COORDINATION STRATEGY FOR A DUAL-CHANNEL ELECTRICITY SUPPLY CHAIN WITH SUSTAINABILITY

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Abstract. This paper describes the construction of a dual-channel electricity supply chain, with an electricity generation enterprise as the leader and an electricity retail enterprise as the follower, examining sustainability and price decision-making, and formulates a coordination contract to improve electricity supply chain performance. The main results are as follows. Firstly, sensitivity to electricity sustainability contributes to increased electricity sustainability, electricity price, electricity demand, and supply chain enterprises’ profits. Secondly, a centralized model is conducive to investment in more sustainable energy production. Finally, electricity supply chain system coordination can be realized by combining revenue-sharing and cost-sharing in a fixed compensation contract.

1. Introduction. With the emergence of new electricity platforms, an increasing number of electricity generation enterprises have deployed a dual-channel mode to sell electricity. For example, Jiangsu and Sichuan have both established provincial electricity trading platforms. Electricity generation enterprises can either sell electricity directly on the electricity trading platform or sell electricity through electricity retail enterprise. In the dual-channel model, electricity generation enterprises and electricity retail enterprises sell electricity of the same quality. When electricity generation enterprises sell electricity on an electricity trading platform, they compete with existing electricity retail enterprises, leading to channel conflicts. Channel conflicts pose a series of problems in the management of an electricity supply chain.

On the one hand, in a dual-channel supply chain, an electricity generation enterprise and an electricity retail enterprise will engage in price competition to maximize their profits. In contrast, to improve the profitability of the supply chain, supply chain enterprises may seek to improve the sustainability of their electricity to improve market attractiveness. For example, improving the efficiency of electricity production, and promoting low-carbon emission of coal-fired electricity,
i.e., electricity sustainability, would generate low-carbon emissions. It then becomes necessary to design a contract that coordinates cooperation between electricity generation enterprises and electricity retail enterprises in the supply chain. Both horizontal price competition and vertical investment cooperation exist in a dual-channel electricity supply chain. Therefore, research on competition and cooperation in an electricity supply chain is conducive to solving practical problems in the electricity market and addressing channel conflicts.

By examining dual-channel supply chains, several researchers have studied green products and coordination. [6] focused on green production in a dual-channel supply chain under a cap-and-trade mechanism. They found that when consumers’ green consciousness meets certain conditions, introducing a dual-channel is beneficial for manufacturers. [14] addressed demand disruption in dual-channel supply chains with green production. They found that the optimal price will increase with demand disruption. [18] focused on green production in a dual-channel supply chain under fuzzy uncertainties. They found that improving the sustainability of products may not be conducive to environmental protection. [1] studied dual-channel social responsibility with manufacturers and retailers under different power market structures. They found that the manufacturer-Stackelberg model can improve green production levels. [12] focused on the subsidy and consumer’s green preference, and they found that the higher subsidy and green preference would lead to the lower price and higher demand. The previous research did not consider the issue of system profit optimization. By examining the coordination of a dual-channel supply chain system, [10] designed a dual-channel supply chain model composed of risk-neutral suppliers and risk-averse retailers and recommended implementing a risk-sharing contract to attain Pareto improvements. [3] focused on the dual-channel recycling decision model with consumers’ preferences for online channel recycling. They designed a composite contract with two-part pricing and revenue-sharing to coordinate the supply chain. [18] focused on pricing and reverse-channel servicing decision-making in a dual-channel closed supply chain. They found that a revenue and cost-sharing contract could improve the profit of supply chain enterprises. [24] focused on the dual-channel closed supply chain with recycling channel selection and found that price contracts could improve the profit of the supply chain enterprise. Although the reports above considered coordination problems in the context of a dual-channel supply chain, these studies did not consider the sustainability of products, an important environmental feature.

Furthermore, previous studies have considered green products and coordination in dual-channel supply chains. For example, [10] focused on pricing and green production decision-making in a dual-channel supply chain and used a two-part tariff contract to coordinate the supply chain. [2] proposed designing a trans-shipment contract to achieve supply chain coordination considering channel disruptions. [15] considered green quality and sales efforts in dual-channel supply chains and found that implementing a revenue-sharing contract can improve the quality of green products. [13] focused on the closed-loop supply chain with dual-channel and illustrated that quality improvement might worsen the whole supply chain. [4] discussed the coordination of green production with eco-label mechanisms and reported that the consumer’s green preference would increase the preference and economic environment for the supply chain. This paper examines pricing and sustainability in coordinating a supply chain at the non-economic scale, unlike the earlier discussed studies.
A dual-channel electricity supply chain game model, including an electricity generation enterprise and an electricity retail enterprise is designed. The electricity generation enterprise at the non-economic scale invests in electricity sustainability to improve carbon emission efficiency and sells electricity through resales and direct sales channels. This paper then compares the supply chain equilibrium results of a decentralized and centralized model and considers the contract coordination mechanism. Finally, through numerical analysis, we investigate the impact of exogenous parameters on the profits of supply chain enterprises.

The primary contributions of this paper are outlined as follows. Firstly, considering the non-economic scale of electricity production, this paper designs and establishes a dual-channel supply chain model, which considers the sustainability of electricity and electricity pricing in the coordination of the supply chain, further advancing sustainability. Secondly, this paper attempts to analyze factors that affect channel conflicts in a dual-channel electricity supply chain, including the sustainability of electricity, the electricity sustainability cost coefficient, and the production cost coefficient. It helps participants understand channel conflicts in the electricity market. Finally, the degree of electricity sustainability and the profit of supply chain enterprises increasing with the degree of sustainability of electricity is established. Increasing consumers’ green awareness is not only conducive to improving the sustainability of energy production but can also increase profits for electricity supply chain enterprises.

