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Strategies of Two-Level Green Technology Investments for Coal Supply Chain under Different Dominant Modes

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Abstract: We consider a coal supply chain with a coal enterprise and a manufacturer, where the coal enterprise invests in clean coal technology, and the manufacturer invests in carbon reduction technology. The government offers subsidies for the investments of clean coal technology and carbon reduction technology. We examine optimal clean coal technology inputs in a coal enterprise and carbon reduction quantity in a manufacturer under the modes of coal-enterprise-led and manufacturer-led, respectively, using a Stackelberg game theory model. We obtain some interesting results. First, carbon reduction by the manufacturer is restrained when clean coal technology cost and carbon reduction cost are increased, regardless of the dominant modes, and clean coal technology input decreases when clean coal technology cost increases; however, a high carbon reduction cost has no effect on clean coal technology input when the manufacturer leads. Second, the clean coal technology subsidy for coal enterprises promotes clean coal technology inputs and carbon reductions, and the carbon reduction subsidy encourages carbon reduction without supporting clean coal technology input. Last, carbon reduction performance is better achieved under the manufacturer-led model than the coal-enterprise-led model. However, it should be noticed that the capital resource only relies on government subsidy in this article. In the future, this study could be used for green supply chain investment, and could be helpful for sustainability development.

Keywords: coal supply chain; carbon reduction; cap-and-trade model; government subsidy; clean coal; dominate mode

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Citation: Da, B.; Liu, C.; Liu, N.; Fan, S. Strategies of Two-Level Green Technology Investments for Coal Supply Chain under Different Dominant Modes. *Sustainability* **2021**, *13*, 3643. https://doi.org/10.3390/su13073643

Academic Editor: Saeed Chehreh Chelgani

Received: 20 January 2021
Accepted: 20 March 2021
Published: 25 March 2021

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1. Introduction

Coal is mostly used as a thermal or other traditional energy source and creates noxious gas, resulting in high carbon emissions that are harmful to the environment. In particular, the downstream industry chain is mainly concentrated in the power plant and coal processing industries, and coal-fire energy power systems could also be optimized in a chain through unification [1,2]. Coal produces a large amount of carbon emissions through combustion and reprocessing, and incomplete gasification can produce H_2-rich gas and porous carbon. Gasification of coal to produce H_2, however, is more efficient with a catalyst. Waste-water could also be involved, as they always conduct a series of processes to tackle carbon emissions, for example the desulfurization and dehydration process. In the Netherlands, more than half of the total primary residential energy consumption comes from indirect energy use [3], and this causes further carbon emissions. Therefore, people are trying to find new clean energy sources to replace high-polluting sources. However, the green and environmental renewable energy movement does not have sufficient resources for sustainable living [4]; renewable energy is a new product compared to coal, is still being explored and discovered, and is not yet stable. Meanwhile, renewable energy is a synthetic product that requires the help of some episodic or less common natural phenomena, such

as wind power. Therefore, coal is still the major power resource for people's living. As a result, people attempt to realize sustainability development by resource or power need rearrangement and allocation [5], and given the wide spread of sustainability development, many countries have begun to execute a series of carbon reduction rules to control carbon emissions and reduce weather fluctuations and greenhouse gas emissions [6]. Carbon reduction has become a worldwide trend [7], even in the iron industry, who have put forward iron coke as a new type of technology to relieve the pressure of carbon reduction [8].

In China, more than two-thirds of available coal reserves are buried under arid grounds, making traditional wet processing infeasible in coal preparation [9], so the cost of carbon reduction has become expensive. To date, 53% of coal resources are still buried under 1000 m. Lignite coal and low metamorphic bituminous coal comprise 55% of these resources [10]. Based on the above information, high-quality coal resources decrease yearly. Subsequently, an innovation-driven development strategy must be conducted. People have started to study clean coal technology, which contributes to producing higher-efficiency and higher-quality energy resources [11]. Clean coal preparation is a new idea and involves a highly efficient manufacturing method based on the water cycle and comprehensive utilization of resources [12]. It usually refers to capturing carbon emissions from burning coal and storing them under the earth. If coal enterprises could produce clean coal to fulfil low-carbon development upstream, it would reduce the pressure on downstream manufacturing to reduce carbon emissions, as seen, for example, in the practice of molten salts [13] or the torrefaction of biomass as a renewable alternative fuel to coal during co-firing [14]. Clean coal technology is already being heavily promoted in the United States—the Obama Administration invested $84 million in clean coal technology. Petra Nova, the world's first post-combustion plant, is approximately 30 miles southwest of Houston and captures 1.6 million tons of carbon dioxide each year. Owing to coal supply chain characteristics, a downstream enterprise also needs to consider reducing carbon emissions during manufacturing.

However, under the normalcy of a new economy, coal enterprises are characterized by high-cost consumption and low profits [15], so the authorities need to implement barriers, including financial dilemmas [16]. Furthermore, external low-carbon environmental regulations stimulate environmental and financial performance [17], with government subsidies serving as policy incentives, and the Chinese government encourages R&D investment for sustainable development [18]. Thus, the government can subsidize clean coal technologies for upstream coal companies or carbon reduction technologies for downstream manufacturing companies in the low-carbon coal supply chain. In practice, the UK's electricity market reform already widely applies subsidy support [19].

In conclusion, clean coal is already the new trend in energy utilization, so people should try to study the different angles of it. Clean coal needs to be widely used and can be promoted with appropriate financial instruments. Therefore, the optimal profit and carbon reduction quantities need to be further observed, as well as the optimal management mode that has less carbon emission.

Figure 1 describes the logic map of the whole supply chain operation, and the capital transfer path between a coal enterprise, a manufacturer, and a carbon emissions trade market. The figure also introduces the product flow path. The coal enterprise produces coal for the manufacturer, for purposes such as generating electric power or firing for heat energy. Here, the coal enterprise and the manufacturer generate carbon emissions. However, the government institutes a limit on carbon emissions. A carbon emissions trading market can allow manufacturers to trade extra emissions rights at regulated prices. At the same time, the subsidy can influence the effect of reducing carbon emissions and the order quantity of clean coal.

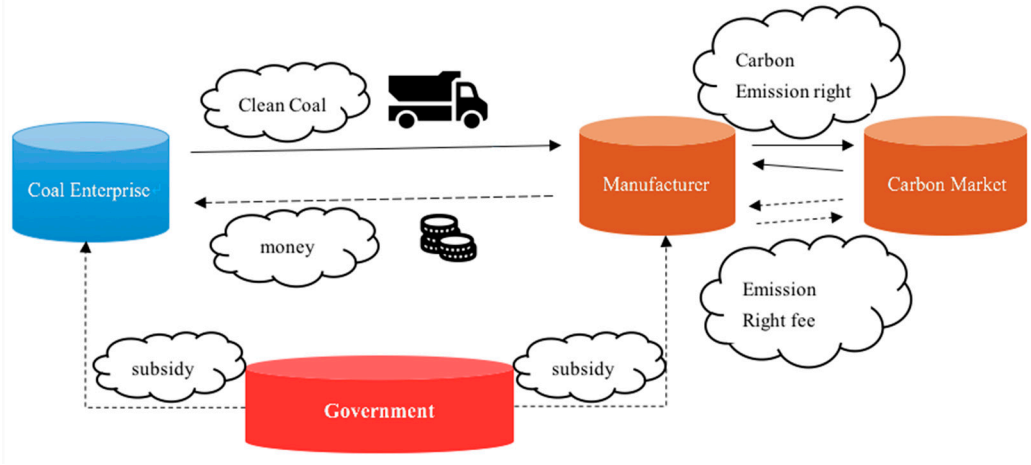


Figure 1. Capital and product flow path in the coal supply chain.

2. Literature Review

This work depends on a coal supply chain that follows a long process with excessive turning points. Thus, the system structure, interface relationship, and coordination system are complicated. With increased awareness in friendly environments, people attempt to reduce carbon emissions using technology under government subsidies. The carbon reduction process is no longer present in the normal two-echelon reductions. Clean coal production is conducted instead of carbon reduction in an upper stream enterprise under a different dominant mode. In conclusion, this paper designed three main background theories: an optimal strategy of a coal supply chain, low-carbon government subsidies, and supply chain finance.

2.1. Optimal Strategy of the Coal Supply Chain

Under the supply chain operation mechanism, the instruction and production materials in a coal enterprise comprise low technical skills, high cash flow requirements, short production periods, and ease of purchase, safety, and availability [20,21]. A coal supply chain belongs to a traditional energy resource chain, and such enterprises have improved the survival environment of the manufacturing industry and increased the efficiency of integrated supply chains [22]. In addition to traditional power, optimal strategies for renewable energy supply chains should also be studied, but greater uncertainty exists in introducing newly influencing parameters compared to the traditional strategy [23]. For example, coal-electric factories are popular in traditional energy supply chains; the model of cooperative interest distribution is calculated based on the profit distribution factor, or the green debit rate influence on carbon reduction is studied [24,25]. In addition, the supply chain can obtain additional profit based on the consumer's low-carbon preference, and many studies have considered the influence of people's low-carbon preference on the strategy of a coal supply chain. If carbon reduction technology investment is necessary, increasing the preference for reduction becomes significant [26]. Ji and colleagues [27] found that the cap-and-trade model could be accepted and the optimal reduction could be achieved when consumers' low-carbon preference matches certain conditions. However, both distribution channels present tighter regulations and a higher reduction preference, which stimulates reduction work by the manufacturer [28]. Conversely, a previous study revealed that the entire chain income and reduction amount also increase with low-carbon preference [29].

Enterprises intend to chase optimal strategies around the chain, as seen in many studies. More than 58% of papers or documents have studied the balanced relationship between the supplier and the manufacturer [30]. Referring to a series of low-carbon supply chain equilibrium studies, scholars have considered many ways to coordinate the optimal strategy, and game theory is usually applied in the low-carbon supply chain to realize

equilibrium balance [31]. Moreover, under an evolutionary game theory background, the manufacturer performs better in a green supply chain than in other types of supply chains [32]. The asymmetric Nash bargaining game also coordinates channel operation and increases profit [33]. Yuan used discrete-time optimal control theory to explore the maximum profit under a cap-and-trade model [34].

