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Optimal production and pricing strategies in auto supply chain when dual credit policy is substituted for subsidy policy

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ABSTRACT

The Chinese government has proposed a dual credit policy (DCP) as a substitute for electric vehicle (EV) subsidies, which fluctuates the auto market. To investigate the policy substitution influences for the production and pricing strategies, we use Stackelberg game paradigms to model a two-stage auto supply chain. The manufacturer regulated by the DCP produces both EV and internal combustion engine vehicles (ICEV). The retailer sells them to heterogeneous consumers. By backward induction, the optimal production and pricing strategies are derived for the subsidy policy only (scenario *B*) and with a joint subsidy policy and DCP (scenario *DS*). Our findings show, 1) different with only one case in scenario *B*, the manufacturer and the retailer have three corresponding optimal production and pricing strategies in scenario *DS*, according to the manufacturer's Corporate Average Fuel Consumption credit (CAFC credit); 2) the demand for the ICEV may also decline like EV as the subsidies are phased out in scenario *DS* when the manufacturer's CAFC credit is in balance case; 3) the changes of DCP rules may have different effects on the optimal production and pricing strategies in different CAFC cases.

1. Introduction

With energy-saving and various government initiatives, electric vehicles (EVs) have captured broad interest worldwide, as useful alternatives to internal combustion engine vehicles (ICEVs) [1–3]. In 2018, the global EV fleet exceeded 5.1 million, up to 2 million from 2017, which was almost double the number of EV sales [4]. China has remained the world's largest EV market in the last five years, due to the influence of governmental subsidy policy [5]. The subsidies are estimated to be RMB 400 billion during the 13th Five Year (2015–2020) Plan period [6]. To reduce the fiscal burden and prompt the sustainable adoption of EV, China started to cut the EV subsidies in 2019 and plans to totally abolish these subsidies in 2022. To eliminate the possible negative effect caused by cutting the subsidies, the Chinese government has proposed a new policy, called the dual credit policy (DCP) that took effect on April 1, 2018.[1] However, EV sales in China dropped for the first time in 2019, by 4% compared with the previous year [7]. In the future, EV subsidies will be continuously cut, and DCP will be sustainably adjusted [8].

During the policy substitution process to move from subsidies to the DCP, the manufacturer will be in a dilemma to select his production and pricing strategies. For one side, with the cutting subsidies the manufacturer may decrease EV production and turn back to ICEV as the two products cannibalize each other in the market [9–11]. On the other hand, the DCP prompts the manufacturer to make new pricing strategies to enlarge EV sales to achieve DCP credits. As such, the DCP significantly complicates the production and pricing optimization problem for both the manufacturer and the retailer.

There has been an increase in research on operational decision-making in auto supply chains given the subsidy policy. Some studies have focused on the effects of government's EV subsidy incentive scheme on stimulating EV sales [12–14]. Bao et al. [15] explored the short- and long-term repeated game behaviors of two parallel auto supply chains, they uncovered that the prices of EVs

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[1] The dual-credit system is similar to the Carbon Cap policy of the European Union (EU) and the Zero Emissions Vehicle policy of California in the United States (U.S.) that took effect on April 1, 2018. It consists of the corporate average fuel consumption credit (CAFC credit) rules, which set targets for the average energy consumption per-mile (AECP) for eligible vehicle, and the new energy credit (NE-credit) rules, which stipulate credits by EV type and require certain NE credit quotas from the production of ICEV (the detailed principles see section 2).

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are more dependent on the reduction of carbon emissions and government subsidy than ICEVs. It shows the scaling back subsidy will have great effects on the auto supply chain, especially for the EVs. Meanwhile, some studies focus on the comparison of subsidy policy with other incentive policies. For instance, Shao et al. [10] compared the subsidy scheme and price discount scheme and found that the government prefers to implement a subsidy incentive scheme due to the lower expenditures involved. Some focus on the optimization of subsidy policy. Luo et al. [16] and Zhang and Cai [17] investigated the optimal subsidy policy in a dynamic way. Gu et al. [18] and Saha et al. [19] studied the optimal subsidy allocations to EV customers and manufacturers. These studies focused on the subsidy policy of EV, and have done too much work in the subsidy policy however, none have evaluated the abolishment of subsidies.

Although the auto enterprises in China are facing the situation that the DCP is substituted for subsidy policy in reality, the research on the abolishment of subsidies and the introduction of DCP is very limited. Wang et al. [20] developed a system dynamics model of China's EV adoption to analyze the effectiveness of EV policies. They found that the decline of EV subsidy policy will result in a sharp decline of EV market share in China, and the DCP has an obvious positive effect on EV promotion. Li et al. [2] explored the substitution effect of the DCP for examining the subsidy policy under different scenarios using a game theory-based analysis model. Li et al. [21] proposed mixed-integer linear programming to develop a stylized production model for an ICEV supply chain and EV supply chain system. These models simultaneously incorporated subsidies and the DCP. However, EV adoption mainly depends on the heterogeneous consumer behavior, which has not been considered. Moreover, the studies described above derived the solutions from the whole market but did not generate analytical solutions from the perspective of the auto supply chain.

It is well known that the DCP has different effects on the different auto manufacturers according to their production circumstances of ICEVs and EVs. The auto enterprises may have different optimal production and pricing strategy changes when the DCP is substituted for subsidy policy. As such, different from these researches, we focus on the production and pricing decision from the auto supply chain perspective. On the supply chain perspective, Zhou et al. [22] generalized the DCP and investigated its effects on green technology investments and pricing decisions in the auto supply chain without considering the phasing out subsidies. As such, to the best of our knowledge, there is a gap in terms of how to make production and pricing strategies during the process of the subsidy policy substituted by the DCP. Moreover, this is a real problem faced by auto manufacturer and retailer in China. Hence, it motivated us to examine the following key questions:

(1) How should the production and pricing strategies be optimized during the process of substituting the DCP for the subsidy policy?
(2) What are the different effects between the scaling back subsidy policy alone and the DCP substitute for the scaling back subsidy policy on production and pricing strategies?
(3) What are the effects of the key factors (i.e., subsidies, the price of the new energy (NE) credit, and the DCP rules on the production and pricing strategies, and the benefits of the manufacturer and the retailer?

To address these questions, we investigated an auto supply chain consisting of one manufacturer, one retailer, and consumers. The manufacturer, regulated by the DCP, determines the wholesale prices and produces both the EVs and the ICEVs based on the order from the retailer. Then, the retailer determines the order quantities and the retail prices of both the EV and the ICEV. The heterogeneous consumers make their purchasing decisions. To capture the underlying strategic interactions among three parties, we use a game theory framework which is commonly used as a tool to evaluate the effectiveness of policies [10,23]. The production and pricing strategies are optimized and compared in, subsidy policy only (scenario *B*) and with a joint subsidy policy and DCP (scenario *DS*), two scenarios. This paper contributes to theory and practice by investigating how the scaling back of subsidies and the DCP rules change influence production and pricing strategies in the supply chain:

(1) Both the subsidy policy and DCP are considered in our model, simultaneously. What's more, different from one optimal production and price strategy case in scenario *B*, we derived three possible optimal production and price strategy cases in scenario *DS* according to the manufacturer's Corporate Average Fuel Consumption credit (CAFC credit) when the credit is negative (Case I), "balanced" or zero (Case II), or positive (Case III). It means the manufacturers and retailers should make their different optimal production and pricing strategies according to their own circumstance of CAFC credit in scenario *DS*, which may have manageable value to their operation management.
(2) When the subsidies are phased out, the demand for the ICEV will always increase in scenario *B*. However, in scenario *DS*, the phasing out subsidy for EV may also damage the demand of ICEV in case II of scenario *DS*. Meanwhile, in scenario *DS*, the demand for the EV will lose more sales in case I and III than in case II.
(3) When the government changes the DCP rules, the optimal production and pricing decisions change differently even opposite in different cases. Further, when the price of the NE credit fluctuated, the optimal solutions not only change differently in different cases, but also the optimal production and pricing strategies may change in the opposite way according to one threshold in Case II.