2. Model framework. The current research considers an electricity dual-channel supply chain with an upstream electricity generation enterprise and a downstream electricity retail enterprise. The electricity generation enterprise produces electricity and invests in sustainable energy, thus providing electricity sustainability for the market. The first marketing channel considered in the electricity market is the resales channel. When electricity generation enterprises sell electricity to an electricity retail enterprise and the electricity retail enterprise sells the electricity to consumers, this is classified as a resale. The alternative channel considered is the direct sales channel. That is, the electricity generation enterprise directly sells electricity to consumers through the electricity trading platform. In the supply chain model, the following assumptions are used:

**Assumption 1.** It is assumed that the electricity generation enterprise produces electricity at a non-economic scale, widely used in previous studies, such as \([8, 16]\). The electricity production cost is \(G(q) = \frac{1}{2}cq^2\), where \(1 > c > 0\) and represents the electricity production cost coefficient. The larger values for \(c\), the lower the power production efficiency is, and the electricity generation enterprise has to bear more cost. The variable \(q\) is electricity demand.

**Assumption 2.** The electricity generation enterprise invests in sustainable electricity production to reduce carbon emissions, assuming that the investment cost function is \(F(e) = \frac{1}{2}ge^2\), where \(g > 0\) represents the cost coefficient of electricity sustainability; \(e > 0\) represents the degree of electricity sustainability, where the higher the sustainability, the higher the investment cost. This green product investment cost function has been widely used in the literature, such as by Ghosh and Shah \([5, 6, 13, 19]\).

**Assumption 3.** When the electricity generation enterprise operates via the resales channel through the electricity retail enterprise with the wholesale price \(w\), then
the electricity retail enterprise sets the electricity price \( p_r \). When the electricity generation enterprise chooses the direct sales channel to sell electricity, they will directly use the electricity price \( p_m \).

**Assumption 4.** Electricity demand not only depends on the electricity price. It also depends on the degree of sustainability of electricity. Also, some consumers have the preference for channels \(^7\). Referring to the literature, such as \([10, 11, 20]\).

\[
\begin{align*}
q_r &= a - p_r + bp_m + fe \\
q_m &= a - p_m + bp_r + fe
\end{align*}
\]  

(1)

where \( a > 0 \) is the potential market demand scale; \( p_r > 0 \) is the electricity sales price of the electricity retailer, i.e., resell price; \( p_m > 0 \) represents the price of electricity sales of electricity generator, i.e., direct price; \( 1 > b > 0 \) indicates the price competition between the two channels; \( f > 0 \) indicates consumer sensitivity to the sustainability of electricity.

**Assumption 5.** In order to ensure that the equilibrium results are greater than zero, we assume that \( \frac{f^2}{(1-b)[1+(1-b)c]} < g \). Similar assumptions can be found in \([11, 17]\).

Notations and definitions of all variables in this paper are shown in Table 1.

| Notation | Definition |
|----------|------------|
| \( q_m \) | Electricity demand of electricity generation enterprise |
| \( q_r \) | Electricity demand of electricity retail enterprise |
| \( a \) | Potential market demand |
| \( b \) | Price competition between the two channels |
| \( f \) | Sensitivity to electricity sustainability |
| \( c \) | Electricity production cost coefficient |
| \( g \) | Cost coefficient of electricity sustainability |
| \( \pi_m \) | Profit of the electricity generation enterprise |
| \( \pi_r \) | Profit of the electricity retail enterprise |

Decision Variables

| \( p_m \) | Electricity price of electricity generation enterprise |
| \( p_r \) | Electricity price of electricity retail enterprise |
| \( w_r \) | Electricity wholesale price for electricity retail enterprise |
| \( e \) | Degree of sustainability of electricity |

This paper considers the decentralized, centralized, and supply chain coordination models, with superscripts \( d*, c*, \) and \( s* \) representing the three individual models, respectively.

3. **Decentralized model.** Both the electricity generation enterprise and the electricity retail enterprise aim to maximize their respective profits. The profit of the electricity generation enterprise, \( \pi_m^d \), and the electricity retailer, \( \pi_r^d \), can be characterized, respectively, as follows,

\[
\pi_m^d = w_rq_r + p_mbq_m - \frac{1}{2}c(q_r + q_m)^2 - \frac{1}{2}ge^2
\]  

(2)
π_r = (p_r - w_r)q_r \tag{3}

with Eqs. (2)-(3) representing a dual-channel electricity supply chain with an electricity generation enterprise as the leader and an electricity retail enterprise as the follower. Decision-making follows the order: Firstly, the electricity generation enterprise decide the degree of sustainability of the electricity (e) and the electricity wholesale price (w_r); Secondly, the electricity generation enterprise and electricity retail enterprise decide on the electricity prices (p_m) and (p_r).

