A Game-Theoretic Analytical Approach for Fostering Energy-Saving Innovation in the Electric Vehicle Supply Chain

Jun-bin Wang¹ and Lu-fei Huang²

Abstract
Motivated by the industrial observation that electric vehicle (EV) manufacturers are often fully or partially outsourcing some specific components, for instance, powertrains and battery systems, and rely on their suppliers’ energy-saving innovation to improve their own EVs’ comprehensive performances, this study builds an analytical framework to investigate how different cooperation modes affect the EV supply chain’s energy-saving performance and firms’ profitability. As a main barrier preventing potential consumers from purchasing EVs, the consumer range anxiety for EVs’ performance was incorporated into the analytical model. Three primary cases and one strategic alliance case are sequentially analyzed. The results show that the supplier always self-motivates to implement energy-saving innovation to improve the performance of the core component, and the EV manufacturer is always willing to participate in its supplier’s energy-saving innovation by sharing a fraction of the investment. Moreover, a strategic alliance between the manufacturer and the supplier can effectively improve the profit of the whole supply chain. This strategic alliance can be coordinated through a generalized Nash-bargaining mechanism.

Keywords
electric vehicle supply chain, energy-saving innovation, consumer range anxiety, strategic alliance, analytical model

Introduction

Problem Motivation
With the excessive emission of greenhouse gases, the electric vehicle (EV) industry has been highly respected. The development of EVs hinges on technology investment, especially for powertrains and battery systems, which determines the energy-saving performance of an EV to a large extent. EV manufacturers have various strategies when sourcing the powertrain and battery system, from nearly full outsourcing to almost full vertical integration (as shown in Table 1). When the key components are outsourced, the degree to control the powertrain and battery supply chain varies, especially for the degree of energy-saving for improving their performances.

From the consumer perspective, the barriers to purchase an EV include high acquisition cost, differentiated style, and cruising range. Research from Deloitte found that, for the people who are reluctant to consider an EV in Belgium, France, Germany, the United Kingdom, Spain, Italy, and Turkey, when asked what concerns them about an EV, one issue stands out: range anxiety (Mitsubishi Heavy Industries, 2018). Range anxiety can be described as a potential EV consumer’s anxious feeling that the EV will not have enough power to complete the trip. Seeing an opportunity to attract curious consumers with range anxiety concerns, some core component suppliers in the EV supply chain try to improve the ability of their components’ performance through energy-saving innovation. For example, Mitsubishi Turbocharger and Engine Europe (MTEE) developed power generators capable of charging the battery of an EV while driving. With that range extenders, the users can be more natural to rely on the EVs.

Given that the EV manufacturers cannot always control the core components supply chain when they fully and partially outsourced them, one may wonder under what circumstances the EV manufacturer should facilitate their suppliers to implement energy-saving innovation. The supplier could be self-motivated to do that or pushed by the customers to do that, while the manufacturer could also formulate the corresponding subsidy plan or vertically integrate the supply chain in some ways. This study builds an analytical framework to study the incentives of members in an EV supply chain to implement energy-saving innovation. More specifically, we focus on analyzing how a
Table 1. Examples of EV Manufacturers’ Powertrain and Battery Supply Chain Strategies.

| EV model         | Battery cell | Battery pack | Battery management system | Power electronics | Motor            | Transmission |
|------------------|--------------|--------------|----------------------------|-------------------|------------------|--------------|
| BYD E6 (2015)    | In-house     | In-house     | In-house                   | In-house          | In-house         | N/A          |
| Tesla S 60 (2013)| Panasonic    | In-house     | In-house                   | In-house          | In-house         | Borg-Warner  |
| BMW i3 (2014)    | Samsung      | In-house     | Preh                       | In-house          | In-house         | In-house     |
| VW e-Golf (2015) | Panasonic    | In-house     | Ficosa                     | Bosch             | In-house         | In-house     |
| Chevrolet Spark (2014) | A123       | In-house     | A123                       | Make              | In-house         | N/A          |
| VW e-up! (2013)  | Panasonic    | In-house     | Ficosa                     | Bosch             | In-house         | In-house     |
| Nissan LEAF (2011)| AESC        | AESC         | Calsonic Kansei            | Calsonic Kansei/Denso | In-house | Aichi        |
| Nissan LEAF (2017)| AESC        | AESC         | Calsonic Kansei            | Calsonic Kansei/Denso | In-house | Aichi        |
| Chevrolet Bolt (2017) | LG          | LG           | LG                         | LG                | LG               |              |

Note. “In-house” means that this component is made by the EV manufacturer itself; “N/A” means the corresponding information is not available; the above information was obtained from McKinsey & Company’s report authored by Mauro et al. in October 2017. EV = electric vehicles.

Supply chain incentive mechanism about energy-saving innovation affects the firms’ product performance and pricing decisions. Moreover, we examine how the consumers’ range anxiety concerns about the emerging EVs affect firms’ energy-saving innovation activities.

**Research Questions and Contributions**

Based on the observed business phenomenon as aforementioned, the following questions are addressed in this research:

**Research Question 1:** How does supply chain cooperation mechanisms affect firms’ choice of energy-saving innovation effort and price?

**Research Question 2:** Can the manufacturer make a higher profit by sharing a fraction of the supplier’s cost of energy-saving innovation (i.e., collaborative energy-saving innovation)?

**Research Question 3:** How does the strength of consumers’ range anxiety concerns affect firms’ optimal pricing and energy-saving innovation decisions and their profit?

**Research Question 4:** Does a strategic alliance foster or hinder firms’ energy-saving innovation incentives?

To address these questions, in the proposed model, a typical EV supply chain consists of an EV manufacturer and a core component supplier (e.g., battery and motor). To facilitate the understanding, readers can refer to the EV manufacturer as Tesla and refer to the core component supplier as Panasonic who supplies battery to Tesla, although our analysis applies to other such EV manufacturers and their core component suppliers. The supplier’s product could affect the energy-saving performance of the manufacturer’s EV product to a large extent, which also will foster or weaken consumers’ range anxiety concerns at the end.

In summary, our work contributes in some distinct way compared with previous studies. First, this study analyzes several different models of the EV supply chain, including (a) no energy-saving innovation case where the supplier keeps the performance of core component at the original level; (b) energy-saving innovation case where the supplier self-motivates to implement energy-saving innovation to improve the performance of its supplied core component; and (c) collaborative energy-saving innovation where the manufacturer agrees to share a fraction of investment cost to support the supplier’s energy-saving innovation activities. Second, this study also first examines the effects of the strategic alliance case on the EV supply chain and shows that strategic alliance could be the right choice for the manufacturer and the supplier.