The remainder of this paper is organized as follows. We present the models for only subsidy policy and both the subsidy policy and the DCP in Section 2. The equilibriums of the two models are presented in Section 3. The analysis and discussion of different parameters are presented in Section 4. Numerical examples are given in Section 5. Section 6 concludes the paper with a discussion of the possible future research direction. All proofs are presented in Appendix.

2. Model description

We investigated an auto supply chain that includes the government, one manufacturer, one retailer, and consumers. The manufacturer is the game's leader and produces both the EV and the ICEV. The manufacturer sells the EV and the ICEV to a retailer with wholesale prices of w_1 and w_2, respectively. The retailer orders the EV and the ICEV and sells them to end consumers with prices of p_1 and p_2, respectively. When consumers buy the EV, they receive subsidies S from the government. The unit cost of the EV is generally greater than the ICEV. As such, we assume the unit costs of the EV and the ICEV are βc, and c respectively, with $\beta > 1$ [24]. The manufacturer makes to order from the retailer [25]. It is assumed that the manufacturer and the retailer in the auto supply chain are risk-neutral and have full and symmetric information. Fig. 1 shows the channel structures.

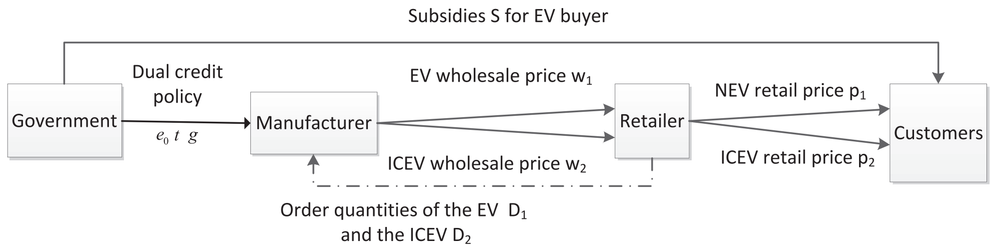

Fig. 1. Process and order of decision-making in the auto supply chain.

2.1. The consumers

Each consumer is going to buy an EV, or an ICEV, or refrain from buying either. Meanwhile, we assume that there is a unit mass of consumers in the market, which is common in the research of supply chain operation [23,26,27]. Similar to Desai and Purohit [28]; Lim et al. [29]; Luo et al. [30]; and Shao et al. [10]; the consumer utility towards the EV and the ICEV are described in Equations (1) and (2), respectively.

$$U_{EV} = [1 + k(e_2 - e_1)]V - (p_1 - S) \quad (1)$$

$$U_{ICEV} = V - p_2 \quad (2)$$

In this expression, V reflects the heterogeneous valuation that consumers place on the vehicle. For simplicity of calculation, we normalize the customer valuation towards the EV in the interval $[0, 1]$. This treatment is commonly used in the research of supply chain management and does not change the results [10,30,31]. The variable k refers to the consumer's environmental awareness. The terms e_1 and e_2 refers to the average energy consumption of the EV and the ICEV, respectively. The EV is more energy efficient than ICEV. The consumers have a higher reservation value towards the environment friendly product, which is the EV [32,33]. Besides, the higher of consumer's environmental awareness, the more extra reservation value can get from the environment-friendly product by the consumer. As such, we assume $e_2 > e_1$. Therefore, the term $[1 + k(e_2 - e_1)]$ in equation (1) reflects the utility coefficient achieved by buying the EV compared with buying the ICEV. The S represents the subsidies received by the consumer when purchasing the EV.

2.2. The retailer

To satisfy demand by heterogeneous consumers, the retailer makes the decision to order specific quantities of the EV and the ICEV based on their respective wholesale prices. Meanwhile, the retailer determines the retail prices of the EV and the ICEV to maximize his (or her) own profit. The profit function of the retailer is expressed in Equation (3).

$$\Pi_r(p_1, p_2) = (p_1 - w_1)D_1(p_1, p_2) + (p_2 - w_1)D_2(p_1, p_2) \quad (3)$$

2.3. The manufacturer

For the manufacturer, this study considered two scenarios. In the benchmark scenario with only the subsidy policy, the government provides subsidies to consumers who buy the EV. This is set as scenario B, and we express the profit function of the manufacturer in scenario B as equation (4).

$$\Pi_m^B(w_1, w_2) = (w_1 - \beta c)D_1(p_1, p_2) + (w_2 - c)D_2(p_1, p_2) \quad (4)$$

In the scenario with both the subsidy and the DCP, the government not only provides the subsidies to consumers but also sets rules for the auto manufacturer for both CAFC credit and the NE credit. This is set as scenario DS. The following discussions explain CAFC credit and NE credit.

1) CAFC credit

For the auto manufacturer, the CAFC credit is expressed as: $\sum_{i=1}^{2}(e_0 - e_i)D_i$ (where $i = 1$ represents the EV and $i = 2$ denotes the ICEVs). In this expression, e_i is the actual energy consumption permile of product i; e_0 is the target AECP set by the government; and D_i is the demand for product i. Generally, e_1 is consistently lower than e_0, as the EV's energy consumption is normally low. However, e_2 can be either higher or lower than e_0 for different auto manufacturers. A negative CAFC credit indicates that the manufacturer does not satisfy the environmental requirement. As such, the manufacturer needs the same NE credits as a deduction. If there are insufficient NE credits, the manufacturer has to buy the corresponding NE credits from the market at price p. Positive NE credits cannot be traded. Therefore, the value of surplus CAFC credits is zero.

2) NE credit

The NE credit for the manufacturer is calculated as $gD_1 - tD_2$, where g represents the NE credits gained by producing the unit EV. The term t represents the NE credit quota which means the manufacturer will lose t NE credit due to produce one unit ICEV. The NE credits can be traded in the market at price p, which is exogenously defined. When the NE credits are negative, the manufacturer needs to buy corresponding NE credits from the market to satisfy the government's requirements. Otherwise, surplus credits can be sold in the market. The manufacturer's year-end credit-settlement should be non-negative. Therefore, the profit function of the manufacturer in scenario DS is expressed as follows:

$$\Pi_m^{DS}(w_1, w_2) = (w_1 - \beta c)D_1(p_1, p_2) + (w_2 - c)D_2(p_1, p_2) + \left\{gD_1(p_1, p_2) - tD_2(p_1, p_2) + \left[\sum_{i=1}^{2}(e_0 - e_i)D_i(p_1, p_2), 0\right]^- \right\}p \quad (5)$$

Note: if $a < b$, $[a, b]^- = a$, and if $a > b$, $[a, b]^- = b$.