Using backward induction, the electricity generation enterprise and the electricity retail enterprise decide on the electricity price (p_m, p_r), respectively, to maximize their profits \(\pi_m, \pi_r\). With Eqs. (2)-(3), according to the first-order condition, \(\frac{\partial \pi_m}{\partial p_m} = 0\), \(\frac{\partial \pi_r}{\partial p_r} = 0\), the optimal electricity prices \((p_m^d, p_r^d)\) are,

\[
p_m^d = \frac{(a + ef)[2 + b + (1-b)(3+b)c] + w_r [3b - (1-b)^2c]}{4 - b^2 + (c-b)^2(2+b)} \tag{4}
\]

\[
p_r^d = \frac{(a + ef) [2 + b + (1-b^2)c] + w_r [2 + b^2 + (-1+b)^2c]}{4 - b^2 + c(1-b)^2(2+b)} \tag{5}
\]

We substitute Eqs. (4)-(5) with Eq. (2). With \(\frac{\partial w_r^d}{\partial e} = 0\), and \(\frac{\partial w_r^d}{\partial w_r} = 0\), we have the optimal electricity wholesale price \(w_r^d\) and the degree of sustainability of electricity \(e^d\),

\[
w_r^d = \frac{ag \left[8 + b^3 + c (1-b) (16 + b^2 + b^3) + 2c^2 (3+b) (1-b)^3 \right]}{(1-b) g \left\{ \begin{array}{l} 2 (8 + b^3) + c \left[20 - b (24 - 5b + b^3)\right] + 2c^2 (3+b) (1-b)^3 \right. \\
- f^2 \left[12 + 4b + b^2 + b^3 + 2c(1-b)^2 (3+b) \right] \end{array} \right\} } \tag{6}
\]

\[
e^d = \frac{ag \left[12 + 4b + b^2 + b^3 + 2c (3+b) (1-b)^2 \right]}{(1-b) g \left\{ \begin{array}{l} 2 (8 + b^2) + c \left[20 - b (24 - 5b + b^3)\right] + 2c^2 (3+b) (1-b)^3 \right. \\
- f^2 \left[12 + 4b + b^2 + b^3 + 2c(1-b)^2 (3+b) \right] \end{array} \right\} } \tag{7}
\]

We substitute Eqs. (6)-(7) with Eqs. (4)-(5), respectively. We obtain the optimal electricity price \((p_m^d, p_r^d)\),

\[
p_m^d = \frac{ag \left[8 + 2b - b^2 + c (1-b) (16 + b^2 + b^3) + 2c^2 (3+b) (1-b)^3 \right]}{(1-b) g \left\{ \begin{array}{l} 2 (8 + b^2) + c \left[20 - b (24 - 5b + b^3)\right] + 2c^2 (3+b) (1-b)^3 \right. \\
- f^2 \left[12 + 4b + b^2 + b^3 + 2c(1-b)^2 (3+b) \right] \end{array} \right\} } \tag{8}
\]

\[
p_r^d = \frac{ag \left[12 - 4b + 2b^2 - b^3 + c (1-b) [18 - (1-b) b (4+b)] + 2 (3+b) c^2 (1-b)^3 \right]}{(1-b) g \left\{ \begin{array}{l} 2 (8 + b^2) + c \left[20 - b (24 - 5b + b^3)\right] + 2c^2 (3+b) (1-b)^3 \right. \\
- f^2 \left[12 + 4b + b^2 + b^3 + 2c(1-b)^2 (3+b) \right] \end{array} \right\} } \tag{9}
\]

Finally, we substitute Eqs. (6)-(9) with Eqs. (1)-(3), respectively. We obtain the optimal electricity demand \((q_m^d, q_r^d)\) and electricity supply chain enterprises' profits

\[
\]
(\(\pi_m^{ds}\), \(\pi_r^{ds}\)), respectively,

\[
q_m^{ds} = \begin{cases} 
ag \left(2 - b - b^2\right) \left[4 - b + b^2 + 2c(1-b)^2\right] 
\end{cases}
\]

\[
q_r^{ds} = \begin{cases} 
2a \left(1-b\right) \left[2 + b^2 + c(1-b)^2\right] 
\end{cases}
\]

\[
\pi_m^{ds} = \begin{cases} 
\frac{ga}{2} \left[12 + 4b + b^3 + 2c(3+b)(1-b)^2\right] 
\end{cases}
\]

\[
\pi_r^{ds} = \begin{cases} 
4a^2 g^2 (1-b)^2 \left[2 + b^2 + c(1-b)^2\right]^2 
\end{cases}
\]

Proposition 1. Under the decentralized model, the optimal solutions for electricity wholesale price (\(w_r^{ds}\)), degree of electricity sustainability (\(e_r^{ds}\)), electricity price (\(p_r^{ds}, \pi_r^{ds}\)), electricity demand (\(d_m^{ds}, q_r^{ds}\)) and profit (\(\pi_m^{ds}, \pi_r^{ds}\)) are given by Eqs. (6) - (15), respectively.

Proposition 2. (1) Comparing the optimal electricity price between the two channels, \(p_m^{ds} < p_r^{ds}\). (2) Comparing the optimal electricity demand between the two channels, \(q_m^{ds} > q_r^{ds}\).

Proposition 2 compares the optimal electricity price and electricity demand between the resales channel and sales channel. It shows that \(p_m^{ds} < p_r^{ds}\), and \(q_m^{ds} > q_r^{ds}\). Although the direct channel could set a lower price, the direct channel could not obtain all the demand. Consumers exercise channel preference (Zheng and Hezarkhani, 2021), as the consumers change the channel of purchasing electricity, they need to pay extra costs, such as information search charges.

The electricity retail enterprise should pay the electricity wholesale price for the electricity generation enterprise, which increases the electricity price. Meanwhile, the electricity generation enterprise directly sells the electricity at a lower price to encourage more electricity demand. This “double marginalization” always exists in the supply chain, as the objectives of different supply chain members may conflict. However, the conflict between channels can be avoided by designing reasonable contracts. One suggestion is that the electricity retail enterprise and electricity generation enterprise should set up appropriate contracts enabling more profits.

