Research on ‘near-zero emission’ technological innovation diffusion based on co-evolutionary game approach

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ABSTRACT
As air pollution becomes increasingly critical, ‘near-zero emission’ technological innovation in coal-fired plants are needed for the government and public consumers. The aim of this paper is to build the evolutionary game for analysing ‘near-zero emission’ technological innovation diffusion in coal-fired plants. According to bionics research of evolution, this paper introduces the co-evolutionary algorithm to simulate the diffusion. By modelling the evolutionary gaming behaviour of coal-fired plants, the simulation can capture the dynamics of coal-fired plants’ strategy, which is adopting ‘near-zero emission’ technological innovation or not. It is key to model the diffusion under the electricity market and government regulation because it can provide some suggestions for promoting the diffusion. Simulations show that with no government regulations, the coal-fired plant fails to adopt the ‘near-zero emission’ technological innovation. However, the coal-fired plant for most profit should adopt independent R&D for ‘near-zero emission’ technology when the government provides subsidy incentives for the low-pollution coal-fired plant. With the promotion of subsidy incentives, all coal-fired plants will adopt ‘near-zero emission’ technology. Moreover, increasing the subsidy intensity has a significant role in promoting the diffusion.

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1. Introduction
The energy consumption of our society is growing due to the ongoing development of the global economy. In order to fulfil the energy demands, the consumption of fossil fuels, such as coal and oil, is also increasing. It is able to result in excessive use of fossil energy, environmental issues, and increased health risks to the living creatures on earth. Therefore, how to achieve emission reduction of air pollutants has been considered as the important energy development issues in most countries and regions in the world (Dai, Xie, Xie, Liu, & Masui, 2016; Hussain, Arif, & Aslam, 2017).

At present, China has become the world’s largest energy consumer (Brockway, Steinberger, Barrett, & Foxon, 2015). With regard to China’s primary energy consumption structure in 2016, coal consumption is accounted for 62%. It can demonstrate that coal has been the main component of China’s primary energy. When it comes to the use of coal, there is no doubt in China that nearly half coal supply is used for power generation while more than 70% of electricity supply is produced from coal power plants. Owing to China’s energy resource endowments, the prospective power production structure is dominated by coal power generation (Yuan et al., 2016). However, the use of coal as a fuel for electricity production will inevitably release the dust, \( \text{SO}_2 \) and \( \text{NO}_x \), which can cause air pollution issues. Thus, the technology for clean use of coal in coal-fired power generation is of particular policy importance to China’s clean energy transition and China’s air pollution emission decrease.

In terms of clean technology innovation for coal-fired power generation, Shenhua Group Corporation conducted the research on the ‘near-zero emission’ technology for coal-fired plants in September 2012. The technology is being promoted in China, and the technology diffusion can result in significant reductions for the emission of the dust, \( \text{SO}_2 \) and \( \text{NO}_x \). In detail, the wet electrostatic precipitator (WESP), as a terminal purification device, can reduce dust and droplet emission concentration (Dong-Ge, Fa-Hua, Sheng, Xiao-Ming, & Zhen, 2015). With regard to \( \text{SO}_2 \), low Sulphur coal with high quality is chosen to used and high efficiency wet desulfurization device is retrofitted for lower \( \text{SO}_2 \) (Wang, Zhu, & Zhao, 2014). As for \( \text{NO}_x \), the low-\( \text{NO}_x \) combustor is used to control the generation for \( \text{NO}_x \) and selective catalytic reduction (SCR) technology can remove \( \text{NO}_x \) in smoke (Wang et al., 2014). And the three technologies have become the major solvents...
for the ‘near-zero emission’ technology. After the technical innovation, it is demonstrated that the dust, SO\textsubscript{2} and NO\textsubscript{X} concentration are lower than that emission limits for the gas turbine power plants with different loads in the long-term studied (Wang, Liu, & Energy, 2016). As the scholar Blaut (1987) put forward, ‘The role of innovation diffusion is more important than innovation itself’, only if the ‘near-zero emission’ technology is adopted by most coal-fired plants can this technology reflect its economic and environmental value. Therefore, the aim of this paper is to explore the micro-interactive mechanism of the ‘near-zero emission’ technological innovation diffusion, and propose some suggestions for promoting the diffusion of ‘near-zero emission’ technology innovation.