The above research considers the method for achieving an optimal strategy. Regarding the research method, the game model has been widely accepted. Most papers discuss carbon reduction preferences with the output or the influence of a distribution model. However, they do not discuss the optimal strategy of a coal supply chain under clean coal technology subsidies with low-carbon preferences. Furthermore, different derivation directions are not considered. In our research, we compare the results under different dominant modes.

2.2. Low-Carbon Subsidy

Normally, the carbon reduction process has a considerable cost to either the coal enterprise or manufacturer, and capital support that serves a low-carbon supply chain is necessary [35]. Furthermore, if the low-carbon supply chain is burdened by cost, a discount loan rate from finance departments will help to solve the capital deficit, resulting in a limited stock in the green chain [36]. The different studies above, assuming that capital is unconstrained, indicate research hypotheses under capital constraints and uncertain backgrounds; the results reveal the relationship between government subsidies, green finance, and carbon reduction [37]. Subsidies support specific production behavior, as governments put forward per-unit subsidies, preventing the green supply chain from undergoing cost influence, while other financial institutions provide green credit to the green supply chain, which undergoes manufacturing or retailing capacity restrictions [38]. Government subsidies have already become a significant method for reducing carbon emissions.

Correspondingly, a study showed that poor government policy cannot optimize energy utilization and that sustainable development requires stable policy intervention [39]. Furthermore, Zhao claimed that if the supply chain receives the necessary government intervention, the carbon reduction strategy and production plan exhibit superior performance [40]. Proper environmental government regulations alleviate the present predicament [41]. Researchers have not only committed to reducing carbon emissions through subsidies, but have also shown interest in the coordination problem. Output could be influenced by subsidies in an uncertain low-carbon supply chain [42]. Moreover, some private financing methods have been evaluated for their ability to coordinate low-carbon supply chains; one example is revenue-sharing contracts with subsidies [42]. In addition, scholars focus on the behavioral effects, and how the extended subsidy indicates that manufacturers promote green supply chain management development [32]. Heterogeneous behavioral effects [43] and supervision strategies have been discussed under different subsidy proposals [44].

Previous studies have not considered subsidies for clean coal production, as opposed to carbon reduction without capital deficit. The effect of upstream subsidies on downstream carbon reduction under different dominant modes has not been considered. These findings indicate that the manufacturer still receives the reduction subsidy, but the coal enterprise replaces the reduction subsidy with the clean coal subsidy. Here, we consider the relationship between subsidy input, carbon reduction, and clean coal technology input under different dominant modes.

2.3. Cap-and-Trade Model and Carbon Reduction Strategy in the Supply Chain

Carbon pricing can be a central pillar of sustainable development, and it could promote internal cooperation worldwide. Such cooperation will help to quickly achieve the targets outlined in the Paris Agreement [45]. Specifically, cap-and-trade is a common term for a government regulatory program designed to limit, or cap, the total level of emissions of

certain chemicals, particularly carbon dioxide, as a result of industrial activity. The point of the cap-and-trade model is to set the quantity of carbon emissions so that traders can trade emissions rights in the carbon trade market. Previous research noted that the government can control carbon emissions effectively by setting a cap-and-trade model without ignoring economic development [46]. Research has shown that the carbon trading price has a positive influence on the carbon reduction quantity. Many studies have compared the cap-and-trade model with other reduction policies. For example, Cao and colleagues (2017) studied the low-carbon subsidy policy and cap-and-trade model. When the environmental pollution coefficient is lower than a governed coefficient, the low-carbon subsidy effectively influences carbon reduction; in contrast, the cap-and-trade policy is better than the low-carbon subsidy [31]. In Li's research, the cap-and-trade model has been thought to be the best policy for reducing carbon emissions in coal enterprises related to energy processes [47]. One scholar indicated that carbon reduction should be valued during the remanufacturing process regardless of the cap-and-trade model [48].

In practice, low-carbon efforts have been introduced into operations of both sides [49, 50]. In other words, carbon reduction processes exist throughout the entire chain [51–53]. Most studies focus on the reduction process rather than high-quality coal in a coal supply chain, and scholars have attempted to use coal type and coal quality as evaluation indexes to optimize coal product flow [54]. For example, organic sulfur could be removed from coal by microwave irradiation combined with NaOH-H_2O_2 [8]. Scholars have concluded that coal production is influenced by the green technology investment cost and the profit, since carbon reduction and different clean coal level selections could affect the output [55]. In China, clean coal is not a new concept, and it is already widespread in academia [56]. However, clean coal still needs support from authoritative departments. Other researchers have discussed the probability of achieving fairness via new low-carbon energy resources in the range of family utilization, and the results show that different risks come from different types of energy resource innovation products [57]. Furthermore, green technology turbulence may affect clean coal [58].

In conclusion, the cap-and-trade model is usually used to encourage carbon reduction in a low-carbon supply chain, and it has been applied to the entire supply chain. Others usually study the influence of different low-carbon policies. However, they do not consider that downstream carbon reduction partly relies on raw material quality in an upstream enterprise, and the coal enterprise could have the option of selecting clean coal products without carbon reduction. The most important is this study, based on considering different dominant modes to seek the optimal one. Moreover, the purpose of technology investment is to improve the quality of raw materials, in turn affecting downstream carbon reduction.

2.4. Motivation and Innovation

In summary, the motivation for this paper is as follows. People attempt to build an environmentally friendly world and to achieve sustainable development depending on the characteristics of the coal supply chain. They establish cap-and-trade models and other forms of financial support to control carbon reduction. In the context of a certain amount of government subsidies, we explore whether upstream firms can invest in technology to improve product quality and thereby reduce the carbon footprint of downstream manufacturers. Manufacturers continue to invest in emissions reductions, but coal enterprises focus on improving product quality through technology.

The innovations of this paper are as follows:

First, coal transferred to a downstream enterprise after a normal process is an energy resource without carbon reduction. In this paper, the coal enterprise invests in clean coal technology and develops high-quality clean coal that emits a small amount of carbon and decreases the order quantity of coal. The cleaner the coal, the cleaner the coal technology input that should be invested. This paper, which studies carbon reduction in a downstream enterprise, has been influenced by clean coal technology input in upstream enterprises under different dominant modes.

Second, this work focuses on identifying the optimal strategy for clean coal technology input in a coal enterprise with government subsidies. It also focuses on investment in carbon reduction technology by a manufacturer with subsidies. Thus, we compare and analyze clean coal technology subsidies in a coal enterprise upstream and carbon reduction technology subsidies in the manufacturer downstream separately.

Third, this study is unique due to the research method used, specifically different dominant modes with a Stackelberg game. This paper intends to study coal enterprise and downstream manufacturer dominance scenarios separately, and compare the effect of the optimal strategy and subsidy policy under different dominance models.

3. Equilibrium Description and Basic Hypotheses

This study investigates a coal supply chain in which the coal enterprise produces clean coal (instead of conducting carbon reduction), while the manufacturer conducts carbon reduction. Under the cap-and-trade scheme and government subsidies, the operation system, reduction strategy, and subsidy policy must be analyzed because these factors influence the coal supply chain. The main parameters and variables declaration are as Table 1.

Table 1. Variable declaration.

Notations	Meaning
	lowercase, representing the coal-enterprise-leading and manufacturer-leading model, respectively;
c, m	lowercase, representing the coal enterprise and manufacturer, respectively;
c_{tc}, c_{tm}	coefficient number for clean coal technology cost for the coal enterprise and carbon reduction cost for the manufacturer;
	clean coal technology subsidy for the coal enterprise and carbon reduction subsidy for the manufacturer;
π_c, π_m	profit of the coal enterprise and manufacturer, respectively;
E_g	limit of carbon emissions for the manufacturer;
p	the price of the energy supply that is produced by clean coal;
w	wholesale price of clean coal;
q_0	quantity of initial coal storage;
q	quantity of coal demand;
e_{m0}	initial quantity of carbon emissions by the manufacturer;
e_0	initial quantity of carbon emissions by the coal enterprise;
e_m	carbon reduction quantity for the manufacturer, decision variable;
e_c	clean coal technology input, decision variable;
p_t	price of carbon emissions right;
c	production cost of clean coal;
λ	coefficient number for carbon reduction preference;
k	the transferred coefficient number of clean coal;

This study makes the following assumptions.

Assumption 1. *The order quantity and reduction equilibriums are*

$$q = q_0 + k\lambda e_c + \lambda e_m$$

Description of Assumption 1:

In China, the heat energy companies have been taken as extremely competitive businesses. The electricity resources produced by coal enterprise can be fully consumed by the population or stored. In the above formula, q is the ordered quantity from the manufacturer, and we assume that the ordered clean coal has been completely converted to energy supply. As the clean coal technology input e_c increases, the clean coal quality increases as well, and clean coal quality affects the order quantity from downstream manufacturing industries. The letter k is the quantity of clean coal conversion parameter: it indicates the amount of heat energy or energy supply that can be converted with a per-unit amount of clean coal. Therefore, k multiple e_c could be explained as the quantity

of energy saved by clean coal utilization. We hypothesize that a relationship exists between clean coal technology inputs and downstream manufacturer carbon reductions. At the same time, both the coal enterprise and manufacturer have carbon reduction preferences λ. Consequently, the order quantity in a downstream enterprise has a relationship with the initial quantity and clean coal input upstream and carbon reduction downstream (the clean coal conversion factor and carbon reduction preference, respectively).