Proposition 3. With the increase in sensitivity to electricity sustainability \(f\), we have
(1) \(\frac{\partial p_m^{ds}}{\partial f} > 0\); (2) \(\frac{\partial q_m^{ds}}{\partial f} > 0\); (3) \(\frac{\partial p_r^{ds}}{\partial f} > 0\); (4) \(\frac{\partial q_r^{ds}}{\partial f} > 0\); (5) \(\frac{\partial \pi_m^{ds}}{\partial f} > 0\); (6) \(\frac{\partial \pi_r^{ds}}{\partial f} > 0\).
Proposition 3 shows the influence of sensitivity of electricity sustainability \((f)\) on the equilibrium solution. The optimal degree of sustainability of electricity \((e^{d*})\), electricity price \((p^{r*}, p^{m*})\), electricity demand \((q^{r*}, q^{m*})\) and profits \((\pi^{r*}, \pi^{m*})\) increase with \(f\).

The consumer sensitivity to electricity sustainability significantly impacts the decision-making of the dual-channel electricity supply chain. The supply chain’s enterprises should consider the preference of consumers. As consumers’ preference for electricity sustainability increases, supply chain enterprises should improve electricity sustainability. Consequently, the supply chain enterprises would increase the electricity price resulting in higher profits, due to higher electricity sustainability.

This conclusion implies that increasing consumers’ sensitivity to the sustainability of electricity improves the sustainability of energy production and increases the profit of supply chain enterprises. It suggests that the enterprises should cultivate consumers’ preference for electricity sustainability.

**Proposition 4.** With the increase in the sustainability cost coefficient, \(g\), \((1)\) \(\frac{\partial e^{d*}}{\partial g} < 0\); \((2)\) \(\frac{\partial p^{r*}}{\partial g} < 0\); \(\frac{\partial p^{m*}}{\partial g} < 0\); \((3)\) \(\frac{\partial q^{r*}}{\partial g} < 0\); \(\frac{\partial q^{m*}}{\partial g} < 0\).

Proposition 4 shows the influence of the sustainability electricity cost coefficient \((f)\) on the optimal solution. We find the optimal degree of sustainability electricity \((e^{d*})\), electricity price \((p^{r*}, p^{m*})\), electricity demand \((q^{r*}, q^{m*})\), and profits \((\pi^{r*}, \pi^{m*})\) decrease with \(g\).

The sustainability electricity cost coefficient could influence the electricity supply chain enterprise’s decision-making. As the enterprise needs to consider the sustainability electricity cost coefficient, the higher cost, the less motivation to invest in sustainable electricity, which is in line with economic intuition. Moreover, the less sustainable electricity could reduce the electricity demand. Therefore, in order to promote electricity demand, both the electricity generation enterprise and electricity retail enterprise are incentivized to reduce their electricity prices to reduce the reduction in supply chain enterprise profits. The electricity generation enterprise and the electricity retail enterprise engage in a “price war” to expand their share of sales so as to protect the profit of supply chain enterprises. Reducing the cost coefficient could avoid price competition among channels. It suggests that the enterprise should reduce the cost coefficient to provide more electricity sustainability and obtain more profits.

4. **Centralized model.** Both the electricity generation enterprise and electricity retail enterprise aim to maximize profit along the entire electricity supply chain. The function of profit is,

\[
\pi^c = p_r q_r + p_m q_m - \frac{1}{2} c (q_r + q_m)^2 - \frac{1}{2} g e^2 \tag{14}
\]

The electricity supply chain decides the degree of sustainability \(e\) and electricity price \(p_m\) and \(p_r\) to maximize the supply chain’s profit \(\pi^c\). With Eq. (14), according to the first-order condition, \(\frac{\partial \pi^c}{\partial p_m} = 0\), \(\frac{\partial \pi^c}{\partial p_r} = 0\), \(\frac{\partial \pi^c}{\partial e} = 0\), the optimal electricity prices \((p_m^{c*}, p_r^{c*}, e^c)\) are respectively,

\[
p_m^{c*} = p_r^{c*} = \frac{ag \left[ 1 + 2 (1 - b) c \right]}{2g \left( 1 - b \right) (1 + (1 - b) c) - 2f^2} \tag{15}
\]

\[
e^{c*} = \frac{af}{\left( 1 - b \right) g \left[ 1 + (1 - b) c \right] - f^2} \tag{16}
\]
We substitute Eqs. (15)-(16) with Eq. (1) and Eq. (14), and obtain the optimal electricity demand \((qc^r, qc^m)\) and profits \(\pi^c\), respectively,

\[
qc^r = q_c^m = \frac{ag(1-b)}{2g(1-b)[1 + (1-b)c]} - \frac{2f^2}{g(1-b)[1 + (1-b)c] - f^2}
\]

(17)

\[
\pi^c = \frac{a^2g}{2} \{g(1-b)[1 + (1-b)c] - f^2\}
\]

(18)

Proposition 5. Under the centralized model, the optimal solutions for the degree of sustainability \(e^c\), electricity price \((pc^r, pc^m)\), electricity demand \((qc^m, qc^r)\), and profit \(\pi^c\) are given by Eqs. (15)-(18), respectively.

Proposition 5 shows that under the centralized model, there is no difference between the direct sales or the resale channels; that is, the electricity supply chain chooses the same price for both channels. Thus, electricity demand across the two channels remains the same.

Proposition 6. Comparing the optimal solution between the decentralized model and centralized model, we have (1) \(e^c > e^d\); (2) \(q_c^r + q_c^m > q_d^r + q_d^m\); (3) \(\pi^c > (\pi^d_m + \pi^d_r)\).

Proposition 6 compares the optimal solution between the decentralized model and the centralized model. The results show that the degree of electricity sustainability, electricity demand, and electricity supply chain total profits under the centralized model are higher than under the decentralized model.