The sequence of events is as follows. First, the manufacturer determines the wholesale prices w_1 and w_2 of EVs and ICEVs, respectively. Then, the retailer decides the retail prices p_1 and p_2 for EVs and ICEVs, respectively. Finally, consumers make their purchase decision.

3. Equilibriums conditions

This section describes the backward deduction method used to derive the equilibrium in scenario *B* and scenario *DS*. Hence, we first derive the consumer demand towards the EV and the ICEV in equilibrium. Based on this, we derive the optimal prices of the EV and the ICEV in equilibrium in both scenario *B* and scenario *DS*. All the detailed solving processes are provided in the Appendix.

3.1. Scenario B with only subsidy policy (benchmark)

To maximize the consumer's own utility, the consumer will purchase the EV when the utility function is $U_{EV}>0$ and $U_{EV}>U_{ICEV}$. In contrast, the consumer will purchase the ICEV, when the consumer's utility function is $U_{ICEV}>0$ and $U_{ICEV}>U_{EV}$. Otherwise, the consumer will not buy either. Hence, we derive the indifferent value V_0 representing the decision to buy the NE or the ICEV, and the indifferent value V_1 representing the decision to buy the ICEV or not. Thresholds in consumer valuation: consumers select the EV if $V\in(V_0,\ 1)$; consumers will select the ICEV, if $V\in(V_1,\ V_0)$, and consumers decide not to buy, if $V\in(0,V_1)$.

$$[1-k(e_1-e_2)]V_0-(p_1-S)=V_0-p_2 \tag{6}$$

$$V_1-p_2=0 \tag{7}$$

$$D_1=1-V_0 \tag{8}$$

$$D_2=V_0-V_1 \tag{9}$$

Equations (6)–(9) are applied to derive the demand function $D_1=1-\frac{p_1-S-p_2}{k(e_2-e_1)}$ and $D_2=\frac{p_1-S-p_2}{k(e_2-e_1)}-p_2$. The demand function indicates three possible cases based on the different subsidies: only EV, only ICEV, and both EV and ICEV. In the real market, most auto enterprises produce both EV and ICEV. As such, this study focused on the case of both the EV and the ICEV, e.g., $D_1>0$ and $D_2>0$. The upper thresholds of the subsidies are obtained: $S_{lower}=p_1-p_2-k(e_2-e_1)$ and $S_{upper}=p_1-p_2-kp_2(e_2-e_1)$. When the subsidies are within the range of $[S_{lower},S_{upper}]$, both EV and ICEV are required by the consumers. Otherwise, only EV or ICEV is required by the consumers.

Based on the demand for EV and ICEV, the retailer makes the retail pricing decision to maximize his own profits. D_1 and D_2 are introduced in the retailer's profit function shown in Equation (10).

$$\Pi_r(p_1,p_2)=(p_1-w_1)\left(1-\frac{p_1-S-p_2}{k(e_2-e_1)}\right)+(p_2-w_1)\left(\frac{p_1-S-p_2}{k(e_2-e_1)}-p_2\right) \tag{10}$$

We further derive the equilibrium retail price in Equations (11) and (12).

$$p_1^*=\frac{1+k(e_2-e_1)+S+w_1}{2} \tag{11}$$

$$p_2^*=\frac{1+w_2}{2} \tag{12}$$

We can find that the optimal retail prices of the EV and the ICEV have a positive linear relationship with wholesale prices. As such, we only need to analyze the changes in the optimal wholesale price. Further, when subsidies increase or consumer environmental awareness improves, the retailer will increase the retail price of the EV. Finally, the manufacturer makes the decision of the wholesale prices for the EV and ICEV. Therefore, we calculate the equilibriums in *scenario B* as Lemma 1.

Lemma 1. *There exists a unique solution in scenario B.* Table 1 *provides the optimal pricing decisions for the manufacturer (w_1^B, w_2^B) and the retailer (p_1^B, p_2^B); the demand for the EV (D_1^B) and the ICEV (D_2^B), and the profit of both the retailer (Π_r^B) and the manufacturer (Π_m^B).*

Table 1 shows that both the wholesale and retail prices of the EV increase when *S* increases. However, the wholesale and retail prices of the ICEV are unrelated to *S*. Hence, as subsidies *S* are phased out, demand for the EV will fall, but demand for the ICEV will increase. This may be why a repeal of a registration tax exemption for EV led to a drop in EV sales in Denmark. Meanwhile, when subsidies are phased out, the manufacturer will experience a decrease in profits. In addition, the lower and the upper thresholds of the subsidies can be derived: $S_{lower}^B=(\beta-1)c-(e_2-e_1)k$ and $S_{upper}^B=c[(\beta-1)-k(e_2-e_1)]$, respectively.

3.2. Scenario DS with both subsidy policy and the DCP

When the government simultaneously implements the subsidy policy and DCP, as is the current practice in China, the manufacturer must trade off the benefits from the product sales and the payoff or expenditures of the DCP credits. Consistent with the benchmark case analysis, we generate the equilibriums in Scenario *DS* as Lemma 2. The profits of the manufacturer and the retailer are provided in the Appendix.

Lemma 2. *With both the subsidy and DCP policies, the manufacturer (w_1^{DS}, w_2^{DS}) and the retailer (p_1^{DS}, p_2^{DS}) have three different optimal pricing decisions in three cases.* Table 2 *shows the corresponding demand of the EV (D_1) and the ICEV (D_2). For concisely, the profit of the manufacturer (Π_m^{DS}) and the retailer (Π_r^{DS}) are provided in the Appendix.*

Table 2 indicates that in contrast to the decisions associated with the "subsidy only" in Lemma 1, the manufacturer and the retailer have three possible optimal production and pricing strategy

Table 1
The optimal solutions with the "subsidy policy only" (**Model** *B*).

$w_1^B=\frac{1+(e_2-e_1)k+\beta c+S}{2}$	$w_2^B=\frac{1+c}{2}$
$p_1^B=\frac{3[1+(e_2-e_1)k+S]+\beta c}{4}$	$p_2^B=\frac{3+c}{4}$
$D_1^B=\frac{c(1-\beta)+(e_2-e_1)k+S}{4k(e_2-e_1)}$	$D_2^B=\frac{c(\beta-1)-ck(e_2-e_1)-S}{4k(e_2-e_1)}$
$\Pi_r^B=\frac{[c(\beta-1)-(e_2-e_1)k-S][\beta c-1-(e_2-e_1)k-S]-(c-1)[c(\beta-1-(e_2-e_1)k)-S]}{16k(e_2-e_1)}$	
$\Pi_m^B=\frac{[c(\beta-1)-(e_2-e_1)k-S][\beta c-1-(e_2-e_1)k-S]-(c-1)[c(\beta-1-(e_2-e_1)k)-S]}{8k(e_2-e_1)}$	

Table 2
The optimal solutions with both subsidy policy and DCP (**Model** *DS*).

