54\,000$ MW with an annual growth rate $\mu_L = 2\%$, and annual volatility rate $\sigma_L = 4.5\%$; the initial installed capacity of the generation company A is 59 000 MW with an annual growth rate $\mu_A = 2\%$, and annual volatility rate $\sigma_A = 4.5\%$; the parameters associated with the escaping rate of the generation capacity μ_d and σ_d are 1.3 and 0.8%, respectively.
(5) The initial CO_2 emission price $p_{\text{co}_2,0}$ is 15 \$/ton with an annual growth rate $\mu_{\text{co}_2} = 5\%$, and an annual volatility rate $\sigma_{\text{co}_2} = 0.1\%$; the scale factor η is 0.

In Scenario 2, the volatility of the CO_2 emission price is set to 20% and the scale factor η to 1. In addition, it is assumed that the emission mitigation policies would have a great change at the year $\tau = 9$. The other specifications are the same as those in Scenario 1.

In Scenario 3, the annual volatility rate σ_{coal} is set to 2%, and σ_{gas} to 4%. The other specifications are the same as those in Scenarios 1 and 2.

By using the method presented in Section 4, the probability and profit of the generation company X to exercise the investment option can be calculated at any specified year under different scenarios. The simulation results for Scenarios 2 and 3 are shown in Table II. In Scenario 1, the investment option would not be triggered. The histograms of the probability distribution of the investment profit under these three scenarios are shown in Figures 2–4.

Table II. The probabilities and profits of exercising the investment option.

Year	Scenario 2		Scenario 3	
	Exercise probability (%)	Exercise profit (10^8\$)	Exercise probability (%)	Exercise profit (10^8\$)
0	0.0		0.0	
1	0.0		0.0	
2	0.0		0.0	
3	0.5	6.25	0.0	
4	0.4	6.42	0.0	
5	0.5	6.58	0.0	
6	0.4	6.72	0.0	
7	0.3	6.92	0.0	
8	3.6	7.05	3.4	
9	4.1	7.27	5.8	8.35
10	3.2	7.43	4.5	8.49
11	0.7	7.78	2.8	8.63
12	0.4	7.22	2.7	9.12
13	0.6	7.37	3.6	9.43
14	0.7	7.14	3.6	9.26
15	0.4	8.31	4.2	9.48
16	0.3	8.05	3.6	10.02
17	0.2	8.12	3.4	11.45
18	1.6	8.22	3.8	11.32
19	1.9	8.14	2.9	11.55

DOI: 10.1002/etep

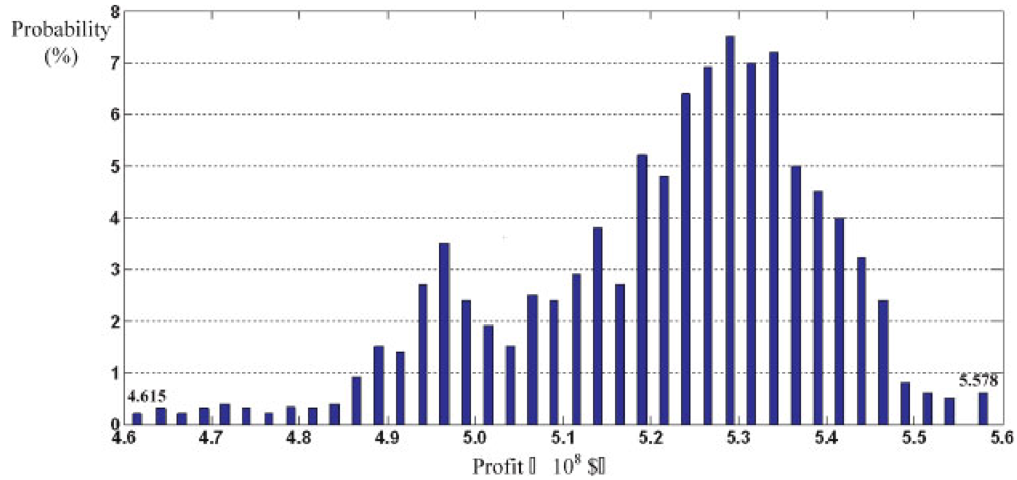

Figure 2. The profit and associated probability distribution in Scenario 1.