The centralized model is more conducive to generating electricity sustainability than the decentralized model. There is no “double marginalization” under the centralized model, and the electricity generation enterprise has more motivation to generate sustainable electricity to attract more electricity demand. Moreover, if the electricity generation enterprise and electricity retail enterprise do not aim at maximizing their own profits, they generate increased profits. Reasonable contracts are necessary to improve the outcome of increasing profits for both enterprises. Additionally, more sustainable electricity can be provided for the market, leading to a Pareto improvement, as the supply chain enterprises create more electricity demand. Therefore, it infers that the centralized model can assist in optimizing the coordination of a dual-channel electricity supply chain through designing reasonable contracts.

5. Coordination model. Under the decentralized model, both the electricity generation enterprise and the electricity retail enterprise are independent decision-makers. Their optimal solutions are suboptimal (compared with the centralized model), as the total profits under the decentralized model are lower than those under the centralized model. When designing the contract coordination mechanism, it is necessary to consider reducing “double marginalization” and improving the sustainability of electricity. The composite contract should include revenue-sharing and electricity sustainability cost-sharing with fixed compensation \((w_r, s, T)\). Specifically, on the one hand, the electricity retail enterprise adopts a revenue-sharing contract, with \((1-t)(pr - wr)d_r\) shared with the electricity generation enterprise. On the other hand, the electricity retail enterprise shares the cost of producing sustainable electricity of \(\frac{1}{2}(1-s)ge^2\) with the electricity generation enterprise. Finally, the electricity generation enterprise provides fixed compensation \(T\) to the electricity
retail enterprise. Under the coordination model, the profit of the electricity generation enterprise \( \pi_m^* \) and the profit of the electricity retailer \( \pi_r^* \) can be characterized, respectively, as follows,

\[
\pi_m^* = w_rq_r + p_mq_m - \frac{1}{2}c(q_r + q_m)^2 - \frac{1}{2}sgge^2 + (1 - t) (p_r - w_r) q_r - T
\]

\[
\pi_r^* = t (p_r - w_r) q_r - \frac{1}{2} (1 - s) ge^2 + T
\]

The electricity generation enterprise and electricity retail enterprise decide on the electricity price \((p_m, p_r)\) to maximize their profits \((\pi_m^*, \pi_r^*)\). With Eqs. (19)-(20), according to the first-order condition, \(\frac{\partial \pi_m}{\partial p_m} = 0, \frac{\partial \pi_r}{\partial p_r} = 0\), the optimal electricity prices \((p_m^{**}, p_r^{**})\) are,

\[
p_m^{**} = \frac{ag [1 + 2c (1 - b)]}{2g (1 - b) [1 + (1 - b) c] - 2f^2}
\]

\[
p_r^{**} = \frac{ag [1 + 2 (1 - b) c]}{2g (1 - b) [1 + (1 - b) c] - 2f^2}
\]

We substitute Eqs. (21)-(22) with Eq. (19). When \(\frac{\partial \pi_m}{\partial e} = 0\), we have the optimal degree of electricity sustainability \((e^{**})\),

\[
e^{**} = \frac{f \left\{ a \left[ 8cf^2 + g (2 - t) - 2 (1 - b) cgt \right] + 2tw_r \left[ g (1 - b) [1 + (1 - b) c] - f^2 \right] \right\}}{2 \left( 4cf^2 + gs \right) \left[ g (1 - b) [1 + (1 - b) c] - f^2 \right]}
\]

Let \(q^{**} = q^{**}, w_r^{**} = p_m^{**}, \) and \(p_r^{**} = p_m^{**}\) be the optimal electricity wholesale price \((w_r^{**})\), the proportion of revenue \((s^{**})\), and the proportion of the cost of sustainable electricity \((t^{**})\),

\[
w_r^{**} = \frac{2f^2 (a + ef) + g \left\{ ab + 2ac (1 - b) - 2ef (1 - b) [1 + (1 - b) c] \right\}}{2g (1 - b) [1 + (1 - b) c] - 2f^2}
\]

\[
s^{**} = \frac{f^2 (a + ef) [1 + 2 (1 - b) c] + g \left\{ ab - ef (1 - b) \left[ 1 + 3c (1 - b) + 2c^2 (1 - b)^2 \right] \right\}}{abg}
\]

\[
t^{**} = \frac{2f \left\{ 1 + 2 (1 - b) c \right\} \left\{ f (a + ef) - eg (1 - b) [1 + (1 - b) c] \right\} - 2g f^2 (a + ef) - bg (1 - b) \left[ a + 2 (1 + c - bc) ef \right]}{2b f^2 (a + ef) - bg (1 - b) \left[ a + 2 (1 + c - bc) ef \right]}
\]

We substitute Eqs. (23)-(26) with Eqs. (19)-(20) to obtain the optimal profit of the electricity retail enterprise, the profit of the electricity generation enterprise, and the total profit,

\[
\pi_r^{**} = T
\]

\[
\pi_m^{**} = \frac{a^2g}{2 \left\{ g (1 - b) [1 + (1 - b) c] - f^2 \right\}} - T \pi
\]

\[
\pi^{sc**} = \pi_r^{**} + \pi_m^{**} = \frac{a^2g}{2 \left\{ g (1 - b) [1 + (1 - b) c] - f^2 \right\}}
\]

**Proposition 7.** A combined contract consisting of revenue-sharing and cost-sharing with fixed compensation \((w_r^{**}, s^{**}, T^{**})\) can effectively realize supply chain system coordination.
Proposition 7 shows that the combined contract \((w^*_r, s^*_s, T^*)\) can realize system coordination. First, the electricity retail enterprise shares the revenue \((1 - t)(p_r - w_r)q_r\) with the electricity generation enterprise to reduce the electricity wholesale price, helping the electricity retail enterprise subsequently lower the electricity price to the optimal price in the centralized model. The revenue-sharing contract can reduce the “double marginalization” between the generator and the retailer. From Proposition 2, the resell price is higher than the direct price, as the electricity retail enterprise should pay a higher electricity wholesale price to the electricity generation enterprise. To gain the advantage of a direct channel, the electricity generation enterprise would reduce the competitiveness of the resale channel via the electricity wholesale price. Thus, the revenue-sharing contract could reduce competition between channels, as the electricity generation enterprise’s profit is related to the electricity retail enterprise’s demand.

