frontiers in Energy Research

ORIGINAL RESEARCH
published: 15 September 2021
doi: 10.3389/fenrg.2021.628206

Efficiency Power Plant Implementation Decision-Making Based on the Profit Function and Its Numerical Simulation

Yiping Zhu and Yue Jin*

School of Management, Nanchang University, Nanchang, China

The efficiency power plant (EPP) is a kind of virtual power plant with zero emission, zero pollution, and low cost and exhibits a high-quality low-carbon production behavior in input-output analysis. In the process of implementing EPP, enterprises not only save electricity but also reduce carbon emissions, while increasing the cost of R&D and equipment. Therefore, it is very necessary to study relationships between carbon quota and EPP implementation decision. In this paper, we build the profit functions of three different types of enterprises implementing EPP and analyze the relationship of main parameters, such as the probability of implementing EPP, electricity saving, income, cost, and carbon quota, and obtain nine relative results. Then, we use 'Maple' software to simulate the results by drawing images of parameters, and all the above nine results passed the simulation test verification. At last, we collect the actual survey data and use VC++ programming to carry out an empirical study in China to prove the practicability of the model and the results. The results show that, under the carbon quota trading system, enterprises should tend to implement EPPs and increase investment in R&D and acquisition of EPPs and are needed to adjust the intensity of implementing EPPs according to the change of carbon quota and unit carbon quota income, to obtain higher income.

Keywords: efficiency power plants, implementation decision, carbon quota, relationship analysis, maple

OPEN ACCESS

Edited by:
Hong-zhou Li,
Dongbei University of Finance and Economics, China

Reviewed by:
Neeraj Dhanraj Bokde,
Aarhus University, Denmark
Shuai Geng,
Shandong Jianzhu University, China

****Correspondence:***
Yiping Zhu
zhuyipingnet@ncu.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies,
a section of the journal Frontiers in Energy Research

Received: *11 November 2020*
Accepted: *18 August 2021*
Published: *15 September 2021*

Citation:
Zhu Y and Jin Y (2021) Efficiency Power Plant Implementation Decision-Making Based on the Profit Function and Its Numerical Simulation. Front. Energy Res. 9:628206. doi: 10.3389/fenrg.2021.628206

INTRODUCTION

Background

Electricity demand side management (DSM) is to let enterprises and users manage their own enterprise electricity situation through the construction of electricity fine management platform. Efficiency power plant (EPP) is a representative DSM energy efficiency resource project. EPP can be considered as a collection of some DSM energy efficiency resource projects with better combination. EPPs use high-efficiency electrical equipment and products, based on the energy-saving transformation plan of an industry or a regional enterprise, to form a regional electricity utilization efficiency optimization in different ways, which has the same important significance with the construction of a new power plant.

Over the past 10 years, the development of DSM has achieved abundant energy conservation and emission reduction effects and formed a certain scale. For example, the State Grid Energy Research Institute of China counts that the generation capacity of the DSM project is 640.7 billion kWh in China from 2011 to 2015 and estimates that the same in 2016–2020 is 1.3254 trillion kWh. It can reach 1.9661 trillion kWh during the period of 2010–2020, equivalent to a reduction of 22,598 kWh in generation capacity, and nearly 57 billion USD in investment compared with the conventional power plants (Energy Research Institute of State Grid of China, 2010).

The China government has introduced a carbon quota management system (Chang et al., 2020), which has a significant impact on the implementation of EPP. Under the carbon quota system, enterprises must control the greenhouse gas emissions, mainly carbon dioxide (CO_2). The implementation of EPP cannot only reduce power consumption but also reduce carbon emissions, which, to some extent improves the willingness of enterprises to implement EPP (Li et al., 2016). Moreover, as the EPP grew in size, massive fiscal and tax subsidies became unsustainable, and carbon quotas became the government's main means of controlling carbon emissions.

In this paper, on the basis of predecessors' research summarized, we further combine government carbon quota with EPP, through the establishment of EPP implementation decision model based on the profit function, analyze the decisions of enterprises under different carbon quota, and verify the correctness and rationality of the results through system simulation. We hope this article could provide a reference for enterprises to make correct decisions under different carbon quota and different technology maturity when implementing EPPs.

Literature Review

EPP and DSM are hot topics in energy management, as they grew in size; they encountered economic, technological, and managerial problems in the development process (Haydt et al., 2014). Thus, most scholars prefer to focus on the three aspects of EPPs, such as in the economic field, such as billing (Çakmak and Altaş, 2020), pricing (Venizelou et al., 2020), and cost-benefit analysis (Wang and Zhu, 2014); in the field of mathematics, such as scheduling (Chamandoust et al., 2020) and planning (Zhu et al., 2017) and energy efficiency (Wang et al., 2015; Wang et al., 2016; Chakraborty et al., 2020); and in the field of technology, such as renewable energy (Kalair et al., 2020), smart distribution system (Reddy et al., 2020), and others (Mendes et al., 2020).

Among the field of energy management, the game analysis of low-carbon investment behavior is meaningful and necessary. Rai and Beck (2017) stated the importance of using behavioral science to address the persistent gaps between the technical potential of low-carbon technologies and the actual adoption of these technologies. The game analysis in low-carbon environment is derived from the low-carbon supply chain research. Du et al. (2015) conducted a game-theoretical analysis and gave low-carbon supply policies for supply chain management (Du et al., 2017). Chen et al. (2014) investigated a practical demand side management scenario where the selfish consumers compete to minimize their individual energy cost through scheduling their future energy consumption profiles using an aggregative game approach. Li et al. (2017) examined the influences of different game structures on the optimal decisions and performance of a low-carbon closed-loop supply chain (CLSC) with price and carbon emission level-dependent market demands. Then, the scholars put forward the game behavior of each participant in low-carbon investment. Du et al. (2013) considered the emission cap of emission-dependent manufacturer allocated by the government as a kind of environmental policy and formally investigated its influence on decision-making within the concerned emission-dependent supply chain and distribution fairness in social welfare. Luo et al. (2016) derived the optimal solutions for the two manufacturers in the purely competitive and co-opetitive market environments, respectively. Based on non-cooperative and cooperative games, Huang et al. (2018) proposed a hierarchical game playing scheme and a simplified multienergy system optimization method to assist stakeholders to participate in technoeconomic analysis process. Sun et al. (2020) constructed a Stackelberg differential game model (dominated by manufacturers) under both centralized and decentralized decisions considering the lag time of emission reduction technologies and the low-carbon preferences of consumers. Zhu et al. (2018) investigated how to optimize the strategy of low carbon investment for suppliers and manufacturers in supply chains and discussed the impacts of various factors on evolutionarily stable strategies. Arai et al. (2014) proposed a comprehensive framework for evaluating the performance of demand-side actors in a demand-side management system using each control scheme according to both communication availability and sampling frequency. Liu et al. (2017) proposed a scenario for DSM programs to schedule household energy consumption considering bidirectional energy trading of PEVs by a Bayesian game approach. Mahmoudi et al. (2019) evaluated the performance of Iranian thermal power plants combined with multivariate data analysis techniques, game theory, Shannon entropy, and the technique for the order of preference by similarity with ideal solution. Dou, 2015, established a dispatching optimization model of regional integrated power and gas energy system and analyzed the node energy price through the node energy balance equation and a demand response model based on evolutionary game.

Implementing EPP is a special low-carbon behavior, which can not only reduce carbon emission but also reduce electricity consumption. Therefore, the decision analysis of EPP needs to consider both low carbon and power-saving benefits. The author puts forward EPP implementation by government and enterprise, but it is far from enough (Zhu et al., 2019). Research on decision analysis among EPP enterprises is likewise important, but unfortunately, there is a lack of research on this aspect, especially about the EPP implementation decision with carbon quotas and carbon reduction benefits. Above all, the literature that analyzes the decision analysis among EPP enterprises urgently needs to be supplemented. Therefore, this study of relationship analysis for EPP implementation decision and carbon quota is innovative and of practical value.

THEORETICAL BASIS

Efficiency Power Plant

EPP is a packaged set of DSM items or collections. The brief summary is EPPs realize energy saving transformation of

TABLE 1 | Comparison of conventional power plants and efficiency power plants.

Parameter	Conventional power plants	Efficiency power plants
Capacity (10,000 kV)	30	30
Electricity produced/saved per year (one billion million kWh)	1.5	1.5
Fuel (standard coal) consumption (g/kWh)	340	0
CO_2 emission (g/kWh)	940	0
$SO_{2.}$ emission (g/kWh)	4	0
Average power generation and supply cost (dollar/kWh)	2.2–2.8	1

energy-consuming equipment, and the energy saved is equivalent to the electricity generated by conventional coal-fired power plants (Zhu et al., 2017). Compared with conventional power plants, which are power plant entities, EPPs are designed to save electricity, not produce electricity, and save as much electricity as they produce. Although an EPP is not a real power plant, compared with power generation resources, it has the same importance in the optimal allocation of regional power supply and demand resources. It is an effective and convenient way to realize energy conservation and emission reduction and control power consumption (Maria et al., 2020). EPPs have many advantages, such as zero emission, zero pollution, low cost, non-land occupation construction cost, and operation benefit. Based on these advantages, EPPs can be used to optimize regional power resource allocation and improve the reliability and stability of the power system.