Assumption 2. *The carbon reduction equilibrium is:*

$$e_{m0} = e_0 - ke_c$$

Description of Assumption 2:

From the first assumption, the amount of coal ordered is closely related to the level of carbon reduction by a downstream manufacturer and clean coal technology input by an upstream coal enterprise. Coal production should be described as $q = q_0 + k\lambda e_c + \lambda e_m$*, and the carbon reduction in this supply chain is expressed as above. The main idea is to express that the upstream enterprise's use of clean coal will affect the downstream manufacturer's carbon reduction, and that the clean coal conversion factor could also influence the order of clean coal. The preferences for carbon reduction by a manufacturer and clean coal by a coal enterprise are the same. The manufacturer's initial carbon reduction quantity is decided by the clean coal quality. The cleaner the coal by the coal enterprise, the lower the carbon emissions by the manufacturer, so* $e_{m0} = e_0 - ke_c$*. Therefore, we try to show that the clean coal input upstream will influence the carbon reduction downstream; the cleaner the coal is, the less carbon emission there will be from the clean coal.*

Assumption 3. *Given that reducing the quantity of carbon emissions is difficult for companies, and that clean coal technology costs are equally high,* c_{tc} *and* c_{tm} *are infinitely large.*

The clean coal technology cost for coal enterprises and the carbon reduction cost for manufacturers are disposable. When viewed as a quadratic function, this assumption is expressed as follows:

$$C_c(e_c) = \frac{1}{2}c_{tc}{e_c}^2,\ C_m(e_m) = \frac{1}{2}c_{tm}{e_m}^2,$$

c_c, c_m *represent the production costs of a coal enterprise and manufacturer, respectively.* e_c, e_m *represent the clean coal technology inputs for a coal enterprise and the carbon reduction quantity for a manufacturer.* c_{tc} *is the coefficient number for clean coal technology costs for a coal enterprise, and* c_{tm} *denotes the coefficient number for the carbon reduction cost for a manufacturer. They indicate that the clean coal technology cost and carbon reduction cost are significant. The function has appeared in prior supply chain research [37,59,60]. It indicates that a high clean coal input results in a high clean coal technology cost, and a high carbon reduction quantity results in a carbon reduction cost.*

Furthermore, this study proposes achieving optimal carbon reduction by applying the supply–demand balance and solving the dilemma of expanding the carbon reduction scale and clean coal in a society with government subsidies. It assumes that capital deficits no longer exist in both enterprises in this chain, but they can obtain government subsidy for clean coal utilization and carbon reduction, respectively. The more the clean coal input is, the less pressure for carbon reduction there is, as per assumption 2. With the increase of clean coal input upstream, carbon reduction is decreased downstream. However, no matter the clean coal technology cost and carbon reduction cost, they are big enough to calculate, and the relationship is no longer in line with the increase of clean coal input and carbon reduction.

Decisions regarding the optimal quantity of clean coal technology input for coal enterprises and carbon reduction quantity for manufacturers under the cap-and-trade model are made. Unlike other studies, the present study proposes a relationship between the corresponding decision variables under different dominant modes that apply backward induction.

4. Coal and Manufacturer Reduction with Government Subsidies under the Cap-and-Trade Model in a Distinct Leading Organization

This study uses the reverse induction of the Stackelberg game theory model, which is a productive leading model. The coal enterprise and manufacturer are chosen. We assume that the coal enterprise produces clean coal directly, exploring the carbon reduction outcome after manufacturing. The following variables are depended on and negotiated: optimal clean coal technology input, the quantity of carbon reduction by the manufacturer, and government subsidies. In the middle, the manufacturer can trade carbon emissions rights in the carbon emissions rights market, and this mechanism is called the cap-and-trade model.

In a decentralized decision, the manufacturer and the coal enterprises are responsible for their profits. A Stackelberg model is built for the profit equilibriums of the two enterprises, and complete contrary dominant modes for the manufacturer and coal enterprises are considered. Through the reduction result and the profit of the different dominant modes, the optimal dominate model can be found. Coal enterprises produce clean coal, then the manufacturers produce electricity or other energy supplies using the clean coal. The coal enterprise and manufacturer are operated separately. Furthermore, the coal enterprise produces the clean coal and sells it to manufacturer. In the next stage, manufacturers process the clean coal, which could be the source of electricity or another energy supply. We assumed that the coal enterprise takes the wholesale price as the traded price with the manufacturer, and the manufacturer's revenue comes from the gap between the price of electricity or other energy supplies and the wholesale price of clean coal. Therefore, the profit includes the income, government subsidy, and net cost. As high clean coal input caused a high clean coal cost, a high carbon reduction quantity must cost more money. However, the high clean coal input makes the coal cleaner, and the carbon emissions due to the coal burning are much decreased. It is definitely the case that the carbon reduction downstream will be much lower.

4.1. Optimal Strategy When the Manufacturer Leads the Supply Chain

In the first part, this assumption stands on Stackelberg game theory, using a manufacturer to decide the chain. Therefore, depending on the industry's supply chain, the profit formula of the coal enterprise and manufacturer can be derived as follows:

$$\begin{cases} \pi_c^{ml} = (w-c)q - \frac{1}{2}c_{tc}^{ml}e_c^{ml^2} + e_c^{ml}s_1 \\ \pi_m^{ml} = pq - wq - p_t\left[(e_{m0} - e_m^{ml})q - E_g\right] - \frac{1}{2}c_{tm}^{ml}e_m^{ml^2} + e_m^{ml}s_2 \end{cases}, \quad (1)$$

The manufacturer's profit is equal to the total income and government subsidy minus the produced cost, the cost deduction in carbon reduction, and the carbon trading income or outcome. Under the cap-and-trade model, the carbon emissions limit that is allocated to the manufacturer is E_g. The manufacturer can trade it at market price p_t when the carbon emission quantity is higher than the limited quantity. Furthermore, when the carbon emission quantity is higher than the limit, it can be expressed as $\left(e_{m0} - e_m^{ml}\right)q - E_g$.

The coal enterprise decides the clean coal technology input to maximize its profit. Therefore, the decision model of the coal enterprise is

$$\max_{e_c} \pi_c^{ml} \quad (2)$$

The optimal decision of the coal enterprise matches Proposition 1.

Proposition 1. *The optimal clean coal technology input of the coal enterprise $e_c^{ml^*}$ is*

$$e_c^{ml^*} = \frac{(w-c)k\lambda + s_1}{c_{tc}^{ml}}, \quad (3)$$

(proof of Proposition 1 is in Appendix A.1).

According to the backward solution, the decision model of the manufacturer is

$$\max_{e_c,e_m} \pi_m^{ml} \quad s.t.(3), \tag{4}$$

Proposition 2. *The optimal carbon reduction level of the manufacturer* $e_m^{ml^*}$ *is*

$$e_m^{ml^*} = \frac{(p - w - p_t e_0)\lambda + s_2 + p_t q_0}{c_{tm}^{ml} - 2p_t\lambda} + \frac{2p_t\lambda^2 k^2(w - c) + 2kp_t\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)}, \tag{5}$$

(proof of Proposition 2 is in Appendix A.2).

From Equations (1) and (2), we can easily obtain the solutions (Propositions 1 and 2). From Proposition 1, we know that when the manufacturer leads, clean coal technology investment is closely related to government subsidies for clean coal technology and clean coal technology cost consumption. In Proposition 2, when the manufacturer leads, its carbon reduction cost could be influenced by clean coal technology cost in a coal enterprise, carbon reduction cost, clean coal subsidy in a coal enterprise, and carbon reduction subsidy in a manufacturer. Therefore, we specifically discuss how the impact factor acts on company operations and reduces the overall carbon footprint of the supply chain in Section 5.

4.2. Optimal Strategy When the Coal Enterprise Leads the Supply Chain

In the second part, this assumption stands on the Stackelberg game theory, using a coal enterprise to decide the entire chain. Therefore, depending on the components of profit, the profit formula of the coal enterprise and the manufacturer could be derived as follows:

$$\begin{cases} \pi_c^{cl} = (w - c)q - \dfrac{1}{2}c_{tc}^{cl}e_c^{cl^2} + e_c^{cl}s_1 \\ \pi_m^{cl} = pq - wq - p_t\left[(e_{m0} - e_m^{cl})q - E_g\right] - \dfrac{1}{2}c_{tm}^{cl}e_m^{cl^2} + e_m^{cl}s_2 \end{cases} \tag{6}$$

The calculation principle is similar to Section 4.1, which is based on the Stackelberg model. Applying backward induction, the description of the variable is the same as the leader, namely, the coal enterprise.

The manufacturer decides on a carbon reduction level to maximize its profit, and the optimal decision model of the manufacturer is

$$\max_{e_m} \pi_m^{cl} \tag{7}$$

The optimal decision of the manufacturer matches Proposition 3.

Proposition 3. *The optimal carbon reduction level of the manufacturer* $e_m^{cl^*}$ *is*

$$e_m^{cl^*} = \frac{(p - w)\lambda + p_t q_0 + s_2 - p_t\lambda\left(e_0 - 2ke_c^{cl}\right)}{c_{tm}^{cl} - 2p_t\lambda}, \tag{8}$$

(proof of Proposition 3 is in Appendix A.3).

According to the backward solution, the decision model of the coal enterprise is

$$\max_{e_c,e_m} \pi_c^{cl} \quad s.t.(8), \tag{9}$$

Proposition 4. *The optimal clean coal technology input of the coal enterprise* $e_c^{cl^*}$ *is*

$$e_c^{cl^*} = \frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)} + \frac{s_1}{c_{tc}^{cl}}, \tag{10}$$

(proof of Proposition 4 is in Appendix A.4).

5. Discussion and Mathematical Examination

This section discusses the results presented above under the system of the cap-and-trade model and the effect mechanism of a government subsidy policy. To prove the results of the study, mathematical examinations and function derivation methods are applied. As found in the research data, the relevant parameters are set as follows: $w = 500$ dollars/ton, $c = 200$ dollars/ton, $q_0 = 10{,}000$ ton, $\lambda = 30$, $k = 1$, $c_{tc} = 5000$, $s_1 = 50{,}000$ dollars, $p_t = 20$ dollars/ton, $p = 1500$ dollars/ton, $e_0 = 80$ tons/ton, $E_{gm} = 100$ thousand tons, $c_{tm} = 7500$ and $s_2 = 50{,}000$ dollars.