It is considered in the innovation diffusion theory that innovation diffusion is a behaviour that the potential adopters imitate the action of adopters. Scholars’ research on the diffusion of technological innovation focuses on two aspects. The first is influencing factors concerning the diffusion of technological innovation. For example, Hu, Wang, and Yu (2004) employed a stochastic evolutionary model to analyse the diffusion of alternative technologies, and the evolutionary characteristics of alternative technologies are obtained by computer simulations. Stephan, Schmidt, Bening, and Hoffmann (2017) pointed out that the department configuration in Japan Aluminium battery company has an important influence on the evolution of Japanese Aluminium battery technology. Eleftheriadis and Anagnostopoulou (2015) investigated the obstacles for the development of renewable energy in Greece, and furthermore analysed wind power and photovoltaic power generation technology diffusion. On the other hand, government plays a key role in the diffusion of technological innovation. For example, Tigabu, Berkhout, and Beukering (2017) presented the effect of official development assistance in the diffusion of renewable energy technologies in Africa. Cantono (2008) proposed a network model for the diffusion of new technologies and explored the impact of limited subsidy policies on diffusion of new technologies. To promote the development of clean technologies, Foxon and Pearson (2008) stimulated the development of a sustainable innovation policy regime, bringing together innovation and environmental policy regimes.

However, the diffusion model for technological innovation in the previous research did not consider the adaptive interaction between participants in the model. They failed to represent the process in which one player observes its opponents behaviour, learns from these observations, and makes the best move in response to what it has learned. In this respect, the Evolutionary Game (Browne & Maire, 2010; Smith, 1982; Wang, Zhi, & Botterud, 2011) derived from biological evolution can capture the dynamic adaptation of market participants better than the traditional model. This paper employs the evolutionary game theory to model ‘near-zero emission’ technology innovation diffusion for coal-fired power plants. In reality, if a coal-fired power plant adopts ‘near-zero emission’ technology, it’s cost could be affected. The competitiveness for coal-fired power plants in electricity markets could be changed. To estimate the economic value for ‘near-zero emission’ technology, the coal-fired power plant can learn and modify it dynamically based on the behaviour of rivals in electricity markets. The evolutionary game theory is considered as a way of thinking about evolution at the phenotypic level when the fitness of particular phenotypes depends on their frequencies in the population. Hence, Co-evolutionary Algorithm is suitable to find the equilibrium point in the evolutionary game. Co-evolutionary Algorithm emphasizes the interactive connection among the species. And each species will co-evolve with other species while seeking their own best propagation. It can be envisioned that co-evolutionary computation has great potential to analyse the diffusion of ‘near-zero emission’ technology innovation in electricity markets by modelling coal-fired companies as the individual species.

In summary, this paper contributes in the following aspects:

1. By using the co-evolutionary game approach, this paper simulates the diffusion of ‘near-zero emission’ technology innovation under the electricity market and government regulation.

2. Some suggestions for promoting the diffusion of ‘near-zero emission’ technology innovation is provided.

The rest of this paper is organized as follows. Section 2 introduces the evolutionary game theory and co-evolutionary computation utilized in this paper. Section 3 provides the simulation of ‘near-zero emission’ technology innovation diffusion under the electricity market and government regulation. Finally, Section 4 concludes the paper.

2. Method

2.1. Evolutionary game theory

Evolutionary game theory (EGT) Broom and Cannings (2010) has been drawing more attention in the past several years. In comparison with the traditional game theory, EGT emphasizes the dynamics of strategy change more than the properties of strategy equilibria. EGT to some extent takes into account the personal knowledge,
belief and risk preference of the agents. The equilibrium derived by the traditional game theory may not be realized in practice since participants have dynamic learning abilities. Nowadays, EGT is widely applied to analyse various gaming behaviour such as firm and industry behaviour, broader biological and dynamical systems, and economic growth theory (David, 1985; Nelson & Winter, 1980).

Motivated by the evolutionary game theory, this paper does an analogous investigation to study diffusion of ‘near-zero emission’ technology innovation. In order to achieve a higher profit, social competitiveness and other goals, coal-fired companies will develop ‘near-zero emission’ technology, launch it into the market and spread it. However, when the original technology has occupied the most market share, it will resist ‘near-zero emission’ technology innovation. On the one hand, the government regulations can gradually increase the efficiency of ‘near-zero emission’ technology innovation diffusion, and eventually make the original technology forced out of the market. In addition, due to the original technology resistance, if the green innovation technology fails to produce more profits, coal-fired companies will abandon it and the diffusion for ‘near-zero emission’ technology will stop.

This paper establishes the game model for the diffusion of ‘near-zero emission’ technology innovation under the market mechanism and government regulation. The coal-fired plant is concerned as participants in the game model. And each coal-fired plant has two strategies: adopting ‘near-zero emission’ technology innovation and not adopting ‘near-zero emission’ technology innovation.

Table 1 shows the evolutionary game model under market mechanism. Here are the payoff for each coal-fired power plant. When two sides of the game choose the strategy (adopt, adopt), the payoff for each coal-fired power plant. When two sides of the game choose the strategy (not adopt, adopt), coal-fired power plant 1 still is $\Pi(C_1 + h)$. However, coal-fired power plant 2 choices the traditional power generation and the payoff is $\Pi(C_2)$. When two sides of the game choose the strategy (not adopt, adopt), both of them choose the traditional power generation and the payoff is $\Pi(C_1)$. However, the payoff for coal-fired power plant 1 and 2 is $\Pi(C_1 + h)$.