Table 1 compares fuel consumption, pollution emissions, and cost comparisons, and the comparison is about producing (or saving) per 1 kWh electricity between conventional power plants and energy-efficient power plants (source: Castro et al., 2020). The conventional power plant in the table takes a typical coal-fired power plant with an installed capacity of 300,000 kW as an example, and the annual utilization hours of its power generation equipment are about 5000 h.

Carbon Quota

Carbon quota refers to the greenhouse gas emission reduction targets that must be completed according to the regulations. For an EPP, it refers to the carbon dioxide emission reduction during the implementation of EPP. Many scholars have conducted research studies on carbon quota, but they almost took carbon quota as a constraint condition, and few literature studies have studied it as an endogenous variable. Carbon cap-and-trade was first proposed by J.H.Dales in his book "*Pollution, Property and Price*" (Dales, 1968), which pointed out that the government could consider pollution as a transfer of the right through the process of mutual trading of emission rights by enterprises and the regulation of the market, so as to improve the efficiency of energy use. At present, the carbon quota trading system is a relatively effective incentive means in the market, which can urge enterprises to take emission reduction measures. There are three typical distribution methods: free distribution, priced sale, and full market (Chen, 2003). There are mainly four typical carbon emission trading systems in the world (Zhang et al., 2014), namely, the European Union Carbon Emission Trading System (EUETS), the United States Regional Greenhouse Gas Initiative (RGGI), Australia's New South Wales Greenhouse Gas Emission Reduction System (NSWGGAS), and Japan's Tokyo Carbon Emissions Trading System (Tokyo ETS).

METHODOLOGY

The Behavior of Implementing Efficiency Power Plant

In China, the initial government subsidies are one of the impetuses of the enterprises implementing EPPs. With the increase of the size of the EPP, government financial subsidies began to gradually withdraw from the market, and carbon quota, as another kind of subsidies for the development of enterprises, began to appear. The government sets different carbon quota levels according to the ability of different enterprises to implement EPP, thus encouraging the development of EPP. The government stipulates a certain amount of carbon quota at the initial stage of the enterprise. With the implementation of the EPP, the government will subsidize a certain amount of carbon quota for unit reduction of electricity consumption. When not implementing the EPP, a certain amount of carbon quota will be consumed in normal enterprise production. At the end of each year, the total amount of carbon quota of the enterprise is accounted. The excess carbon quota can be exported by the enterprise to obtain funds. If the excess carbon quota is less than zero, the enterprise needs to buy excess carbon quota, or it will have to pay high compensation to the government.

This paper takes the government carbon quota level as an endogenous variable and studies how enterprises should formulate EPP implementation decision with the change of carbon quota level to ensure the maximization of their own income.

1) For enterprises that choose to implement EPP, we analyze the carbon quota level that enterprises will reach the critical value of R&D investment, and with the constant change of the carbon quota level, we research how the electricity reduced and the income obtained by implementing EPP will change with the change of carbon quota. 2) For enterprises that do not choose to implement EPP, we study the carbon quota level that enterprises will start to tend to implement EPP and research what extent will they continue to ignore EPP. 3) For enterprises that are uncertain whether to implement EPP or not, we study how should they make EPP decision with the change of carbon quota, that is, determine the tendency (probability) of implementing EPP, so as

to maximize their own income, and research the change trend of enterprise output and income with the change of carbon quota.

Assumptions

1) Subject

There are three different types of enterprises, namely, enterprise E_1 which always implements EPP, enterprise E_2 which never implements EPP, and enterprise E_3 which implements EPP as the case may be.

2) Electricity saved or consumed (unit: kWh, MWh, and GWh)

Set the electricity saved in enterprise E_1 as Q_1; enterprise E_2 does not save electricity, but consumes electricity, so the electricity consumed by enterprise E_2 can be set as Q_2; when EPP is implemented for enterprise E_3, electric energy is saved; when EPP is not implemented, electric energy is consumed, so set the electricity saved by enterprise E_3 at last as Q_3.

In addition, we can set the probability, tendency, or strength $\lambda(0<\lambda<1)$ of enterprise E_3 to implement EPP, and then, the probability of not implementing EPP is $1-\lambda$.

3) Price (this is the price at which EPP saves electricity, not the market price)

In fact, the electricity reduced by implementing EPP has exactly the same function as the electricity generated by the power plant, and the products can be completely replaced. But unlike electricity prices, which are controlled by the government, we assume that the price of electricity reduced by EPP is affected by market supply and demand, and its price can be expressed as P. $P=\alpha-bQ$, where α is the market acceptable price caps and b is the market demand-back coefficient. The larger the demand-back coefficient is, the smaller the market is.

4) Cost

It is assumed that the cost of EPP implementation is mainly divided into two parts: R&D cost and operation cost. R&D cost includes the costs of key processes, technologies, and equipment of EPP, expressed as C_1; operating costs include energy-efficient processes and equipment produced or purchased for EPP implementation, as well as personnel inputs, etc., expressed as C_2. For enterprise E_1 and E_3, the unit R&D cost and unit operation cost decrease with the increase of power saving. For enterprise E_2, this kind of enterprise has no R&D cost but only has operation cost.

4) Carbon quotas

It mainly refers to the carbon emission quota determined by the government according to the situation of enterprises. Assume that the carbon quota stipulated by the government for each enterprise is H. The government will subsidize the carbon quota of h for every 1 kWh of electric quantity reduced by EPP. The government will deduct the carbon quota of h for every 1 kWh of electric quantity consumed by the enterprise without EPP. The carbon quota can be sold or purchased, and the economic benefit of carbon quota of h unit is d.

The main parameters and implications of the above assumptions can be represented in **Table 2**, and the revenue, costs, and variable returns of three different kinds of enterprises implementing EPP are presented in **Figure 1**.

Building the Profit Functions

1) Business revenue functions for three types of enterprises:

1) Set π_1 as the revenue function of enterprise E_1, according to the hypothesis; then,

$$\pi_1 = PQ_1 + hdQ_1 + \frac{H}{h}d - C_1 - C_2Q_1. \tag{1}$$

Put $P=\alpha-bQ$, $P=a-bq$, and $Q=Q_1+Q_2+Q_3$ into **Eq. 1** to get

$$\pi_1 = aQ_1 - bQ_1^2 - bQ_1Q_2 - bQ_1Q_3 + hdQ_1 + \frac{H}{h}d - C_1 - C_2Q_1. \tag{2}$$

Take the derivative of Q_1 first order and set it equal to 0 in **Eq. 1**.

$$\frac{\partial\pi_1}{\partial Q_1} = a - 2bQ_1 - bQ_2 - bQ_3 + hd - C_2 = 0. \tag{3}$$

Thus, the optimal power saving Q_1^* can be obtained:

$$Q_1^* = \frac{a - bQ_2 - bQ_3 + hd - C_2}{2b}. \tag{4}$$

2) Set π_2 as the revenue function of enterprise E_2, according to the hypothesis; then,

$$\pi_2 = PQ_2 + \frac{H}{h}d - hdQ_2 - C_2Q_2. \tag{5}$$

In the same way, take the derivative of Q_2 first order and set it equal to 0 in **Eq. 5**. Thus, the optimal power consumption Q_2^* of enterprise E_2 can be obtained:

$$Q_2^* = \frac{a - bQ_1 - bQ_2 - hd - C_2}{2b}. \tag{6}$$

3) Set π_3 as the revenue function of enterprise E_2, according to the hypothesis; then,

$$\pi_3 = PQ_3 + \frac{H}{h}d + \lambda Q_3hd - (1-\lambda)Q_3hd - C_1 - C_2Q_3. \tag{7}$$

In the same way, take the derivative of Q_3 first order and set it equal to 0 in **Eq. 7**. Thus, the optimal power consumption Q_3^* of enterprise E_3 can be obtained.

$$Q_3^* = \frac{a - bQ_1 - bQ_2 + 2\lambda hd - hd - C_2}{2b}. \tag{8}$$

Joint establishment of optimal power consumption of three kinds of enterprises, which can be simplified to

TABLE 2 | Variables and meanings in the assumptions.