Proposition 5.

$$(1)\frac{de_c^{ml}}{dc_{tc}^{ml}} < 0, \frac{de_m^{ml}}{dc_{tc}^{ml}} < 0, \frac{de_c^{cl}}{dc_{tc}^{cl}} < 0, \frac{de_m^{cl}}{dc_{tc}^{cl}} < 0;$$
$$(2)\frac{de_m^{cl}}{dc_{tm}^{cl}} < 0, \frac{de_m^{ml}}{dc_{tm}^{ml}} < 0, \frac{de_c^{cl}}{dc_{tm}^{cl}} < 0, \frac{de_c^{ml}}{dc_{tm}^{ml}} = 0$$

(proof of Proposition 5 is in Appendix A.5).

The propositions are proven by mathematical calculations based on putting realistic data into already-derived functions, and the proposition keeps up with the figures' trend. The figures below show the same results.

Figure 2 shows the relationship of clean coal technology cost with clean coal technology input and carbon reduction in the coal supply chain. Comparing Figure 2 with Proposition 5, we can tell that Figure 2 converges with Proposition 8. With the increase in clean coal technology cost in a coal enterprise, the clean coal input in the coal enterprise and carbon reduction in the manufacturer decreases. Overall, the clean coal technology cost for coal enterprises inhibits the clean coal technology input and the carbon reduction quantity for downstream manufacturers. The above result may indicate that when clean coal technology cost increases, clean coal technology input decreases; therefore, the order quantity of clean coal decreases, resulting in a decrease in the carbon reduction quantity.

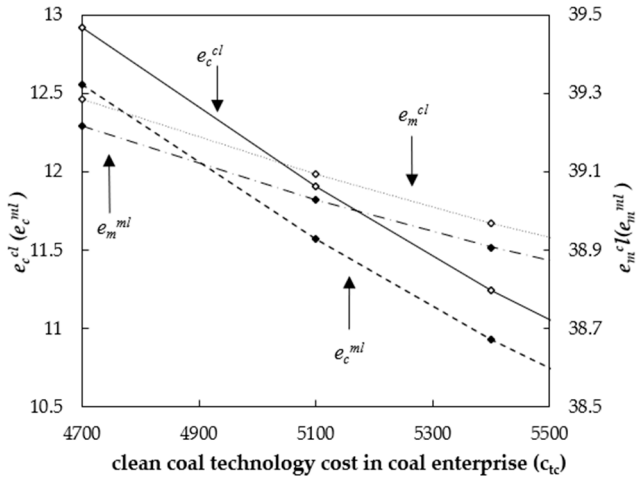


Figure 2. Correlation of clean coal technology cost with clean coal technology input and reduction.

Figure 3 shows the impact of downstream carbon reductions on the upstream and downstream supply chains, and the results shown in Figure 3 are consistent with the conclusions of Proposition 5. The carbon reduction cost does not have any relationship with the clean coal technology input in the coal enterprise when the manufacturer leads. Furthermore, the clean coal input slightly decreases with the increase in carbon reduction cost when the coal enterprise leads. These findings imply that downstream carbon reduction costs have little or no impact on clean coal technology input by coal companies. Evidently, the carbon reduction cost mainly influences the carbon reduction quantity of the manufacturer. However, the carbon reduction cost affects the carbon reduction quantity of the manufacturer, and as the carbon reduction cost increases, the carbon reduction quantity decreases. Overall, the carbon reduction cost mainly affects downstream manufacturers.

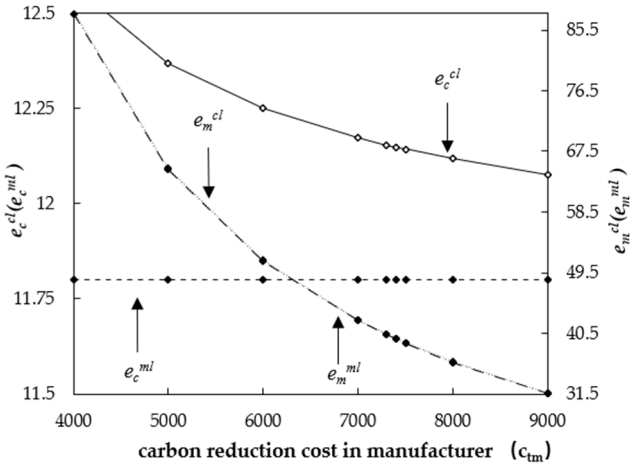


Figure 3. Correlation of carbon reduction cost with clean coal technology input and reduction.

This leads to the following management insights. The government or authorities need to promptly subsidize the cost of high-tech clean coal. At the same time, manufacturers downstream could also support clean coal technology investment, which has benefits for reducing carbon emissions.

Proposition 6.

$$(1)\frac{de_c^{ml}}{ds_1} > 0, \frac{de_m^{ml}}{ds_1} > 0, \frac{de_c^{cl}}{ds_1} > 0, \frac{de_m^{cl}}{ds_1} > 0;$$
$$(2)\frac{de_m^{cl}}{ds_2} > 0, \frac{de_m^{ml}}{ds_2} > 0, \frac{de_c^{cl}}{ds_2} = 0, \frac{de_c^{ml}}{ds_2} = 0$$

(proof of Proposition 6 is in Appendix A.6).

This part addresses the influence of subsidies on trade. Figures 4 and 5 show the effects of clean coal subsidies and carbon reduction subsidies on the whole supply chain. The conclusions drawn from the chart are consistent with the proposition.

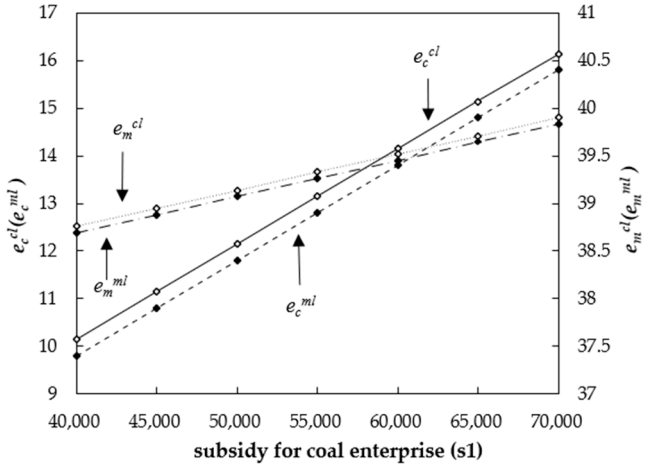


Figure 4. Correlation of clean coal technology subsidy with clean coal technology input and reduction.

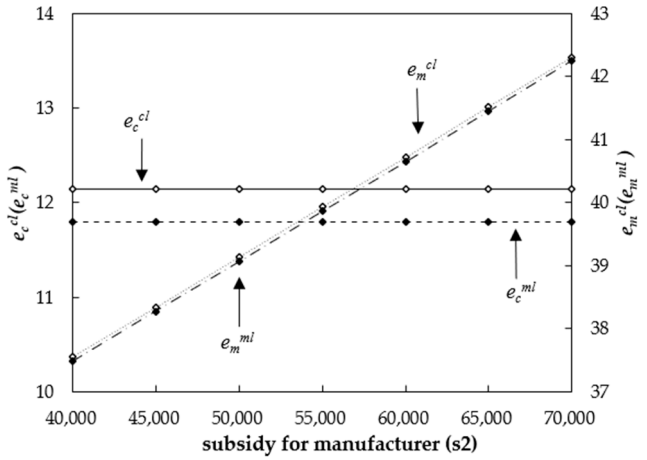


Figure 5. Correlation of carbon reduction subsidy with clean coal technology input and reduction.

Figure 4 shows that clean coal technology subsidies in coal enterprises support clean coal technology input for coal enterprises and carbon reduction motivation for manufacturers, regardless of who has a prior right to dominate. The reason for this result is that subsidizing clean coal technology takes the burden of a part of the cost, which could promote the production of clean coal by coal enterprises and help coal enterprises invest in clean coal technology. If so, the clean coal technology input increases, and the clean coal quantity that was ordered increases based on Assumption 1; thus, the carbon reduction quantity increases. With the help of government subsidies, a coal enterprise will improve its ability to produce clean coal, and clean coal input will be expanded.

Figure 5 shows that carbon reduction subsidies have a catalytic effect on downstream manufacturers to reduce emissions, but that carbon reduction subsidies do not have a significant impact on upstream coal companies' clean coal input, although the subsidy offsets the clean coal utilization cost. Due to the high carbon reduction cost, the manufacturer will reduce the carbon reduction quantity; thus, carbon reduction efforts increase along with carbon reduction subsidies. Whereas when the government subsidizes carbon reduction by manufacturers, the manufacturer will correspondingly increase downstream carbon reductions, and since clean coal is made by upstream coal companies, the amount ordered will not change, even though it does not affect the investment in upstream clean coal technology.

The relevant management insights are as follows. The government should increase clean coal subsidies to coal companies. Meanwhile, authorities should appropriately subsidize the carbon reduction of manufacturers.

Proposition 7.

$$(1)\frac{de_c^{ml}}{d\lambda} > 0, \frac{de_m^{ml}}{d\lambda} > 0, \frac{de_c^{cl}}{d\lambda} > 0, \frac{de_m^{cl}}{d\lambda} > 0;$$
$$(2)\frac{de_c^{ml}}{dk} > 0, \frac{de_m^{ml}}{dk} > 0, \frac{de_c^{cl}}{dk} > 0, \frac{de_m^{cl}}{dk} > 0$$

(proof of Proposition 7 is in Appendix A.7).

The pictures above show the results on carbon reduction preference and clean coal conversion factor regardless of the decision order, and the proposition is consistent with what it shown in Figures 6 and 7.

