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ORIGINAL RESEARCH

Forward–reverse blockchain traceability: promoting electric vehicles with battery recycling in the presence of subsidy

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Abstract

Electric vehicles (EVs) and their battery recycling have recently garnered heightened attention from both firms and consumers, primarily driven by concerns related to environmental sustainability. However, consumers often grapple with uncertainties regarding the green valuation of EVs. Integrating blockchain traceability technology presents a promising solution to mitigate these ambiguities by providing traceable, immutable, and precise information. Within this context, this research, grounded in a game-theoretical framework, delves into the strategies involving blockchain traceability in the pre-purchase and post-purchase stages of EVs. Specifically, the paper analytically studies the influence of three distinct strategies, namely, non-blockchain traceability, forward blockchain traceability, and Forward–reverse blockchain traceability, on the willingness of EV manufacturers to adopt blockchain technology. In addition, the study incorporates two prevalent government subsidies to scrutinize and contrast their implications on optimal outcomes. The findings of this study uncover the nuanced relationship between adopting blockchain traceability and its impact on EV sales. Notably, the research shows that the positive impact on consumers' surplus from blockchain adoption depends on the cost coefficient of green low-carbon levels not exceeding a particular threshold. Moreover, regarding the use of government subsidies to enhance overall social welfare, it is shown that the forward blockchain traceability strategy should align with consumer-oriented subsidies and the Forward–reverse blockchain traceability strategy with EV maker-oriented subsidies.

Keywords Electric vehicles · Blockchain technology · Forward–reverse traceability · Subsidy · Battery recycling

1 Introduction

The automobile industry's sustainable development has gained growing attention in recent years due to fossil energy depletion and climate change. Approximately 97% of energy in the transportation sector originates from fossil sources, which accounts for over 25% of global carbon emissions (Zhang and Zeng, 2021). As a result, electric vehicles (EVs) have emerged as a desirable alternative to conventional fuel vehicles in the following lenses (EPA, 2022). First, electricity for accelerating EVs can be mainly generated from green renewable sources, including solar and wind power, contributing to less reliance on fossil energy and

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Extended author information available on the last page of the article alleviating carbon emissions. Second, EVs have more energy conversion efficiency than fuel vehicles, thus leading to more significant energy savings (Sohu, 2020). Third, the lifespan of EV batteries can be dramatically extended via the secondary use or recycling of retired EV batteries, thus reducing environmental pollution (Gu et al., 2018).

With these benefits combined with growing consumers' environmental awareness and government subsidies, the global EV market has dramatically expanded in recent years (Toraman et al., 2023). For example, in 2022, China's EV sales reached 6.88 million, 1.9 times of previous year's sales. This tendency is aligned with the *Ali research survey*, revealing that approximately 68% of consumers will purchase EVs in five years because of EVs' green and economic attributes (AliResearch, 2022). However, the whole EV production process requires consuming a large colossal of energy, particularly in making EV battery electrodes; this energy consumption primarily relies on 'dirty' coal. To deal with consumers' low-carbon and green concerns and to meet the government's carbon-peak and carbon-neutralization requirement, many EV makers transfer their focus from the green EV products alone to the whole green supply chain involving EV design, EV manufacturing, battery recycling and reuse technology, and logistics process (CITICS, 2022; Zhang, 2020).

Although EV makers have actively promoted their green EV products, some consumers are still suspicious or uncertain about the EV low-carbon and green attributes due to information asymmetry, mainly because these EV green attributes can not easily be observed in the EV *ex-ante*-purchase stage (i.e., the forward manufacturing stage) and the *post*-purchase stage (i.e., the reverse recycling stage). For example, in the *ex-ante*-purchase stage, *BYD, as* the worldwide leading EV maker, has built its battery manufacturing plant in *Yibin* City of Sichuan Province with green hydroelectricity instead of coal-powered electricity to cut off carbon emissions (China Daily, 2022). Meanwhile, in the *post*-purchase stage, *BYD* has cooperated with *China Tower Corporation* and *Meituan Bike Sharing* for the secondary use of EV recycled batteries, thus extending battery lifespan and mitigating environmental pollution (China Daily, 2020). Eco-friendly consumers with little knowledge about this information will hesitate to purchase BYD EVs or will take time to search for EV-related green information, incurring "non-trivial hassle cost" and deterring their purchase intention.

Blockchain as a digital traceability technology enhances consumers' perception of EVs' green attributes from ex-ante to post-purchase. A typical example is that *Chery*, another of China's famous EV makers, utilizes blockchain technology to monitor EV production, usage, and recycling, ensure the whole process is monitored and any data related to each EV and battery production, driving, and recycling is encrypted and transferred on the blockchain system, which guarantees that the source data is safe, reliable, untampered, and not abused (China Daily, 2022). Consumers can use their own smartphones to scan the quick response code and obtain traceability information; hence, this significantly removes or abates consumers' valuation uncertainty about EVs' green attributes.

However, not all EV makers are willing to implement blockchain traceability because they are unsure whether blockchain adoption could increase EV sales and improve profitability. Besides, it remains unclear if different types of subsidies offered by the government can offset EV makers' costs to encourage their blockchain adoption. Furthermore, EV makers are uncertain how blockchain traceability implementation (from the *ex-ante* to the *post*-purchase stage) can yield different outcomes. Answers to these questions are still obscure due to insufficient relevant research.

Against this backdrop, this research develops a game-theoretic model of an EV supply chain in the presence of government subsidies to explore the optimal solutions and conditions. The model considers three typical traceability strategies—non, forward, and Forward–reverse blockchain traceability strategy—and captures different *ex-ante* and *post*-purchase stages. Specifically, this study addresses the following research questions.

(1) Under which circumstances will the EV maker adopt blockchain traceability to mitigate consumers' uncertainties about EVs' green and low-carbon values?
(2) What is the best strategy for the EV maker to implement blockchain traceability? Can the market demand be enlarged or stabilized? Can the EV supply chain performance be improved?
(3) How do government subsidies differ when offered to the EV maker versus consumers for different blockchain traceability strategies? Which type of subsidies benefits the EV supply chain member's performance and the adoption of blockchain technology? For the three traceability strategies, how do the critical factors influence the EV supply chain and social welfare?

The main novelties of this paper are as follows. First, prior work related to blockchain adoption has rarely considered different blockchain traceability strategies, which is addressed in this paper. Specifically, based on the practices in the EV industry, we examine three typical blockchain traceability strategies—non, forward, and Forward–reverse blockchain traceability strategy—in the *ex-ante* and *post*-purchase stages and analyze the conditions to adopt blockchain technology. Second, we explore how two typical government subsidy policies match different blockchain traceability strategies, which have seldom been studied.

The remaining of this study is organized as follows. Section 2 reviews relevant prior research. In Sects. 3 and 4, we define our methodology and research problem. Section 5 describes three blockchain traceability models and presents the main results. In Sect. 6, by comparing three traceability strategies, we illustrate the optimal blockchain traceability selection and the related conditions. Section 7 investigates three traceability strategies in the two subsidy policies and explores consumer surplus, social welfare, and profits. Section 8 concludes the work with proposals for future research.

2 Literature review

Our paper features the impact of different blockchain traceability strategies on the EV maker's performance in the context of the supply chain. Thus, we review two streams of literature in this section: (i) EV supply chains and (ii) blockchain traceability in operation management.