	Enterprise E_1	Enterprise E_2	Enterprise E_3
Electricity saved	Q_1	Q_2	Q_3
Research and development costs	C_1	0	C_1
Operating costs	C_2	C_2	C_2
Initial carbon quota	H	H	H
Carbon quota for saving electricity per unit	h	$-h$	h
Carbon quota revenue for saving electricity per unit	d	$-d$	d
Probability of choosing to implement EPP	1	0	λ

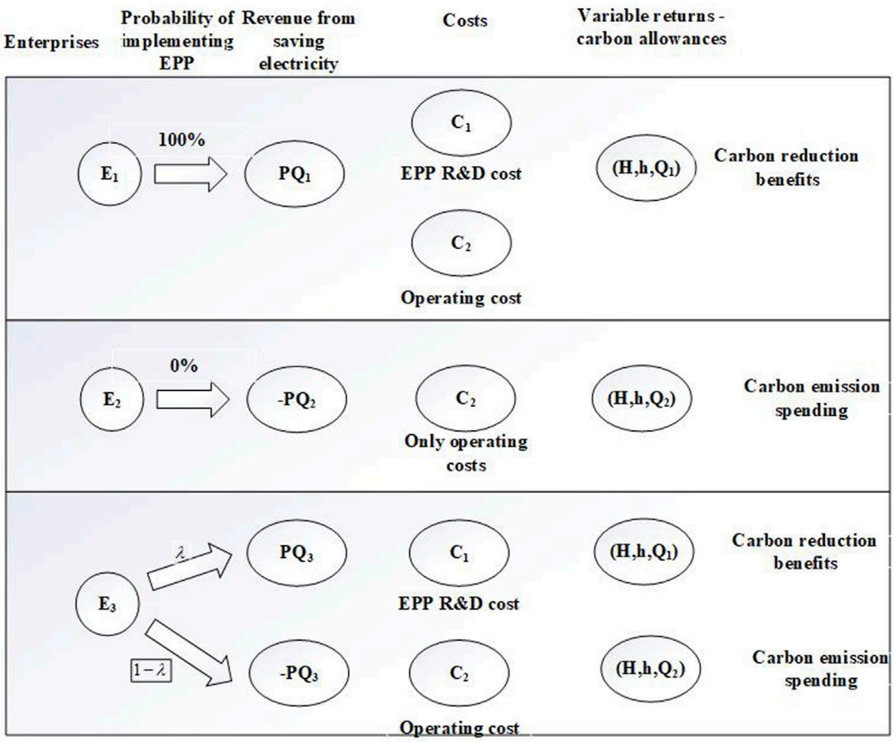

FIGURE 1 | The revenue, costs, and variable returns of three different kinds of enterprises implementing EPP.

$$\begin{cases} Q_1^* = \dfrac{a - 2\lambda hd + 5hd - C_2}{4b} \\ Q_2^* = \dfrac{a - 2\lambda |hd - 3hd - C_2}{4b} \\ Q_3^* = \dfrac{a + 6\lambda hd - 3hd - C_2}{4b} \\ Q^* = \dfrac{3a + 2\lambda hd - hd - 3C_2}{4b} \end{cases} . \tag{9}$$

By substituting the optimal solution of the above formula into the profit function of the respective enterprises, the optimal earnings of the three types of enterprises can be further obtained as follows:

$$\begin{cases} \pi_1^* = \dfrac{(a - 2\lambda hd + 5hd - C_2)^2}{16b} + \dfrac{Hd}{h} - C_1 \\ \pi_2^* = \dfrac{(a - 2\lambda |hd - 3hd - C_2)^2}{16b} + \dfrac{Hd}{h} \\ \pi_3^* = \dfrac{(a + 6\lambda hd - 3hd - C_2)^2}{|16b} + \dfrac{Hd}{h} - C_1 \end{cases} . \tag{10}$$

RESULTS

Relationship Analysis of Main Parameters

1) For enterprise E_1

According to **Eq. 9**, the electricity saved by enterprise E_1 has no relationship with the total carbon quota set by the government for the enterprise and is related to the carbon quota obtained by saving each unit of electricity and the benefit of unit carbon quota. In **Eq. 9**, the optimized first-order derivative of Q_1^* to h can be obtained as follows:

$$\frac{\partial Q_1^*}{\partial h} = \frac{5d - 2\lambda d}{4b}. \tag{11}$$

Then, result 1 can be obtained as follows. Result 1: the income of enterprise E_1 is directly related to the carbon quota for implementing EPP. There is a unit of carbon quotas h_0. When the carbon quota obtained by the implementation of EPP is higher than h_0, the income of enterprise E_1 will increase with the increase of unit carbon quota, and enterprise E_1 will continuously increase its sales volume to obtain greater income. When the carbon quota obtained from the implementation of EPP is lower than h_0, the enterprise income decreases with the increase of unit carbon quota, and the enterprise reduces the intensity of the implementation of EPP to ensure its own interests within a reasonable range.

Then, we analyze the relationship between revenue and R&D investment. The optimized first derivative of revenue π_1 with respect to R&D investment C_1can be obtained as follows:

$$\frac{\partial \pi_1}{\partial C_1} = -1. \tag{12}$$

Then, result 2 can be obtained as follows. Result 2: in **Eq. 12**, $\frac{\partial \pi_1}{\partial C_1} < 0$, therefore, for enterprise E_1, its incomes are negatively correlated with R&D investment, and enterprise income π_1 decreases with the increase of R&D investment C_1. In order to ensure the normal operation of the enterprise, there must be a critical value of the R&D investment. Below this value, the enterprise can operate normally and obtain profits. If the R&D investment exceeds this value, the enterprise will be unprofitable and gradually eliminated by the market.

Then, we analyzed the relationship between income π_1 of enterprise E_1 and income d from the unit carbon quota. In **Eq. 10**, the optimized first derivative of the enterprise income with respect to the unit carbon quota income can be obtained as follows:

$$\frac{\partial \pi_1}{\partial d} = \frac{(10 - 4\lambda)ah + 8\lambda^2 h^2 d + (50 - 40\lambda)h^2 d + 4\lambda h C_2}{16b} + \frac{H}{h}. \tag{13}$$

Then, result 3 can be obtained as follows. Result 3: in **Eq. 13**, all the unknowns are positive values, and we know $0 < \lambda < 1$; so, $(10 - 4\lambda)ah > 0$, $(50 - 40\lambda)h^2 d > 0$, and so $\frac{\partial \pi_1}{\partial d} > 0$. There is a positive correlation between the income of enterprise E_1 and the income of unit carbon quota, that is, with the increase of the income of unit carbon quota formulated by the government, the income of enterprises is gradually increasing. Similarly, the income of enterprise E_1 is positively correlated with the total carbon quota set by the government and the higher the carbon quota set by the government, the higher the profit obtained by the enterprise.

2) For enterprise E_2

In **Eq. 10**, the optimized first-order derivative of revenue π_2 of enterprise E_2 with respect to revenue d of the unit carbon quota can be obtained as follows:

$$\frac{\partial \pi_2}{\partial d} = \frac{-(6 + 4\lambda)ah + 8\lambda^2 h^2 d + 24\lambda h^2 d + 4\lambda h C_2 + 18h^2 d + 6hC_2}{16b} + \frac{H}{h}. \tag{14}$$

We cannot determine if $\frac{\partial \pi_2}{\partial d}$ is greater than 0 in **Eq. 14**. Let $\frac{\partial \pi_2}{\partial d} = 0$, we can get

$$d_0 = -\frac{16bh}{8\lambda^2 h^3 + 24\lambda h^3 + 18h^2} + \frac{6a + 4\lambda a + 4\lambda C_2 + 6h}{8\lambda^2 h + 24\lambda h + 18h}. \tag{15}$$

In **Eq. 15**, when $d = d_0$, $\frac{\partial \pi_2}{\partial d} = 0$. Therefore, the second derivative of **Eq. 14** can be obtained as follows:

$$\frac{\partial^2 \pi_2}{\partial d^2} = \frac{8\lambda^2 h^2 + 24h^2 + 18\lambda h^2}{16b}. \tag{16}$$

Then, result 4 is obtained as follows. Result 4: in **Eq. 16**, h and b are constants greater than 0, $0<\lambda<1$. That is, $\frac{\partial^2 \pi_2}{\partial d^2} > 0$, and the second derivative is greater than 0, indicating that the first derivative is monotonically increasing function. When $d > d_0$, the first derivative is greater than 0, and the first derivative is a monotonically increasing function. Therefore, the original function π_2 is a monotonically increasing function, that is, enterprise E_2 and incomeπ_2 increase with the increase of income d of the unit carbon quota. When $d < d_0$, the first derivative is less than 0, that is, the original function π_2 is a monotonically decreasing function, and the enterprise incomeπ_2 decreases with the increase of income d of the unit carbon quota. Enterprise E_2 income decreases first and then increases with the increase of the carbon quota income, and when $d = d_0$, the enterprise income is the smallest.

Similarly, in order to study the relationship between enterprise E_2, income π_2, and carbon quota h consumption, the modeling process is similar to the above contents. Taking the second derivative of income π_2 and carbon quota h of consumption,h_0 can be obtained; making $\frac{\partial \pi_2}{\partial h} = 0$ and then judging the monotonicity of the function, result 5 can be obtained as follows.

Result 5: there is a negative correlation between enterprise E_2 income and consumed carbon quota, that is, the income decreases with the increase of unit carbon quota. Within a certain range of unit carbon quota h, enterprise E_2 income will increase with the increase of carbon quota consumed, but beyond a certain range, the enterprise income will decrease with the increase of carbon quota consumed. For the government, the carbon quota of E_2 per unit enterprise determined must be greater than h_0, so that enterprises can be urged to reduce energy consumption in traditional production and then transform to implement EPP.

2) For enterprise E_3

In this part, we analyze the electricity saved and the revenue from enterprise E_3 and discuss how the parameter changes with carbon quota and the value of the probability a of implementing EPP, so as to maximize the enterprise revenue. That is, to study the electricity saved by enterprise E_3 and analyze the variation trend between electricity saved and carbon quota h, revenue d per unit carbon quota, and probability λ of EPP implementation.