From Table II and Figures 2–4, the following points could be made:

(1) *Scenario* 1: If both the fuel and CO_2 prices are stable under the given price specifications used in the case study, the investment for transferring the coal-fired power plant to a CCGT one will not take place. The current coal-fired power plant will have the profit of at least $\$4.615 \times 10^8$ during its lifetime. Given a confidence level of 95%, the profit of the existing coal-fired plant will not exceed $\$ 5.44 \times 10^8$.

(2) *Scenario* 2: If only the fuel price is stable while the CO_2 emission price is highly volatile, then the investment for transferring to a CCGT may occur in the 3rd year. Taking into account of the investment cost, the happening probability of an investment loss is about 1.9%. The maximum value of the loss can reach \$80 million, accounting for 32.2% of the investment capital. On the other hand, however, the probability of a profitable investment is 98.1%, and the probability of having more profits than the maximum probable profit in Scenario 1 is 44%.

(3) *Scenario* 3: If both the fuel price and CO_2 emission price are highly volatile, the investment for transferring to a CCGT plant may be happened in the 9th year. The probability of the investment loss is about 2.4%, and the maximum value of the loss could reach $\$1.08 \times 10^8$, and this accounts for 43.1% of the investment capital. If the confidence level is given at 95%, the profit will not exceed $\$ 9.96 \times 10^8$, representing 3.98 times of the investment capital. The investment profit will have an 62.7% probability of more than the maximum possible profit in Scenario 1.

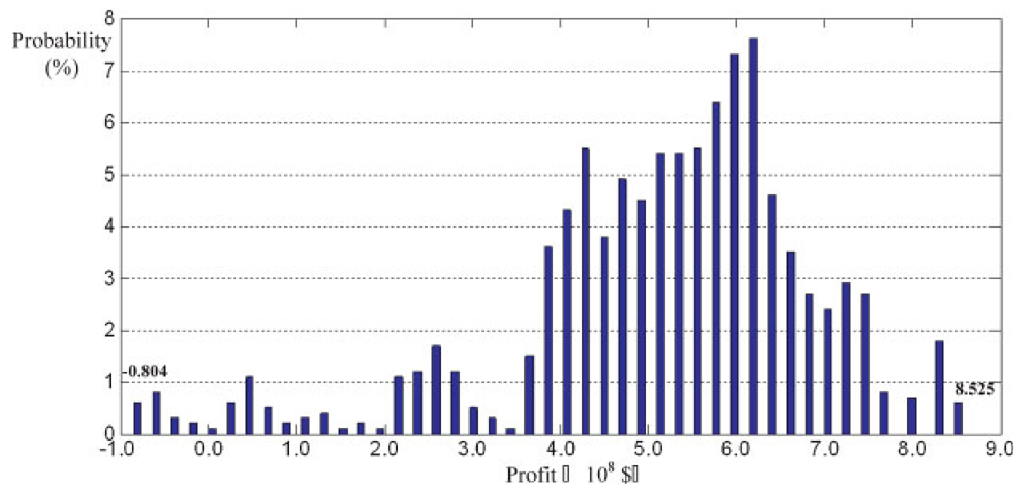

Figure 3. The profit and associated probability distribution in Scenario 2.