Second, the electricity retail enterprise shares the cost of electricity sustainability \(\frac{1}{2}(1 - s)ge^2\), in order to incentivize green production by the electricity generation enterprise. When the electricity generation enterprise bears this cost, the degree of electricity sustainability is decreased. The electricity retail enterprise shares part of this cost, improving the degree of electricity sustainability. Moreover, the electricity generation enterprise has a corresponding incentive for lower electricity wholesale prices for the resell sales channels. Therefore, coordinated cost-sharing contracts could generate more electricity demand for the direct and resell channels, leading to more profits for the electricity supply chain.

Finally, the electricity retail enterprise shares their profits and shares the cost of electricity sustainability from the electricity generation enterprise, increasing the profit of the supply chain. To motivate the electricity retail enterprise to implement the revenue and cost-sharing contracts, the electricity generation enterprise needs to give fixed compensation to the retailer.

This combined, coordinated contract shows that revenue-sharing and cost-sharing with fixed compensation are complementary and indispensable. Only when the “double marginalization” between supply chain enterprises is reduced and the degree of sustainability is improved that system coordination is achieved.

**Proposition 8.** Adjusting \(T\), the effect of arbitrarily distributing the profits between the supply chain enterprise can be determined; (2) When \(\pi^{d*}_r \leq T \leq \pi^{c*} - \pi^{m*}_r\), both the electricity generation enterprise and the electricity retail enterprise are willing to accept the combined contract \((w^*_r, s^*_s, T^*)\).

Proposition 8 considers the feasibility of the contract. It shows that in the coordination model, the profits of the electricity generation enterprise and electricity retail enterprise are affected by the fixed compensation \(T\). Specifically, the profit of the electricity retail enterprise increases with \(T\), while the profit of the electricity generation enterprise decreases with \(T\) \(\left(\frac{\partial \pi^{c*}_r}{\partial T} > 0\right)\). When \(T = 0\), the profit of the electricity retail enterprise is zero, and the electricity generation enterprise will obtain all the profits in the supply chain. When \(T = \frac{a^*_g}{2g(1 - k_1) + (1 - b)|c| - f^2}\), the electricity retail enterprise will draw the total profits in the supply chain, while the electricity generation enterprise will obtain zero profits. Intuitively, under the coordination model, it is only when supply chain enterprises earn profits not lower than those under the decentralized model that there will be an incentive to accept the coordination contract. Too high or too low fixed compensation contracts will not be conducive to electricity generation enterprise and electricity retail enterprise
participation. Therefore, when \( \pi_r^{d*} \leq T \leq \pi_c - \pi_m^{d*} \), the profits of the electricity generation enterprise and the electricity retail enterprise in the coordination model will not be lower than those under the decentralized model.

Only a contract that benefits both electricity generation enterprises and retail enterprises will be implemented. The revenue and cost-sharing contracts benefit the electricity generation enterprise, and the fixed compensation benefits the electricity retail enterprise. It suggests that only contracts with mutual benefits, with a win-win scenario, will be mitigated by supply chain enterprises.

6. **Numerical study.** In this section, a numerical study is undertaken to verify the result from the mathematical models and provide more insights into contract coordination. In Figure 1, the impact of the price competition between the two channels \( (b) \) on the electricity dual-channel supply chain’s profit is investigated. The parameters values are derived as follows: \( a = 25, c = 0.1, f = 0.2, g = 2 \), and \( b \in [0.1, 0.8] \). The profits increase with price competition between the two channels. The more intense the competition is, the smaller the difference between channels is, thus increasing the profits. Actually, the electricity demand would increase with the price competition between the two channels. It suggests that supply chain enterprises benefit from increased competition between channels.

In Figure 2, the impact of the electricity production cost coefficient \( (c) \) on the electric dual-channel supply chain’ profits is analyzed. The parameters value derived are: \( a = 25, b = 0.1, f = 0.2, g = 2 \), and \( c \in [0.1, 0.8] \). The profits decrease with the electricity production cost coefficient. The higher cost paid by the electricity generation enterprise for generating electricity causes erosion of the profits. Moreover, the electricity generation enterprise would transfer this cost to the electricity retail enterprise. Therefore, reducing the electricity production cost coefficient is conducive to the improvement of the whole supply chain.

In Figure 3, the impact of the cost coefficient of electricity sustainability \( (g) \) on the electricity dual-channel supply chain’ profits is analyzed. The parameters value derived are: \( a = 25, b = 0.1, f = 0.2, c = 0.1 \), and \( g \in [0.1, 0.8] \). The profits decrease with the cost coefficient of electricity sustainability. The electricity generation enterprise would bear the cost of electricity sustainability, which erodes the profits. It suggests that reducing the cost coefficient of electricity sustainability is conducive to the improvement of the whole supply chain.

In Figure 4, the impact of the sensitivity to electricity sustainability \( (f) \) on the electricity dual-channel supply chain’ profits is analyzed. The parameters value derived are: \( a = 25, b = 0.1, g = 2, c = 0.1 \), and \( f \in [0.1, 0.8] \). The profits increase with the sensitivity to electricity sustainability. Consumers’ preference for electricity sustainability would improve the profits of supply chain enterprises, as the consumer pays a higher price for the electricity sustainability. It suggests that increasing consumer preference is beneficial to the total overall supply chain.