Firstly, in **Eq. 9**, the first derivative of electricity quantity Q_3 consumed by the enterprise with respect to carbon quota h and revenue d of the unit carbon quota can be obtained as follows:

$$\begin{cases} \frac{\partial Q_3}{\partial h} = \frac{12\lambda d - 6d}{8b} \\ \frac{\partial Q_3}{\partial d} = -\frac{12\lambda h - 6h}{8b} \end{cases}. \tag{17}$$

Then, result 6 can be obtained as follows. Result 6: in **Eq. 17**, h, d and b are constants greater than 0, and $0<\lambda<1$. When $0<\lambda<0.5$, $12\lambda d - 6d < 0$, and $12\lambda h - 6h < 0$, that is, $\frac{\partial Q_3}{\partial h} > 0$ and $\frac{\partial Q_3}{\partial d} > 0$, the electricity saved by enterprise E_3 decreases with the increase of the unit carbon quota h and unit carbon quota income d; when $0.5<\lambda<1$, $12\lambda d - 6d > 0$, and $12\lambda h - 6h > 0$, that is, $\frac{\partial Q_3}{\partial h} > 0$ and $\frac{\partial Q_3}{\partial d} > 0$, the electricity saved by enterprise E_3 increases with the increase of unit carbon quota d and unit carbon quota revenue d.

Secondly, we analyze the income in **Eq. 10** of enterprise E_3 and find that the factors affecting enterprise income are related to the development cost, the total carbon quota given by the government, the income of carbon quota per unit, and the carbon quota obtained (or consumed) from energy saving (consumption). The relationship between the enterprise income and unit carbon quota income is analyzed as follows. In **Eq. 10**, the first derivative of the enterprise income π_3 with respect to revenue d of the unit carbon quota can be obtained as follows:

$$\frac{\partial \pi_3}{\partial d} = \frac{12\lambda ah - 6ah + 72\lambda^2 h^2 d - 72\lambda h^2 d + 18h^2 d + 6hC_2 - 12\lambda hC_2}{16b} + \frac{H}{h}. \tag{18}$$

We cannot determine whether $\frac{\partial \pi_3}{\partial d}$ is greater than 0 in **Eq. 18**. Therefore, the second derivative of d can be obtained as follows:

$$\frac{\partial^2 \pi_3}{\partial d^2} = \frac{72\lambda^2 h^2 - 72\lambda h^2 + 18h^2}{16b}. \tag{19}$$

In **Eq. 19**, h and b are constants greater than 0, and $0<\lambda<1$. So, $\frac{\partial^2 \pi_3}{\partial d^2}$ is greater than 0 is equal to $72\lambda^2 h^2 - 72\lambda h^2 + 18h^2$ is greater than 0. Because h^2 must be greater than 0, we just need to determine whether $72\lambda^2 h^2 - 72\lambda h^2 + 18$ is greater than 0. Let $72\lambda^2 h^2 - 72\lambda h^2 + 18 = 0$, we get $\lambda = 12\lambda = 12$; in other words, this quadratic opens up and only intersects the X-axis at one point. Therefore, it can be concluded that $\frac{\partial^2 \pi_3}{\partial d^2} \geq 0$ is always true, that is, the first derivative function is monotonically increasing function. Set the first derivative function equal to 0, and we can get $d_0^{'}$:

$$d_0^{'} = -\frac{8Hb}{36\lambda^2 h^3 - 36\lambda h^3 + 9h^3} - \frac{2a\lambda - a + C_2 - 2\lambda C_2}{12\lambda^2 h - 12\lambda h + 3h}. \tag{20}$$

Then, result 7 can be obtained as follows. Result 7: when $d < d_0^{'}$, $\frac{\partial \pi_3}{\partial d} < 0$, and the second derivative function $\frac{\partial^2 \pi_3}{\partial d^2}$ is a monotonically increasing function, so the original function π_3 is a monotonically decreasing function. That is, enterprise E_3 income π_3 is negatively correlated with unit carbon quota income d, that is, the enterprise income decreases with the increase of unit carbon quota income. When $d > d_0^{'}$, $\frac{\partial \pi_3}{\partial d} > 0$, and the second derivative function $\frac{\partial^2 \pi_3}{\partial d^2}$ is a monotonically increasing function, so the original function π_3 is a monotonically increasing function. In other words, enterprise E_3 income $\pi_3$increases with the increase of unit carbon quota income d. With the increase of the unit carbon quota income, enterprise E_3 income shows a trend of decreasing first and then increasing, and when unit carbon quota income $d = d_0^{'}$, the enterprise income is the lowest and then increases with the increase of the unit carbon quota. When $d < d_0^{'}$, the enterprise income decreases with the increase of the unit carbon quota. The main reason is that enterprises are unwilling to implement EPP in the early stage; the higher the income of unit carbon quota increases, the higher the government punishment the enterprises will accept. When $d > d_0^{'}$, the enterprise begins to implement EPP, and the increase of unit carbon quota income will greatly increase the income brought by power saving, so the enterprise income will gradually increase.

Similarly, the change trend between enterprise benefit and unit carbon quota h is as same as the relationship between enterprise income and unit carbon quota income d, and we would not analyze separately. In other words, enterprise E_3 income will decrease first and then increase with the increase of the unit carbon quota, and when $h = h_0$, the income reaches the minimum value.

Next, we analyze the relationship between the corporate income and total carbon quota. In **Eq. 10**, the first derivative of enterprise E_3 incomeπ_3 with respect to the total carbon quota H can be obtained as follows:

$$\frac{\partial \pi_3}{\partial H} = \frac{d}{h}. \tag{21}$$

Then, result 8 can be obtained as follows. Result 8: in **Eq. 21**, d and h are constants greater than 0, so $\frac{\partial \pi_3}{\partial H} > 0$. And, the original function is a monotonically increasing function. In other words, there is a positive correlation between enterprise E_3 income π_3 and total carbon quota H, and enterprise E_3 income increases with the increase of the total carbon quota given by the government.

Then, the first derivative of enterprise E_3 income π_3 with respect to the probability λ of EPP implementation can be obtained as follows:

$$\frac{\partial \pi_3}{\partial \lambda} = \frac{3hd(a + 6\lambda hd) - 3hd - C_2}{4b}. \tag{22}$$

In **Eq. 22**, we cannot determine whether $\frac{\partial \pi_3}{\partial \lambda}$ is greater than 0, so the second derivative of λ can be obtained as follows:

TABLE 3 | The value setting of some parameters in simulation.

a	b	C_1	C_2	H	h	d
10	2	3	2	5	0.03	0.2

$$\frac{\partial^2 \pi_3}{\partial \lambda^2} = \frac{27h^2 d^2}{2b}. \tag{23}$$

In **Eq. 23**, h, d, and b are constants greater than 0, so $\frac{\partial^2 \pi_3}{\partial \lambda^2} > 0$. The first derivative $\frac{\partial \pi_3}{\partial \lambda}$ is a monotonically increasing function. Let $\frac{\partial \pi_3}{\partial \lambda} = 0$, we get λ_0:

$$\lambda_0 = \frac{C_2 + 3hd - a}{6hd}. \tag{25}$$

Then, result 9 can be obtained as follows. Result 9: when $\lambda < \lambda_0$, $\frac{\partial \pi_3}{\partial \lambda} < 0$, and the first derivative function is monotonically increasing function. Therefore, the function π_3 is a monotonically decreasing function, and enterprise E_3 earnings π_3 decreases with the increase of λ. When $\lambda > \lambda_0$, the first derivative is a monotonically increasing function, and $\frac{\partial \pi_3}{\partial \lambda} > 0$, the function$\pi_3$is a monotonically increasing function, that is, enterprise E_3 earnings $\pi_3$increases with the increase of λ. In the change process of probability λ of implementing EPP, the enterprise income first gradually decreases and then increases. The previous enterprise income will decrease with the increase of λ, The main reason lies in the large investment in the research and development of EPP technology and equipment in the early stage. With the increase of λ, EPP is gradually recognized and promoted by the government and enterprises due to its advantages of zero emission and energy saving. After a period of promotion and gradual improvement of government policies, the benefits brought to enterprises by the implementation of EPP are gradually reflected. Therefore, when$\lambda > \lambda_0$, the enterprise income will increase with the increase of λ.For enterprise E_3, λ should not be set asλ_0 because the enterprise income is the lowest at this time; if the enterprise prefers not to implement EPP, the ratio λ should be set below λ_0; if the enterprise is inclined to implement EPP, the production ratio λ should be set above λ_0 $(0 < \lambda_0 < 1)$, and the higher the proportion is set, the greater the profit of the enterprise will be.

Verification of Results

The previous nine results are mainly obtained through mathematical model construction and derivation. In order to verify the validity of the results, this part uses Maple, simulation software, to verify the validity of the results. Maple software is one of the most general mathematical and engineering computing software in the world and is widely used in the field of mathematics and science, among which the application of Maple software to test the correctness of decision results is one of its main applications. Main steps of Maple simulation include four steps, namely, assignment of variables, establishment of simulation model, analysis model, and conclusion. Among them, numerical setting plays a crucial role in the establishment of the simulation model, which determines whether the simulation model can correctly verify the decision results.