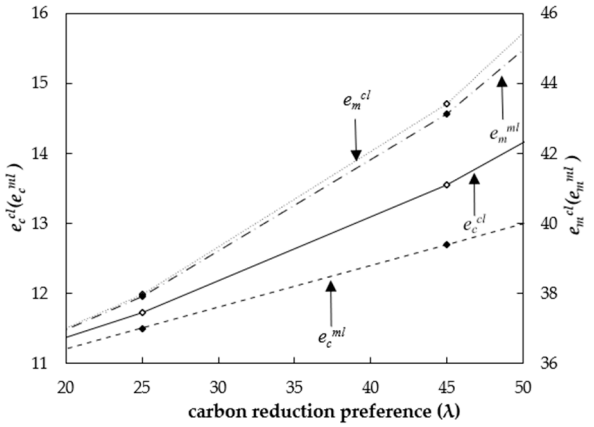


Figure 6. Correlation of carbon reduction preference with clean coal technology input and reduction.

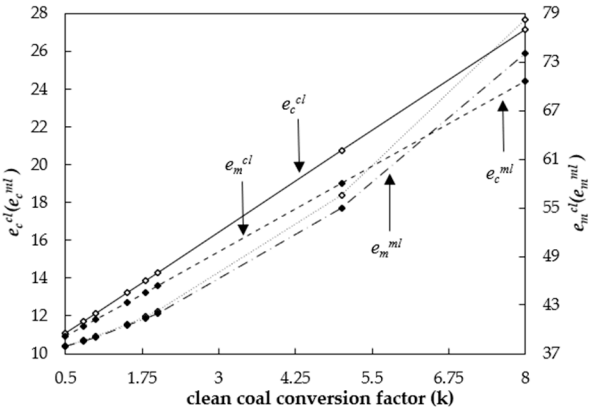


Figure 7. Correlation of the clean coal conversion factor with clean coal technology input and reduction.

Figure 6 indicates that carbon reduction preference benefits clean coal technology input and promotes carbon reduction. An increase in carbon reduction preference encourages coal enterprises to invest in clean coal technology, and promotes an increase in carbon reductions. The ordered clean coal quantity increases based on Assumption 1, due to the higher carbon reduction preference resulting from the higher clean coal technology input. Because of the high clean coal quantity, there is a corresponding increase in carbon reductions downstream.

As shown in Figure 7, as the clean coal conversion factor increases, clean coal technology input and carbon reduction quantity can grow. Consequently, enterprises accept clean coal to achieve high efficiency of the green supply chain, and clean coal helps the world become environmentally friendly. With the high clean coal conversion factor, the clean coal enterprise can achieve more clean coal production, and the clean coal technology

input also increases. Moreover, the clean coal conversion factor influences carbon reduction in downstream enterprises; when coal enterprises transfer more clean coal products, the manufacturer emits less carbon.

We can get the following management insights. Coal enterprises need to increase the clean coal conversion factor and establish additional incentives to promote clean coal technology input. As regards high conversion factor, coal enterprises can achieve this by improving clean coal production technologies. On the other hand, it could help coal enterprises develop clean coal products with high technology input, or urge coal enterprises to produce more clean coal products. More importantly, there should be widespread awareness of the need to reduce carbon emissions by enterprises, and the government should publish advertisements for guiding enterprises to use clean coal.

Proposition 8. $ke_c^{cl} + e_m^{cl} < ke_c^{ml} + e_m^{ml}$ *(proof of Proposition 8 is in Appendix A.8).*

In Proposition 8, when the manufacturer leads the chain, a low-carbon supply chain can be executed. We can compare the two different dominant models by calculating the total carbon reduction quantity of the supply chain under the two different dominant models, and using the difference between positive and negative values to determine which mode is better for supply chain carbon reduction. The carbon reduction effect across the coal supply chain comprises the clean coal technology input and the manufacturers' carbon reductions, using k for transferred coefficient number of multiple clean coal investments to keep units consistent with the carbon reduction quantity. In Figure 8, it clearly shows that the total outputs in carbon reduction increased when the clean coal technology subsidy increased, no matter which one led, and the carbon reduction result performed better under the manufacturer-led mode. Specifically, carbon reduction performance combines clean coal technology input for upstream enterprises and carbon reduction for downstream enterprises, and the manufacturer-leading model is superior to the coal-enterprise-leading model. In other words, under a manufacturer-led mode, the coal supply chain can achieve a higher carbon reduction level, which testifies to the hypothesis we made before.

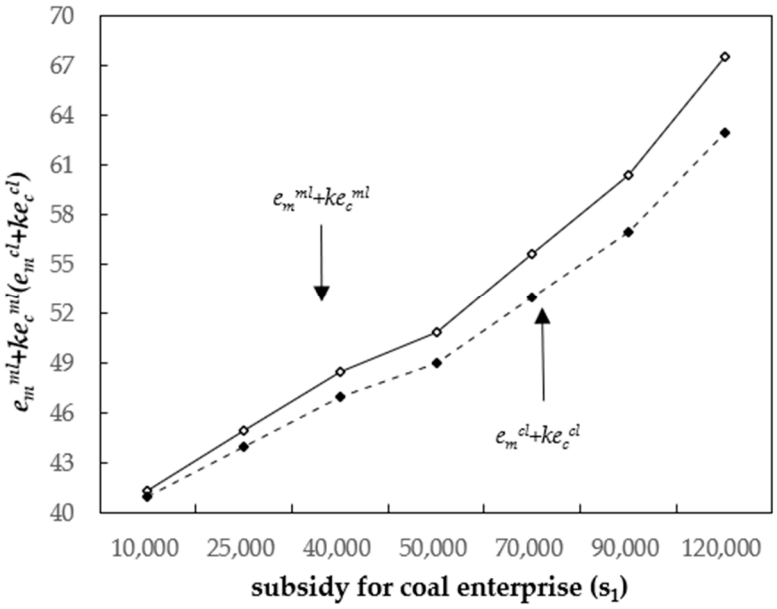


Figure 8. Difference between two different dominant models.

When this proposition is combined with prior conclusions, the manufacturer is considered the leader, with the manufacturer-led model prior to the coal-enterprise-led. Thus, authorities need to focus on manufacturer management, and support it with low-carbon policymaking, such as subsidies; meanwhile, governments should regulate the coal product

or energy market, whether the price is reasonable or not. Considering social and economic development targets can make suitable policies for sustainability development.

6. Conclusions

Low-carbon supply chains are popular around the world, and the sustainability principle suggests that humans should decrease carbon emissions as much as they can. According to the literature review, our work focuses on the coal product supply chain, which includes one coal enterprise and one manufacturer. The production of environmentally friendly clean coal products by coal enterprises is one of the innovations of this paper. Another is the focus on the dominant mode that can influence carbon reduction under a cap-and-trade model with government subsidies in different leading models.

Through scientific research, clean coal utilization can improve the carbon reduction effect on downstream factories. First, no matter which dominant mode, as clean coal technology costs increase, coal enterprises decrease their clean coal technology inputs, and downstream manufacturers decrease their carbon reductions. Therefore, high-cost technology investment can inhibit downstream firms' choices, except when the manufacturer leads and the carbon reduction cost does not influence the clean coal technology input. Coal enterprises need to invest further in clean coal technology and upgrade their production lines for clean products to lower the cost. It is also necessary that governments appropriate subsidize clean coal. Second, the government subsidy encourages clean coal input in coal enterprises and carbon reduction quantity in manufacturers. Nevertheless, regardless of the dominant model, carbon reduction subsidies for manufacturers are not directly relevant to upstream clean coal inputs in coal enterprises. This result indicates that the large-scale use of clean coal needs subsidies, and subsidies for carbon reduction downstream will promote carbon reduction by downstream manufacturers. However, the carbon reduction subsidy for the manufacturer will not affect clean coal production in coal enterprises. Thus, a purposeful increase in government subsidies for clean coal products benefits further investment in clean coal technology and carbon reduction in a downstream manufacturer, which helps coal enterprises introduce clean coal and promote the widespread application of clean coal, possibly improving efficiency, decreasing carbon emissions from combustion, and reducing the pressure on downstream enterprises to reduce carbon emissions. Third, in different leading models, when the manufacturer leads the chain, the low-carbon supply chain exhibits improved clean coal utilization and carbon reduction. The government should suggest that manufacturers dominate the supply chain in the market, so that the whole chain can realize better carbon reduction performance.

The coverage of this study can be further explored. Here, we mainly discuss the coal supply chain and carbon reduction, in which the research area is fixed. We could not present a normal industry chain rule. This paper aims to protect the environment and encourage environmentally friendly enterprise development. In the next study, flexible financing solutions for enterprises should be considered. In practical life, most enterprises lack money, and they need to obtain money from finance departments and through other approaches. Although clean coal was introduced years ago, its use is not widespread due to the lack of laws and suitable regulations that apply to clean coal [61]. Other researchers claim that additional research on low-carbon systems developed during the turbulence of restructuring is needed [62].

Author Contributions: Conceptualization, B.D.; data curation, B.D.; formal analysis, B.D. and C.L.; funding acquisition, C.L.; investigation, B.D.; methodology, B.D.; resources, B.D.; software, B.D.; supervision, C.L.; writing—original draft, B.D.; writing—review and editing, B.D. and N.L., S.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the "Project of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province" (No.2020SJA2369).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data which belong to this paper are all available, but this studies not involving humans or animals.

Acknowledgments: The authors are grateful for the financial support provided by the "Project of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province". (No. 2020SJA2369).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; collection, analyses, or interpretation of data; writing of the manuscript; and decision to publish the results.