**Key Findings**

The following interesting implications of this study are revealed. First, our analysis shows that the supplier always self-motivates to implement energy-saving innovation to improve the performance of the core component. Meanwhile, a collaborative energy-saving innovation always occurs in equilibrium. In other words, the EV manufacturer is willing to participate in its supplier’s energy-saving innovation by sharing a fraction of the investment. Second, our analysis also suggests that a strategic alliance between the manufacturer and the supplier can effectively improve the profit of the whole supply chain. Moreover, our results show that the manufacturer and the supplier in the strategic alliance can be coordinated through a generalized Nash-bargaining (GNB) mechanism. By incorporating the risk attitudes and bargaining power parameters into the model, a specific profit-sharing scheme for the coordination mechanism was proposed.

The remainder of this article is organized as follows. Section “Literature Review” reviews the related literature. Section “Method” introduces the model development processes and presents the first three cases. Section “Analysis” analyzes each model and obtains forms’ optimal decisions on price, energy-saving innovation, and their profits. Section “Effects of Energy-Saving Innovation” makes a comparison among the three cases and obtains the main insights from the results. Section “Extended Case: Strategic Alliance (ATI)” introduces an extended case as a strategic alliance and compares it with previous cases. Section “Discussion” concludes...
the study with some discussions for future research. All detailed proofs are provided in the Appendix.

Literature Review

Three streams of literature are closely related to this study: (a) coordination of green supply chains, (b) management of EV supply chain, and (c) energy-saving innovation mechanism. We review studies relevant to each stream and highlight this study’s contributions by comparing the existing literature.

A growing amount of literature examines the coordination of green supply chains. Q. Zhu et al. (2012) empirically show that industrial manufacturers will seek to adopt green supply chain management practices at different levels of sophistication. Hong and Guo (2019) analytically examine a green supply chain consists of a manufacturer and a retailer who resells the products to consumers, and analyzes how the cooperation contracts affect environmental performance. Under a dual-channel green supply chain context, Zhen et al. (2019) develop a strategic decision problem on determining the optimal location of (re)manufacturers and distribution centers with the facility scales consideration in a closed-loop supply chain network. In the area of sustainable energy supply chains, Kesharwani et al. (2019) propose two supply chain restructuring strategies, that is, distributed and centralized preprocessing deployment, for implementing biomass preprocessing for second-generation biofuel manufacturing. Gabrielli et al. (2020) investigate the optimal design of low-carbon hydrogen supply chains on a national scale. Hydrogen production based on several feedstocks and energy sources is considered sequentially.

In recent years, the academic has paid more and more attention to the research on the EV supply chain and optimization problem considering EVs. Gallagher and Muehleggler (2011) investigate the relative efficacy of state sales tax waivers, income tax credits, and nontax incentives, respectively, and they find that the type of tax incentive offered is as important as the generosity of the incentive. Gu et al. (2019) mathematically model a four-echelon electric/gasoline vehicle (GV) supply chain and analyze how the government allocates subsidies to achieve the maximization of the total profit of the whole supply chain under imperfect information. They suggest that a subsidy should first be allotted for EV customers in the EV supply chain. Clinton and Steinberg (2019) examine the impact of vehicle purchase subsidies on adoption of national data set of vehicle registrations and state-level financial incentives. From an across-chain perspective, J. Li et al. (2020) investigate the impacts of subsidy policy on EVs and conventional vehicle production decisions; they find that, in a cooperative context, there exists an EV supply chain and a conventional vehicle supply chain with government subsidies and dual credit involved. In the context of the EV battery closed-loop supply chain, L. Li et al. (2018) investigate a closed-loop supply chain network model for lithium-ion battery remanufacturing considering different quality levels of spent battery returns. In addition, hybrid EVs are a new trend in EV research. Sulaiman et al. (2018) propose a critical review of the different types of fuel cell hybrid EV energy management systems and their optimization algorithms to solve existing limitations; enhance the performance of future fuel cell hybrid EVs; and inspect the effects of government subsidies on a supply chain that involves a supplier, a manufacturer, and consumers with EVs. Zhen et al. (2020) investigate the mode selection system in hybrid EVs based on the background of green logistics. Chakraborty et al. (2021) investigate the effect of using a combination of subsidy on EV and green-tax on conventional GV on overall social welfare, environmental impact, and vehicle stock in monopoly and duopoly forms of market structures.

Our work is also related to the stream of literature on the determinants of energy-saving innovation in the supply chain. Liu et al. (2017) present a guided tour on the state-of-art of typical and innovative carbon capture and storage technologies integrated with energy infrastructures supply analysis. Aydin and Parker (2018) model a two-tier supply chain and investigate how different levels of upstream technology are adopted by downstream firms and how an upstream technology leader determines its pricing policy. Orji and Liu (2020) employ fuzzy logic and Technique for Order Performance by Similarity to Ideal Solution (Fuzzy TOPSIS) to study the dynamic behavior of the key drivers of innovation-led lean approaches, and investigate their influence on sustainable performance in the manufacturing supply chain. Gao et al. (2020) investigated the effect of innovation institution on the spatial transfer of the energy industry in Jiangsu, China.

Different from the above-mentioned research, this study focuses on the cooperation mechanism and energy-saving innovation issues in the EV supply chain, and we also incorporate consumers’ range anxiety concerns in the model to line the critical performance of EV and consumer market more naturally. Moreover, our study contributes to the literature by comparing the collaborative energy-saving with a strategic alliance, and further posed a Nash-barging game-based profit-sharing mechanism to gain a higher profit for the whole supply chain under a strategic alliance.

Method

To study the different cases of energy-saving innovation in the EV supply chain, we adopt game theory as an analytical approach for properly capturing the strategic interaction between the supply chain members. Even though the existing research often utilizes an empirical toolbox to gauge the energy-saving innovation (e.g., W. Li et al., 2019; Stieß et et al., 2019; Zhang et al., 2020), it is difficult for the focal firm to take into account the other player strategies to form its own decisions in these empirical studies (Amrouche et al.,
The game-theoretic analytical study is also widely not only for marketing but also for other fields such as economy, biology, and psychology (Martin, 1978). In this section, we will introduce the formulation of the basic model as well as the game sequence.

In the proposed model, we consider an EV supply chain that consists of an EV manufacturer (E) and a core component supplier (M; for example, battery and motor). Figure 1 depicts the proposed analytical model. For ease of understanding, readers can refer to the EV manufacturer as Tesla and refer to the core component supplier as Panasonic, who supplies battery to Tesla, although our analysis applies to other such EV manufacturers and their core component suppliers. For ease of exposition, we use the subscript “e” to represent the EV manufacturer and subscript “m” to denote the supplier in the remainder of the study.