According to the above parameter setting and requirements and referring to literature studies (Du et al., 2015; Luo et al., 2016; Huang et al., 2018), we set the values of each parameter as shown in **Table 3**.

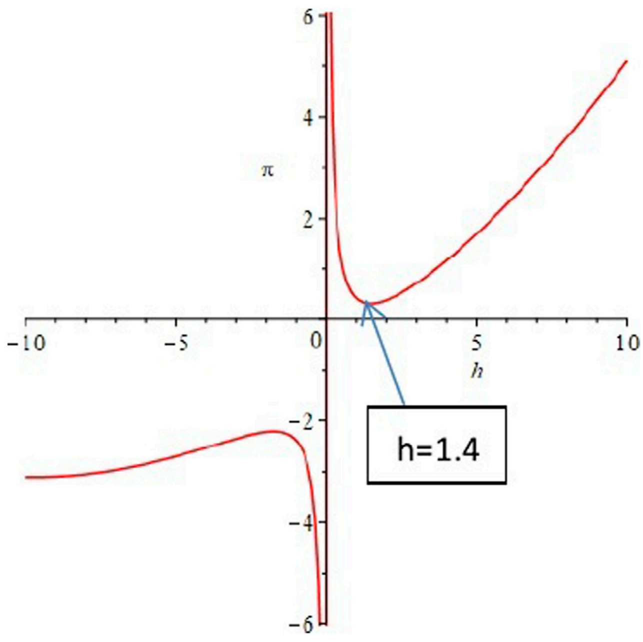

FIGURE 2 | The relationship between enterprise E_1 income π_1 and h.

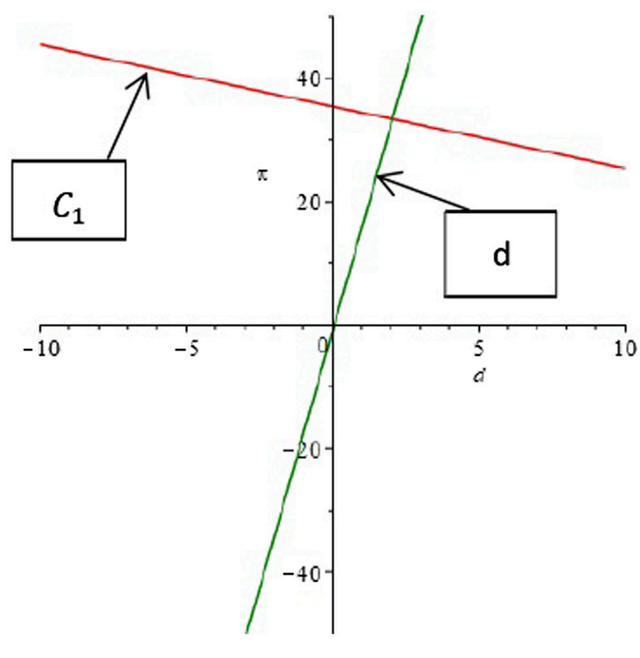

FIGURE 3 | The relationship between enterprise E_1 income π_1 with $C_1$and d.

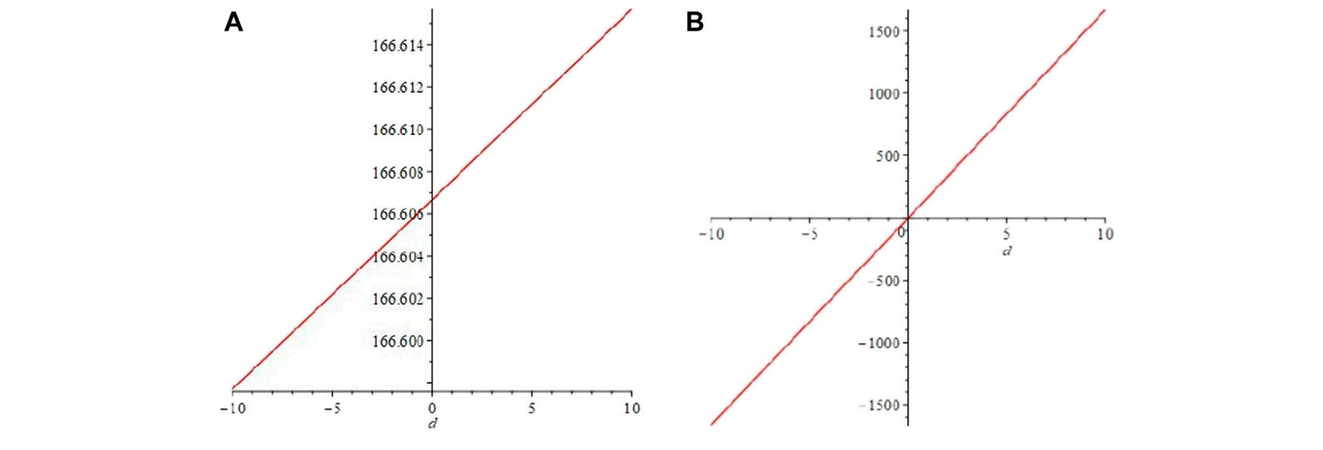

FIGURE 4 | (A) The function image of the derivative of π_2 with respect to d. **(B)** The relationship between π_2 and d.

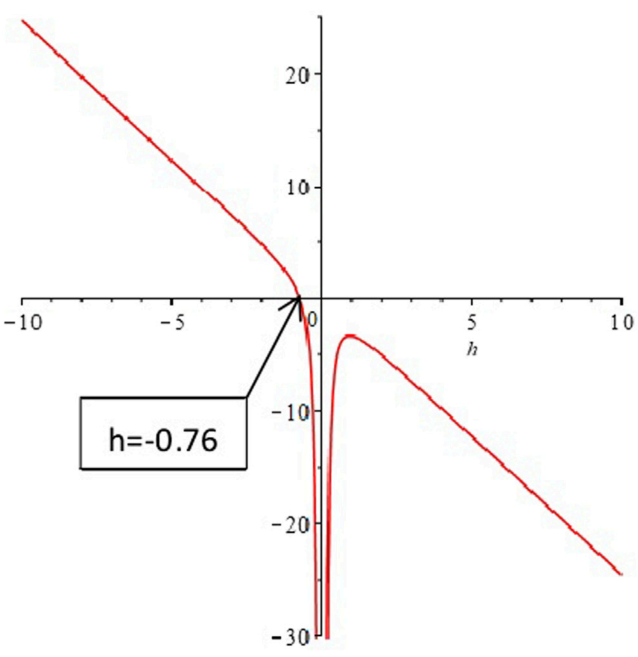

FIGURE 5 | The function image of the derivative of π_2 with respect to h.

Now, Maple software was used to verify nine results of the changes of industry income, output, and other variables of three kinds of enterprises, respectively, and the verification processes are as follows.

1) For enterprises E_1

Verification of result 1: the relationship image between enterprise E_1 income π_1 and unit carbon quota h is plotted according to known conditions, as shown in **Figure 2**. It can be seen that when $0 < h < 1.4$, the enterprise income decreases with the increase of the unit carbon quota. When $h > 1.4$, the enterprise income increases with the increase of the unit carbon quota, and the increasing amplitude is gradually expanding. When $h = 1.4$, the enterprise income reaches the minimum, which is consistent with result 2.

Verification of results 2 and 3: similarly, we set $\lambda = 0.5$ and plot the relationship image between enterprise E_1 income π_1, R&D cost C_1, and unit carbon quota income d, as shown in **Figure 3**. It can be seen that π_1 decreases with the increase of R&D cost and increases with the increase of the unit carbon quota income. In other words, the larger the income per unit carbon quota is, the higher the income from implementing EPP to save electricity will be, and the more enterprises tend to implement EPP, the more conducive to the development of EPP, which is consistent with result 3 and result 4. It should be noted that the above situation does not hold indefinitely because in the actual cases, the enterprise income will increase with the increase of carbon quota income over a period of time. However, after a certain range, under the influence of some factors such as policies, market saturation, and diminishing marginal return, the enterprise income will not continue to increase with the increase of carbon quota income.