From Figs. 1-4, we could draw similar conclusions. Firstly, the total profits of the electricity supply chain under the centralized model are higher than those under the decentralized model, which highlights the necessity of designing the appropriate contract. The most suitable contract can promote the electricity supply chain enterprises to generate more profits. Secondly, the profit of electricity generation enterprises is higher than that of electricity retail enterprise, as the electricity generation enterprise is the leader of the electricity supply chain. In contrast, the electricity retail enterprise is the follower. The electricity generation enterprise
makes larger profits by taking advantage of their position as leaders, which also explains why supply chain enterprises strive to be leaders. On the one hand, it suggests that the profit of electricity supply chain enterprises can be improved by optimizing contracts; on the other hand, large profit gaps between enterprises should be prevented.

7. Conclusion. This paper studies the degree of electricity sustainability, pricing decisions, and contract coordination in a dual-channel electricity supply chain, where the electricity generation enterprise is the leader, and the electricity retail enterprise is the follower. The electricity generation enterprise sells electricity of the same quality through resales and direct sales channels. Based on the optimal solution under the decentralized and centralized models, the optimal electricity price and degree of sustainability across the two sales channels are compared. Furthermore, the impact of the electricity sustainability cost coefficient and sensitivity to electricity sustainability on the optimal solution is investigated, and a coordinated contract is considered. The main results are as follows: (1) the degree of electricity sustainability,
the electricity price, electricity demand, and supply chain enterprise profit are reduced with the electricity sustainability cost coefficient; (2) a centralized model is conducive to investment in more sustainable energy production; (3) Supply chain coordination can be realized by deploying a combined contract composed of revenue-sharing and sustainable electricity production cost-sharing with fixed compensation.

This paper analyzes the competition between direct channel and resale channel based on the background of electricity dual-channel. The suggestions are as follows. Firstly, electricity supply chain enterprises should cultivate consumers’ preference for electricity sustainability. Cultivating consumers’ preference, supply chain enterprises can provide more electricity sustainability and obtain more profits. The degree of electricity sustainability in the dual-channel supply chain would change due to consumers’ preferences. Secondly, electricity generation enterprises should reduce the cost of electricity sustainability. The government should actively guide enterprises to increase the R & D investment in electricity sustainability. This is beneficial to the development of electricity sustainability and improving the quality of the environment. Finally, both electricity generation enterprises and electricity retail enterprises should realize that decentralized decision-making would reduce the profits of supply chain enterprises. In contrast, centralized decision-making increases the profits of supply chain enterprises by including feasible contracts that avoid “double marginalization” in decentralized decision-making. The inclusion of a feasible contract causes the profits of the electricity generation enterprises and electricity retail enterprise to increase.

The current study focuses on the degree of sustainability, pricing, and contract coordination in a dual-channel electricity supply chain. However, several aspects are worthy of further research. Firstly, this paper focuses on coordinating the traditional model, including an electricity generation enterprise and an electricity retail enterprise. Other powerful models, such as the medium and long-term contracts, can be considered in future research. Secondly, this paper only considers the degree of electricity sustainability of the electricity generation enterprise while disregarding the service quality of the electricity retail enterprise, which should be considered in future studies. Thirdly, this paper focuses on the competition channels in the electricity supply chain. Future research should consider the competition between chains.

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Appendix.

Proof. Comparing the optimal solution in Proposition 1, we have,

\[
p_{m}^{d*} - p_{r}^{d*} = -\frac{ag(1-b)[2(2+c) - b(2-b)(1+2c)]}{(1-b)g[2(8+b^2) + c[20 - b(24-5b+b^3)] + 2c^2(3+b)(1-b)^3] - f^2[12 + 4b + b^2 + b^3 + 2c(1-b)^2(3+b)]} < 0
\]
With the optimal solution in Proposition 1, we have,

\[
\frac{\partial e^*}{\partial p} = \frac{\partial f^*}{\partial p} = \frac{\partial g^*}{\partial p} = \frac{\partial \pi^*}{\partial p} = 0
\]

Therefore, we can obtain Proposition 2.

Proof. With the optimal solution in Proposition 1, we have,

\[
q_m^*-q_c^* = \begin{cases}
\frac{ag}{1-b^2}[2(2+c)-b(2-b)(1+2c)] \\
+2c^2(3+b)(1-b)^3 \\
(1-b)g[2(8+b^2)+c[20-b(24-5b+b^3)] \\
+2c^2(3+b)(1-b)^3 \\
\end{cases} > 0
\]

\[
\frac{\partial e^*}{\partial f} = \begin{cases}
\frac{2afg[12+4b+b^2+b^3+2(1-b)^2(3+b)]}{[8+2b-b^2+c(1-b)(16+b^2+b^3)+2c^2(3+b)(1-b)^3]} \\
\frac{2afg[12+4b+b^2+b^3+2(1-b)^2(3+b)]}{[12-4b+2b^2+b^3+c(1-b)(16+b^2+b^3)+2c^2(3+b)(1-b)^3]} > 0
\end{cases}
\]

\[
\frac{\partial g^*}{\partial f} = \begin{cases}
\frac{4afg(1-b)[2+b^2+c(1-b)^2]}{[12+4b+b^2+b^3+2c(3+b)(1-b)^2]} \\
\frac{fga^2[12+4b+b^2+b^3+2c(3+b)(1-b)^2]}{[12-4b+2b^2+b^3+c(1-b)(16+b^2+b^3)+2c^2(3+b)(1-b)^3]} > 0
\end{cases}
\]

\[
\frac{\partial \pi^*}{\partial f} = \begin{cases}
\frac{16fga^2(1-b)^2[2+b^2+c(1-b)^2]}{[12+4b+b^2+b^3+2c(1-b)^2(3+b)]} \\
\frac{fga^2[12+4b+b^2+b^3+2c(3+b)(1-b)^2]}{[12-4b+2b^2+b^3+c(1-b)(16+b^2+b^3)+2c^2(3+b)(1-b)^3]} > 0
\end{cases}
\]
Therefore, we obtain Proposition 3.