Appendix A

Appendix A.1. Proof of Proposition 1

As Function (1) and Assumptions (1) and (2) show,

$$\frac{d\pi_c^{ml}}{de_c^{ml}} = (w-c)k\lambda - c_{tc}^{ml}e_c^{ml} + s_1,$$

and taking $e_c^{ml^*} = \dfrac{(w-c)k\lambda + s_1}{c_{tc}^{ml}}$ into π_m^{ml},

$$\begin{aligned}\frac{d\pi_m^{ml}}{de_m^{ml}} &= (p-w)\lambda - c_{tm}^{ml}e_m^{ml} + s_2 + p_t q_0 - p_t e_0\lambda + p_t k\lambda e_c^{ml} + p_t k\lambda e_c^{ml} + 2p_t\lambda e_m^{ml} \\ &= (p-w)\lambda - c_{tm}^{ml}e_m^{ml} + 2p_t\lambda e_m^{ml} + s_2 + 2p_t k\lambda \cdot \frac{\lambda k(w-c)+s_1}{c_{tc}} + p_t q_0 - p_t e_0\lambda \\ &= \lambda(p-w-p_t e_0) - e_m^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right) + s_2 + p_t q_0 + \frac{2p_t\lambda^2k^2(w-c) + 2p_t k\lambda s_1}{c_{tc}} \\ &= \lambda(p-w-p_t e_0) - e_m^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right) + s_2 + p_t q_0 + \frac{2p_t k\lambda[k\lambda(w-c)+s_1]}{c_{tc}}\end{aligned},$$

because c_{tm}^{ml} is significant enough, so

$$\frac{d^2\pi_c^{ml}}{d^2e_c^{ml}} = -c_{tc}^{ml} < 0,\ \frac{d^2\pi_m^{ml}}{d^2e_m^{ml}} = 2\mathrm{p}_t\lambda - c_{tm}^{ml} < 0,\ \frac{d^2\pi_c^{ml}}{de_c^{ml}de_m^{ml}} = 0,\ \frac{d^2\pi_m^{ml}}{de_c^{ml}de_m^{ml}} = 0.$$

Thus, it can be concluded as a Hessian matrix.

$$H = \begin{bmatrix} -c_{tc}^{ml} & 0 \\ 0 & -c_{tm}^{ml} \end{bmatrix}.$$

However, $\det(H_{11}) = -c_{tc}^{ml} < 0$, $\det(H) = c_{tc}^{ml}\cdot c_{tm}^{ml} > 0$, such that the Hessian matrix is positive, and the optimal clean coal technology input is $e_c^{ml^*}$ exists. Supposing that $\dfrac{d\pi_c^{ml}}{de_c^{ml}} = 0$, from the above, the optimal $e_c^{ml^*}$ can be obtained in Equation (3).

Appendix A.2. Proof of Proposition 2

As Equations (1) and (3) and Assumptions (1) and (2) show,

$$\frac{d^2\pi_c^{ml}}{d^2e_c^{ml}} = -c_{tc}^{ml} < 0,\ \frac{d^2\pi_m^{ml}}{d^2e_m^{ml}} = 2\mathrm{p}_t\lambda - c_{tm}^{ml} < 0,\ \frac{d^2\pi_c^{ml}}{de_c^{ml}de_m^{ml}} = 0,\ \frac{d^2\pi_m^{ml}}{de_c^{ml}de_m^{ml}} = 0.$$

Thus, it can be concluded as a Hessian matrix.

$$H = \begin{bmatrix} -c_{tc}^{ml} & 0 \\ 0 & 2\mathrm{p}_t\lambda - c_{tm}^{ml} \end{bmatrix}.$$

However, $\det(H_{11}) = -c_{tc}^{ml} < 0$, $\det(H) = c_{tc}^{ml} \cdot \left(c_{tm}^{ml} - 2p_t\lambda\right) > 0$, such that the Hessian matrix is positive, which indicates that the optimal quantity of carbon reduction $e_m^{ml^*}$ exists. Supposing that $\frac{d\pi_m^{ml}}{de_m^{ml}} = 0$, from the above, the optimal $e_m^{ml^*}$ can be obtained in Equation (5).

Appendix A.3. Proof of Proposition 3

As above, Equation (6) and Assumptions (1) and (2) show

$$\begin{aligned}\frac{d\pi_m^{cl}}{de_m^{cl}} &= (p-w)\lambda - p_t\left(e_0\lambda - \lambda k e_c^{cl} - 2\lambda e_m^{cl} - q_0 - \lambda k e_c^{cl}\right) - c_{tm}^{cl}e_m^{cl} + s_2 \\ &= (p-w)\lambda - p_t\lambda\left(e_0 - 2ke_c^{cl}\right) + p_tq_0 + 2p_t\lambda e_m^{cl} - c_{tm}^{cl}e_m^{cl} + s_2 \\ &= (p-w)\lambda - p_t\lambda\left(e_0 - 2ke_c^{cl}\right) + p_tq_0 + e_m^{cl}\left(2p_t\lambda - c_{tm}^{cl}\right) + s_2\end{aligned},$$

if $\frac{d\pi_m^{cl}}{de_m^{cl}} = 0$, so $(p-w)\lambda - p_t\lambda\left(e_0 - 2ke_c^{cl}\right) + p_tq_0 + e_m^{cl}\left(2p_t\lambda - c_{tm}^{cl}\right) + s_2 = 0$ and $e_m^{cl^*} = \frac{(p-w)\lambda + p_tq_0 + s_2 - p_t\lambda\left(e_0 - 2ke_c^{cl}\right)}{c_{tm}^{cl} - 2p_t\lambda}$,

$$\begin{aligned}\frac{d\pi_c^{cl}}{de_c^{cl}} &= \lambda k(w-c) - c_{tc}^{cl}e_c^{cl} + s_1 + (w-c)\cdot\frac{2p_t\lambda^2k}{c_{tm}^{cl} - 2p_t\lambda} \\ &= \lambda k(w-c)\left[1 + \frac{2p_t\lambda}{c_{tm}^{cl} - 2p_t\lambda}\right] - c_{tc}^{cl}e_c^{cl} + s_1 \\ &= \lambda k(w-c)\cdot\frac{c_{tm}^{cl} - 2p_t\lambda + 2p_t\lambda}{c_{tm}^{cl} - 2p_t\lambda} + s_1 - c_{tc}^{cl}e_c^{cl} \\ &= \frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tm}^{cl} - 2p_t\lambda} + s_1 - c_{tc}^{cl}e_c^{cl}\end{aligned},$$

The function can be derived as $\frac{d^2\pi_m^{cl}}{d^2e_m^{cl}} = -\left(c_{tm}^{cl} - 2p_t\lambda\right) < 0$, $\frac{d^2\pi_c^{cl}}{d^2e_c^{cl}} = -c_{tc}^{cl} < 0$.

Additionally, $\frac{d^2\pi_m^{cl}}{de_m^{cl}de_c^{cl}} = 2p_t\lambda k > 0$, $\frac{d^2\pi_c^{cl}}{de_c^{cl}de_m^{cl}} = 0$. It can be solved by the Hessian matrix:

$$H = \begin{bmatrix} -\left(c_{tm}^{cl} - 2p_t\lambda\right) & 2p_t\lambda k \\ 0 & -c_{tc}^{cl} \end{bmatrix}.$$

As shown by Assumption 3, c_{tm} is infinitely large. It can be solved as

$$\det(H_{11}) = -\left(c_{tm}^{cl} - 2p_t\lambda\right) < 0,\ \det(H) = -\left(c_{tm}^{cl} - 2p_t\lambda\right)\cdot\left(-c_{tc}^{cl}\right) > 0.$$

The above Hessian matrix is positive. The optimal quantity of carbon reduction is $e_m^{cl^*}$. Supposing that $\frac{d\pi_m^{cl}}{de_m^{cl}} = 0$, from the above, the optimal $e_m^{cl^*}$ can be obtained in Equation (8).

Appendix A.4. Proof of Proposition 4

As above, Equation (6) shows $\frac{d\pi_m^{cl}}{de_m^{cl}} = (p - w - p_t e_0)\lambda + 2p_t\lambda k e_c^{cl} + p_t q_0 + s_2 - e_m^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)$. It depends on the composite function derivation in the next part, as $\frac{d\pi_c}{de_c} = \frac{\partial\pi_c}{\partial e_c} + \frac{\partial\pi_c}{\partial e_m}.\frac{\partial e_m}{\partial e_c}$. The function can be derived as

$$\frac{d\pi_c^{cl}}{de_c^{cl}} = \lambda k(w - c) + \frac{2p_t\lambda^2 k(w - c)}{c_{tm}^{cl} - 2p_t\lambda} + s_1 - c_{tc}^{cl} e_c^{cl},$$

and $\frac{d^2\pi_m^{cl}}{d^2 e_m^{cl}} = -\left(c_{tm}^{cl} - 2p_t\lambda k\right) < 0$, $\frac{d^2\pi_c^{cl}}{d^2 e_c^{cl}} = -c_{tc}^{cl} < 0$.

Therefore, $\frac{d^2\pi_m^{cl}}{de_m^{cl} de_c^{cl}} = 2p_t\lambda k > 0$, $\frac{d^2\pi_c^{cl}}{de_c^{cl} de_m^{cl}} = 0$. It can be solved by the Hessian matrix:

$$H = \begin{bmatrix} -\left(c_{tm}^{cl} - 2p_t\lambda k\right) & p_t\lambda k(k+1) \\ 0 & -c_{tc}^{cl} \end{bmatrix}.$$

As shown by Assumption 3, c_{tm} is infinitely large. It can be solved as

$$\det(H_{11}) = -\left(c_{tm}^{cl} - 2p_t\lambda k\right) < 0,\ \det(H) = -\left(c_{tm}^{cl} - 2p_t\lambda k\right)\cdot\left(-c_{tc}^{cl}\right) > 0.$$

The above Hessian matrix is positive, and the optimal clean coal technology input e_c^{cl*} exists. Supposing that $\frac{d\pi_m^{cl}}{de_m^{cl}} = 0$ and $\frac{d\pi_c^{cl}}{de_c^{cl}} = 0$, from the above, the optimal e_m^{cl*} and e_c^{cl*} can be obtained in Equation (10).