2.1 EV supply chains

A growing amount of literature studies EV supply chains, which are divided into three categories: EV manufacturing, EV battery recycling, and subsidies (Adnan et al., 2023). For EV manufacturing, Fan and Chen et al. (2022) examine the outsourcing-manufacturing decision by EV makers in a two-echelon supply chain. Zhu et al. (2022) analyze the EV manufacturing competition in supply chains consisting of a high-end encroachment manufacturer and an incumbent manufacturer sourcing from the same battery supplier. Wang and Huang (2021) study the EV manufacturing decision-making in a supply chain with a supplier and an EV maker and explore how different cooperation modes affect the EV supply chain's energy-saving performance and profitability. Addressing the EV battery recycling issue (Gu and Zhou, 2021), Gu et al. (2018) investigate EV battery recycling in a reused closed-loop supply chain and obtain the optimal pricing policy between the EV manufacturer and the re-manufacturer. Zhang et al. (2023) examine three EV battery collection/recycling modes and the echelon utilization in the context of carbon emission reduction, finding that when the collection competition is above a threshold, the co-collection model is inferior, and a single-channel collection model should be selected. Furthermore, Gong and Gao (2022) propose a dual-channel EV supply chain consisting of a formal and an informal EV battery recycler under a subsidy-and-penalty policy. Comprehensively, Zhao et al. (2021) consider a three-echelon EV supply chain, including a power battery manufacturer, an EV maker, and a retailer, to study the optimal pricing strategies in three different EV battery recycling channels.

To study subsidy, Pi (2023) develops three analytical models under the pure subsidy, pure regulation, and hybrid subsidy-regulation policy, respectively, and examines an automaker's entry intention into the EV market under each policy. Chen et al. (2022) specifically explore the optimal subsidy rate based on the government's different goals, namely, social welfare or governmental utility maximization. Fan and Cao (2020) design the optimal government subsidy and tariff policies to improve the profit of domestic EV makers and social welfare in the market where domestic and imported EV makers exist. Additionally, Chen and Ulya (2019) address the subsidy-penalty mechanism, revealing that the return rate and green efforts can be improved in retired EV batteries.

Unlike prior studies focusing on EV manufacturing, EV battery recycling, and subsidies, this paper highlights the impact of different EV-supply-chain blockchain traceability strategies on the EV supply chain member's performance.

2.2 Blockchain traceability in operation management

The literature on blockchain traceability in operational management mainly covers two domains: forward and reverse traceability. The former typically involves product quality (Júnior et al., 2022; Wu & Wang, 2023), counterfeit combat (Choi, 2019; Pun et al., 2021), logistics process (Liu et al., 2022), information authenticity (Xu & Choi, 2021), while the latter addresses the topic associated with recycling trace (Cheng et al., 2021).

In view of the forward blockchain traceability, Wu and Wang (2023) use the blockchain to monitor quality in a supply chain under three modes (agency, reselling, and hybrid contract), find that the platform is most likely to adopt blockchain when the supplier with higher quality prefers to use the agency contract and another supplier to use the reselling contract. Fan et al., (2020a, 2020b) identify three factors: traceability awareness of consumers, production costs, and ease of use, and confirm their critical role in adopting blockchain traceability for monitoring product quality. In addition, Júnior et al. (2022) reveal that blockchain traceability has enabled firms to serve their customers well with a more reliable quality in the shortest time.

In combating counterfeits, Choi (2019) explores the values of blockchain technology against forgeries in the diamond industry by considering three models (traditional retail operations, blockchain technology-supported selling platform, and blockchain technology-supported certification platform). Pun et al. (2021) consider a fake market with a manufacturer and a deceptive counterfeiter, discovering that blockchain should be used only when the counterfeit quality is intermediate or when customers have intermediate distrust about products in the market.

Addressing logistics process and information authenticity, Liu et al. (2022) investigate how blockchain traceability affects a producer's decision to outsource delivery to a third-party logistics firm, revealing that blockchain traceability can resolve the logistics firm's moral hazard and encourage the producer to improve production. Sun et al. (2023) examine a blockchain introduction strategy for fresh agricultural enterprises in a competitive environment considering consumer traceability preferences and show that when the blockchain influencing power meets a specific range, introducing blockchain technique in the traceability system could shift demand from traditional enterprises to blockchain enterprises. Xu and Choi (2021) highlight the green production process under cap-and-trade regulation via blockchain traceability. They find that blockchain traceability's aptitude to enhance the profitability of a manufacturer's offline channel depends on the cross-channel effect.

Compared with forward blockchain traceability, very few studies have addressed the issue of reverse blockchain traceability. Cheng et al. (2021) propose a blockchain traceability platform to manage retired power batteries, thus effectively helping move more spent power batteries via formal recycling channels. Feng et al. (2023) explore the impact of various carbon emission reduction policies on blockchain technology adoption in recycling EV batteries; three policies are considered—carbon tax, carbon cap-and-trade regulations, and both. Gong et al. (2023) investigate a supply chain consisting of an OEM, a third-party re-manufacturer, and a retailer to determine if the OEM should adopt blockchain technology and sell products directly or indirectly through the retailer.

However, prior literature merely considers forward or reverse traceability disjointly; few have combined both types of traceability and jointly taken them into account. Our study involves the traceability in both the *ex-ante*-purchase stage (forward blockchain traceability) and the *post*-purchase stage (reverse recycling blockchain traceability) and compares the differences between three typical traceability strategies and two subsidy schemes.

3 Research methodology

We employ the Stackelberg game method in this paper because the dynamics of real-world markets are not always steady and can result in unpredictable changes that exhibit various firm's behaviors. The duopoly Stackelberg model helps analyze such a dynamic competition between firms where a leader decides while others follow, i.e., the leader firm is dominant, and the follower firms are adaptable.

In the EV supply chain of this paper, the EV maker is a leader who has a dominant position with the key green and low-carbon technologies, enabling its stronger price bargaining power than the downstream retailer (i.e., the follower). Meanwhile, in reality, the EV maker actively adopts blockchain technology to trace product information covering the ex-ante and post-purchase stages, but the retailer has to passively respond to this move to strengthen the green perception of EVs. Hence, a Stackelberg game model is established in our paper to capture this decision-making process.

Such a game-theoretical frame is utilized to examine three traceability strategies (non, forward, and Forward–reverse blockchain traceability strategy) in the EV supply chain with the consideration of government subsidies. The leader (the EV maker) first determines which traceability strategy to adopt, the corresponding wholesale price, and a green, low-carbon investment level. Observing the leader's decision, the follower (the retailer) declares its retailing price.

The consumer utility theory method is also introduced to yield the EV supply chain market demand based on consumers' perceived valuation of the EVs and the related retired battery secondary use, along with the retailing price and consumers' time cost for uncovering EVs' green, low-carbon values. Afterward, the market demand is utilized to formulate the profit functions of the EV maker and the retailer, respectively. Finally, we will obtain the

EV supply chain game-equilibrium outcomes with the backward induction method, thus deducing meaningful insights under three traceability blockchain strategies.

4 Problem formulation

We consider an EV supply chain composed of an EV maker and a retailer, represented by the superscript '*M*' and '*R*,' respectively. The EV maker produces EVs of only one type and wholesales them to the retailer. Consumers have green preferences, so low-carbon EVs may enhance their willingness to purchase. The EV maker will invest in both production process innovation and product innovation to reduce carbon emissions, but the EVs' green, low-carbon investment also swells the EV maker's production costs. The government may offer subsidies to the EV maker or the consumers in different patterns to accelerate EV green technology or product innovation.