Table 2 shows the evolutionary game model under government regulation. To develop clean technology for coal-fired power generation, the government must adopt macro-control measures to encourage and guide coal-fired power plants to adopt ‘near-zero emission’ technology innovation. The government’s regulation on the diffusion of ‘near-zero emission’ technologies is price regulation. In terms of price regulation, the subsidy, which is denoted by $a$, is available for the coal-fired power plants adopting ‘near-zero emission’ technology innovation.

### 2.2. Co-evolutionary computation

The co-evolutionary algorithm introduces the concept of ecosystem based on the traditional evolutionary algorithm and maps the problem to be solved into an ecosystem composed of interacting and interacting species. The purpose of the problem is solved by the evolution of the ecosystem (Sim, Lee, & Kim, 2008). This paper combines evolutionary game theory and co-evolutionary algorithm to propose a co-evolutionary game algorithm to solve the model. Experimental results show that it has good performance.

In co-evolutionary game algorithms, coal-fired power plants are considered as individuals in the game. This paper assumes that coal-fired power plants belong to power generation companies and there are three different types of power generation companies that generate populations $P_1$, $P_2$, and $P_3$, respectively. Power generation company 1 has independently developed ‘near-zero emission’ technology. And some coal-fired power plants in power generation company 1 have adopt ‘near-zero emission’ technology innovation.
emission’ technologies. Hence, there are only two strategies for the other coal-fired power plants: adopting and not adopting ‘near-zero emission’ technology. The power generation company 2 introduces the ‘near-zero emission’ technology. The strategies for power generation company 2 is the same as power generation company 1. However, due to the cost of independent research and development and introduction of technology, the cost for power generation company 2 is larger. The power generation company 3 fails to research and develop independently or introduce the technology. Therefore, there are three strategies for power generation company 3: adopting the introduced technology, adopting the technology for independent research and development and not adopting the technology.

Figure 1 shows the framework of a co-evolutionary game algorithm. In the process of cooperative evolutionary game, the three populations, such as the three coal-fired companies, separately perform standard genetic algorithm (GA) and constantly update their respective strategies until the optimal strategy or the number of iterations is maximized. For the calculation of fitness in GA, the profit of the coal-fired power plant in the electricity markets is used as fitness. The independent operators (ISO) in the electricity market calculate the on-grid power and market clearing prices of all coal-fired power plants based on the quotes of coal-fired power plants, and feed back to the coal-fired power plants. To improve the fitness value of the standard GA, a hybrid GA algorithm with pattern search is employed after the GA terminates. The final point from the GA is set as the initial point of the pattern search. The pattern search samples points and searches the space calculating the fitness value to find a maximum around this starting point in a fixed pattern. When it finds a new maximum, the pattern search will change its centre of pattern to this point and iterate until it cannot find a new maximum.

To model the agents, we apply two agent rules that are based on the theory of individual choice:

1. Rational choice: Individuals decide which action is the best for them to take
2. Bounded rationality: Individuals reasoning is partially rational due to limited knowledge and abilities

The rational choices are demonstrated by coal-fired power plants’ evaluating and choosing the representatives that have the best fitness values as the strategies. Meanwhile, the continuously updated estimation of the payoff for ‘near-zero emission’ technology embodies the bounded rationality, which means coal-fired power plants have to estimate the payoff for ‘near-zero emission’ technology because of lack of perfect information, and refine the strategies dynamically with the development of the game.

The solution steps for co-evolutionary computation are as follows.

Step 1: Input the original data and parameters, set the population distribution probability, randomly generate the initial population, and generate the initial feasible strategy combination.
Step 2: Simulate the market clearing process and yield profits for each individual in P1, P2, and P3.
Step 3: The power generation company 3 estimates the payoff for ‘near-zero emission’ technology according to the profits of power generation company 1 and power generation company 2, and then changing their estimations.
Step 4: Evaluate the fitness for each individual in P1, P2, and P3.
Step 5: Three populations are selected, crossed and mutated to generate the next generation, respectively.
Step 6: Repeat steps 2–5 until the entire population reaches evolutionary stability or reaches the maximum evolution algebra.

3. Simulation result and discussion
To simulate the diffusion for ‘near-zero emission’ technology innovation using co-evolutionary algorithm, we firstly analyse the diffusion under electricity markets. Furthermore, the diffusion under government regulations is modelled.