Appendix A.5. Proof of Proposition 5

From Equations (3) and (5),

$$e_c^{ml*} = \frac{(w - c)k\lambda + s_1}{c_{tc}^{ml}},$$

$$e_m^{ml*} = \frac{(p - w - p_t e_0)\lambda + s_2 + p_t q_0}{c_{tm}^{ml} - 2p_t\lambda} + \frac{2p_t\lambda^2 k^2(w - c) + 2kp_t\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)}$$

Thus, $\frac{de_c^{ml}}{dc_{tc}^{ml}} = \frac{-(w - c)k\lambda - s_1}{c_{tc}^{ml2}} < 0$, $\frac{de_c^{ml}}{dc_{tm}^{ml}} = 0$;

Because c_{tc}^{ml} is infinitely positive and large, and $p > w$, $w > c$,

$$\frac{de_m^{ml}}{dc_{tm}^{ml}} = \frac{-[(p - w - p_t e_0)\lambda + p_t q_0 + s_2]}{\left(c_{tm}^{ml} - 2p_t\lambda\right)^2} + \frac{-2c_{tc}^{ml} p_t\lambda k[(w - c)\lambda k + s_1]}{c_{tc}^{ml2}\left(c_{tm}^{ml} - 2p_t\lambda\right)^2} < 0,$$

$$\begin{aligned} \frac{de_m^{ml}}{dc_{tc}^{ml}} &= \frac{-2p_t\lambda k\left(c_{tm}^{ml} - 2p_t\lambda\right)[(w - c)\lambda k + s_1]}{c_{tc}^{ml2}\left(c_{tm}^{ml} - 2p_t\lambda\right)^2} \\ &= \frac{-2p_t\lambda k[(w - c)\lambda k + s_1]}{c_{tc}^{ml2}\left(c_{tm}^{ml} - 2p_t\lambda\right)} \end{aligned},$$

because $(w - c) > 0$; therefore, $\frac{de_m^{ml}}{dc_{tc}^{ml}} < 0$;

Meanwhile, $e_c^{cl*} = \frac{c_{tm}^{cl}\lambda k(w - c)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)} + \frac{s_1}{c_{tc}^{cl}}$, $e_m^{cl*} = \frac{(p - w)\lambda + p_t q_0 + s_2 - p_t\lambda\left(e_0 - 2ke_c^{cl}\right)}{c_{tm}^{cl} - 2p_t\lambda}$.

Thus, $\frac{de_c^{cl}}{dc_{tc}^{cl}} = -\frac{c_{tm}^{cl}\lambda k(w-c)\left(c_{tm}^{cl}-2p_t\lambda\right)}{c_{tc}^{cl^2}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} - \frac{s_1}{c_{tc}^{cl^2}}$, because c_{tm}^{cl} is infinitely positive

$$= -\frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl^2}\left(c_{tm}^{cl}-2p_t\lambda\right)} - \frac{s_1}{c_{tc}^{cl^2}}$$

and big, $\left(c_{tm}^{cl}-2p_t\lambda\right)$ is positive, and $w-c>0$, so $\frac{de_c^{cl}}{dc_{tc}^{cl}} < 0$.

It should be mentioned that c_{tc}^{ml}, c_{tm}^{ml}, c_{tc}^{cl}, c_{tm}^{cl} are all infinitely large.

$$\begin{aligned}\frac{de_c^{cl}}{dc_{tm}^{cl}} &= \frac{\lambda k c_{tc}^{cl}(w-c)\left(c_{tm}^{cl}-2p_t\lambda\right) - c_{tm}^{cl}c_{tc}^{cl}\lambda k(w-c)}{c_{tc}^{cl^2}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} \\ &= \frac{\lambda k(w-c)\left(c_{tm}^{cl}-2p_t\lambda\right) - c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} \\ &= \frac{\lambda k(w-c)\left(c_{tm}^{cl}-2p_t\lambda-c_{tm}^{cl}\right)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} \\ &= \frac{-2p_t\lambda^2 k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)^2}\end{aligned},$$

because $w-c>0$, so $\frac{de_c^{cl}}{dc_{tm}^{cl}} < 0$.

$$\frac{de_m^{cl}}{dc_{tc}^{cl}} = \frac{\partial e_m^{cl}}{\partial c_{tc}^{cl}} + \frac{\partial e_m^{cl}}{\partial e_c^{cl}}\cdot\frac{\partial e_c^{cl}}{\partial c_{tc}^{cl}} = \frac{2p_t\lambda k}{c_{tm}^{cl}-2p_t\lambda}\cdot\left[-\frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl^2}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} - \frac{s_1}{c_{tc}^{cl^2}}\right] < 0,$$

$$\begin{aligned}\frac{de_m^{cl}}{dc_{tm}^{cl}} &= \frac{\partial e_m^{cl}}{\partial c_{tm}^{cl}} + \frac{\partial e_m^{cl}}{\partial e_c^{cl}}\cdot\frac{\partial e_c^{cl}}{\partial c_{tm}^{cl}} \\ &= \frac{2p_t\lambda k}{c_{tm}^{cl}-2p_t\lambda}\cdot\frac{\lambda k c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)(w-c) - c_{tm}^{cl}c_{tc}^{cl}\lambda k(w-c)}{c_{tc}^{cl^2}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} \\ &= \frac{2p_t\lambda k}{c_{tm}^{cl}-2p_t\lambda}\cdot\frac{\lambda k\left(c_{tm}^{cl}-2p_t\lambda\right)(w-c) - c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} \\ &= \frac{2p_t\lambda k}{c_{tm}^{cl}-2p_t\lambda}\cdot\frac{\lambda k(w-c)\left(c_{tm}^{cl}-2p_t\lambda-c_{tm}^{cl}\right)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)^2} \\ &= \frac{-4p_t^2\lambda^3 k^2(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)^3}\end{aligned},$$

due to c_{tm}^{cl} being definitely large enough, and $w-c>0$, $c_{tm}^{cl}-2p_t\lambda>0$, so $\frac{de_m^{cl}}{dc_{tm}^{cl}} < 0$, $\frac{de_m^{cl}}{dc_{tc}^{cl}} < 0$,

Hence, $\frac{de_m^{cl}}{dc_{tm}^{cl}} < 0$, $\frac{de_m^{ml}}{dc_{tm}^{ml}} < 0$, $\frac{de_c^{cl}}{dc_{tm}^{cl}} < 0$, $\frac{de_c^{ml}}{dc_{tm}^{ml}} = 0$, $\frac{de_c^{ml}}{dc_{tc}^{ml}} < 0$, $\frac{de_m^{ml}}{dc_{tc}^{ml}} < 0$, $\frac{de_c^{cl}}{dc_{tc}^{cl}} < 0$, $\frac{de_m^{cl}}{dc_{tc}^{cl}} < 0$.

Appendix A.6. Proof of Proposition 6

From Equations (3) and (5),

$$e_c^{ml^*} = \frac{(w-c)k\lambda + s_1}{c_{tc}^{ml}},$$

$$e_m^{ml^*} = \frac{(p-w-p_te_0)\lambda + s_2 + p_tq_0}{c_{tm}^{ml} - 2p_t\lambda} + \frac{2p_t\lambda^2k^2(w-c) + 2kp_t\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)}.$$

Thus, $\frac{de_c^{ml}}{ds_1} = \frac{1}{c_{tc}^{ml}} > 0$, $\frac{de_c^{ml}}{ds_2} = 0$, $\frac{de_m^{ml}}{ds_2} = \frac{1}{c_{tm}^{ml} - 2p_t\lambda} > 0$, $\frac{de_m^{ml}}{ds_1} = \frac{2kp_t\lambda}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)} > 0$.

$$e_c^{cl^*} = \frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)} + \frac{s_1}{c_{tc}^{cl}},\ e_m^{cl^*} = \frac{(p-w)\lambda + p_tq_0 + s_2 - p_t\lambda\left(e_0 - 2ke_c^{cl}\right)}{c_{tm}^{cl} - 2p_t\lambda}$$

Thus, $\frac{de_c^{cl}}{ds_1} = \frac{1}{c_{tc}^{cl}} > 0$, $\frac{de_m^{cl}}{ds_2} = \frac{1}{c_{tm}^{cl} - 2p_t\lambda} > 0$, $\frac{de_c^{cl}}{ds_2} = 0$,

$$\frac{de_m^{cl}}{ds_1} = \frac{\partial e_m^{cl}}{\partial s_1} + \frac{\partial e_m^{cl}}{\partial e_c^{cl}} \cdot \frac{\partial e_c^{cl}}{\partial s_1} = \frac{2kp_t\lambda}{c_{tm}^{cl} - 2p_t\lambda} \cdot \frac{1}{c_{tc}^{cl}} > 0.$$

In conclusion, $\frac{de_c^{ml}}{ds_1} > 0$, $\frac{de_m^{ml}}{ds_2} > 0$, $\frac{de_m^{ml}}{ds_1} > 0$, $\frac{de_c^{ml}}{ds_2} = 0$, $\frac{de_c^{cl}}{ds_1} > 0$, $\frac{de_m^{cl}}{ds_1} > 0$, $\frac{de_m^{cl}}{ds_2} > 0$, $\frac{de_c^{cl}}{ds_2} = 0$.