S	$[S^{DS}_{lower}, G_{S1}]$ /case I	$[G_{S1}, G_{S2}]$ /case II	$[G_{S2}, S^{DS}_{upper}]$ /case III
w_1	$\frac{1+(e_2-e_1)k+S-(e_0-e_1+g)p+\beta c}{2}$	$\frac{[c+pt-2e_1k+kpt(e_2-e_0)](e_0-e_1)+[c(\beta-e_1k)+(ce_0k-gp)](e_2-e_0)+e_2-e_1+2k(e_0^2+e_2^2)-2ke_2(e_0+e_1)+k[\beta c-gp+S+(e_2-e_1)k](e_0-e_2)^2+(e_0+e_2-2e_1)S}{2[e_1-e_2-k(e_2-e_0)^2]}$	$\frac{1+(e_2-e_1)k+S-gp+\beta c}{2}$
w_2	$\frac{1+c+(e_2-e_0+t)p}{2}$	$\frac{(c+pt)(e_0-e_1)+k(2e_0-e_2-e_1)(e_0-e_2)+(\beta c-gp-S)(e_2-e_0)+e_2-e_1}{2[e_2-e_1+k(e_2-e_0)^2]}$	$\frac{1+c+tp}{2}$
p_1	$\frac{3[1+(e_2-e_1)k+S-(e_0-e_1+g)p]+\beta c}{4}$	$\frac{1+(e_2-e_1)k+S+w_1}{2}$	$\frac{3[1+(e_2-e_1)k+S-gp]+\beta c}{4}$
p_2	$\frac{3+c+(e_2-e_0+t)p}{4}$	$\frac{1+w_2}{2}$	$\frac{3+c+tp}{4}$
D_1	$\frac{c(1-\beta)+(e_2-e_1+g+t)p+S}{4k(e_2-e_1)}+\frac{1}{4}$	$\frac{(e_0-e_2)((c+pt)(e_0-e_1)+(k(e_0-e_2)-1)(e_2-e_1)+(c\beta-gp-S)(e_2-e_0))}{4(e_2-e_1)[e_2-e_1+k(e_2-e_0)^2]}$	$\frac{c(1-\beta)+(g+t)p+S}{4k(e_2-e_1)}+\frac{1}{4}$
D_2	$\frac{c(\beta-1)-p(g+t)-S}{4k(e_2-e_1)}-\frac{p}{4k}-\frac{c+(e_2-e_0+t)p}{4}$	$\frac{(e_0-e_1)((c-pt)(e_0-e_1)+(k(e_0-e_2)-1)(e_2-e_1)+(c\beta-gp-S)(e_2-e_0))}{4(e_1-e_2)[e_2-e_1+k(e_2-e_0)^2]}$	$\frac{c(\beta-1)-(g+t)p-S}{4k(e_2-e_1)}-\frac{pt+c}{4}$

Note: $S^{DS}_{lower} = (\beta-1)c-(e_2-e_1)k-(e_2-e_1+g+t)p$; $S^{DS}_{upper} = (\beta-1)c-k(c+pt)(e_2-e_1)-p(g+t)$; $G_{S1} = (\beta-1)c+k(e_1-e_0)+k(c+pt)(e_0-e_2)-p(e_2-e_1+g+t)-kp(e_0-e_2)^2$ $G_{S2} = (\beta-1)c+k(e_1-e_0)+k(c+pt)(e_0-e_2)-p(g+t)$.

cases. The three possible cases are associated with two thresholds G_{S1} and G_{S2}. To express this concisely, we denote $S\in[S^{DS}_{lower}, G_{S1}]$ as Case I, $S\in[G_{S1}, G_{S2}]$ as Case II, $S\in[G_{S2}, S^{DS}_{upper}]$ as Case III. The three cases reflect how the manufacturer should optimize pricing decisions when the CAFC credits are negative, zero (or balanced), and positive, respectively. In other words, with the DCP, the government sets a target AECP for the manufacturer to reflect the effects of products on the environmental externality. In Case I, the manufacturer's actual AECP exceeds the target when the optimal production and pricing decisions are optimal. This means that in Case I, the manufacturer creates a negative environmental externality; the opposite is true in Case III. Hence, with the DCP, the manufacturer is required to pay for the negative environmental externality by purchasing an equal number of NE credits from the other manufacturers, like Case III. Further, the wholesale and retail prices of the EV decrease as subsidies are scaled back. Meanwhile, consistent with Lemma 1, the actual subsidies should fall in the range of $[S^{DS}_{lower}, S^{DS}_{upper}]$ to maintain both EV and ICEV sales.

4. Discussion

This section first discusses the effects of DCP on EV and ICEV production and pricing strategies. Then, we analyze the effects of phasing out subsidies on EV and ICEV production and pricing decisions. Third, we analyze the NE credit's price on the production and pricing decision. Finally, we analyze the effects of DCP rules.

4.1. The DCP on the production and pricing strategies

Corollary 1. *The DCP can stimulate the demand for the EV, because of the relationship of the subsidy thresholds between scenario B and scenario DS: $S^B_{lower} > S^{DS}_{lower}$; $S^B_{upper} > S^{DS}_{upper}$.*

Corollary 1 reflects the effects of the DCP on the manufacturer's production (or the retailer's order) choice of products. We can find if the actual subsidies are phased into the interval between S^{DS}_{lower} and S^B_{lower}, both the EV and ICEV might be needed in scenario *DS* but only ICEV is needed in scenario *B*. This reflects that the DCP has a stimulating effect, promoting the EV. When the subsidies are significantly phased out, the retailer may order fewer or, even abandon the EV. Because of the high cost of the EV, the EV may not be acceptable to consumers. Further, the EV may cannibalize the ICEV market. As such, it may be wise for the manufacturer to give up EV production at this time. However, in the scenario where there is both the subsidy and DCP policy, the manufacturer determines the tradeoff between the benefit of product sales and the payoff or expenditure of credits. This increases the payoff of the EV unit and decreases the payoff of the ICEV unit. Hence, in this circumstance, the manufacturer and the retailer are more motivated to produce and retail the EV.

In addition, in scenario *DS*, we further calculate that as subsidies are phased out to a level less than $(e_2-e_1+g+t)p$, the retailer should order both the EV and the ICEV. In extreme cases, if subsidies are high enough, the profit per unit EV is significantly higher than the ICEV. To prevent the ICEV from cannibalizing the EV market, the retailer is likely to stop ordering the ICEV. Similarly, the retailer is likely to stop ordering the ICEV when provided with the DCP.

Corollary 2. *In scenario DS, the prices (w^{DS}_1, p^{DS}_1) of the EV and the demand for ICEV D^{DS}_2 are consistently lower compared to scenario B. However, in scenario DS, the prices (w^{DS}_2, p^{DS}_2) of the ICEV and the demand for EV D^{DS}_1 are consistently higher compared to scenario B.*

Corollary 2 reflects the effects of the DCP on the optimal production and pricing strategies. This demonstrates that although the DCP stimulates the EV adoption and decreases EV prices, it improves ICEV transaction costs, increasing the ICEV price. As such, the DCP negatively impacts the ICEV market when it stimulates EV adoption.