We follow established norms in the green operations literature (Dong et al., 2019; Hong et al., 2019; Hong & Guo, 2019; W. Zhu & He, 2017) and the EV demand function is:

\[ D(p, v) = \theta - \beta p + \mu v, \]  

where \( D \) and \( P \) refer to the realized demand and sales price for the EV, respectively, and \( \theta \) denotes the market potential for the EV. \( \beta > 0 \) is the measure of the consumer’s sensitivity to the price of an EV. \( v > 0 \) denotes the “cruising ability” of the EV which is commonly regarded as the core performance index of EVs most concerned by consumers, compared with the conventional vehicles. In line with the EV industrial practice, the focal firm is an EV manufacturer that benefits from improvement in the value of \( v \), and the core component supplier designs and decides which degree of \( v \) to reach. However, \( v \) also reflects the consumer’s “range anxiety” for the EV, and \( \mu > 0 \) measures the magnitude of such anxiety with higher values indicating a greater degree of range anxiety concerns. Regarding the magnitude of range anxiety concern \( \mu \), Olson (2013) empirically shows that consumer owns strong preference for green products and expects to pay a price premium for them \( (\mu > 0) \), while the tradeoffs such as reduced size and performance can also limit their appeal to consumers. In our study, the poor “cruising ability” could reduce the intention of consumers to buy an EV and thus leads to lower demand.

We further let \( v_0 > 0 \) represent the basic value obtained by customers when \( v \) was set at a minimum level, and characterize the greenness (e.g., cruising ability) improvement after energy-saving innovation by \( \tau > 0 \). \( \tau \) denotes the improvement rate of current-generation EVs to the new generation ones through energy-saving innovation, that is, \( v = (1 + \tau)v_0 \). With limitations of current scientific and technological capabilities, the range of core performance improvement in the EV industry is not too big; thus, we assume \( 0 \leq \tau \leq 1 \). We model \( \tau \) as a function of the energy-saving innovation cost, which is denoted by \( K \), the investment in energy-saving innovation activities. Such investments can be considered as research and development (R&D) expenditures undertaken by the core component supplier M. To characterize the diminishing returns from R&D expenditures, we use the cost structure \( \tau = \sqrt{K/a} \), where \( a \) is a scaling parameter. Convex costs are often attributed to diseconomies of scale that, for example, in a larger firm, bureaucracy could stifle creativity and impede innovation. Moreover, diseconomies in offering employment contracts with energy-saving innovation increases could also lead to diminishing returns from R&D (Bhaskaran & Krishnan, 2009). Also, we assume \( a > (\mu^2 v_0^2 / 4\beta) \), which means the investment cost for energy-saving innovation is costly. This assumption is consistent with practical observation, and it also ensures the unique Nash equilibrium across the three cases. This study investigates tradeoffs that are...
similar to those in the above study in an energy-saving innovation context.

The supplier will incur the unit cost $c_m$ of manufacturing a component and sell it to EV manufacturer with price $p_m$. In line with Ma et al. (2018), we assume the EV manufacturer will bear the cost $c_e = \lambda p_m$ of manufacturing an EV, where $\lambda > 1$ and $1/\lambda$ represent the proportion of the core component in the total cost of an EV. As per a survey by Bloomberg, the battery made up more than 57% of the total cost for a midsize EV in the United States in 2015. In 2019, it was 33%, and it is estimated that the battery will be 20% of total vehicle costs by 2025 (Nathaniel, 2017). Both firms should obtain a positive profit margin so that $p > c_e > p_m > c_m > 0$ should hold.

Three potential EV supply chain models evaluated are as follows:

- Case NTI: no energy-saving innovation. Under this case, supplier M keeps the performance of the core component at the original level $v_0$, and we set Case NTI to be the benchmark (current) case.
- Case TI: energy-saving innovation. This case represents a setting where the supplier M self-motivates to implement energy-saving innovation to improve the performance of its supplied core component, or the manufacturer E pushes it to do that.
- Case CTI: collaborative energy-saving innovation. Similar to Case TI, under this case, E agrees to share a fraction of investment cost to support M’s energy-saving innovation activities.

Given the above setting of each case, the sequence of events for each case of operation is as follows.

- Case NTI: In this benchmark (current) case, given M set $v$ on $v_0$, M moves as Stackelberg leader to determine the price $p_m$ for the key component to E; in turn, E chooses price $P$ to consumers for the EV.
- Case TI: In this case, M determines to invest the energy-saving innovation and improve the index $v_0$ to $\tau$, that is, to set a positive energy-saving level $\tau$; except that, M also simultaneously determines the price $p_m$ for the component to E; in turn, E chooses price $P$ to consumers for the EV.
- Case CTI: In this case, for motivating supplier’s energy-saving innovation, E decides to share a fraction of M’s investment cost for energy-saving innovation activities, which is denoted by $\sigma \in [0,1]$ and called as “participation rate” throughout this study. Given $\sigma$, M simultaneously determines the energy-saving level $\tau$ and price $p_m$ to E; in turn, E choose price $P$ to consumers for the EV.

Note that all three cases are analyzed under a complete information setting. We use standard backward induction to solve the game in each case. The notations are summarized in Table 2. The superscript (*) is used to denote the equilibrium outcome. We use superscripts “NTI,” “TI,” and “CTI” to denote Case NTI, Case TI, and Case CTI, respectively.

### Analysis

The subsection below described the results under the benchmark (current) case under which the supplier M keeps the component’s performance at the current level (Case NTI). Next, we examine the case under which M implements energy-saving innovation and improve the component’s performance to a higher level, although the manufacturer E does...
not participate in M’s energy-saving innovation investment (Case TI). Finally, we investigate the case under which M implements energy-saving innovation, and E also participates in by sharing a fraction of M’s investment cost (Case CTI). In obtaining these outcomes, the necessary conditions for the existence of two latter cases (i.e., TI and CTI) are that M’s equilibrium profit should be at least as large as the profits realized in the current case (i.e., NTI).

Case NTI

In this benchmark (current) case, given M keeps the component’s performance of \( v_0 \), M first determines the price \( p_m \), and then E chooses price \( p \) to consumers for the EV. The EV manufacturer and supplier solve profit maximization problems as follows:

\[
\max_{p_m} \pi_{NTI}^{m} = (p_m - c_m)\left(\theta - \beta p + \mu v_0\right),
\]

\[
\max_{p} \pi_{NTI}^{e} = (p - c_e)\left(\theta - \beta p + \mu v_0\right).
\]

By standard backward induction method, given \( p_m \), we first derive the best response of E’s sales price for the EV that maximize \( \pi_{NTI}^{e} \); and then derive the optimal intermediate price \( p_m \) for the component that maximizes \( \pi_{NTI}^{m} \). Throughout this study, we focus on the inner solutions of profit functions. The results are summarized in the lemma as follows.