Based on the Stackelberg game-theoretical framework, the event sequence of this paper (4 stages) is shown in Fig. 1. In the first stage, the government determines its subsidy policies—whether to offer subsidies to the EV maker or consumers. In the second stage, the EV maker decides on adopting blockchain technology and traceability strategy, i.e., the non, forward, and Forward–reverse traceability strategy, sub-scripted by 'NB,' 'FB,' and 'FRB.' Due to the EV maker's dominant role in the EV supply chain, the EV maker bears the operational cost of information traceability in blockchain adoption. The unit operating cost under the forward blockchain traceability strategy is denoted by c_b and that under the Forward–reverse traceability blockchain strategy is $c_{rb} = \delta c_b (\delta > 1)$.

If the EV maker does not implement blockchain technology, EV consumers may be uncertain about EVs' green, low-carbon value with an uncertainty degree τ $(0 \le \tau < 1)$. To mitigate such uncertainties, consumers may spend time identifying EVs' low-carbon and green authenticity, resulting in a time cost c_t. We use η to represent the consumer sensitivity coefficient with respect to this time cost. If the EV maker adopts blockchain technology, consumers will have complete information about the green, low-carbon characteristics of EVs; thus $\tau = 0$.

Furthermore, suppose the EV maker extends to Forward–reverse traceability from forward traceability. In that case, consumers will know more green, low-carbon information related to retired EV battery recycling and secondary use because these retired EV batteries for secondary use can still be utilized in home energy storage after being replaced by new ones due to safety and environmental concerns (Gu and Zhou, 2021). The secondary use and recycling of these retired batteries significantly increase the total lifespan value of EV batteries, which

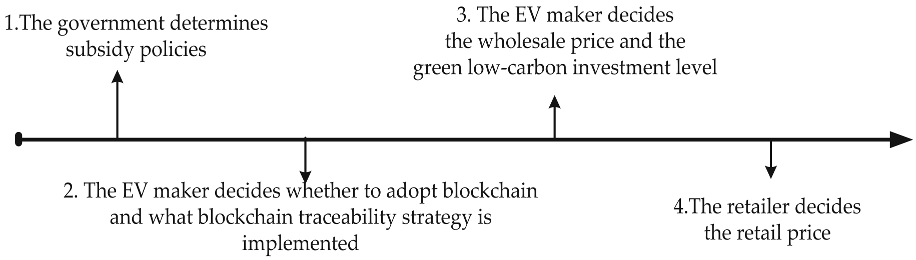


Fig. 1 Event sequence

enhances consumers' utility of EV purchasing and reduces environmental pollution accordingly (Gu et al., 2018). Without reverse blockchain traceability, the EV maker has to rely on manual assessment to identify the retiring points and quality of EV batteries, thus leading to reverse traceability inaccuracy. The manual assessment entails tracing and managing EV batteries throughout their life span. A lower manual assessment level implies less accurate retirement timing, inferior quality, and lower green values for consumers. Adopting reverse blockchain traceability can dramatically diminish inaccuracy in the timings and preciseness of information in EV supply chains.

As a result, we assume the consumer's utility obtained from the retired batteries is $q(1 - e^{-\lambda})$, where λ is the EV maker's manual assessment level of the retired batteries and q is the reference quality level of retired batteries, which signifies the fundamental benchmark for retired battery quality. When the EV maker adopts the Forward–reverse blockchain traceability strategy, it can precisely identify the status of retired batteries, so the manual assessment level $\lambda \to +\infty$, i.e., consumers' utility is q. In contrast, if the reverse blockchain traceability is not implemented, consumers' utility is $q(1 - e^{-\lambda})$, which is less than q.

In the third stage, displayed in Fig. 1, the EV maker determines its green and low-carbon investment level l and wholesale price w. Following Gong et al. (2023), we assume the EV maker's green low-carbon investment cost is a quadratic function $kl^2\big/2$, where k is the cost coefficient. To clear the models and not impact the outcomes, we assume that the EV maker's production cost is zero.

Finally, the retailer sells to consumers at a retail price p. The heterogeneous consumers' perceived EV value contains two components: basic value v and green and low-carbon value θl. Consumers' basic value of EVs v is uniformly distributed over [0,1], and their green low-carbon value θl relies on the green low-carbon investment level l and its sensitivity coefficient θ (Shen et al., 2020). The market size is normalized to 1, where consumers purchase one EV at most. The main notations in this paper are summarized in Table 1.

5 Equilibrium analysis without subsidies

This section focuses on the basic models under three traceability strategies if the government determines not to offer subsidies. First, we study the equilibrium of the EV maker and the retailer for the three blockchain traceability strategies.

5.1 Model under the non-blockchain traceability strategy

Under the non-blockchain traceability strategy (Fig. 2), the EV maker does not adopt blockchain technology. Thus, the consumer utility function is formulated as

$$\begin{aligned} U_{NB} &= (1-\tau)(v + \theta l_{NB}) - p_{NB} - \eta c_t + \xi_{NB} \\ &= (1-\tau)(v + \theta l_{NB}) - p_{NB} - \eta c_t + q(1 - e^{-\lambda}). \end{aligned} \tag{1}$$

From Eq. (1), the consumer utility includes five components: EV basic valuation (v), consumers' perceived low-carbon value of EVs (θl_{NB}), price, and information search cost (i.e., hassle cost), and the perceived value obtained from the retired battery secondary use. τ indicates the consumer's uncertainty degree about EV value, including the basic and green low-carbon value. Additionally, when the EV maker does not adopt blockchain technology, consumers will spend more time searching for EV-related information, suppressing their

Table 1 The main notations in this paper

Parameters	
τ	The degree of consumer uncertainty about the EV basic and green low-carbon value, $0 \le \tau < 1$
v	The basic value of the EV
θ	The sensitivity coefficient of consumer surplus,$\theta \ge 0$
η	The consumer sensitivity coefficient with respect to time cost
c_t	The time cost related to the search for green, low-carbon information on the EVs
ξ	The perceived value obtained from the retired batteries due to their secondary use
q	The reference quality level of retired batteries
λ	The EV maker's manual assessment level of retired batteries
k	The cost coefficient of green low-carbon level
c_b	The unit operational cost under the forward blockchain traceability strategy
δ	The operational cost coefficient under the Forward–reverse blockchain traceability strategy,$\delta > 1$
d	The demand for EVs
α	The proportion of green low-carbon production cost shared by the government,$0 \le \alpha < 1$
β	The subsidy amount to consumers,$0 \le \beta < 1$
r	The carbon reduction benefit of purchasing an EV
Decision variables	
w	The wholesale price of an EV
p	The retail price of an EV
l	The green low-carbon level of EVs

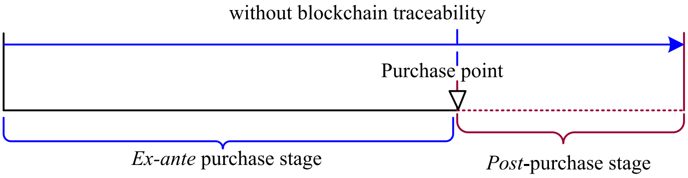


Fig. 2 The non-blockchain traceability strategy

purchase impulses, especially for those relatively sensitive to hassle cost. Meanwhile, a higher retail price p_{NB} reduces consumers' desire to purchase EVs. Furthermore, consumers also perceive the value ξ_{NB} of spent batteries after eight-to-ten-year renewals/recycling due to the secondary use of retired EV power batteries, $\xi_{NB} = q(1 - e^{-\lambda})$, where $\xi_{NB} < q$.