3.1. The diffusion under electricity markets
In this section, the diffusion under electricity markets is considered as the baseline scenario. The hypothesis of this scenario is as follows. In the electricity markets, if the cost for coal-fired power generation is low, the coal-fired power plant has the market power to obtain more market share for power. Consequently, the cost has the significant influence on the profit of the coal-fired power
plant. It is assumed that $C$ for the traditional generation cost is 0.40 Yuan/KWh, $I$ for the additional generation cost by independent research for the technology is 0.0075 Yuan/KWh, $I'$ for the additional generation cost by introduction of the technology is 0.0085 Yuan/KWh.

Figures 2–4 shows the 'near-zero emission' technology innovation diffusion for three coal-fired companies under electricity markets. The $X$-axis for the above figures means the iteration in co-evolutionary computation and the $Y$-axis denotes the strategy for adopting 'near-zero emission' technology innovation or not. Besides, in Figure 4, the diamond curve means the probability for choosing independent R&D, and the square curve means the probability for choosing the introduction of the technology.

**Figure 2.** Innovation diffusion for coal-fired company 1 under electricity markets.

**Figure 3.** Innovation diffusion for coal-fired company 2 under electricity markets.
As the above figures indicate, coal-fired company 1 will not adopt ‘near-zero emission’ technology innovation. The cost for coal-fired companies adopting ‘near-zero emission’ technology innovation is larger than those not adopting ‘near-zero emission’ technology innovation. Under the influence of economic interests, it is very likely that they will choose not to adopt the technology until the diffusion evolves to a steady state with a diffusion depth of zero. It is concluded that with no government regulations, ‘near-zero emission’ technology innovation fails to be promoted.

### 3.2. The diffusion under government regulation

Based on the diffusion under electricity markets, this section considers the government’s regulation, which is

**Figure 4.** Innovation diffusion for coal-fired company 3 under electricity markets.

**Figure 5.** Innovation diffusion for coal-fired company 1 under government regulation.
price regulation. When it comes to price regulation, the subsidy $a$ is set as 0.006, 0.008, and 0.01 Yuan/KWh.

Figures 5–7 shows the ‘near-zero emission’ technology innovation diffusion for three coal-fired companies under government regulation. The $X$-axis for the above figures means the iteration in co-evolutionary computation and the $Y$-axis denotes the strategy for adopting ‘near-zero emission’ technology innovation or not. Besides, the diamond curve, the square curve and the star curve mean the subsidy as 0.006, 0.008, and 0.01 Yuan/KWh, respectively.

From Figures 5–7, it can be seen that if the subsidy $a$ is 0.01 Yuan/KWh, the diffusion evolves to a steady state with a diffusion depth of 100%, which means coal-fired company 1 and coal-fired company 2 will
adopt ‘near-zero emission’ technology innovation. Furthermore, with regard to coal-fired company 3, it will adopt independent R&D for the technology. When it comes to subsidy a 0.008 Yuan/KWh, coal-fired company 1 and coal-fired company 3 will adopt independent R&D for the technology. However, coal-fired company 2 fails to adopt ‘near-zero emission’ technology innovation. To carry out the subsidy a 0.006 Yuan/KWh, it is demonstrated that all coal-fired companies will not adopt the technology. It is concluded that increasing the subsidy intensity has a significant role in promoting the diffusion of ‘near-zero emission’ technology innovation. Besides, independent R&D for the technology is more advantageous than introduction of the technology in the diffusion of ‘near-zero emission’ technology innovation.

It should be noted that the aim of subsidy incentives is to increase the benefit of coal-fired plants. Only when the benefit of the coal-fired plant is greater than the input of the coal-fired plant, the diffusion evolves to a steady state with a diffusion depth of 100%, realizing the complete diffusion of ‘near-zero emission’ technology innovation in coal-fired plants. Figures 5–7 can represent three types of subsidy influence the result and speed of the diffusion and help government make subsidy policy.

4. Conclusion

From the perspective of stakeholder theory and co-evolutionary game theory, this paper analyses the diffusion of ‘near-zero emission’ technology innovation in coal-fired plants. By the simulation of the diffusion of the technology using Co-evolutionary game approach, it is concluded that:

(1) With no government regulations, ‘near-zero emission’ technology innovation fails to be promoted in the electricity markets.

(2) Under the circumstance of government regulation, power generation companies will gradually adopt ‘near-zero emission’ technologies, and power generation companies may choose to independent R&D rather than introduce technology.

(3) Only when the benefit of the coal-fired plant is greater than the input of the coal-fired plant, the diffusion evolves to a steady state with a diffusion depth of 100%, realizing the complete diffusion of ‘near-zero emission’ technology innovation in coal-fired plants.

(4) Increasing the subsidy intensity has a significant role in promoting the diffusion of ‘near-zero emission’ technology innovation. To be compared with introduction of the technology, coal-fired companies will gradually choose independent research and development.

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