Appendix A.7. Proof of Proposition 7

From Equations (3) and (5),

$$e_c^{ml^*} = \frac{(w-c)k\lambda + s_1}{c_{tc}^{ml}},$$

$$e_m^{ml^*} = \frac{(p-w-p_te_0)\lambda + s_2 + p_tq_0}{c_{tm}^{ml} - 2p_t\lambda} + \frac{2p_t\lambda^2k^2(w-c) + 2kp_t\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)}.$$

and $w - c > 0$; thus, $\frac{de_c^{ml}}{d\lambda} = \frac{(w-c)k}{c_{tc}^{ml}} > 0$, $\frac{de_c^{ml}}{dk} = \frac{(w-c)\lambda}{c_{tc}^{ml}} > 0$,

$$\begin{aligned}\frac{de_m^{ml}}{d\lambda} &= \frac{(p-w-p_te_0)\left(c_{tm}^{ml} - 2p_t\lambda\right) + 2p_t[(p-w-p_te_0)\lambda + s_2 + p_tq_0]}{\left(c_{tm}^{ml} - 2p_t\lambda\right)^2} \\ &+ \frac{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)\left[4p_t\lambda k^2(w-c) + 2kp_ts_1\right] + 2p_tc_{tc}^{ml}\left[2p_t\lambda^2k^2(w-c) + 2kp_t\lambda s_1\right]}{c_{tc}^{ml2}\left(c_{tm}^{ml} - 2p_t\lambda\right)^2} \\ &= \frac{c_{tm}^{ml}(p-w-p_te_0) + 2p_ts_2 + 2p_t^2q_0}{\left(c_{tm}^{ml} - 2p_t\lambda\right)^2} \\ &+ \frac{2\left(c_{tm}^{ml} - 2p_t\lambda\right)\left[2p_t\lambda k^2(w-c) + kp_ts_1\right] + 4kp_t^2\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)^2}\end{aligned},$$

Because $\left(c_{tm}^{ml} - 2p_t\lambda\right) > 0$, $\frac{de_m^{ml}}{d\lambda} > 0$,

$$\frac{de_m^{ml}}{dk} = \frac{4p_t\lambda^2k(w-c) + 2p_t\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml} - 2p_t\lambda\right)},$$

Because $\left(c_{tm}^{ml} - 2p_t\lambda\right) > 0$ and $(w-c) > 0$, $\frac{de_m^{ml}}{dk} > 0$.

The results showed the following:

$$e_c^{cl*} = \frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)} + \frac{s_1}{c_{tc}^{cl}},\ e_m^{cl*} = \frac{(p-w)\lambda + p_t q_0 + s_2 - p_t\lambda\left(e_0 - 2ke_c^{cl}\right)}{c_{tm}^{cl} - 2p_t\lambda}$$

Then,

$$\begin{aligned}\frac{de_c^{cl}}{d\lambda} &= \frac{c_{tm}^{cl}kc_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)(w-c) + 2p_tc_{tc}^{cl}c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl2}\left(c_{tm}^{cl} - 2p_t\lambda\right)^2} \\ &= \frac{c_{tm}^{cl}k(w-c)\left(c_{tm}^{cl} - 2p_t\lambda + 2p_t\lambda\right)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)^2} \\ &= \frac{c_{tm}^{cl2}k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)^2}\end{aligned},$$

Because c_{tm}^{cl}, c_{tc}^{cl} are definitely large, $\left(c_{tm}^{cl} - 2p_t\lambda\right)$ and $(w-c) > 0$ are positive, $\frac{de_c^{cl}}{d\lambda} > 0$.

At the same time,

$$\frac{de_c^{cl}}{dk} = \frac{c_{tm}^{cl}\lambda(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)},$$

$\left(c_{tm}^{cl} - 2p_t\lambda\right) > 0$ and c_{tm}^{cl} is definitely large enough; therefore, $\frac{de_c^{cl}}{dk} > 0$.

$$\begin{aligned}\frac{de_m^{cl}}{d\lambda} &= \frac{\partial e_m^{cl}}{\partial\lambda} + \frac{\partial e_m^{cl}}{\partial e_c^{cl}}\cdot\frac{\partial e_c^{cl}}{\partial\lambda} \\ &= \frac{2p_t\lambda k}{c_{tm}^{cl} - 2p_t\lambda}\cdot\frac{c_{tm}^{cl}k(w-c)}{c_{tc}^{cl2}\left(c_{tm}^{cl} - 2p_t\lambda\right)^2} \\ &= \frac{2p_tc_{tm}^{cl}\lambda k^2(w-c)}{c_{tc}^{cl2}\left(c_{tm}^{cl} - 2p_t\lambda\right)^3}\end{aligned},$$

Because $\left(c_{tm}^{cl} - 2p_t\lambda\right) > 0$, $w - c > 0$, $\frac{de_m^{cl}}{d\lambda} > 0$,

$$\begin{aligned}\frac{de_m^{cl}}{dk} &= \frac{\partial e_m^{cl}}{\partial\lambda} + \frac{\partial e_m^{cl}}{\partial e_c^{cl}}\cdot\frac{\partial e_c^{cl}}{\partial k} \\ &= \frac{2p_t\lambda k}{c_{tm}^{cl} - 2p_t\lambda}\cdot\frac{c_{tm}^{cl}\lambda(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl} - 2p_t\lambda\right)}\end{aligned},$$

$w - c > 0$, c_{tm}^{cl}, c_{tc}^{cl} are definitely large,

Therefore, $\frac{de_m^{cl}}{dk} > 0$.

The conclusion is as follows:

$$\frac{de_c^{ml}}{d\lambda} > 0,\ \frac{de_m^{ml}}{d\lambda} > 0,\ \frac{de_c^{ml}}{dk} > 0,\ \frac{de_m^{ml}}{dk} > 0,\ \frac{de_c^{cl}}{d\lambda} > 0,\ \frac{de_c^{cl}}{dk} > 0,\ \frac{de_m^{cl}}{d\lambda} > 0,\ \frac{de_m^{cl}}{dk} > 0.$$

Appendix A.8. Proof of Proposition 8

From Equations (3) and (5):

$$e_c^{ml*} = \frac{(w-c)k\lambda + s_1}{c_{tc}^{ml}},$$

$$e_m^{ml^*} = \frac{(p-w-p_te_0)\lambda+s_2+p_tq_0}{c_{tm}^{ml}-2p_t\lambda} + \frac{2p_t\lambda^2k^2(w-c)+2kp_t\lambda s_1}{c_{tc}^{ml}\left(c_{tm}^{ml}-2p_t\lambda\right)}$$, and Equations (8) and (10):

$$e_m^{cl^*} = \frac{(p-w)\lambda+p_tq_0+s_2-p_t\lambda\left(e_0-2ke_c^{cl}\right)}{c_{tm}^{cl}-2p_t\lambda},\ e_c^{cl^*} = \frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)} + \frac{s_1}{c_{tc}^{cl}};$$

When the coal enterprise and manufacturer spend the same cost, we can obtain:

$$\begin{aligned}
E^{ml}-E^{cl} &= ke_c^{ml}+e_m^{ml}-e_m^{cl}-ke_c^{cl}\\
&= k\cdot\frac{(w-c)k\lambda+s_1}{c_{tc}} + \frac{(p-w-p_te_0)\lambda+s_2+p_tq_0}{c_{tm}-2p_t\lambda} + \frac{2p_t\lambda^2k^2(w-c)+2kp_t\lambda s_1}{c_{tc}(c_{tm}-2p_t\lambda)}\\
&-\frac{(p-w)\lambda+p_tq_0+s_2-p_t\lambda e_0}{c_{tm}-2p_t\lambda} - k\cdot\frac{c_{tm}\lambda k(w-c)}{c_{tc}(c_{tm}-2p_t\lambda)} - k\cdot\frac{s_1}{c_{tc}}\\
&-\frac{2p_t\lambda k}{c_{tm}-2p_t\lambda}\left[\frac{c_{tm}^{cl}\lambda k(w-c)}{c_{tc}^{cl}\left(c_{tm}^{cl}-2p_t\lambda\right)}+\frac{s_1}{c_{tc}^{cl}}\right]\\
&= \frac{(w-c)k^2\lambda}{c_{tc}} - \frac{2p_tc_{tm}\lambda^2k^2(w-c)+2p_ts_1\lambda k(c_{tm}-2p_t\lambda)}{c_{tc}(c_{tm}-2p_t\lambda)^2}\\
&-\frac{\lambda k^2(w-c)(2p_t\lambda-c_{tm})+2p_t\lambda ks_1}{c_{tc}(c_{tm}-2p_t\lambda)},\\
&= \frac{k\lambda\left[(c_{tm}-2p_t\lambda)^2(w-c)k-2c_{tm}p_t\lambda k(w-c)-2p_ts_1(c_{tm}-2p_t\lambda)+k(w-c)(c_{tm}-2p_t\lambda)^2-2p_ts_1\right]}{c_{tc}(c_{tm}-2p_t\lambda)^2}\\
&= \frac{k\lambda\left[2(c_{tm}-2p_t\lambda)^2(w-c)k-2c_{tm}p_t\lambda k(w-c)-2p_ts_1(c_{tm}-2p_t\lambda)-2p_ts_1\right]}{c_{tc}(c_{tm}-2p_t\lambda)^2}\\
&= \frac{k\lambda\left\{2(w-c)k\left[c_{tm}^2+4p_t^2\lambda^2-4c_{tm}p_t\lambda-c_{tm}p_t\lambda\right]-2c_{tm}p_t\lambda k(w-c)-2p_ts_1(c_{tm}-2p_t\lambda)-2p_ts_1\right\}}{c_{tc}(c_{tm}-2p_t\lambda)^2}\\
&= \frac{k\lambda\left[2(w-c)k\left(c_{tm}^2+4p_t^2\lambda^2-5c_{tm}p_t\lambda\right)-2c_{tm}p_t\lambda k(w-c)-2p_ts_1(c_{tm}-2p_t\lambda)-2p_ts_1\right]}{c_{tc}(c_{tm}-2p_t\lambda)^2}
\end{aligned}$$

because $(c_{tm}-2p_t\lambda)>0$, $w-c>0$, $c_{tm}^2+4p_t^2\lambda^2-5c_{tm}p_t\lambda>0$,

$$-2c_{tm}p_t\lambda k(w-c)-2p_ts_1(c_{tm}-2p_t\lambda)<0,$$

so $ke_c^{ml}+e_m^{ml}-e_m^{cl}-ke_c^{cl}>0$; therefore, $E^{ml}-E^{cl}>0$.

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