Consumers determine whether or not to purchase EVs depending on their utility. When $U_{NB} > 0$, i.e.,$v \ge \hat{v} = \frac{p_{NB}+\eta c_t - q(1-e^{-\lambda})}{1-\tau} - \theta l_{NB}$, consumers will purchase EVs; otherwise, consumers will quit. The demand is $d_{NB} = \int_{\hat{v}}^{1} dv$, owning to that v is uniformly distributed over [0,1]. Thereby, the demand function is formulated as follows:

$$d_{NB} = \int_{\frac{p_{NB}+\eta c_t - q(1-e^{-\lambda})}{1-\tau} - \theta l_{NB}}^{1} dv = 1+\theta l_{NB} - \frac{p_{NB} + \eta c_t - q(1-e^{-\lambda})}{1-\tau} \tag{2}$$

Therefore, the retailer's profit function is formulated by

$$\pi_{NB}^{R}(p_{NB}) = (p_{NB} - w_{NB})d_{NB} \tag{3}$$

The EV maker's profit function is formulated as

$$\pi_{NB}^{M}(w_{NB}, l_{NB}) = w_{NB}d_{NB} - \frac{1}{2}kl_{NB}^{2} \tag{4}$$

Using the backward induction method to derive the equilibrium results by maximizing the retailer's and EV maker's profits, we obtain Lemma 1 as follows (the proof is presented in the Appendix).

Lemma 1 *Under the non-blockchain traceability strategy when* $k > \frac{\theta^2(1-\tau)}{4}$, *the equilibrium can be obtained as follows:*

(1) Retail price, wholesale price, and green low-carbon level: $p_{NB}^{*} = \frac{3k(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{4k-\theta^2(1-\tau)}$, $w_{NB}^{*} = \frac{2k(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{4k-\theta^2(1-\tau)}$, $l_{NB}^{*} = \frac{\theta(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{4k-\theta^2(1-\tau)}$;

(2) Demand for EVs: $d_{NB}^{*} = \frac{k(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{(1-\tau)(4k-\theta^2(1-\tau))}$;

(3) Profits: $\pi_{NB}^{M*} = \frac{k(1+q(1-e^{-\lambda})-\eta c_t-\tau)^2}{2(1-\tau)(4k-\theta^2(1-\tau))}$, $\pi_{NB}^{R*} = \frac{k(1+q(1-e^{-\lambda})-\eta c_t-\tau)^2}{(1-\tau)(4k-\theta^2(1-\tau))^2}$.

Lemma 1 demonstrates the equilibrium demand and profits of the EV maker and the retailer under the non-blockchain traceability strategy. Based on the first-order condition, it is implied that π_{NB}^{M*} *and* π_{NB}^{R*} *decrease with* τ *and* c_t. *This indicates that consumers' uncertainty about the green, low-carbon attributes of EVs impairs the profitability of both the EV maker and the retailer. The rationale is that such uncertainty drives consumers to search for related information and yields the corresponding hassle cost, particularly for the more cost-sensitive consumers, so their purchase intention and demand will diminish. As a result, the EV maker has to mark down the wholesale price, and the retailer lowers the retail price, intending to lure more consumers to purchase.*

5.2 Model under the forward blockchain traceability strategy

If the EV maker introduces the forward blockchain traceability strategy (Fig. 3), the blockchain traceability merely covers the *ex-ante*-purchase stage without extending to the *post*-purchase stage. In this context, consumers will be well informed of the basic and the green low-carbon information in the *ex-ante*-purchase stage (i.e., the forward part). This enhances consumers' purchase confidence due to blockchain ensuring EV-related information transparency, so consumer uncertainty regarding EV's basic and green low-carbon information will disappear; thus $\tau = 0$.

However, for the *post*-purchase stage (i.e., the reverse part), due to the lack of reverse blockchain traceability, consumers perceive the same value of the retired batteries at the *post*-purchase stage as that under the non-blockchain traceability strategy, i.e., $\xi_{FB} = q(1 - e^{-\lambda})$.

Additionally, because of blockchain adoption, the EV maker bears an extra related operational cost (c_b). Therefore, the consumer utility function under the forward blockchain traceability strategy is illustrated by

$$\begin{aligned} U_{FB} &= v + \theta l_{FB} - p_{FB} + \xi_{FB} \\ &= v + \theta l_{FB} - p_{FB} + q(1 - e^{-\lambda}). \end{aligned} \tag{5}$$

With the same logic, the demand function is derived below:

$$d_{FB} = \int_{p_{FB} - \theta l_{FB} - q(1-e^{-\lambda})}^{1} dv = 1 + \theta l_{FB} - p_{FB} + q\left(1 - e^{-\lambda}\right) \tag{6}$$

The profit functions of the retailer and the EV maker are shown as

$$\pi_{FB}^{R}(p_{FB}) = (p_{FB} - w_{FB}) d_{FB}, \tag{7}$$

$$\pi_{FB}^{M}(w_{FB}, l_{FB}) = (w_{FB} - c_b) d_{FB} - \frac{1}{2} k l_{FB}^{2} \tag{8}$$

Using the same method as that for the non-blockchain traceability strategy, we obtain Lemma 2.

Lemma 2 *Under the forward blockchain traceability strategy, when* $k > \frac{\theta^2}{4}$*, the equilibrium outcomes can be obtained as follows:*

(1) Retail price, wholesale price, and low-carbon level:

$$p_{FB}^{*} = \frac{(k - \theta^2)c_b + 3k(1 + q(1 - e^{-\lambda}))}{4k - \theta^2}, \; w_{FB}^{*} = \frac{(2k - \theta^2)c_b + 2k(1 + q(1 - e^{-\lambda}))}{4k - \theta^2}, \; l_{FB}^{*} = \frac{\theta(1 + q(1 - e^{-\lambda}) - c_b)}{4k - \theta^2};$$

(2) Demand for EVs: $d_{FB}^{*} = \frac{k(1+q(1-e^{-\lambda})-c_b)}{4k-\theta^2}$*;*

(3) Profits of the EV maker and the retailer: $\pi_{FB}^{M*} = \frac{k(1+q(1-e^{-\lambda})-c_b)^2}{2(4k-\theta^2)}$, $\pi_{FB}^{R*} = \frac{k^2(1+q(1-e^{-\lambda})-c_b)^2}{2(4k-\theta^2)^2}$.

Lemma 2 shows the equilibrium outcomes under the forward blockchain traceability strategy where the green low-carbon level and the demand decrease with the operational cost of blockchain. Moreover, retail and wholesale prices are monotonic, along with the

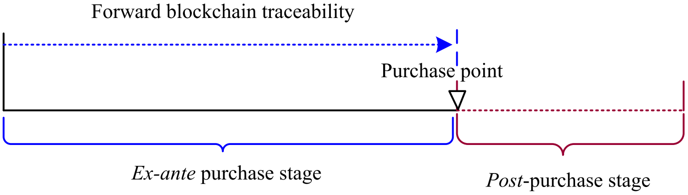


Fig. 3 The forward blockchain traceability strategy

operational cost of blockchain. Meanwhile, the EV maker's margin ($w^*_{FB} - c_b$) and the retailer's margin ($p^*_{FB} - w^*_{FB}$) decrease with the operational cost of blockchain. This implies that the EV maker should carefully balance the relationship between the operational cost of blockchain and EV-related green information transparency.