2) For enterprise E_2

Verification of result 4: let $\lambda = 0.5$ and draw the graph of the first-order derivative function of enterprise E_2 income π_2 with respect to unit carbon quota income d, as shown in **Figure 4A**. According to the image, when $d > 0$, only the value of the first derivative function of enterprise E_2 income π_2 with respect to unit carbon quota income d is constant when the value is greater than 0. In other words, the enterprise income is positively correlated with the unit carbon quota income, which increases with the increase of the unit carbon quota income. When the first derivative is equal to $d = d_0 < 0$, in the actual operation of an enterprise, the income per unit carbon quota will not be negative. So, the function of $d_0 < 0$ is not analyzed. Plot the relationship image between enterprise E_2 income π_2 and unit carbon quota income d, as shown in **Figure 4B**. The analysis based on **Figure 5A** shows that when $d_0 > 0$, enterprise the income

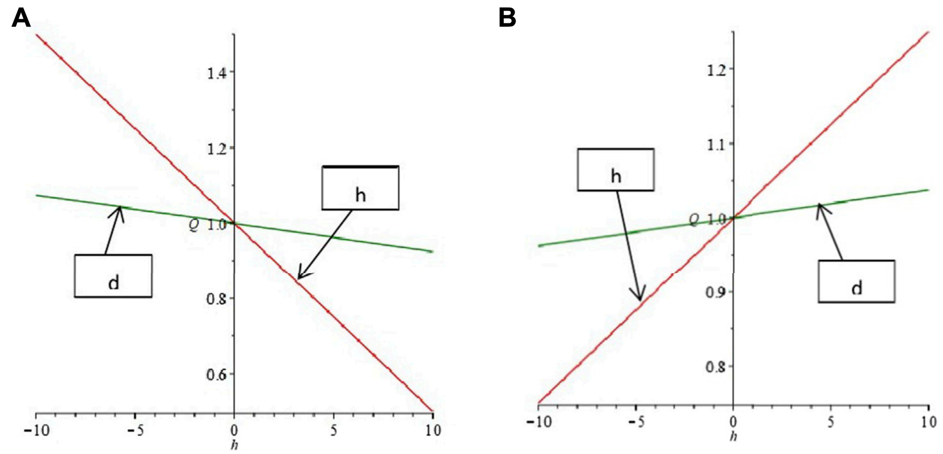

FIGURE 6 | (A) The relationship between electricity Q_3saving in enterprise E_3 with h and $d\,(0 < \lambda < 0.5)$. **(B)** The relationship between electricity Q_3saving in enterprise E_3 with h and $d\,(0.5 < \lambda < 1)$.

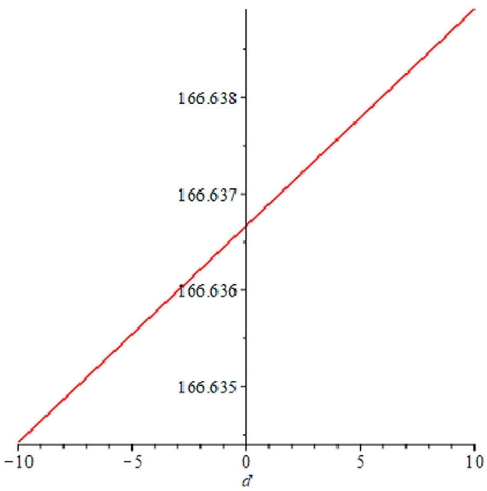

FIGURE 7 | The function image of the derivative of π_3 with respect to d.

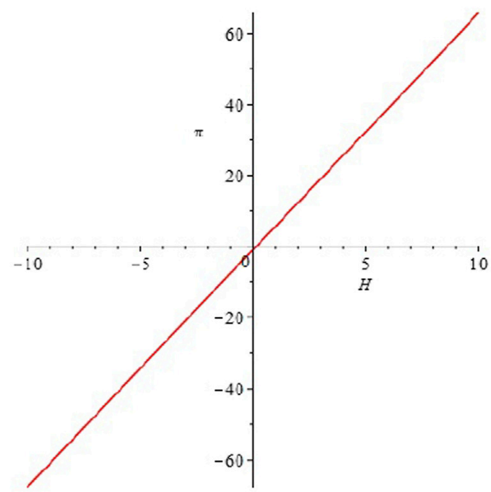

FIGURE 8 | The relationship between π_3 and total carbon quota H.

increases with the increase of unit carbon quota, which is consistent with result 4.

Verification of result 5: let $\lambda = 0.5$ and draw the graph of the first-order derivative function of enterprise E_2 income π_2 with respect to unit carbon quota h, as shown in **Figure 5**. In practice, it is impossible to take a negative value of carbon quota h, so the function image is taken as the function image of $h > 0$. According to the image, when $h < -0.76$, $\frac{\partial \pi_2}{\partial h} > 0$, that is, enterprise E_2 income π_2 increases with the increase of carbon quota h consumed; when $h > -0.76$, $\frac{\partial \pi_2}{\partial h} < 0$, that is, enterprise E_2 income$\pi_2$decreases with the increase of carbon quota h consumed, which is consistent with result 5.

3) For enterprise E_3

Verification of result 6: we analyze the relationship between electric quantity Q_3 saved by enterprise E_3 with unit carbon quota d and unit carbon quota income h. In this model, there are two stages according to whether λ is greater than 0.5. When $0<\lambda<0.5$, set $\lambda = \frac{1}{6}$, and draw the changing trend image of the relationship between Q_3, d, and h. As shown in **Figure 6A**, Q_3 decreases with the increase of d and h. However, since the slope of curve h is significantly higher than that of curve d, the degree of influence of h is higher than that of d. When the two factors influence the output of an enterprise at the same time, the range of change of variable h should be given the priority. When $0.5 < \lambda < 1$, set $\lambda = \frac{2}{3}$, and draw the changing trend image of the relationship between enterprise electric saved quantity Q_3, d, and h, as shown in **Figure 6B**. Q_3 increases with the increase of d and h, similarly, h has a higher influence on Q_3 than d. The result of this part is consistent with result 6, which verifies the correctness of result 6.

Verification of result 7: study the relationship between enterprise E_3 income π_3 and unit carbon quota revenue d, set

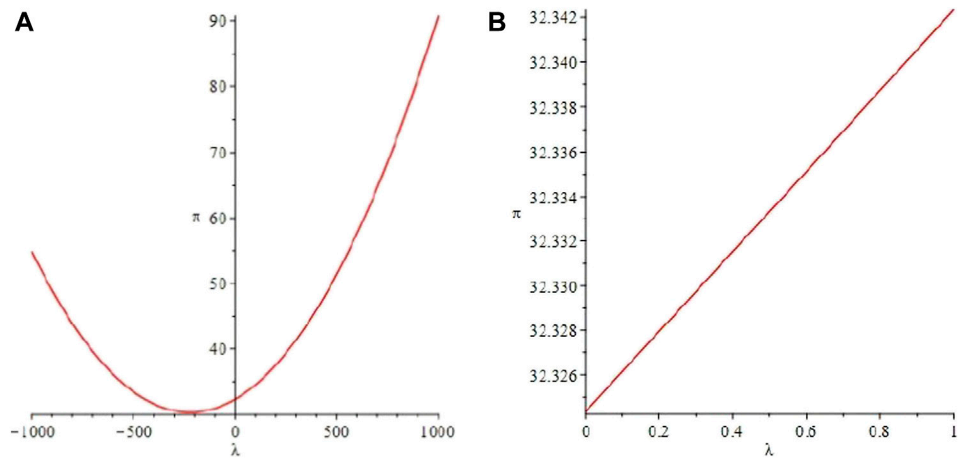

FIGURE 9 | (A) The relationship between enterprise E_3 earnings π_3 and $\lambda (-1000 \le \lambda \le 1000)$. **(B)** The relationship between enterprise E_3 earnings π_3 and $\lambda (0 \le \lambda \le 1)$.

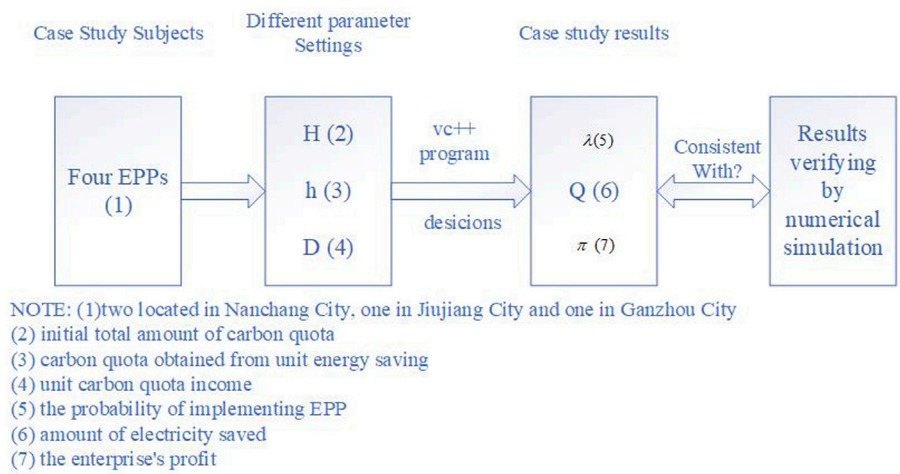

FIGURE 10 | The block diagram of the case study.

$\lambda = \frac{1}{6}$, and draw the first-order derivative function image of π_3 with respect to d, as shown in **Figure 7**. According to the figure, when d is small enough, the first-order derivative function will be less than 0. At this time, the enterprise income will decrease with the increase of unit carbon quota. Subsequently, with the gradual increase of d, the enterprise income will increase with the increase of the unit carbon quota income, which is consistent with result 7.

Verification result 8: now, study the relationship between enterprise E_3 income π_3 and total carbon quota H, set $\lambda = 0.5$, and draw the changing trend diagram between π_3 and total carbon quota according to known data, as shown in **Figure 8**. According to **Figure 8**, the enterprise income is positively correlated with the total carbon quota, that is, the enterprise income continues to increase with the increase of the total carbon quota, which is consistent with result 8. In addition, for every unit of change in the total carbon quota obtained from the image, the enterprise income will change by $\frac{20}{3}$ units, that is, the total carbon quota has a great impact on the enterprise income, which is a key factor that enterprises must consider in production.