**Lemma 1.** In the no energy-saving innovation case (NTI), the optimal sales price for the EV \( p_{NTI}^{e} \), the price for the core component \( p_{NTI}^{m} \), and the corresponding realized demand \( D_{NTI} \), and firms’ profits \( \pi_{NTI}^{m} \) and \( \pi_{NTI}^{e} \) are as follows: \( p_{NTI}^{e} = (30 + \beta \lambda c_m + 3 \mu v_0) / 4 \), \( p_{NTI}^{m} = (\theta + \beta \lambda c_m + \mu v_0) / 2 \beta \lambda \), \( D_{NTI} = (\theta - \beta \lambda c_m + \mu v_0) / 4 \), \( \pi_{NTI}^{m} = (\theta - \beta \lambda c_m + \mu v_0)^2 / 8 \beta \lambda \), and \( \pi_{NTI}^{e} = (\theta - \beta \lambda c_m + \mu v_0) / 16 \beta \).

Lemma 1 indicates that the consumers’ responses to price and range anxiety will affect both firms’ pricing decisions and profits, but the degree of impact varies. One can quickly obtain that \((\partial p_{NTI}^{e} / \partial \lambda) = (3/2)(\partial D_{NTI} / \partial \lambda)\), which signifies that consumers’ range anxiety concerns that affect the manufacturer is more than those that affect the supplier. Thus, the manufacturer should be more incentive to improve the performance of EV by energy-saving innovation.

**Case TI**

In this case, M determines to invest the energy-saving innovation and improve the component’s performance from \( v_0 \) to \( v \), that is, to set a positive energy-saving level \( \tau \); meanwhile, M also determines the price \( p_m \) for the component, and then, E sets the sales price \( p \) of the EV. The EV manufacturer and supplier solve profit maximization problems as follows:

\[
\max_{p, \tau} \pi_{TI}^{m} = (p_m - c_m)\left[\theta - \beta p + \mu (1 + \tau) v_0\right] - K,
\]

s.t. \( \max_{p} \pi_{TI}^{e} = (p - c_e)\left[\theta - \beta p + \mu (1 + \tau) v_0\right] - \sigma K \).

Similar to Case NTI, given \( p_m \) as well as the energy-saving level \( \tau \) determined by M, we first obtain the best response of E’s sales price \( P \) that maximizes \( \pi_{TI}^{e} \) and then calculate the optimal price \( p_m \) for the component and \( \tau \) that jointly maximize \( \pi_{TI}^{m} \). The results are summarized in the lemma as follows.

**Lemma 2.** In the energy-saving innovation case (TI), the optimal sales price for the EV \( p_{TI}^{e} \), the price for the core component \( p_{TI}^{m} \), the energy-saving level \( \tau_{TI} \), and the corresponding realized demand \( D_{TI} \), and firms’ profits \( \pi_{TI}^{m} \) and \( \pi_{TI}^{e} \) are as follows: \( p_{TI}^{e} = \lambda (c_m + (6a(\theta - \beta \lambda c_m + \mu v_0)/(8a \beta \lambda - v_0^2 \mu^2)) \), \( \tau_{TI} = \mu v_0 (\theta - \beta \lambda c_m + \mu v_0) / (8a \beta \lambda - v_0^2 \mu^2) \), \( p_{TI}^{m} = c_m + (4a (\theta - \beta \lambda c_m + \mu v_0)/(8a \beta \lambda - v_0^2 \mu^2)) \), \( D_{TI} = 2a \beta \lambda (\theta - \beta \lambda c_m + \mu v_0) / (8a \beta \lambda - v_0^2 \mu^2) \), \( \pi_{NTI}^{m} = a(0 - \beta \lambda c_m + \mu v_0)(8a \beta \lambda - v_0^2 \mu^2) \), and \( \pi_{NTI}^{e} = 4a^2 \beta \lambda^2 (\theta - \beta \lambda c_m + \mu v_0) / (8a \beta \lambda - v_0^2 \mu^2) \).

Lemma 2 indicates that there exist cost effects for firms’ price decisions and profits caused by the investment in energy-saving innovation. Different from Case NTI, the consumers’ responses to price and range anxiety’s impacts on firms are not straightforward. To carry out sensitivity analysis for \( \tau_{TI} \) with respect to \( \mu \), we can obtain the following proposition.

**Proposition 1.** In the energy-saving innovation case (TI), the energy-saving level \( \tau_{TI} \) increases with the degree of range anxiety concerns \( \mu \).

**Case CTI**

In this case, for motivating supplier’s energy-saving innovation, E bears a fraction \( \sigma \) of investment cost for energy-saving innovation, and M will pay the rest \((1 - \sigma)\) of investment cost. Given \( \sigma \), M chooses the optimal energy-saving level \( \tau \) and price \( p_m \) for the component. Finally, E chooses sales price \( p \) for the EV. The EV manufacturer and supplier solve profit maximization problems as follows:

\[
\max_{\sigma} \pi_{CTI}^{e} = (p - c_e)\left[\theta - \beta p + \mu (1 + \tau) v_0\right] - \sigma K,
\]

s.t. \( \max_{p} \pi_{CTI}^{m} = (p_m - c_m)\left[\theta - \beta p + \mu (1 + \tau) v_0\right] - (1 - \sigma) K \),

s.t. \( \max_{p} \pi_{CTI}^{m} = (p_m - c_m)\left[\theta - \beta p + \mu (1 + \tau) v_0\right] - \sigma K \).

Different from the two-stage game in Case TI, in this case, the game is a three-stage one. Given the participation rate \( \sigma \), energy-saving level \( \tau \), and component price \( p_m \), we first
obtain the best response of E’s sales price \( p \) that maximizes \( \pi_e^{CTI} \); then, given \( \sigma \), we calculate the optimal price \( p_m \) and \( \tau \) that jointly maximize \( \pi_m^{CTI} \); finally, we derive the optimal participation rate \( \sigma \) that maximizes \( \pi_e^{CTI} \). The results, in this case, are summarized in the lemma as follows.