5.3 Model under the forward–reverse blockchain traceability strategy

When the EV maker leverages the Forward–reverse blockchain traceability strategy (Fig. 4), the traceability extends from the *ex-ante purchase* to the *post-purchase* stage. Hence, blockchain technology not only eliminates consumers' uncertainty related to the basic and green low-carbon information in the *ex-ante*-purchase stage (the forward part), i.e., $\tau = 0$, but also helps the EV maker precisely identify the optimal retired point and quality level of EV batteries through the reverse traceability, thus increasing consumers' utilities from retired battery secondary use (the reverse part). Hence, for $\xi_{FRB} = q(1 - e^{-\lambda})$, $\lambda \to +\infty$, consumers' utility from retired batteries is q. Additionally, because blockchain traceability extends from the forward traceability to the reverse one, the operational cost under the Forward–reverse traceability is higher than that under the forward traceability accordingly, denoted by $\delta c_b (\delta > 1)$. Thereby, under the Forward–reverse blockchain traceability strategy, the consumer utility function is given by

$$\begin{aligned} U_{FRB} &= v + \theta l_{FRB} - p_{FRB} + \xi_{FRB} \\ &= v + \theta l_{FRB} - p_{FRB} + q. \end{aligned} \tag{9}$$

The demand function can be expressed as follows:

$$d_{FRB} = \int_{p_{FRB} - \theta l_{FRB} - q}^{1} dv = 1 + \theta l_{FRB} - p_{FRB} + q. \tag{10}$$

The profit function of the retailer and the EV maker is shown as

$$\pi^R_{FRB}(p_{FRB}) = (p_{FRB} - w_{FRB}) d_{FRB}, \tag{11}$$

$$\pi^M_{FRB}(w_{FRB}, l_{FRB}) = (w_{FRB} - \delta c_b) d_{FRB} - \frac{1}{2} k l^2_{FRB}. \tag{12}$$

Using the same method as those for the above two traceability strategies, we obtain Lemma 3.

Lemma 3 *Under the Forward–reverse blockchain traceability strategy, when* $k > \frac{\theta^2}{4}$, *the equilibrium outcomes can be obtained as follows:*

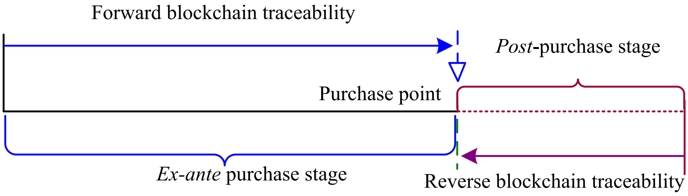


Fig. 4 The Forward–reverse blockchain traceability strategy

(1) Retail price, the wholesale price, and green low-carbon level:

$$p_{FRB}^{*} = \frac{(k-\theta^2)\delta c_b + 3k(1+q)}{4k-\theta^2},\ w_{FRB}^{*} = \frac{(2k-\theta^2)\delta c_b + 2k(1+q)}{4k-\theta^2},\ l_{FRB}^{*} = \frac{\theta(1+q-\delta c_b)}{4k-\theta^2};$$

(2) Demand for EVs: $d_{FRB}^{*} = \frac{k(1+q-\delta c_b)}{4k-\theta^2}$*;*

(3) Profits of the EV maker and the retailer: $\pi_{FRB}^{M*} = \frac{k(1+q-\delta c_b)^2}{2(4k-\theta^2)}$, $\pi_{FRB}^{R*} = \frac{k^2(1+q-\delta c_b)^2}{(4k-\theta^2)^2}$.

Lemma 3 illustrates the equilibrium demand and profits of the EV maker and the retailer under the Forward–reverse blockchain traceability strategy, where the equilibrium decisions mainly rely on the extra blockchain operational cost and the benefit from the Forward–reverse blockchain traceability. The following section further explores the decision on blockchain traceability adoption and compares the performance of different traceability strategies. To avoid trivial cases, we assume that the condtion, $k > \frac{\theta^2}{4}$, always holds throughout the whole paper.

6 Optimal blockchain traceability strategy selection

Although blockchain traceability can ease consumers' uncertainty about EVs' basic and green low-carbon information and effectively enhance the precise assessment of near-retirement battery quality for secondary usage, it inevitably increases the EV maker's operational cost. To this end, we next examine the circumstances under which the EV maker leverages the blockchain technology and what kind of blockchain traceability strategy is optimal or more suitable for the EV maker, the retailer, or consumers, and evaluate its impact on decision-making with respect to price, demand, and green low-carbon level.

Proposition 1 *The EV maker prefers to choose the non-blockchain traceability strategy if and only if* $c_b > \max\{\bar{c}_b, \tilde{c}_b\}$*; The EV maker prefers to choose the forward blockchain traceability strategy if and only if* $\hat{c}_b < c_b < \bar{c}_b$*; The EV maker prefers to choose the Forward–reverse blockchain traceability strategy if and only if* $c_b < \min\{\hat{c}_b, \tilde{c}_b\}$*,*

where $\hat{c}_b = \frac{qe^{-\lambda}}{\delta-1}$, $\bar{c}_b = 1 + q(1-e^{-\lambda}) - \sqrt{\frac{4k-\theta^2}{(1-\tau)(4k-\theta^2(1-\tau))}}(1 + q(1-e^{-\lambda}) - \eta c_t - \tau)$ *and* $\tilde{c}_b = \frac{1}{\delta}(1 + q - \sqrt{\frac{4k-\theta^2}{(1-\tau)(4k-\theta^2(1-\tau))}}(1 + q(1-e^{-\lambda}) - \eta c_t - \tau))$*.*

Proposition 1 implies the conditions for the EV maker to be profitable when adopting blockchain traceability strategies and choosing a specific blockchain traceability strategy. Specifically, when the operational cost of blockchain is at a higher level, exceeding a certain threshold, i.e., $c_b > \max\{\bar{c}_b, \tilde{c}_b\}$, the EV maker will not adopt the blockchain technology. Based on this, if the operational cost of blockchain falls in a lower range, i.e., $\hat{c}_b < c_b < \bar{c}_b$, the forward traceability strategy is the EV maker's best choice, and if the operational cost of blockchain is even lower, the Forward–reverse blockchain traceability strategy is the optimal strategy.

These outcomes are consistent with the implications in practice. The insight is that the benefits generated by blockchain adoption should cover the related incremental costs. In particular, such a benefit is not confined to the EV maker but to social welfare. This is also why governments expect to issue relevant policies to incentivize EV makers to adopt new technology actively. For instance, governments offer tax reductions or direct subsidies to lower the innovation pressure, including blockchain adoption.

We also derive the following propositions by comparing the optimal outcomes with and without blockchain adoption.

Proposition 2 *The comparison of retailer's profit and consumer surplus under three strategies is as follows:*

(1) The retailer's profit is better off for blockchain technology adoption when $c_b < \max\{\overline{c}_b, \tilde{c}_b\}$*, while consumer surplus increases when* $c_b < \max\{\overline{c}_b, \tilde{c}_b\}$ *and* $k < \frac{(2-\tau)\theta^2}{4}$*.*

(2) The retailer and consumers benefit more from the forward blockchain traceability strategy than the Forward–reverse strategy if and only if $c_b > \hat{c}_b$*. In contrast, they benefit more from the Forward–reverse blockchain traceability strategy than the forward strategy if and only if* $c_b < \hat{c}_b$*.*

Proposition 2 illustrates that when the unit operating cost of blockchain technology falls in the middle and lower range, blockchain enables the retailer and the consumers to be better off if the cost coefficient of green low-carbon level is below a certain threshold. The EV maker's adoption of blockchain traceability strategy has two different effects on the retailer. From Lemmas 2 and 3 (Sect. 4), we observe that the EV maker's operational cost of blockchain reduces the retailer's profit. However, the retailer's sales revenue increases when consumers eliminate their valuation uncertainty due to the traceability and reliability of the information via blockchain technology. When the latter effect dominates, the retailer's profit will increase when the EV maker adopts the blockchain traceability strategy. Moreover, consumers benefit from blockchain adoption as blockchain traceability enables them to easily obtain basic and green low-carbon information without hassle, thus enhancing their surplus.