Verification of result 9: finally, we study the relationship between enterprise E_3 income π_3 and total carbon quota H, set $\lambda = 0.5$, and draw the changing trend diagram between π_3 and willingness (probability) λ to implement EPP according to known data, as shown in **Figure 9A**. According to **Figure 10A**, the enterprise income first decreases and then increases with the gradual increase of λ. However, the effective value range of λ in this paper is $0 \le \lambda \le 1$. Therefore, we select part of the function images in **Figure 10A** to obtain **Figure 9B**, and when $0 \le \lambda \le 1$, the enterprise income π_3 continues to increase with the increase of λ. It can be seen from the figure that when $\lambda = 0$ and the enterprise does not implement EPP, the enterprise has a certain income, and with the gradual increase of λ, the enterprise income

TABLE 4 | The survey object descriptions and fixed parameter setting.

Respondents	Description	Remark
Four representative EPP projects in Jiangxi	Two located in Nanchang City: one in Jiujiang City and one in Ganzhou City	
Basic information data	Unit	Value
Average annual power saving (from 2015–2019)	kWh	6.325*10[6]
[1]Sales price of power saved by EPP	Dollar/kWh	0.042
The market power price	Dollar/kWh	0.057
[2]Average annual carbon emissions	Ton	2,500
[3]Average annual cost of EPP implementation	Dollar	180,000

TABLE 5 | The probability λ of EPP implementation and its power saving Q and revenue π_3 under different H, h, and d.

H (ton)	*h* (kg/kWh)	*d* (dollar/t)	λ	Q (10^3 kWh)	π_3(10^3USD)
2,500	0.11	15	0.6839	688	171.71
2,500	0.11	13	0.5050	634	156.20
2,500	0.11	11	0.4632	609	132.61
2,500	0.15	13	0.712	763	189.63
2,500	0.11	13	0.5050	634	156.20
2,500	0.07	13	0.4154	482	107.45
1,500	0.11	13	0.7021	742	175.42
2,500	0.11	13	0.5050	634	156.20
3,500	0.11	13	0.3870	394	94.31
2,500	0.15	11	0.6132	658	164.89
2,500	0.11	13	0.5050	634	156.20
2,500	0.07	15	0.4732	617	143.57

continues to increase. When $\lambda = 1$, enterprise income reaches the maximum, which is consistent with result 9.

CASE STUDY

To prove the practicability of the model and the results, this part will use a case study to analyze the influence on the initial total amount of carbon quota H, carbon quota h obtained from unit energy saving, and unit carbon quota income d to the probabilityλ the enterprise implementing EPP. The authors and their research team members conducted a 2-month field survey at four EPP projects in Jiangxi Province in July and August 2019, to collect two kinds of original data as follows, aiming at providing basic data for VC++ program operation:

1) The basic information and data of the EPP project, such as project name, investment amount, annual power saving, annual carbon emission, equipment life, and other information come from field investigation of EPP project in Jiangxi province.
2) The common parameters, such as sales price of power saved by EPP, cost of EPP implementation, and other data are referred to recent data released by authorities and Energy Statistics Yearbook.

Table 4 shows the survey object descriptions and fixed parameter setting.

Note: [1]Sales price of power saved by EPP fluctuates with the market, but this part does not take electricity price as the focus problem. In order to simplify the problem, we take the average selling electricity price during the observation period as the final value. [3]For the cost of EPP implementation, which is also variable, we take the average value.

[2]The implementation of EPP has zero carbon emission, and enterprises only have carbon emissions when they do not implement EPP. Therefore, the carbon emission of the investigated enterprises is much lower than that of ordinary small or medium-sized manufacturing enterprises.

Next, we will adjust the initial total amount of carbon quota H, carbon quota h obtained from unit energy saving, and unit carbon quota income d, which will influence the decision of enterprises to implement EPP, and finally calculate the power saving and income of enterprises under the specified decision. Because the data in this study are complex and there are multifarious index operations, the VC++ (version 6.0) is used to construct a program to achieve the solution of this case study. The main code of VC++ program can refer to the code in the attachment of a previous article by Zhu et al., 2019. The block diagram of this case study can be shown in **Figure 10**.

The results are shown in **Table 5**.

According to **Table 5**, lines 1 through line 3 show that unit carbon quota income d has a positive effect on power saving Q and revenue π_3. With the increase of d, enterprises are more inclined to implement EPP. Line 4 through line 6 show that carbon quota h obtained from unit energy saving has a positive effect on power saving Q and revenue π_3. With the increase of h, enterprises are more inclined to implement EPP. Line 7 through line 9 show that initial total amount of carbon quota H has a positive effect on power saving Q and revenue π_3. With the increase of H, enterprises are more inclined to implement EPP. Line 10 through line 12 show that h has a greater influence than d, and the change of h plays a more important role in the decision of enterprises to implement EPP.

The results in **Table 5** are consistent with those obtained in *Relationship Analysis of Main Parameters*, that is, we prove the above results from the perspective of empirical analysis.

DISCUSSION

In this paper, three important contents are put forward:

Firstly, we build the profit functions of three types of enterprises, analyze the relationships of main parameters, and get nine results.

Secondly, we use Maple, the simulation software, to verify the validity of the results by drawing images of parameters. All the above nine results passed the simulation test.

Finally, we carry out an empirical analysis of a Chinese case and verify the practicability of the profit functions and the results of parameter relationship analysis through the actual survey data, which has practical guiding significance.

Compared to Zhu et al.'s, 2018, study about the general study of low-carbon investment, low-carbon investment is translated into implementation of EPP, and specific research conclusions and specific recommendations are given. Compared to literature studies by Li et al., 2017 and Sun et al., 2020, about the income study of carbon emission, the carbon emission energy savings are considered as one of the benefits of implementing EPP. Compared to (Arai et al.'s, 2014, study, correlation analysis of parameters is constructed based on three different types of enterprises and under different carbon quota constraints. Compared to literature studies by Zhu et al., 2018 and Dou et al., 2020, a simulation by Maple software and a case study in China are put forward to verify the research results.

Above all, this paper has three innovation points or improvements:

First, most research objects in literature studies about general low-carbon investment only have the function of reducing carbon emission or pollutant emission, while our research object-EPP in this paper is a special low-carbon behavior, which can reduce power consumption and carbon emission at the same time.

Second, the correlation analysis of parameters we constructed takes into account not only three types of different enterprises but also different carbon quota constraints.

Finally, through simulation and empirical analysis, we double test the profit function model and relevant results to verify their scientific effectiveness.

CONCLUSION AND SUGGESTION

Conclusion

Firstly, the paper analyzed the factors affecting the earnings and output of EPP enterprises, non-EPP enterprises, and selective EPP enterprises by establishing the profit functions, and then, we studied how the income and output of three kinds of enterprises change with the carbon quota. Thus, production decisions of different types of enterprises under different carbon quotas are obtained, and the results through Maple simulation software and empirical analysis are verified, in order to provide theoretical reference for different types of enterprises to make production decisions under different carbon quotas.

Suggestions

1) As the carbon quota given by the government and the carbon quota obtained by implementing EPP increase, the enterprise will gain more disposable carbon quotas, so enterprises can sell excess carbon quotas to reap the benefits and their profits will soar. At this time, enterprises should increase the investment in EPP research and input to acquisition, continuously improve the ability of EPP core technology, so as to expand their market share, and obtain the long-term development of the enterprise.
2) The effect of carbon quota obtained by implementing EPP on the output of enterprises is much greater than that of carbon quota income per unit. When both factors have an impact on the output of an enterprise, the enterprise should give priority to the carbon quota obtained by implementing EPP, so as to ensure the maximum income of the enterprise.
3) According to the change of carbon quota and unit carbon quota income, enterprises should adjust the intensity of EPP implementation to obtain higher income. Enterprise income is positively correlated with total carbon quota, carbon quota income per unit, and the intensity (probability) of EPP implementation. Therefore, when the total carbon quota and revenue per unit of carbon quota given by the government increase, enterprises should enhance the implementation of EPP, so that enterprises can obtain higher revenue.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

YZ constructed the theoretical framework of the manuscript. YJ collected the data and made statistical analysis.

FUNDING

This work was supported by the Natural Science Foundation of China (NSFC; grant number: 71964022, grant number: 72164026), Educational Science Project of Jiangxi Province (grant number: 18YB012), and Jiangxi Culture, Art and Science Planning Project (grant number: YG2018037).