**Lemma 3.** In the collaborative energy-saving innovation case \((CTI)\), the participation rate \( \sigma^{CTI} \), the optimal sales price for the EV \( p^{CTI} \), the price for the core component \( p_m^{CTI} \), and energy-saving level \( \tau^{CTI} \) are as follows:

\[
\sigma^{CTI} = \frac{2}{3\lambda} (3 \theta \lambda \mu + 4 \lambda \mu v_0),
\]

\[
p^{CTI} = \frac{2}{3\lambda} (3 \theta \lambda \mu + 4 \lambda \mu v_0),
\]

\[
p_m^{CTI} = \frac{2}{3\lambda} (3 \theta \lambda \mu + 4 \lambda \mu v_0),
\]

\[
\tau^{CTI} = \frac{1 + \lambda} {2\lambda} v_0 \left( \theta \lambda \mu v_0 + 4 \lambda \mu v_0 \right),
\]

and the corresponding realized demand \( D^{CTI} \) and firms’ profits \( \pi_m^{CTI} \) and \( \pi_e^{CTI} \) are as follows:

\[
D^{CTI} = \frac{(1 - \lambda) \mu v_0 (3 \theta \lambda \mu + 4 \lambda \mu v_0)}{16\lambda^2 \mu v_0^2},
\]

\[
\pi_m^{CTI} = \frac{(1 - \lambda) \mu v_0 (3 \theta \lambda \mu + 4 \lambda \mu v_0)}{16\lambda^2 \mu v_0^2},
\]

\[
\pi_e^{CTI} = \frac{(1 - \lambda) \mu v_0 (3 \theta \lambda \mu + 4 \lambda \mu v_0)}{16\lambda^2 \mu v_0^2}.
\]

Lemma 3 shows that the consumers’ responses to range anxiety have a positive direct effect on the manufacturer’s participation rate for the collaborative energy-saving innovation, while the consumers’ responses to price and the investment cost have negative direct effects on that. Interestingly, the consumer’s high sensitivity to market price could hinder the manufacturer’s willingness for collaborative innovation. This is because when the price tool is more efficient to stimulate demand than product performance, then the manufacturer will be more profitable to lower the price than involved in the innovation.

**Price and Demand**

The below proposition summarizes a comparison across the three cases from pricing and demand perspectives.

**Proposition 2.** (a) \( p^{NTI*} < p^{TI*} < p^{CTI*} \); (b) \( p_m^{NTI*} < p_m^{TI*} < p_m^{CTI*} \); (c) \( D^{NTI*} < D^{TI*} < D^{CTI*} \).

**Proposition 2** shows that energy-saving innovation increases the prices of the product and the component, hence increases both firms’ profit margin, while collaborative energy-saving innovation further increases them. With the same trend, market demand is also expanded under energy-saving innovation. It signifies that the demand expansion caused by the performance improvement of the EV exceeds the increment of sales price, so the aggregate market demand is going to go up.

**Energy-Saving Level**

The below proposition summarizes a comparison between both cases with energy-saving innovation from an energy-saving level perspective.

**Proposition 3.** The collaborative energy-saving innovation increases the energy-saving level, that is, \( \tau^{CTI*} > \tau^{TI*} \).

Proposition 3 shows that the manufacturer sharing a fraction of the supplier’s energy-saving innovation cost (i.e., collaborative energy-saving innovation) can stimulate the strength of performance improvement. This is because the performance improvement is more efficient to increase the consumer’s demand than the price. Meanwhile, the supplier also is motivated to enhance energy-saving innovation with less cost pressure.

**Profits**

The below proposition summarizes a comparison across the three cases from a profit perspective.

**Proposition 4.** The supplier implementing energy-saving innovation always increases both firms’ profits, and collaborative energy-saving innovation can further increase those.

Proposition 4 indicates that both the price increasing and demand expanding benefit both firms, even though the energy-saving innovation brings the extra cost for the supplier or the manufacturer (in Case CTI). In other words, the profit margin increase and market expansion offset the cost with the energy-saving innovation; moreover, the surpluses are appropriately allocated between the manufacturer and the supplier so that the collaborative energy-saving innovation can achieve coordination in equilibrium.
Extended Case: Strategic Alliance (ATI)

In this section, we analyze the strategic alliance case, where two EV supply chain members maximize their total profits. This case is interest for us currently because we see it occurs broadly in the EV industry. For example, Tesla signed partnership contracts in 2012 with Daimler AG and Toyota Motor Corp. The Daimler partnership gave Tesla a much-needed cash injection; the Toyota partnership assisted Tesla to build up a world-class automobile manufacturing facility (Välikangas, 2018). Evergrande New Energy Auto signed a strategic alliance agreement in 2019 with five leading engineering companies in the automotive industry, including FEV Group, EDAG, IAV GmbH, AVL, and Magna International, to develop new models (NEVS Cars, 2019).

Case ATI

When the EV manufacturer and the supplier are in a strategic alliance, the manufacturer and the supplier make decisions like a single firm (A). Thus, they maximize a single profit function as follows:

$$\max_{p, \tau} \pi^A_{\tau} = \left[ p - (\lambda - 1) p_m - e_m \right] [0 - \beta p + \mu (1 + \tau) v_0] - K,$$

(9)

where $p_m = e_m$ because the supply chain members act as a single firm so that the double marginalization problem is eliminated. Given the above setting, we solve the above profit maximization problem and summarize the optimal results in the following lemma.

**Lemma 4.** In the strategic alliance case (ATI), the optimal sales price for the EV $p^A_{\tau*}$, the energy-saving level $\tau^A_{\tau*}$, and the corresponding realized demand $D^A_{\tau*}$ and the supply chain’s profit $\pi^A_{\tau*}$ are as follows: $p^A_{\tau*} = \kappa e_m + (2a(0 - \lambda e_m + \mu v_0) / 4a\beta - v_0^2 \mu^2)$, $\tau^A_{\tau*} = \mu v_0 (0 - \beta \lambda e_m + \mu v_0) / 4a\beta - v_0^2 \mu^2$, $D^A_{\tau*} = 2a\beta\lambda(0 - \beta \lambda e_m + \mu v_0) / 4a\beta - v_0^2 \mu^2$, and $\pi^A_{\tau*} = a(0 - \beta \lambda e_m + \mu v_0)^2 / 4a\beta - v_0^2 \mu^2$.

We first denote the total supply chain’s profit by $\pi_T = \pi_e + \pi_m$, and then we obtain some main results regarding the profit and optimum strategies for firms under the case of strategic alliance and the most profitable Case CTI in the following proposition.

**Proposition 5.** When the EV manufacturer and the supplier form a strategic alliance, such that

1. The profit of the whole supply chain is higher than that of a collaborative energy-saving innovation setting, that is, $\pi^A_{\tau*} > \pi^CTI_{\tau*}$.

2. The energy-saving level through energy-saving innovation in the strategic alliance is higher than that in the collaborative energy-saving innovation setting, that is, $\tau^A_{\tau*} > \tau^CTI_{\tau*}$.