Additionally, the retailer and consumers prefer the Forward–reverse over the forward blockchain traceability when the unit operating cost of blockchain technology is lower, i.e., $c_b < \hat{c}_b$. The reason is that the incremental gains from the retired battery recycling and secondary usage offset the additional blockchain operating cost under the Forward–reverse traceability strategy. However, if the unit operating cost of blockchain technology is at a higher level, i.e., $c_b > \hat{c}_b$, the retailer's profit and consumers' surplus will decline under the Forward–reverse traceability strategy. As a result, they will prefer the forward rather than the Forward–reverse blockchain traceability.

Proposition 3 *The comparison of retail prices under three strategies is as follows:*

(1) When $\lambda > \hat{\lambda}^p$ *and* $\tau < \hat{\tau}^p$, $p^*_{NB} > p^*_{FB} > p^*_{FRB}$*; when* $\lambda > \hat{\lambda}^p$ *and* $\hat{\tau}^p < \tau < \overline{\tau}^p$, $p^*_{FB} > p^*_{NB} > p^*_{FRB}$*; when* $\lambda > \hat{\lambda}^p$ *and* $\tau > \overline{\tau}^p$, $p^*_{FB} > p^*_{FRB} > p^*_{NB}$*.*

(2) When $\lambda < \hat{\lambda}^p$ *and* $\tau < \hat{\tau}^p$, $p^*_{NB} > p^*_{FRB} > p^*_{FB}$*; when* $\lambda < \hat{\lambda}^p$ *and* $\hat{\tau}^p < \tau < \overline{\tau}^p$, $p^*_{FRB} > p^*_{NB} > p^*_{FB}$*; when* $\lambda < \hat{\lambda}^p$ *and* $\tau > \overline{\tau}^p$, $p^*_{FRB} > p^*_{FB} > p^*_{NB}$*;*
where $\hat{\tau}^p = \frac{(4k-\theta^2)((3\eta c_t+c_b)k-c_b\theta^2)}{\theta^2(k-\theta^2)c_b+3(1+q(1-e^{-\lambda}))k+3(4k-\theta^2)k}$, $\hat{\lambda}^p = \ln\left(\frac{3kq}{c_b(\delta-1)(\theta^2-k)}\right)$ *and* $\overline{\tau}^p = \frac{(4k-\theta^2)((k-\theta^2)\delta c_b+3k(\eta c_t+qe^{-\lambda}))}{\theta^2(k-\theta^2)c_b+3(1+q)k+3(4k-\theta^2)k}$.

Proposition 3 shows that the retail prices under different strategies are affected by the manual assessment level of retired batteries λ. When the EV maker implements blockchain traceability, if the manual assessment level of retired batteries λ surpasses the value $\hat{\lambda}^p$,

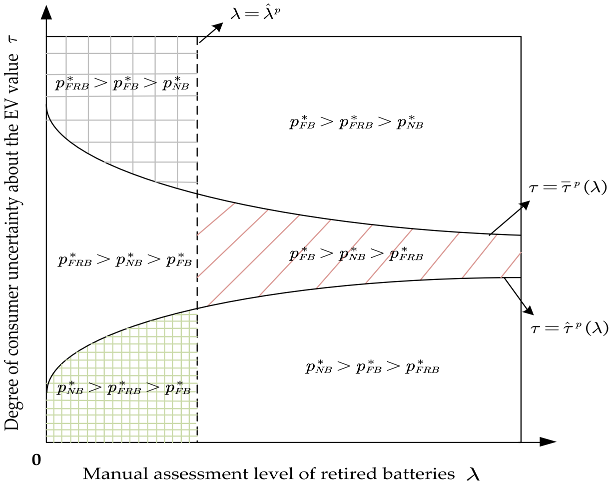


Fig. 5 The retail price relations between the three strategies

the retail price for the forward traceability strategy is greater than that for the Forward–reverse strategy. Conversely, if the manual assessment level of retired batteries λ is below the value $\hat{\lambda}^p$, the retail price for the forward traceability strategy is lower than that for the Forward–reverse strategy. This implies that the lower manual assessment level induces the retailer to increase its price with Forward–reverse traceability, but the higher manual assessment level drives up the retailer's price with forward traceability. The rationale of this result is that when the high manual assessment level reaches the maximal level, it is unnecessary to implement blockchain reverse traceability. Although reverse blockchain traceability significantly improves the assessment level of retired batteries, more related costs may be incurred accordingly. In this way, the higher manual assessment level for the forward traceability strategy could afford the retailer more capacity to increase its price. However, the lower manual assessment level induces the retailer to implement blockchain reverse traceability to alleviate consumers' uncertainties about retired battery recycling. The related blockchain-adopted cost inevitably leads to an increase in retail price.

To better illustrate Proposition 3, we apply a numerical example by setting $k = 10, q = 10$, and $\eta = 5$; thus, we have $\lambda = 3$. Furthermore, we set $\tau = 0.25$ and $\tau = 0.5$, representing a low and high value; the related parameter values, including those in the following numerical analysis, are based on the work by Gu et al. (2021) and Liu et al. (2023). As illustrated in Fig. 5, when adding the non-blockchain traceability strategy to comparing the retail prices, although the prices for the two blockchain traceability strategies remain unchanged, the retail price for the non-blockchain traceability strategy changes with the degree of consumer uncertainties about the EV green low-carbon value τ (Fig. 5). Specifically, when the degree of consumer uncertainty is at a lower level ($\tau < \hat{\tau}^p$): $p^*_{NB} > p^*_{FB} > p^*_{FRB}$ or $p^*_{NB} > p^*_{FRB} > p^*_{FB}$, the retail price for the non-blockchain traceability strategy is always highest, followed by the other two blockchain traceability strategies. When the uncertainty degree is at a medium level ($\hat{\tau}^p < \tau < \bar{\tau}^p$): $p^*_{FB} > p^*_{NB} > p^*_{FRB}$ or $p^*_{FRB} > p^*_{NB} > p^*_{FB}$, the retail price for the non-blockchain traceability strategy is always in the middle among the three strategies. When the uncertainty degree is at a higher level ($\tau > \bar{\tau}^p$): $p^*_{FB} > p^*_{NB} > p^*_{FRB}$ or $p^*_{FRB} > p^*_{FB} > p^*_{NB}$, the retail price for the non-blockchain traceability strategy is invariably the lowest among the three strategies. It intuitively implies that when consumers are more uncertain about the EV green low-carbon value for the non-blockchain traceability strategy, it is prudent for the retailer to lower the retail price to attract consumers, thus offsetting their green concerns.

Proposition 4 *The comparison of wholesale prices under three strategies is as follows: (1) When* $q < \hat{q}^w$ *and* $\eta < \hat{\eta}^w$, $w^*_{NB} > w^*_{FB} > w^*_{FRB}$; *when* $q < \hat{q}^w$ *and* $\hat{\eta}^w < \eta < \overline{\eta}^w$, $w^*_{FB} > w^*_{NB} > w^*_{FRB}$; *when* $q < \hat{q}^w$ *and* $\eta > \overline{\eta}^w$, $w^*_{FB} > w^*_{FRB} > w^*_{NB}$. *(2) When* $q > \hat{q}^w$ *and* $\eta < \hat{\eta}^w$, $w^*_{NB} > w^*_{FRB} > w^*_{FB}$; *when* $q > \hat{q}^w$ *and* $\hat{\eta}^w < \eta < \overline{\eta}^w$, $w^*_{FRB} > w^*_{NB} > w^*_{FB}$; *when* $q > \hat{q}^w$ *and* $\eta > \overline{\eta}^w$, $w^*_{FRB} > w^*_{FB} > w^*_{NB}$;

where $\hat{q}^w = \frac{(\delta-1)(\theta^2-2k)}{2e^{-\lambda}k}$, $\hat{\eta}^w = \frac{\theta^2(2k(\tau(q(e^{-\lambda}-1)-c_b)+3c_b)-c_b\theta^2(1-\tau))-8k^2(c_b+\tau)}{2kc_t(4k-\theta^2)}$ *and* $\overline{\eta}^w = \frac{2k(1+q(1-e^{-\lambda})-\tau)(4k-\theta^2)-(4k-\theta^2(1-\tau))((2k-\theta^2)\delta c_b+2(1+q)k)}{2kc_t(4k-\theta^2)}$.