DOI: 10.1002/etep

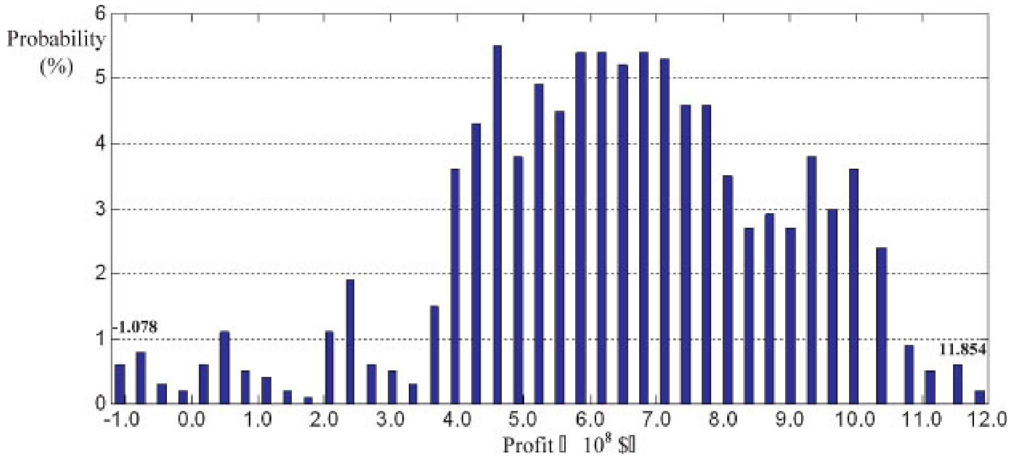

Figure 4. The profit and associated probability distribution in Scenario 3.

(4) The uncertainties of the fuel price and CO_2 emission price have significant impacts on the uncertainties of the investment profit. The degree of the uncertainties in Scenario 3 is obviously higher than that in Scenario 1. The range of the profit in Scenario 1 is from \$4.615 $\times 10^8$ to \$5.578 $\times 10^8$, while in Scenario 3 it is from $-$\$1.078 $\times 10^8$ to \$11.854 $\times 10^8$. This means that the more significant the uncertainties are, the wider the range of the investment profit will be.

(5) When the volatilities of the fuel and CO_2 emission prices are set to be very low (Scenario 1), the investment options would not be triggered. However, when the volatility of the CO_2 emission price is set to be high, the options would be triggered, for instance, in the 3rd year. Should the investment have been taken place, the generation company would have 0.5% chance for achieving a profit of up to 2.5 times of the investment cost (\$6.25 $\times 10^8$). The probability of transforming the coal-fired power plant to the CCGT plant over the whole planning time horizon is not high (only 19.8%). However, if all the prices (including natural gas, coal, electricity, and CO_2) are highly volatile during the whole planning period as shown in Scenario 3, the investment will become much more attractive. The total probability of transforming the coal-fired power plant to the CCGT plant over the whole planning time horizon is over 44%, which is much higher than the probabilities in Scenarios 1 and 2.

7. CONCLUSION

In this work, given that the CO_2 emission price is uncertain resulting from the uncertain climate change policies, a new methodological framework for generation investment decision-making is presented based on the well-developed ROA, with the uncertain electricity prices and uncertain fuel prices in the electricity market environment taken into account. In this way, the impact of the uncertainties on generation investment can be quantified and this has been illustrated with a numerical example.

As a preliminary work, the investment activities from other generation companies and their interactions have not yet been modeled in detail, and represent our future research efforts.

ACKNOWLEDGEMENTS

This work is supported by ARC Discovery Grant of Australia.

8. LIST OF SYMBOLS AND ABBREVIATIONS

8.1. Symbols

μco_2 Expected growth rate of $p_{co_2,t}$
μ_f Expected growth rate of $p_{fuel,t}$

DOI: 10.1002/etep

μ_L	Expected growth rate of $L_{max,t}$
σco_2	Expected volatility rate of $p_{co_2,t}$
σ_f	Expected volatility rate of $p_{fuel,t}$
σ_L	Expected volatility rate of $L_{max,t}$

8.2. *Abbreviations*

A_t	Profits of the coal-fired plant in the t^{th} year
B_t	Profits of the CCGT plant in the t^{th} year
$C_{A,t}$	Installed capacity of Company A in the t^{th} year
C_{fuel}	Fuel cost of the power plant
$C_{fuel,CO2}$	CO_2 emission cost of the power plant
$C_{var,X}$	Variable cost of the power plant
$C_{var,O\&M,fuel}$	Operation and maintenance cost of the power plant
$C_{var,X,coal}$	Variable costs of the coal-fired plant
$C_{var,X,gas}$	Variable costs of the CCGT plant
C_X	Installed capacity of generation company X
dw_t	The increment of a Wiener process
I_X	Capital investment
$\tilde{k}_A$	Installed capacity increasing rate
$L_{max,t}$	Maximum load in the t^{th} year
$p_{e,t,w}$	Average electricity price in the w^{th} week of the t^{th} year
$p_{fuel,t}$	Fuel price in the t^{th} year
$p_{co2,t}$	CO_2 emission price in the t^{th} year
r	Risk-free interest rate
rt, w	Average capacity adequacy in the w^{th} week of the t^{th} year
t_0	Current year
T_{exp}	Last time to invest
V_t^{inv}	Investment profit
T_{lf}	Lifetime of the power plant
V_t^{wait}	Profit of waiting to invest
$V^*_{(t+1)}$	Maximum profit when an optimal investment time is chosen during the time period $[t+1, T_{exp}]$