Proposition 5 indicates that a collaborative energy-saving innovation structure gains a lower profit for the whole supply chain compared with the strategic alliance. So, the strategic alliance coordinates the EV supply chain better. Also, under the strategic alliance, the energy-saving level is higher than one under the collaborative energy-saving innovation structure. Predictably, there exist optimal profit schemes between the manufacturer and the supplier, by which a strategic alliance can be implemented among the EV supply chain, and the overall profit of the supply chain can be effectively improved.

Nash-Bargaining Mechanism

Our earlier analyses show that a strategic alliance can effectively improve the whole EV supply chain’s profit; hence, an advanced coordination mechanism is needed to coordinate the manufacturer and the supplier in the strategic alliance. Thus, we propose a suitable coordination mechanism to optimize the profit for each supply chain player through a generalized bargaining model. Bargaining models are commonly used in literature to identify a suitable division of profits between two or more players. In this study, we use a GNB mechanism (Draganska et al., 2010), where the manufacturer holds bargaining power $\alpha \epsilon [0, 1]$ and the supplier holds $1 - \alpha$. In this GNB setting, we denote the increased profit gain $\Delta \pi = \pi^A_{\tau*} - \pi^CTI_{\tau*}$; furthermore, the manufacturer shares the amount $\Delta \pi_e$, and the supplier shares the remainder $\Delta \pi_m$. Thus, under the GNB setting, the manufacturer’s profit is $\pi^G_{\tau*} = \pi^CTI_{\tau*} + \Delta \pi_m$, and the supplier’s profit is $\pi^G_{\tau*} = \pi^CTI_{\tau*} + \Delta \pi_e$. In the EV supply chain, we solve the following GNB problem:

$$\max_{\Delta \pi, \Delta \pi_e} \pi^G_{\tau*} \delta_e (\Delta \pi_m)^{1-\delta_e},$$

s.t. $\Delta \pi = \Delta \pi_e + \Delta \pi_m$, $\Delta \pi_e > 0, \Delta \pi_m > 0$,

(10)

where $\delta_e$ and $\delta_m$ are positive parameters reflecting the manufacturer and supplier’s risk attitudes, respectively. Note that $\delta_e = \delta_m$ means both parties have an equal risk attitude; $\delta_e > \delta_m$ means the EV manufacturer is more risk-seeking than the supplier, while $\delta_e < \delta_m$ means the supplier is more risk-seeking than the EV manufacturer. We solve the above optimization problem to obtain the following proposition.

**Proposition 6.** The Nash-bargaining mechanism leads to the following profit-sharing scheme to coordinate the whole supply chain:

$$\Delta \pi_e = \frac{\alpha \delta_e}{(1-\alpha) \delta_m + \alpha \delta_e} \Delta \pi.$$
2. $\Delta \pi_i = \frac{(1 - \alpha) \delta_m}{(1 - \alpha) \delta_m + \alpha \delta_e} \Delta \pi_e$

Looking at Proposition 6, given the equal barging power (i.e., $\alpha = 1/2$), an equal risk attitude (i.e., $\delta = \delta_m$) leads $\Delta \pi_e = \Delta \pi_m$. When the EV manufacturer is more risk-seeking than the supplier ($\delta > \delta_m$), the manufacturer shares a bigger fraction of the profit gain in the strategic alliance, that is, $\Delta \pi_e < \Delta \pi_m$. When the supplier is more risk-seeking than the EV manufacturer ($\delta < \delta_m$), the manufacturer shares a smaller fraction of the profit gain in the strategic alliance, $\Delta \pi_e > \Delta \pi_m$. By doing so, the supplier can be motivated to increase the energy-saving innovation effort, which in turn increases the market demand. Both firms will increase their prices to gain more profit margin, and thus, they are better off under the collaborative energy-saving innovation setting.

Third, our analysis also suggests that a strategic alliance between the manufacturer and the supplier can effectively improve the profit of the whole supply chain. Because the strategic alliance can improve the level of energy-saving and lower the sales price to consumers, the market demand is largely increased. Also, the integrated supply chain eliminates the double marginalization problem; thus, it improves the supply chain’s efficiency. Previous study also suggested that if the collaborative innovation does not properly guide the policy, firms will enable to form a passive innovation behavior and inhibit the influence on innovation (W. Li et al., 2019).

Finally, our results show that the manufacturer and the supplier in the strategic alliance can be coordinated through a GNB mechanism. By incorporating the risk attitudes and barging power parameters into the model, we also propose a specific profit-sharing scheme for the coordination mechanism. Similarly, Shen et al. (2021) study the impact of innovation leadership of the supply chain (i.e., the supplier- and manufacturer-led) on innovation efficiency. Unlike their finding that under the manufacturer-led innovation game, the product with a higher innovation level will be more likely to be offered, we provided a more detailed solution for the game.

**Discussion**

In our model, three different energy-saving innovation cases are examined in pricing, energy-saving innovation effort, collaborative innovation participation, and profits. That is, (a) no energy-saving innovation (Case NTI) where the supplier keeps the performance of core component at the original level; (b) energy-saving innovation (Case TI) where the supplier self-motivates to implement energy-saving innovation to improve the performance of its supplied core component; and (c) collaborative energy-saving innovation (Case CTI) where the manufacturer agrees to share a fraction of investment cost to support the supplier’s energy-saving innovation activities. Furthermore, our model also checks the effects of the strategic alliance (Case ATI) on the EV supply chain.

Several results are derived from the proposed model. First, different from the previous study documented that energy-saving policies were needed to drive firm innovation behaviors (Zhang et al., 2020), our analysis shows that the supplier always self-motivates to implement energy-saving innovation to improve the performance of the core component. This is because the improvement of EV’s performance can increase the market demand which in turn will increase the whole supply chain’s profit. By charging a higher sales price for EV and a higher price for the component, both supply chain members can benefit from the supplier’s energy-saving innovation.

Second, we find that collaborative energy-saving innovation always occurs in equilibrium. In other words, the EV manufacturer is willing to participate in its supplier’s energy-saving innovation by sharing a fraction of the investment. By doing

**Conclusion**

This study proposes a typical EV supply chain with one manufacturer and one core component supplier to investigate how to foster energy-saving innovation. In line with reality, the core component can largely determine the critical energy-saving performance of an EV like cruising ability. This component could be a power battery cell, battery pack, battery monument system, power electronics, or other related parts. The critical performance of an EV may cause potential EV consumers’ range anxiety, which in turn will primarily affect the EV’s market demand. Given the market response, the supply chain members could take energy-saving innovation activities separately or collaboratively to improve critical performance or reduce consumers’ range anxiety concerns. In this study, we build an analytical framework to analyze how different cooperation modes affect the EV supply chain’s energy-saving innovation performance and firms’ profitability.