Proposition 4 reveals that when the reference quality of retired batteries $q < \hat{q}^w$, the wholesale price for the forward traceability strategy is higher than that for the Forward–reverse strategy, i.e., $w^*_{FB} > w^*_{FRB}$. On the contrary, when $q > \hat{q}^w$, the wholesale price for the forward traceability strategy is lower than that for the Forward–reverse one, i.e., $w^*_{FB} < w^*_{FRB}$. This indicates that setting a relatively higher reference quality for retired batteries enables the EV maker to increase its wholesale price with the Forward–reverse blockchain traceability strategy. In contrast, a relatively lower reference quality results in the EV maker's unwillingness to raise its price. The reason is that with a higher reference quality in the absence of the Forward–reverse blockchain traceability, the unreliability and inaccuracy of the manual assessment could lead to consumers' perceived value of retired batteries being far less than the actual reference quality level, thus lowering consumers' purchase EV intention. Therefore, the EV maker has no choice but to leverage the Forward–reverse blockchain traceability strategy, aiming to remove consumers' green information ambiguity. The corresponding blockchain adoption cost will also reflect the wholesale price increment.

Additionally, to better illustrate Proposition 4, we demonstrate a numerical example by setting $k = 10$, $\lambda = 2$, and $\tau = 0.3$; thus, we have $q = 5.6$. Furthermore, we set $\eta = 5.7$ and $\eta = 6.5$, representing a low and high value. As illustrated in Fig. 6, when considering the non-blockchain traceability strategy, the sensitivity coefficient of time cost η plays a critical role. When the time cost coefficient η is at a lower level ($\eta < \hat{\eta}^w$), the wholesale price for the non-blockchain traceability strategy is always the highest among the three strategies. When the time cost coefficient η is at a medium level ($\hat{\eta}^w < \eta < \overline{\eta}^w$) and at a higher level ($\eta > \overline{\eta}^w$), the wholesale price under the non-blockchain traceability strategy is the second and lowest among the three strategies, respectively. This implies that if consumers are less sensitive to time costs, the EV maker may have more space to increase its wholesale price for the non-blockchain traceability strategy than the two blockchain traceability strategies.

Proposition 5 *The comparison of demand and the green low-carbon level for three strategies is shown as follows:*

(1) For the EV demand, (i) if $c_b > \hat{c}_b$ *and* $\eta < \hat{\eta}^d$, $d^*_{NB} > d^*_{FB} > d^*_{FRB}$; *if* $c_b > \hat{c}_b$ *and* $\hat{\eta}^d < \eta < \overline{\eta}^d$, $d^*_{FB} > d^*_{NB} > d^*_{FRB}$; *if* $c_b > \hat{c}_b$ *and* $\eta > \overline{\eta}^d$, $d^*_{FB} > d^*_{FRB} > d^*_{NB}$; *(ii) if* $c_b < \hat{c}_b$ *and* $\eta < \hat{\eta}^d$, $d^*_{NB} > d^*_{FRB} > d^*_{FB}$; *(iii) if* $c_b < \hat{c}_b$ *and* $\hat{\eta}^d < \eta < \overline{\eta}^d$, $d^*_{FRB} > d^*_{NB} > d^*_{FB}$; *if* $c_b < \hat{c}_b$ *and* $\eta > \overline{\eta}^d$, $d^*_{FRB} > d^*_{FB} > d^*_{NB}$;

(2) For the green low-carbon level, (i) if $c_b > \hat{c}_b$ *and* $\eta < \hat{\eta}^l$, $l^*_{NB} > l^*_{FB} > l^*_{FRB}$; *if* $c_b > \hat{c}_b$ *and* $\hat{\eta}^l < \eta < \overline{\eta}^l$, $l^*_{FB} > l^*_{NB} > l^*_{FRB}$; *if* $c_b > \hat{c}_b$ *and* $\eta > \overline{\eta}^l$, $l^*_{FB} > l^*_{FRB} > l^*_{NB}$;

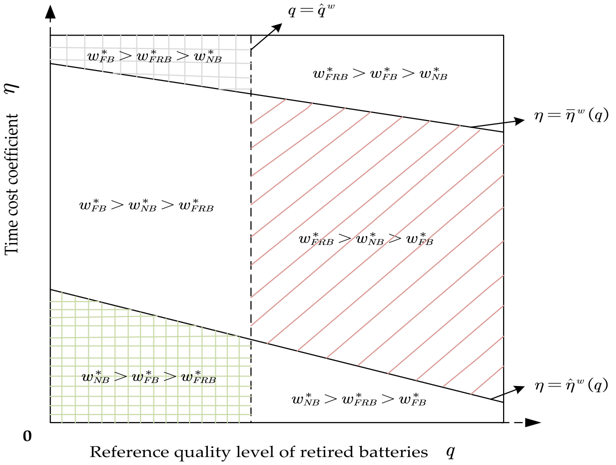


Fig. 6 The wholesale price relations between the three strategies

(ii) if $c_b < \hat{c}_b$ *and* $\eta < \hat{\eta}^l$, $l_{NB}^* > l_{FRB}^* > l_{FB}^*$*; (iii) if* $c_b < \hat{c}_b$ *and* $\hat{\eta}^l < \eta < \overline{\eta}^l$, $l_{FRB}^* > l_{NB}^* > l_{FB}^*$*; if* $c_b < \hat{c}_b$ *and* $\eta > \overline{\eta}^l$, $l_{FRB}^* > l_{FB}^* > l_{NB}^*$,
where

$$\hat{\eta}^d = \frac{1 + q(1 - e^{-\lambda}) - \tau}{c_t} - \frac{(1 + q(1 - e^{-\lambda}) - c_b)(4k - \theta^2(1 - \tau))(1 - \tau)}{(4k - \theta^2)c_t},$$

$$\overline{\eta}^d = \frac{1 + q(1 - e^{-\lambda}) - \tau}{c_t} - \frac{(1 + q - \delta c_b)(4k - \theta^2(1 - \tau))(1 - \tau)}{(4k - \theta^2)c_t},$$

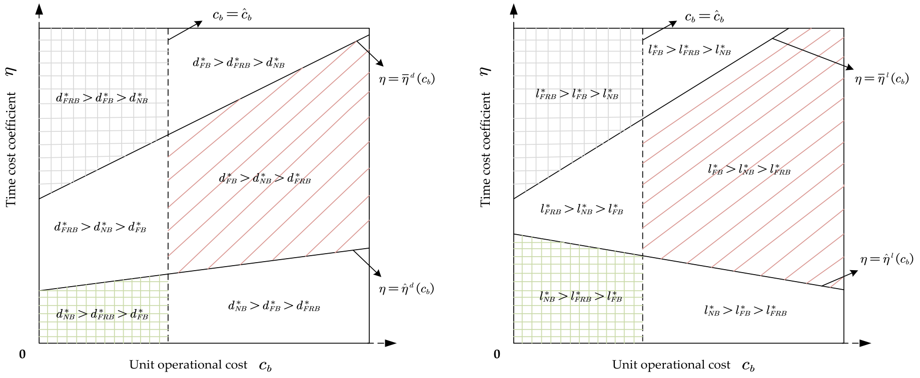
$$\hat{\eta}^l = \frac{(\eta c_t - (1 - \tau)c_b)\theta^2 + 4k(c_b - \tau - \eta c_t)}{\theta^2 \tau (1 - e^{-\lambda})},$$

and

$$\overline{\eta}^l = \frac{4k(\delta c_b - \tau) - (\delta c_b(1 - \tau) + q\tau)\theta^2 - (4k - \theta^2)qe^{-\lambda}}{(4k - \theta^2)c_t}.$$