4.2. The phasing out of subsidies on production and pricing decisions

Proposition 1. *The phasing out of subsidies has a nonmonotonic effect on the prices and the demand for the ICEV when comparing scenarios B and DS.*

(1) *In scenario B, the subsidies S do not affect the wholesale and retail price of the ICEV w^B_2, p^B_2. However, in scenario DS, as subsidies S decrease, the wholesale and retail price of the ICEV w^{DS}_2, p^{DS}_2 increases when the subsidies $S\in[G_{S1}, G_{S2}]$, and remain the same as $S\in[S^{DS}_{lower}, G_{S1}]\cup[G_{S2}, S^{DS}_{upper}]$.*

(2) *In scenario B, the demand for ICEV D_2^B increases as S decreases. However, in scenario DS, the demand for the ICEV D_2^{DS} decreases as $S \in [G_{S1}, G_{S2}]$, and increases as $S \in [S_{lower}^{DS}, G_{S1}] \cup [G_{S2}, S_{upper}^{DS}]$.*

Proposition 1 reflects the effects of phasing out subsidies on the pricing decisions and demand for ICEV. The demand for the ICEV increases and the demand for the EV decreases when phasing out subsidies, because of the cannibalization effects between EV and ICEV. However, in scenario *DS*, ICEV sales may also decrease as subsidies decrease. This is because the subsidies range within $[G_{S1}, G_{S2}]$ when affected by the DCP; the manufacturer should try to keep the CAFC credits in balance to avoid the expense of negative CAFC credits. In these circumstances, when subsidies are phased out, the manufacturer should decrease the wholesale price of EV and increase the wholesale price of ICEV. This leads to a decrease in demand for both the EV and the ICEV.

Corollary 3. *In both scenario B and DS, the demand for the EV D_1 and the profit of the manufacturer Π_m and the retailer Π_r decrease as the subsidies are phased out. However, in scenario DS, the demand for the EV D_1^{DS} is associated with a greater loss in Case I and III compared to II.*

Corollary 3 reflects the effects of phasing out subsidies on EV demand and the manufacturer's profit. It indicates that the auto firms will experience a loss in economic benefits as subsidies are scaled back. In addition, in the case of positive or negative CAFC credits, the manufacturer will lose more demand for EVs compared to the cases with balanced CAFC credits. It is because to balance the CAFC credits, these auto manufacturers have to decrease more wholesale price of EVs.

4.3. The impact of the NE-credit price on production and pricing decisions

Proposition 2. *We derive the different production and pricing strategies of the EV and the ICEV in three cases when the NE-credit price p increases. All are shown in* Table 3.

Note: $p_{low} = \frac{(\beta-1)c+(e_1-e_2)k-S}{e_2-e_1+g+t}$; $p_{S1} = \frac{(\beta-1)c+(e_1-e_0)k+ck(e_0-e_2)-S}{e_2-e_1+g+t+k(e_0-e_2)^2+kt(e_2-e_0)}$; $p_{S2} = \frac{(\beta-1)c+(e_1-e_0)k+ck(e_0-e_2)-S}{g+t+kt(e_2-e_0)}$; $p_{up} = \frac{(\beta-1)c+ck(e_1-e_2)-S}{e_2-e_1+g+t}$.

Proposition 2 reflects the effects of the price of NE credits on production and pricing decisions. Table 5 shows that the increased price of the NE credit, have different effects on the production and pricing decisions in different cases. In Case I, the manufacturer's products cannot reach the target AECP. When the price of the NE credit increases, the manufacturer should expend more on credits. This makes it wise for the manufacturer to decrease the wholesale price of the EV and raise the wholesale price of the ICEV. This improves the relative competitiveness of the EV, which leads to more EVs and fewer ICEVs. In Case III, the change in the optimal production and pricing decision should reflect the same trend as Case I. In Case II, the change in the decision may lead to opposite results. When $\frac{(e_0-e_1)}{(e_2-e_0)} > \frac{g}{t}$, the manufacturer should raise the wholesale price of both the EV and the ICEV; the reverse is also true.

The term $\frac{(e_0-e_1)}{(e_2-e_0)}$ and the term $\frac{g}{t}$ represent the moderate AECP rate and the earned NE credit rate by producing the EV and the ICEV, respectively. When the moderate AECP rate is relatively large and the earned NE credit rate is relatively small, the benefit of producing EV and ICEV units decrease with the total production quantities of both products. As such, in this circumstance, the manufacturer should implement a market-skimming pricing strategy. However, when the moderate AECP rate is relatively small, but the rate of the earned NE credit is relatively large, the benefit of producing EV and ICEV units increased as the total production quantities of both products increase. As such, in these circumstances, the manufacturer should develop a penetrating pricing strategy.

Table 4
The effects of parameters t on production and pricing decisions.

parameters	Cases	w_1^{DS}	w_2^{DS}	D_1^{DS}	D_2^{DS}
$t\uparrow$	$t \in [t_{low}, t_{S1}]$	→	↑	↑	↓
	$t \in [t_{S1}, t_{S2}]$	↑	↑	↑	↓
	$t \in [t_{S2}, t_{up}]$	→	↑	↑	↓

Note: $t_{low} = \frac{(\beta-1)c+k(e_1-e_2)+(e_1-e_2-g)p-S}{p}$; $t_{S1} = \frac{(\beta-1)c+(e_1-e_0)k+ck(e_0-e_2)+(e_1-e_2-g)p-kp(e_0-e_2)^2-S}{p+kp(e_2-e_0)}$; $t_{S2} = \frac{(\beta-1)c+k(e_1-e_0)+ck(e_0-e_2)-gp-S}{p+kp(e_2-e_0)}$; $t_{up} = \frac{(\beta-1)c+ck(e_1-e_2)-gp-S}{p+kp(e_2-e_1)}$.

Table 5
The effects of parameters g on production and pricing decisions.

parameters	Cases	w_1^{DS}	w_2^{DS}	D_1^{DS}	D_2^{DS}
$g\downarrow$	$g \in [g_{low}, g_{S1}]$	↑	→	↓	↑
	$g \in [g_{S1}, g_{S2}]$	↑	↑	↓	↓
	$g \in [g_{S2}, g_{up}]$	↑	→	↓	↑

Note: $g_{low} = \frac{(\beta-1)c+k(e_1-e_2)-S}{p} + (e_1 - e_2 - t)$; $g_{S1} = \frac{(\beta-1)c+k[(e_1-e_0)+(c+pt)(e_0-e_2)-p(e_0-e_2)^2]-S}{p} + (e_1 - e_2 - t)$; $g_{S2} = \frac{(\beta-1)c+k(e_1-e_0)+k(pt+c)(e_0-e_2)-S}{p} - t$; $g_{up} = \frac{(\beta-1)c+k(e_1-e_2)(pt+c)-S}{p} - t$.

Table 3
The effects of p on production and prices.