The findings in our research provide managerial implications for business managers and policymakers. First, although the key performance is critical to attracting the consumers, managers of EV manufacturers should realize that the suppliers have the motivation to improve the key components’ performances. Therefore, when they negotiate with suppliers to implement energy-saving innovation activities, they should let the suppliers understand the benefit of their effort for the improvement of performance.
Second, the managers of EV manufacturers can also positively participate in suppliers’ energy-saving innovation with financial support. Our results also propose which degree of financial support the manufacturer should give. Similar to this study, Aydin and Parker (2018) investigated the effects of consumer market factors on an upstream innovation in the context of the supply chain. They specified the condition under which the upstream firm does not invest in innovation, while our result shows that the downstream firm should positively participate upstream firm’s innovation.

Third, to continue to improve the efficiency of energy-saving and performance, manufacturers or suppliers should actively promote the formation of strategic alliances. If possible, manufacturers can also actively adopt an integrated strategy to acquire or integrate core component suppliers. Finally, our results also suggest that managers of EV manufacturers and suppliers use a profit-sharing scheme to achieve energy-saving innovation cooperation under strategic alliances. Notably, the managers should research and analyze their partners’ market position and risk appetite, and then the Nash-barging mechanism could be applied appropriately in cooperation with those market dynamics.

This study has limitations in several aspects. First, although our model considers the vertical competition in a typical EV supply chain, future studies can consider the competition of upstream suppliers, downstream manufacturers, or both. Second, for the tractability of the model, we use the linear demand system for our analysis; other types of demand systems may yield new insights. Finally, we consider deterministin market demand, and the stochastic market demand may yield more insights.

Appendix

Proof of Lemma 1

In the second stage of the game, as per the first-order condition (FOC) \( \frac{\partial \pi_{m}^{NTI}}{\partial p} = 0 \), we have \( p(p_m) = (\theta + \beta p_m + \mu \nu_0) / 2 \beta \). Inserting \( p(p_m) \) into \( \pi_{m}^{NTI} \), we have \( \pi_{m}^{NTI} (p_m) = 1/2(p_m - c_m)(\theta - \beta p_m + \mu \nu_0) \). In the first stage of the game, as per the FOC (\( \frac{\partial \pi_{m}^{NTI} (p_m)}{\partial p_m} = 0 \)), we have \( P_m^{NTI} = (\theta + \beta c_m + \mu \nu_0) / 2 \beta \). Inserting \( P_m^{NTI} \) into the respective expression of decision variables as well as the demand and profit functions, one can obtain the results as summarized in Lemma 1. Q.E.D.

Proof of Lemma 2

In the second stage of the game, given \( p_m \) and \( \tau \), we first solve \( \pi_{m}^{TI} \)'s maximization problem with respect to \( p_m \). As per the FOC, we have \( p(p_m, \tau) = (\theta + \beta p_m + \mu \nu_0 (1 + \tau)) / 2 \beta \). Inserting \( p(p_m, \tau) \) into \( \pi_{m}^{TI} \), we have \( \pi_{m}^{TI} (p_m, \tau) = 1/2(p_m - c_m)(\theta - \beta p_m + \mu \nu_0 (1 + \tau)) - a \tau^2 \). Because \( \pi_{m}^{TI} (p_m, \tau) \)'s Hessian matrix with respect to \( p_m \) and \( \tau \) is \( H = \begin{bmatrix} -\beta \lambda & \frac{\mu \nu_0}{2} \\ \frac{\mu \nu_0}{2} & -2a \end{bmatrix} \), one can obtain that |\( H_1 \)| = -\( \beta \lambda < 0 \) always holds, and |\( H_2 \)| = \( (8a \beta \lambda - \nu_0 \mu \nu_0^2) / 4 \).

Proof of Proposition 1

Given the expression of \( \tau^{TI^*} \) in Lemma 2, we have:

\[
\frac{\partial \tau^{TI^*}}{\partial \mu} = \frac{8a \beta \lambda \nu_0 (\theta - \beta c_m + 2 \mu \nu_0)}{(8a \beta \lambda - \nu_0 \mu \nu_0^2)^2} + \frac{\mu \nu_0^2 [8a \beta \lambda - \nu_0 \mu \nu_0^2 + \mu \nu_0 (\theta - \beta c_m + \mu \nu_0)]}{(8a \beta \lambda - \nu_0 \mu \nu_0^2)^2} + \frac{8a \beta \lambda \nu_0 (\theta - \beta c_m + \mu \nu_0)}{(8a \beta \lambda - \nu_0 \mu \nu_0^2)^2}.
\]

Given \( \theta - \beta c_m + \mu \nu_0 \geq 0 \) and \( a > (\nu_0 \mu \nu_0^2 / 4 \beta \lambda) > (\nu_0 \mu \nu_0^2 / 8 \beta \lambda) \), we can obtain \( (\partial \tau^{TI^*} / \partial \mu) > 0 \) holds. Q.E.D.

Proof of Lemma 3

In the third stage of the game, given \( p_m, \tau, \) and \( \sigma \), we first solve \( \pi_{e}^{CTI} \)'s maximization problem with respect to \( p \). As per the FOC, we have \( p(p_m, \tau, \sigma) = (\theta + \beta p_m + \mu \nu_0 (1 + \tau)) / 2 \beta \). Inserting \( p(p_m, \tau, \sigma) \) into \( \pi_{e}^{CTI} \) and \( \pi_{m}^{CTI} \), we have \( \pi_{e}^{CTI} (p_m, \tau, \sigma) = (\theta - \beta p_m + \mu \nu_0 (1 + \tau^2) / 4 \beta) - a \sigma \tau^2 \) and \( \pi_{m}^{CTI} (p_m, \tau, \sigma) = 1/2(p_m - c_m) (\theta - \beta p_m + \mu \nu_0 (1 + \tau)) - a (1 - \sigma) \tau^2 \). Because \( \pi_{m}^{CTI} (p_m, \tau, \sigma) \)'s Hessian matrix with respect to \( p_m \) and \( \tau \) is \( H = \begin{bmatrix} -\beta \lambda & \frac{\mu \nu_0}{2} \\ \frac{\mu \nu_0}{2} & -2a (1 - \sigma) \end{bmatrix} \), one can obtain that |\( H_1 \)| = -\( \beta \lambda < 0 \) always holds, and |\( H_2 \)| = \( (8a \beta \lambda (1 - \sigma) - \nu_0 \mu \nu_0^2) / 4 \).
Proof of Proposition 2