REFERENCES

1. Agusdinata B. Exploratory analysis to support real options analysis: an example from electricity infrastructure investment. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics*, Vol. 4, 2005; 3689–3696.
2. Min KJ, Wang CH. Generation planning for inter-related generation units: a real options approach. In *Proceedings of IEEE Power Engineering Society Summer Meeting*, Vol. 4, Seattle, Washington, USA, 2000; 2261–2265.
3. Wang CH. *Generation Planning for Electric Power Utilities under Market Uncertainties: A Real Options Approach [D]*. Iowa State University: Iowa, 2001.
4. Keppo J, Hao LU. Real options and a large producer: the case of electricity markets. *Energy Economics* 2003; **25**(5):459–472.
5. Botterrud A, Ilic MD, Wangensteen I. Optimal investments in power generation under centralized and decentralized decision making. *IEEE Transactions on Power Systems* 2005; **20**(1):254–263.
6. Grabl H, Kokott J, Kulessa M, *et al*. Climate protection strategies for the 21st century: Kyoto and beyond. *Report Prepared by the German Advisory Council on Global Change*, Berlin, 2003.
7. Oppenheimer M, Petsonk A. Article 2 of the UNFCCC: historical origins, recent interpretations. *Climatic Change* 2005; **73**(3):195–226.
8. Abadie LM, Chamorro JM. European CO_2 price and carbon capture investments. *Energy Economics* 2008; **30**(6): 2992–3015.
9. China Climate Change Info-Net. Available at: Http://www.ccchina.gov.cn
10. Ellerman AD, Buchner BK. The European Union Emissions Trading Scheme: origins, allocation and early results. *Review of Environmental Economics and Policy* 2007; **1**(1):66–87.
11. Ellerman AD, Buchner BK, Carraro C, *et al*. *Allocation in the European Emissions Trading Scheme: Rights, Rents and Fairness*. Cambridge University Press: Cambridge, 2007.

12. Rothwell G. A real options approach to evaluating new nuclear power plants. *Energy Journal* 2006; **27**(1):37–53.
13. Laurikka H. The impact of climate policy on heat and power capacity investment decisions. In *Emissions trading and business*, Antes R, Hansjurgens B, Letmathe P (eds). Physica-Verlag: Helsinki, 2007.
14. Laurikka H, Koljonen T. Emissions trading and investment decisions in the power sector-a case study of Finland. *Energy Policy* 2006; **34**(9):1063–1074.
15. Kiriyama E, Suzuki A. Use of real options in nuclear power plant valuation in the presence of uncertainty with CO_2 emission credit. *Journal of Nuclear Science and Technology* 2004; **41**(7):756–764.
16. Reedman L, Graham P, Coombes P. Using a real options approach to model technology adoption under carbon price uncertainty: an application to the Australian electricity generation sector. *Economic Record* 2006; **82**(1):64–73.
17. Dixit AK, Pindyck RS. *Investment Under Uncertainty*. Princeton University Press: Princeton, New Jersey, 1994.
18. Weron R, Bierbrauer M, Trück S. Modeling electricity prices: jump diffusion and regime switching. *Physica A: Statistical and Theoretical Physics* 2004; **336**(1–2):39–48.
19. PJM ISO website. Available at: http://www.pjm.com/Search%20Results.aspx?q=2001
20. Doorman GL. Capacity subscription: solving the peak demand challenge in electricity markets. *IEEE Transactions on Power Systems* 2005; **20**(1):239–245.
21. NEA-IEA (NEA: Nuclear Energy Agency of the OECD). Projected costs of generating electricity: 2005 update. OECD: Paris, 2005.

DOI: 10.1002/etep