$p\uparrow$		w_1^{DS}	w_2^{DS}	D_1^{DS}	D_2^{DS}
$p \in [p_{low}, p_{S1}]$		↓	↑	↑	↓
$p \in [p_{S1}, p_{S2}]$	if $\frac{(e_0-e_1)}{(e_2-e_0)} > \frac{g}{t}$	↑	↑	↓	↓
	if $\frac{(e_0-e_1)}{(e_2-e_0)} = \frac{g}{t}$	→	→	→	→
	if $\frac{(e_0-e_1)}{(e_2-e_0)} < \frac{g}{t}$	↓	↓	↑	↑
$p \in [p_{S2}, p_{up}]$	↓	↑	↑	↓	

4.4. The impact of DCP parameters on production and pricing decisions

The Chinese government announced that in 2021, 2022, and 2023, the NE credit quota for producing an ICEV unit will be 14%, 16%, and 18% respectively. The credit quota in 2024 and later shall be separately announced by the Ministry of Industry and Information Technology. In the meanwhile, the NE credit earned by producing an EV unit also changes significantly [8]. This leads to an analysis focusing on the changes of NE credit quota by producing an ICEV unit and the earned NE credit by producing an EV unit, as Proposition 3 and Proposition 4, respectively.

Proposition 3. *When the NE credit quota by producing unit ICEV t increases, we can derive the production and pricing strategies change shown in* Table 4.

Proposition 3 reflects the fact that when the government improves the NE credit quota by producing an ICEV unit, the wholesale and the retail price of the ICEV should increase. This may lead to the production of more EVs and fewer ICEVs. However, the EV wholesale and the retail prices may vary in different cases. When the manufacturer's CAFC credit is positive or negative, the ICEV wholesale price should remain the same as before; however, it should increase as the manufacturer's CAFC credit is balanced.

Proposition 4. *When the earned NE credit by producing the unit EV g changes, we can derive the production and pricing strategies, as shown in* Table 5.

Proposition 4 reflects the fact that when the government decreases the NE credit earned by producing the EV unit, the wholesale and the retail price of the EV should be increased. However, the ICEV wholesale and retail prices may vary in different cases. When the manufacturer's CAFC credit is positive or negative, the ICEV wholesale price should remain the same. However, the ICEV price should be increased when the manufacturer's CAFC credit is in balance. In addition, the demand for ICEV will increase when the manufacturer's CAFC credit is negative, but it will decrease when the manufacturer's CAFC credit is balanced.

5. Numerical simulation

This section presents a numerical simulation to investigate three main areas: (1) a comparative analysis of subsidies on the optimal production, pricing decisions, and profit in scenario B and scenario DS; (2) the impact of the trading price of the NE credits to identify the optimal solutions; and (3) a sensitivity analysis of DCP rules. Based on the assumptions above and the previous researches like Avci et al. [34]; Zhu et al. [35]; and Deng and Tian [36]; we established the following parameters: $\beta = 1.5$; $c = 0.8$; $e_1 = 0.2$; $e_2 = 0.6$; $e_0 = 0.5$; $k = 0.8$; $g = 0.1$ $t = 0.1$; $p = 0.05$. All the subsequent parameters in the numerical experiments use these settings; where changes were needed, we will make a clear statement.

5.1. Example 1

Applying Lemma 1 and 2 yields, the lower threshold and the upper threshold of the subsidies in the "subsidy only" policy (scenario B) and in subsidy and the DCP (scenario DS), respectively, shown in Table 6.

Table 6 shows that both the lower threshold and the upper threshold in Model B is higher than the case in Model DS (0.0800 > 0.0600 and 0.1520 > 0414), which verifies Corollary 1. Then, we further derive that $G_{S1} = 0.0954$ and $G_{S2} = 0.1057$. Fig. 2 and Fig. 3 show the effects of the subsidies on the optimal pricing and production, levels in scenario B and scenario DS, respectively. Fig. 4 shows the impact of subsidies on the manufacturer's and the retailer's profits.

Table 6
The two thresholds of subsidies in scenario B and scenario DS.

	Lower threshold S_{lower}	Upper threshold S_{upper}
Model *B*	0.0800	0.1520
Model *DS*	0.0600	0.1414

Fig. 2 corresponds with Theorem 2 and indicates that the optimal wholesale prices for the EV and ICEV have three different cases. When the subsidies are below 0.1057, the wholesale price of the ICEV should increase as the subsidies are phased out; the increase stops when the subsidies are below 0.0954. Thus, when the subsidies are within the range of [0.0954, 0.1057], the required quantities of both the EV and the ICEV will be improved. It corresponds to Proposition 1. Besides, the wholesale price of the EV in scenario B is consistently lower compared to scenario DS. However, the opposite is true for ICEV. This corresponds to Corollary 2.

Fig. 3 shows that the demand for EV in scenario DS is consistently larger compared to scenario B, vice versa the ICEV. This reflects that the DCP stimulates EV adoption, but it hinders the ICEV sales which correspond to the conclusion of Corollary 2. In addition, the demand for both the ICEV and EV decreases as the subsidies are phased out when the subsidies are in an intermediate-range: [0.0954, 0.1057]. Hence, the scaling back of subsidies may shrink ICEV sales when the manufacturer's CAFC credit is in balance. This corresponds to the results of Proposition 1.

Fig. 4 demonstrates that both the manufacturer and the retailer's profits will decrease as the subsidies are phased out. However, both the manufacturer and the retailer can benefit from the DCP when the subsidies are high enough. The retailer may lose more profit than the manufacturer with the DCP. Fig. 4 shows that when the subsidy is below 0.1057, the manufacturer will lose profits because of the DCP policy. Otherwise, the manufacturer will benefit from the DCP. However, the retailer will suffer a decrease in profits, unless the subsidy exceeds 0.1245.

5.2. Example 2

Denoting $S = 0.1$ reveals the effects of the price of the NE -credit p on the optimal wholesale prices, the demand, and the profits from the EV and the ICEV. This is shown in Fig. 5.

Fig. 5 shows that changes in the optimal wholesale price, the demand, and the profit differ when p is in three different ranges. This verifies the Proposition 2 as $\frac{(e_0-e_1)}{(e_2-e_0)} = \frac{g}{t}$.

5.3. Example 3

This example involves a sensitivity analysis of the DCP parameters. The subsidies are denoted as $S = 0.1$. Fig. 6 and Fig. 7 show the sensitivity analysis of parameters associated with the NE credit quota by producing an ICEV unit and receiving NE credits by producing an EV unit.

Fig. 6 shows that when the NE credit quota for producing an ICEV unit is in an intermediate region [0.0132, 0.2075], both the demand for the EV and the ICEV decrease as t increases. This corresponds to Proposition 3. The manufacturer's and the retailer's profits decrease as t increases.

Fig. 7 verifies Proposition 5. To achieve NE credits by producing the unit EV g in the range of [0.0080, 0.2140], the demand for ICEV increases as g increases. The profits of the manufacturer and the retailer increase as g increases.