Given \(a > ((2 + \lambda)\mu^2 v_0^2 / 16\lambda) > ((\mu^2 v_0^2 / 8\lambda))\), we have \(p^{T*} - p^{NTT*} = (3(\theta - \beta\lambda c_m + \mu v_0)\mu^2 v_0^2) / 48(8\alpha\beta - v_0^2\mu^2) > 0\) and \(p^{T*} - p^{NTT*} = ((\theta - \beta\lambda c_m + \mu v_0) v_0^2\mu^2) / (2(8\alpha\beta - v_0^2\mu^2)) > 0\) hold; hence, both \(p^{T*} > p^{NTT*}\) and \(p^{T*} > p^{NTT*}\) hold; similarly, we have \(p^{CIT*} - p^{T*} = 3v_0^2\mu^2(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / 48(8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) and \(p^{CIT*} - p^{T*} = \mu^2 v_0^2(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / 2(8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) hold; hence, both \(p^{CIT*} > p^{T*}\) and \(p^{CIT*} > p^{T*}\) hold. Similarly, one can obtain \(D^{NTT*} < D^{T*} < D^{CIT*}\) also holds. Q.E.D.

Proof of Proposition 3

Given \(a > ((2 + \lambda)\mu^2 v_0^2 / 16\lambda) > ((\mu^2 v_0^2 / 8\lambda))\), we have \(\tau^{CIT*} - \tau^{TT*} = \mu v_0(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / (8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) . Thus, \(\tau^{CIT*} > \tau^{TT*}\) holds. Q.E.D.

Proof of Proposition 4

Given \(a > ((2 + \lambda)\mu^2 v_0^2 / 16\lambda) > ((\mu^2 v_0^2 / 8\lambda))\), we have \(\tau^{CIT*} - \tau^{TT*} = \mu^2 v_0^2(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / (8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) and \(\tau^{CIT*} - \tau^{TT*} = \mu v_0(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / (8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) hold; hence, both \(\tau^{CIT*} > \tau^{TT*}\) and \(\tau^{CIT*} > \tau^{TT*}\) hold. Similarly, we have \(\tau^{CIT*} - \tau^{TT*} = \mu^2 v_0^2(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / (8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) and \(\tau^{CIT*} - \tau^{TT*} = \mu v_0(\theta - c\beta\lambda + \mu v_0)(\mu^2 v_0^2 - 8\alpha\beta(1 - \lambda)\lambda)) / (8\alpha\beta - v_0^2\mu^2)((16\alpha\beta\lambda - (2 + \lambda)v_0^2\mu^2) > 0\) hold; hence, both \(\tau^{CIT*} > \tau^{TT*}\) and \(\tau^{CIT*} > \tau^{TT*}\) hold. Put together, we also have both \(\tau^{CIT*} > \tau^{TT*}\) and \(\tau^{CIT*} > \tau^{TT*}\) hold. Q.E.D.

Proof of Lemma 4

Given the expression of \(\pi^{ATT'}\) in Equation (9), because \(\pi^{ATT'}\)'s
Hessian matrix with respect to \(p\) and \(\tau\) is \(H = \begin{bmatrix} -2\beta & \mu v_0 \\ \mu v_0 & -2a \end{bmatrix}\), one can obtain that \(|H_1| = -2\beta < 0\) always holds, and \(|H_2| = 4\alpha\beta - v_0^2\mu^2\) requires \(a > (v_0^2\mu^2 / 4\beta)\). Suppose \(a > (v_0^2\mu^2 / 4\beta)\) sustains, thus from the concavity of the objective functions \(\pi^{ATT'}\) with respect to \(p\) and \(\tau\), we use FOCs to jointly derive optimal \(p\) and \(\tau\) as \(p^{ATT'} = \lambda c_m + (2a(0 - \beta\lambda c_m + \mu v_0)) / (4\alpha\beta - v_0^2\mu^2)\), and \(\tau^{ATT'} = \mu v_0(0 - \beta\lambda c_m + \mu v_0) / (4\alpha\beta - v_0^2\mu^2)\). Inserting \(p^{ATT'}\) and \(\tau^{ATT'}\) into respective variables or functions, we can obtain the results summarized in Lemma 4. Q.E.D.
Proof of Proposition 5
Given \( a > (\mu^2 v_0^2 / 4\beta) > ((2 + \lambda)\mu^2 v_0^2) / 16\beta\lambda \), we have
\[
\pi_A^{\text{ATI}} - \pi_T^{\text{CTI}} = \frac{(\theta - \beta\lambda c_m + \mu v_0)^2}{16\beta\lambda(4\beta - v_0^2\mu^2)(16\beta\lambda - (2 + \lambda)v_0^2\mu^2)} > 0
\]
holds. Similarly, \( \tau_A^{\text{ATI}} - \tau_T^{\text{CTI}} = \frac{(4\beta(3\lambda - 1) - v_0^2\mu^2)}{(4\beta - v_0^2\mu^2)(16\beta\lambda) - (2 + \lambda)v_0^2\mu^2} > 0 \) holds. Thus, we obtain that both \( \pi_A^{\text{ATI}} > \pi_T^{\text{CTI}} \) and \( \tau_A^{\text{ATI}} > \tau_T^{\text{CTI}} \) hold. Q.E.D.

Proof of Proposition 6
Given the optimization problem stated in Equation (10), inserting the constraint into the objective function yields:
\[
\max (\Delta \pi_c)_{\alpha^h, (\Delta \pi_m)^{1-\alpha^h}} = (\Delta \pi_c)_{\alpha^h} (\Delta \pi - \Delta \pi_c)^{(1-\alpha^h)}.
\]
The FOC with respect to \( \Delta \pi_c \) yields:
\[
\alpha^h \delta_c (\Delta \pi_c)_{\alpha^h-1} - (1-\alpha^h) \delta_m (\Delta \pi_c)_{\alpha^h} \quad (\Delta \pi - \Delta \pi_c)^{(1-\alpha^h)} = 0.
\]
Solving this equation yields:
\[
\Delta \pi_c = \frac{\alpha^h \delta_c}{(1-\alpha^h) \delta_m + \alpha^h \delta_c} \Delta \pi.
\]

In the same way, one can calculate the optimal expression of \( \Delta \pi_m = ((1-\alpha)\delta_m)/(1-\alpha) \delta_m + \alpha^h \delta_c) \Delta \pi \). Put together, and we can obtain the results in Proposition 6. Q.E.D.

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ORCID ID
Lu-fei Huang https://orcid.org/0000-0002-6237-9891

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