Proof. With the optimal solution in Proposition 1, we have,

\[
\frac{\partial \pi_{ds}^*}{\partial g} = \begin{cases}
    \frac{a f(1-b)[12 + 4b + b^2 + b^3 + 2c(3 + b)(1-b)^2]}{2(8 + b^2) + c[20 - b(24 - 5b + b^3)] + 2c^2(3 + b)(1-b)^3} \\
    (1-b)g2(8 + b^2) + c[20 - b(24 - 5b + b^3)] + 2c^2(3 + b)(1-b)^3 \\
    -f^2[12 + 4b + b^2 + b^3 + 2(1-b)^2(3+b)c]
\end{cases} < 0
\]

\[
\frac{\partial p_{m}^*}{\partial g} = \begin{cases}
    \frac{af^2[12 + 4b + b^2 + b^3 + 2c(3 + b)(1-b)^2]}{[8 + 2b - b^2 + c(1-b)(16 + b^2 + b^3) + 2c^2(3 + b)(1-b)^3] \\
    (1-b)g2(8 + b^2) + c[20 - b(24 - 5b + b^3)] + 2c^2(3 + b)(1-b)^3 \\
    -f^2[12 + 4b + b^2 + b^3 + 2(1-b)^2(3+b)c]
\end{cases} < 0
\]

\[
\frac{\partial p_{r}^*}{\partial g} = -\begin{cases}
    \frac{a f^2[12 + 4b + b^2 + b^3 + 2c(3 + b)(1-b)^2] \\
    12 - 4b + 2b^2 - b^3 + c(1-b)[18 - (1-b)b(4+b)] \\
    +2(1-b)^3(3+b)c^2}
\end{cases} < 0
\]

\[
\frac{\partial d_{ms}^*}{\partial g} = -\begin{cases}
    \frac{a(2 - b - b^2) (4 - b + b^2 + 2(1-b)^2c)}{\left[12 + 4b + b^2 + b^3 + 2(1-b)^2 (3+b)c\right] f^2} \\
    (1-b)g2(8 + b^2) + c[20 - b(24 - 5b + b^3)] \\
    +2c^2(3 + b)(1-b)^3 \\
    -f^2[12 + 4b + b^2 + b^3 + 2(1-b)^2(3+b)c]
\end{cases} < 0
\]

\[
\frac{\partial d_{ds}^*}{\partial g} = -\begin{cases}
    \frac{2a f^2 (1-b) \left(2 + b^2 + c(1-b)^2\right)}{\left[12 + 4b + b^2 + b^3 + 2c(3 + b)(1-b)^2\right]^2} \\
    (1-b)g2(8 + b^2) + c[20 - b(24 - 5b + b^3)] \\
    +2c^2(3 + b)(1-b)^3 \\
    -f^2[12 + 4b + b^2 + b^3 + 2(1-b)^2(3+b)c]
\end{cases} < 0
\]

\[
\frac{\partial \pi_{ds}^*}{\partial g} = -\begin{cases}
    \frac{a^2 f^2 \left[12 + 4b + b^2 + b^3 + 2c(3 + b)(1-b)^2\right]^2}{2} \\
    (1-b)g2(8 + b^2) + c[20 - b(24 - 5b + b^3)] \\
    +2c^2(3 + b)(1-b)^3 \\
    -f^2[12 + 4b + b^2 + b^3 + 2(1-b)^2(3+b)c]
\end{cases} < 0
\]

\[
\frac{\partial \pi_{dr}^*}{\partial g} = -\begin{cases}
    \frac{8gf^2 a^2(1-b)^2 \left[2 + b^2 + c(1-b)^2\right]^2}{\left[12 + 4b + b^2 + b^3 + 2(-1+b)^2 (3+b)c\right]^3} \\
    (1-b)g2(8 + b^2) + c[20 - b(24 - 5b + b^3)] \\
    +2c^2(3 + b)(1-b)^3 \\
    -f^2[12 + 4b + b^2 + b^3 + 2(1-b)^2(3+b)c]
\end{cases} < 0
\]

Therefore, we obtain Proposition 4.
Proof. Comparing the optimal solution of the decentralization model and the centralization model, we have,

\[
e^{c^*} - e^{d^*} = \frac{afg(1 - b)^2[4 + b^2 + 2c(1 - b)^2]}{2f^2 - g(1 - b)[1 + (1 - b)c]} > 0
\]

\[
q^{c^*} + q^{d^*} - p^{d^*} - q^{d^*} = \frac{ag(1 - b)^2[b(2 + b - 2c) + 2(2 + c)] - 2bf^2}{2f^2 - g(1 - b)[1 + (1 - b)c]} > 0
\]

\[
\pi^{c^*} - \pi^{d^*} - \pi^{d^*} = \frac{f^2[12 + 4b + b^2 + b^3 + 2c(3 + b)(1 - b)^2] - g(1 - b)(3 + b)c^2(1 - b)^3}{2(8 + b^2) + c[20 - b(24 - 5b + b^3)] + 2(3 + b)c^2(1 - b)^3} > 0
\]

Therefore, we obtain Proposition 6. \qed

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