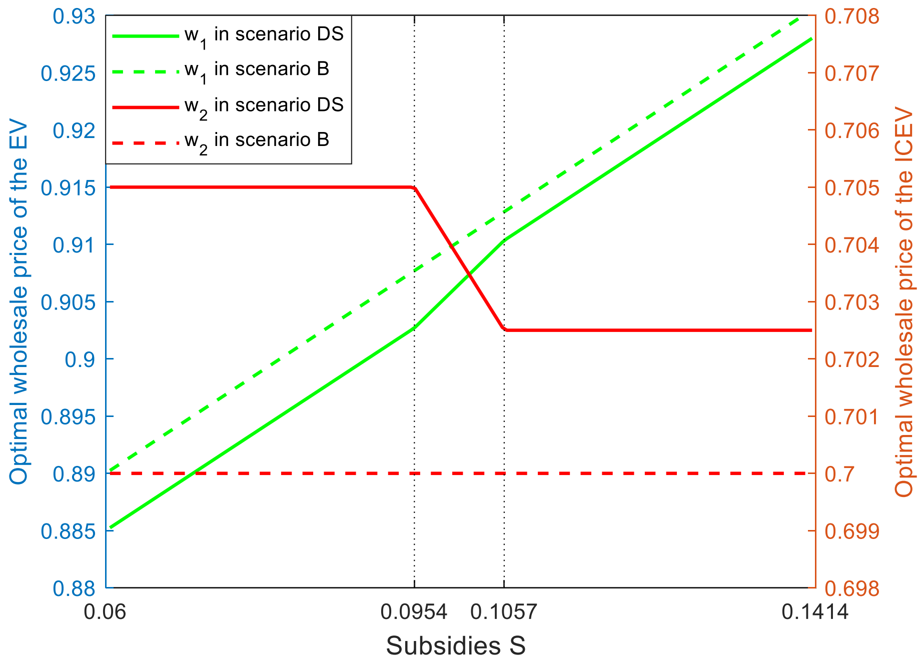

Fig. 2. The impact of subsidies on the wholesale price.

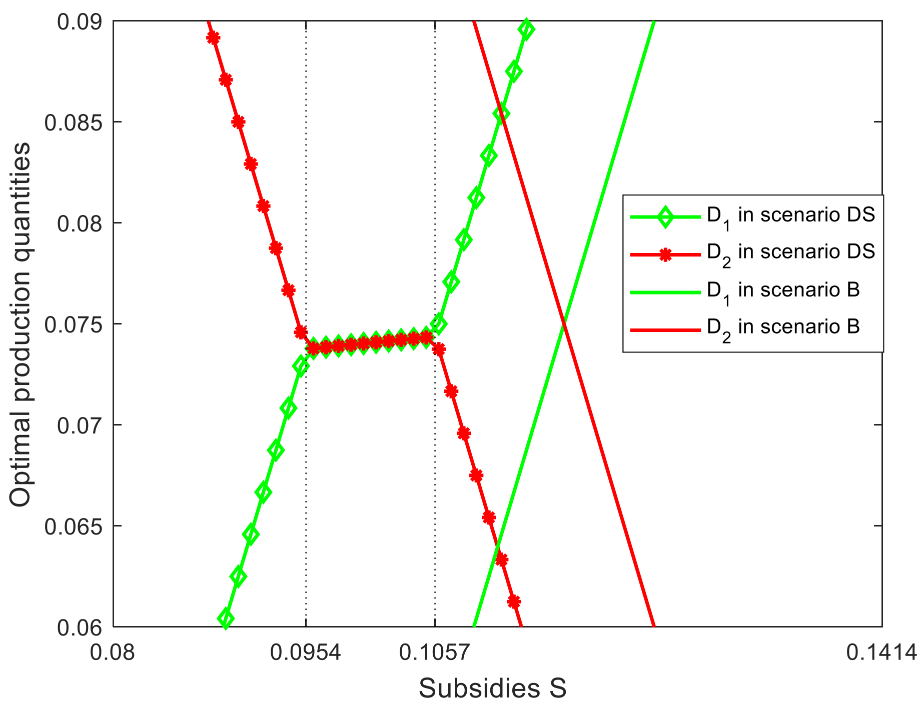

Fig. 3. The impact of subsidies on the optimal production quantities.

6. Conclusion

This study was motivated by new challenges in production and pricing in auto supply chains, caused by the advancing of DCP policy and the phasing out of the subsidy policy. The study investigated an auto supply chain with consumers, and one manufacturer, and one retailer. The manufacturer regulated by the DCP produces both the EV and the ICEV based on the quantities ordered by the retailer. Consumers are heterogeneous in their valuation of EV and ICEV. Stackelberg game paradigms were applied to develop models with the "subsidy only" policy, and with both the subsidy and the DCP. Key observations and implications are as follows.

A lower threshold and an upper threshold were identified to quantify the product production choice decision. The DCP lowers the two thresholds and stimulates EV adaption, however, it also increases the transaction cost of the ICEV. This lowers the demand for the ICEV. This means the auto firms should consistently implement the conversion to EV production as the DCP replaces the subsidy policy. In addition, during the policy substitution process, the manufacturer and the retailer should optimize their production

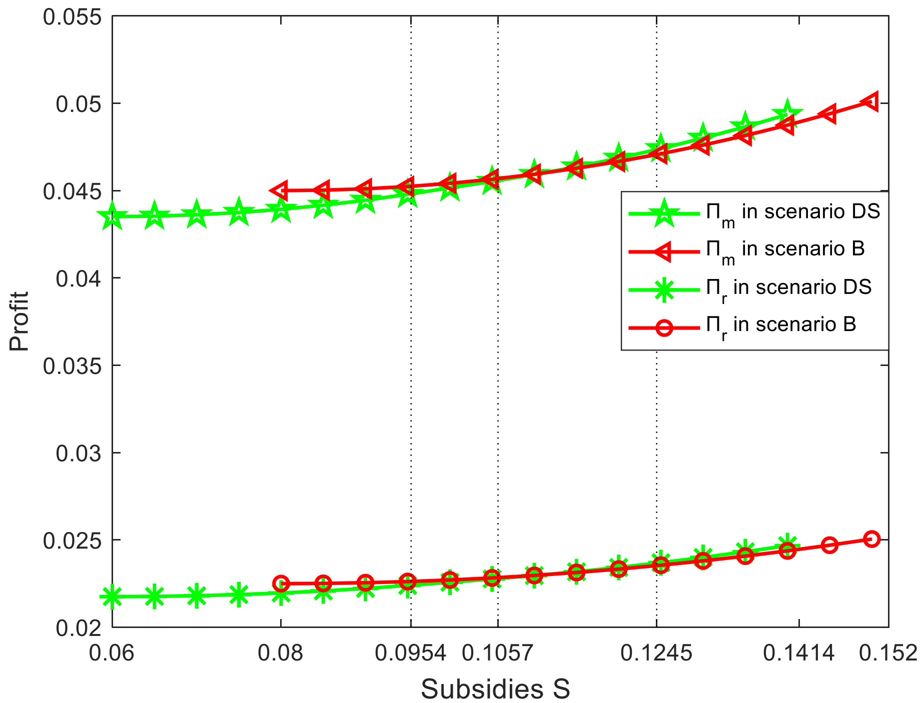

Fig. 4. The impact of subsidies on the manufacturer and the retailer's profit.