REFERENCES

Arai, R., Yamamoto, K., Nishio, T., and Morikura, M. (2014). Differential Game-Theoretic Analysis on Information Availability in Decentralized Demand-Side Energy Management Systems. *IEICE Trans. Commun.* E97.B (9), 1817–1825. doi:10.1587/transcom.e97.b.1817

Çakmak, R., and Altaş, İ. H. (2020). A Novel Billing Approach for Fair and Effective Demand Side Management: Appliance Level Billing (AppLeBill). *Int. J. Electr. Power Energ. Syst.* 121, 106062. doi:10.1016/j.ijepes.2020.106062

Castro, M. d. F., Colclough, S., Machado, B., Andrade, J., and Bragança, L. (2020). European Legislation and Incentives Programmes for Demand Side Management. *Solar Energy* 200, 114–124. doi:10.1016/j.solener.2019.12.004

Castro, M. d. F., Colclough, S., Machado, B., Andrade, J., and Bragança, L. (2020). European Legislation and Incentives Programmes for Demand Side Management. *Solar Energy* 200, 114–124. doi:10.1016/j.solener.2019.12.004
Chakraborty, N., Mondal, A., and Mondal, S. (2020). Efficient Load Control Based Demand Side Management Schemes towards a Smart Energy Grid System. *Sustain. Cities Soc.* 59, 102175. doi:10.1016/j.scs.2020.102175
Chamandoust, H., Bahramara, S., and Derakhshan, G. (2020). Day-ahead Scheduling Problem of Smart Micro-grid with High Penetration of Wind Energy and Demand Side Management Strategies. *Sustainable Energ. Tech. Assessments* 40, 100747. doi:10.1016/j.seta.2020.100747
Chang, L., Hao, X., Song, M., Wu, J., Feng, Y., Qiao, Y., et al. (2020). Carbon Emission Performance and Quota Allocation in the Bohai Rim Economic Circle. *J. Clean. Prod.* 258, 120722. doi:10.1016/j.jclepro.2020.120722
Chen, H., Li, Y., Louie, R. H. Y., and Vucetic, B. (2014). Autonomous Demand Side Management Based on Energy Consumption Scheduling and Instantaneous Load Billing: an Aggregative Game Approach. *IEEE Trans. Smart Grid* 5 (4), 1744–1754. doi:10.1109/tsg.2014.2311122
Chen, W. (2003). Carbon Quota price and CDM Potentials after Marrakesh. *Energy Policy* 31 (8), 709–719. doi:10.1016/s0301-4215(02)00122-2
Dales, J. H. (1968). *Pollution, Property and Prices: An Essay in Policy-Making and Economics*. Toronto: University of Toronto Press.
Dou, X. (2015). The Essence, Feature and Role of Low Carbon Economy. *Environ. Dev. Sustain.* 17 (1), 123–136. doi:10.1007/s10668-014-9542-9
Dou, X., Wang, J., Wang, X. Y., and Wu, L. (2020). Analysis of User Demand Side Response Behavior of Regional Integrated Power and Gas Energy Systems Based on Evolutionary Game. *Proc. Chin. Soc. Electr. Eng.* 40 (12), 3775–3785. doi:10.13334/j.0258-8013.pcsee.190581
Du, S., Hu, L., and Wang, L. (2017). Low-carbon Supply Policies and Supply Chain Performance with Carbon Concerned Demand. *Ann. Oper. Res.* 255 (1-2), 569–590. doi:10.1007/s10479-015-1988-0
Du, S., Zhu, J., Jiao, H., and Ye, W. (2015). Game-theoretical Analysis for Supply Chain with Consumer Preference to Low Carbon. *Int. J. Prod. Res.* 53 (12), 3753–3768. doi:10.1080/00207543.2014.988888
Du, S., Zhu, L., Liang, L., and Ma, F. (2013). Emission-dependent Supply Chain and Environment-Policy-Making in the 'cap-And-Trade' System. *Energy Policy* 57, 61–67. doi:10.1016/j.enpol.2012.09.042
Energy Research Institute of State Grid of China (2010). *Study on Ways and Means to the Construction of EPP*. Beijing, China: China Electric Power Press. (In Chinese).
Haydt, G., Leal, V., and Dias, L. (2014). A Multi-Objective Approach for Developing National Energy Efficiency Plans. *Energy Policy* 67, 16–27. doi:10.1016/j.enpol.2013.06.133
Huang, Z., Yu, H., Chu, X., and Peng, Z. (2018). A Novel Optimization Model Based on Game Tree for Multi-Energy Conversion Systems. *Energy* 150, 109–121. doi:10.1016/j.energy.2018.02.091
Kalair, A. R., Abas, N., Hasan, Q. U., Seyedmahmoudian, M., and Khan, N. (2020). Demand Side Management in Hybrid Rooftop Photovoltaic Integrated Smart Nano Grid. *J. Clean. Prod.* 258, 120747. doi:10.1016/j.jclepro.2020.120747
Li, H., Wang, C., Xu, L., and Ou, W. (2017). Pricing, Carbon Emission Reduction, Collection Decision, and Coordination in a Low-Carbon Closed-Loop Supply Chain. *J. Renew. Sustain. Energ.* 9 (6), 065907. doi:10.1063/1.4991668
Li, M.-J., Song, C.-X., and Tao, W.-Q. (2016). A Hybrid Model for Explaining the Short-Term Dynamics of Energy Efficiency of China's thermal Power Plants. *Appl. Energ.* 169, 738–747. doi:10.1016/j.apenergy.2016.02.082
Liu, X., Gao, B., Wu, C., and Tang, Y. (2018). Demand-Side Management with Household Plug-In Electric Vehicles: a Bayesian Game-Theoretic Approach. *IEEE Syst. J.* 12 (3), 2894–2904. doi:10.1109/jsyst.2017.2741719
Luo, Z., Chen, X., and Wang, X. (2016). The Role of Co-opetition in Low Carbon Manufacturing. *Eur. J. Oper. Res.* 253 (2), 392–403. doi:10.1016/j.ejor.2016.02.030
Mahmoudi, R., Emrouznejad, A., Khosroshahi, H., Khashei, M., and Rajabi, P. (2019). Performance Evaluation of thermal Power Plants Considering CO2 Emission: A Multistage PCA, Clustering, Game Theory and Data Envelopment Analysis. *J. Clean. Prod.* 223, 641–650. doi:10.1016/j.jclepro.2019.03.047
Mendes, D. L. S., Rabelo, R. A. L., Veloso, A. F. S., Rodrigues, J. J. P. C., and dos Reis Junior, J. V. (2020). An Adaptive Data Compression Mechanism for Smart Meters Considering a Demand Side Management Scenario. *J. Clean. Prod.* 255, 120190. doi:10.1016/j.jclepro.2020.120190
Rai, V., and Beck, A. L. (2017). Play and Learn: Serious Games in Breaking Informational Barriers in Residential Solar Energy Adoption in the United States. *Energ. Res. Soc. Sci.* 27, 70–77. doi:10.1016/j.erss.2017.03.001
Srikanth Reddy, K., Lokesh Kumar Panwar, L. K., Panigrahi, B. K., Rajesh Kumar, R., and Xu, Y. (2020). A Dual Objective Approach for Aggregator Managed Demand Side Management (DSM) in Cloud Based Cyber Physical Smart Distribution System. *Future Generation Comput. Syst.* 105, 843–854. doi:10.1016/j.future.2017.08.019
Sun, L., Cao, X., Alharthi, M., Zhang, J., Taghizadeh-Hesary, F., and Mohsin, M. (2020). Carbon Emission Transfer Strategies in Supply Chain with Lag Time of Emission Reduction Technologies and Low-Carbon Preference of Consumers. *J. Clean. Prod.* 264, 121664. doi:10.1016/j.jclepro.2020.121664
Venizelou, V., Makrides, G., Efthymiou, V., and Georghiou, G. E. (2020). Methodology for Deploying Cost-Optimum price-based Demand Side Management for Residential Prosumers. *Renew. Energ.* 153, 228–240. doi:10.1016/j.renene.2020.02.025
Wang, J.-M., Ge, X., Zhang, L., and Zhang, H. (2016). Management Index Systems and Energy Efficiency Diagnosis Model for Power Plant: Cases in China. *Math. Probl. Eng.* 2016, 1–13. doi:10.1155/2016/8159871
Wang, J. M., and Zhu, Y. P. (2014). Cost-benefit Analysis of DSM Energy-Efficiency Project in Low-Carbon Vision: a Case in China. Energy Education Science and Technology Part A. *Energ. Sci. Res.* 32 (1), 645–658. doi:10.1016/j.enbuild.2014.07.008
Wang, J., Zhu, Y., and Li, Y. (2015). EPP Energy Efficiency Calculation and Influencing Factor Analysis: Cases in China. *Math. Probl. Eng.* 2015, 1–8. doi:10.1155/2015/986562
Zhang, Y.-J., Wang, A.-D., and Da, Y.-B. (2014). Regional Allocation of Carbon Emission Quotas in China: Evidence from the Shapley Value Method. *Energy Policy* 74, 454–464. doi:10.1016/j.enpol.2014.08.006
Zhu, G., Pan, G., and Zhang, W. (2018). Evolutionary Game Theoretic Analysis of Low Carbon Investment in Supply Chains under Governmental Subsidies. *Ijerph* 15 (11), 2465. doi:10.3390/ijerph15112465
Zhu, Y., Hu, Y., and Zhang, F. (2017). Progressive IRP Models for Power Resources Including EPP. *Math. Probl. Eng.* 2017, 1–7. doi:10.1155/2017/2520346
Zhu, Y. P., Feng, W., and Fan, L. Z. (2019). An Evolutionary Game Study on Implementation of Energy Efficiency Power Plants between Government and enterprise Considering Carbon Emission Right Trading. *Appl. Ecol. Env. Res.* 17 (1), 699–722. doi:10.15666/aeer/1701_699722

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.