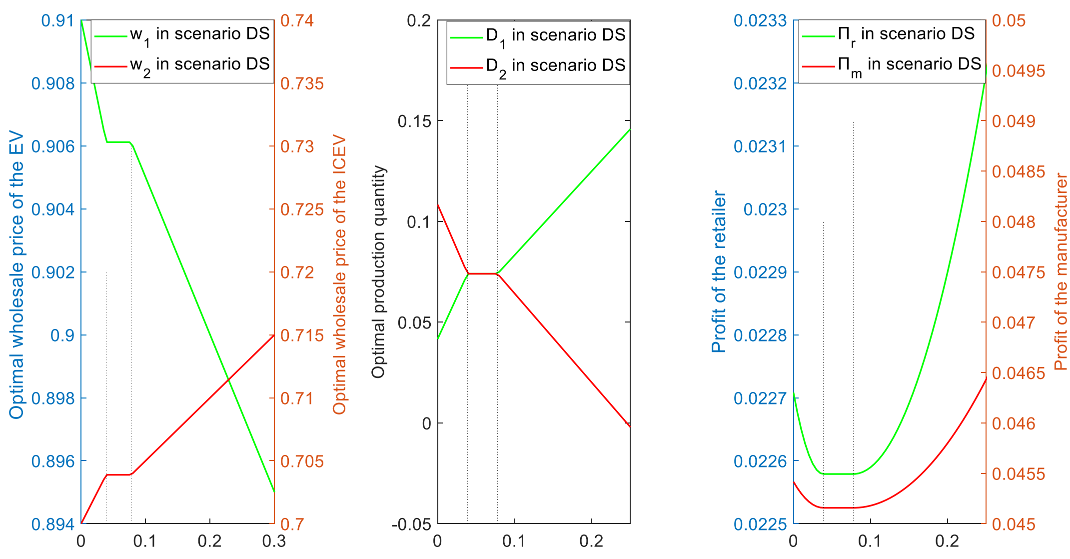

Fig. 5. The impact of NE credits price on the wholesale price, production quantities, and profit.

and price decisions depending on the values of the manufacturer's CAFC credit. The scaling back of subsidies, counter-intuitively, will decrease both the demand of ICEV and EV when the manufacturer's CAFC-credits is balanced. The production and pricing strategies vary based on the DCP rules change in different cases associated with the manufacturer's CAFC credit level. Further, as the price of NE credit changes, optimal solutions may also change in the opposite direction, based on one threshold.

This study provides a general analytical framework for production and pricing strategies, based on customer value in a supply chain structure involving subsidy and the DCP. We analyzed the manufacturer and the retailer's optimal production and pricing decision with subsidy and DCP in different cases. Our study provides manufacturers and retailers with decision supports to help them develop accurate production and pricing strategies to improve their profits during the process of the subsidy policy being substituted by the DCP. Besides, our study proves that the DCP has stimulation effects on EV promotion and gives the parameter sensitivity analysis of the DCP, which would give some policy implications for the government.

Consistent with the models used in previous literature, the model in this study is based on the assumption of a monopoly setting. An extension of this work could be to consider two or multiple competing manufacturers and retailers. Other future

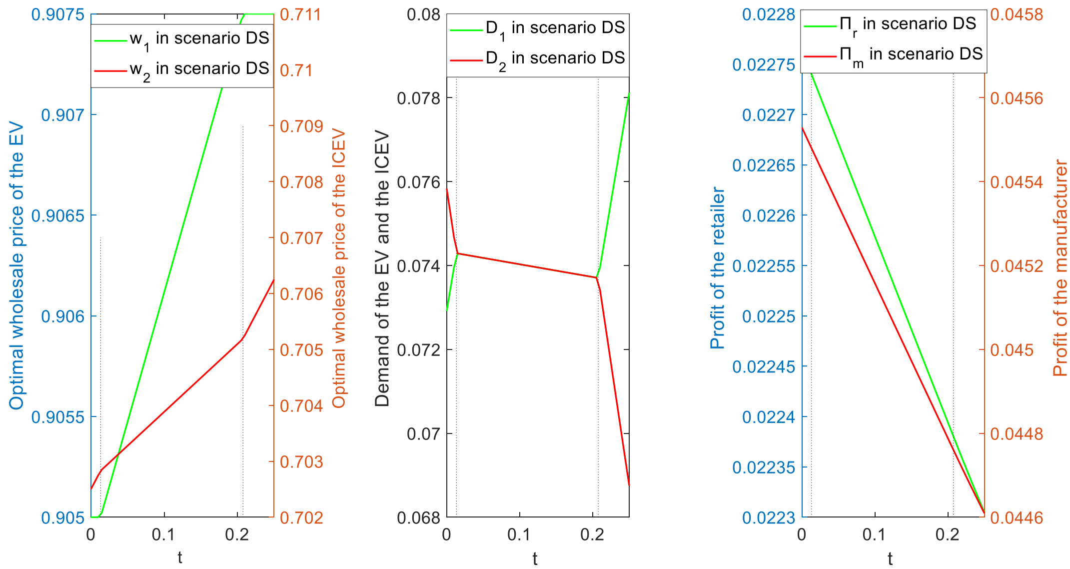

Fig. 6. The impact of the NE credit quota by producing an ICEV unit on the wholesale price, production quantities, and profit.

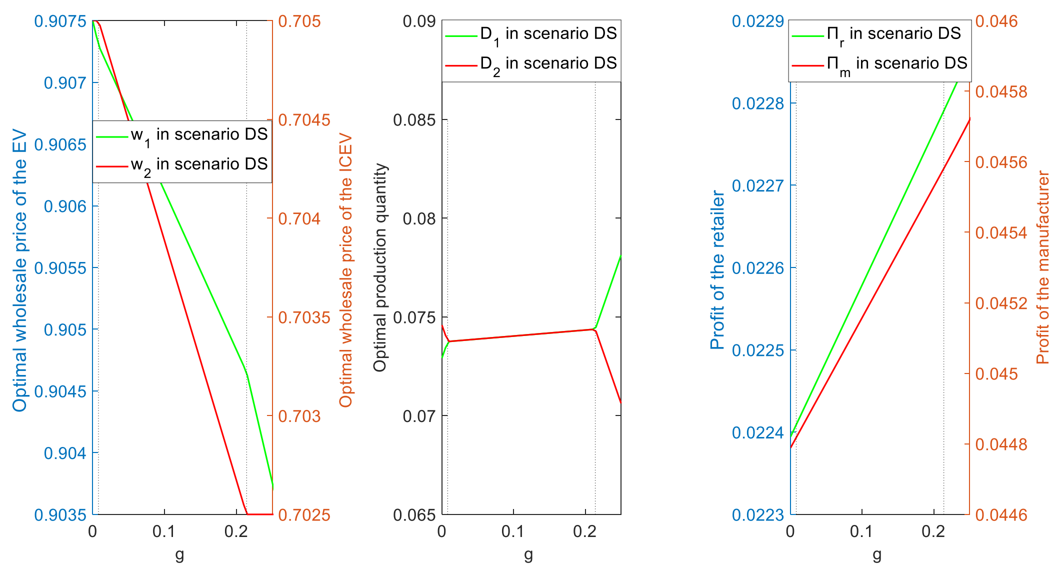

Fig. 7. The impact of achieving NE credits by producing a unit EV on wholesale price, production quantities, and profit.

studies could be to consider stochastic demand based on customer value theory. This would examine the impact of demand uncertainty on production and pricing decisions.

Authorship contribution statement

Yi Yu: Methodology, Software, Writing – original draft. Dequn Zhou: Supervision, Writing – review & editing. Donglan Zha: Resources, Writing – review & editing. Qunwei Wang: Resources & editing. Qingyuan Zhu: editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.120369.

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