Proposition 5 illustrates that, given the adoption of blockchain technology, when the unit operational cost falls in a higher range ($c_b > \hat{c}_b$), the demand and the green low-carbon level for the Forward–reverse traceability strategy are better than the forward traceability strategy, i.e., $d_{FRB}^* > d_{FB}^*$ and $l_{FRB}^* > l_{FB}^*$. When the unit operational cost falls in a lower range ($c_b < \hat{c}_b$), the demand and the green low-carbon level for the forward traceability strategy are higher than the Forward–reverse strategy, i.e., $d_{FB}^* > d_{FRB}^*$ and $l_{FB}^* > l_{FRB}^*$.

To better illustrate Proposition 5, we show a numerical example by setting $k = 10$, $q = 10$, and $\lambda = 2$; thus, we have $c_b = 1$. Then, $\eta = 2.2$ and $\eta = 5.3$; $\eta = 3.7$ and $\eta = 4.5$, representing a low and high value. As illustrated in Fig. 7, when comparing three strategies, we should consider the influence of the time cost coefficient η. Figure 7 illustrates that the demand and the green low-carbon level are not always higher in the presence of blockchain adoption. Specifically, adopting blockchain technology can increase demand and enhance the green low-carbon level when the time cost coefficient is relatively large. However, when the time cost coefficient is moderate or small, the adoption of blockchain leads to lesser demand and a lower green, low-carbon level. The reason is evident; although blockchain traceability



(a) Demand

(b) Low-carbon level

Fig. 7 The demand and the low-carbon level relations between the three strategies

eliminates consumers' time cost, it also triggers a higher retail price, but if the time cost coefficient falls in the moderate or small range, the positive effect of time–cost saving could be eroded by the incremental retail price, thus leading to consumers' demand decline, and in turn, negatively impact the low-carbon level.

7 Analysis of models with subsidies

To promote EV sales and encourage EV makers to invest in EVs' green, low-carbon innovation related to the production process and products, the governments usually offer subsidies to EV makers or consumers (Bian et al., 2020; Yu et al., 2018). In this paper, we do not consider the subsidy to retailers because the government does not offer this in practice, owning to retailers' less critical role in EV development than other agents. Next, we examine the impact of two typical subsidy policies on blockchain traceability.

7.1 Subsidies to the EV maker

We use the subscript '*NM*,' '*FM*,' and '*FRM*' to denote three strategies for the subsidy-to-EV-maker policy. The subsidy scheme for EV makers is widely adopted worldwide, including in the EU, USA, and China (Bian et al., 2020). In this subsidy scheme, the governments bear a portion of the cost of EV maker investment, which we assume the proportion as α.

Thereby, the EV maker's profit functions under three strategies are given by

$$\pi^M_{NM}(w_{NM}, l_{NM}) = w_{NM}d_{NM} - \frac{1}{2}kl^2_{NM}(1-\alpha), \tag{13}$$

$$\pi^M_{FM}(w_{FM}, l_{FM}) = (w_{FM} - c_b)d_{FM} - \frac{1}{2}kl^2_{FM}(1-\alpha), \tag{14}$$

$$\pi^M_{FRM}(w_{FRM}, l_{FRM}) = (w_{FRM} - \delta c_b)d_{FRM} - \frac{1}{2}kl^2_{FRM}(1-\alpha). \tag{15}$$

Using the same method as before, we obtain Lemma 5.

Lemma 5 *With the subsidy to the EV maker, the EV maker will choose the forward traceability strategy if and only if* $\hat{c}_b^{StoM} < c_b < \bar{c}_b^{StoM}$ *and the Forward–reverse traceability strategy if and only if* $c_b < \min\{\hat{c}_b^{StoM}, \tilde{c}_b^{StoM}\}$, *where* $\bar{c}_b^{StoM} = 1 + q(1 - e^{-\lambda}) - \sqrt{\frac{4k(1-\alpha)-\theta^2}{(1-\tau)(4k(1-\alpha)-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau)$, $\hat{c}_b^{StoM} = \frac{qe^{-\lambda}}{\delta-1}$, *and* $\tilde{c}_b^{StoM} = \frac{1}{\delta}(1 + q - \sqrt{\frac{4k(1-\alpha)-\theta^2}{(1-\tau)(4k(1-\alpha)-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau))$.

Lemma 5 shows that the EV maker will adopt the forward traceability strategy if the blockchain's unit operational cost is at a medium level. If the unit operational cost is lower, it will convert to the Forward–reverse traceability strategy. Since $\hat{c}_b^{StoM}$, $\bar{c}_b^{StoM}$ and $\tilde{c}_b^{StoM}$ are related with α, the proportion of government subsidy policy and the blockchain's unit operational cost impact the EV maker's decision to adopt blockchain technology. It verifies the robustness/validation of the blockchain traceability models and indicates that the government should increase subsidies to encourage EV makers at the nascent stage of EV and blockchain traceability development.

7.2 Subsidies to consumers

We use the subscript '*NC*,' '*FC*,' and '*FRC*' to denote three strategies for the subsidy-to-consumers policy (Yu et al., 2018). Assume that the government offers a subsidy ratio β to consumers purchasing EVs. To this end, the utility functions of consumers under three strategies are demonstrated by

$$U_{NC} = (1 - \tau)(v + \theta l_{NC}) - p_{NC}(1 - \beta) - \eta c_t + \xi_{NB}, \tag{16}$$

$$U_{FC} = v + \theta l_{FC} - p_{FC}(1 - \beta) + \xi_{FB}, \tag{17}$$

$$U_{FRC} = v + \theta l_{FRC} - p_{FRC}(1 - \beta) + \xi_{FRB}. \tag{18}$$

Using the same method as before, we obtain Lemma 6.

Lemma 6 *With the subsidy to consumers, the EV maker will select the forward traceability strategy if and only if* $\hat{c}_b^{StoC} < c_b < \bar{c}_b^{StoC}$ *and the Forward–reverse traceability strategy if and only if* $c_b < \min\{\hat{c}_b^{StoC}, \tilde{c}_b^{StoC}\}$, *where* $\bar{c}_b^{StoC} = \frac{1}{1-\beta}(1 + q(1 - e^{-\lambda}) - \sqrt{\frac{4k(1-\beta)-\theta^2}{(1-\tau)(4k(1-\beta)-\theta^2(1-\tau))}}(1+q(1 - e^{-\lambda})-\eta c_t - \tau))$, $\hat{c}_b^{StoC} = \frac{qe^{-\lambda}}{(\delta-1)(1-\beta)}$, *and* $\tilde{c}_b^{StoC} = \frac{1}{\delta(1-\beta)}(1 + q - \sqrt{\frac{4k(1-\beta)-\theta^2}{(1-\tau)(4k(1-\beta)-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau))$.

Like Lemmas 5, 6 shows that the government subsidy policy to consumers still influences the EV maker's decision to adopt blockchain technology and also verifies the robustness/validation of the blockchain traceability models. Further comparative analysis of subsidies to consumers and EV makers, in terms of the member's profit, consumer surplus, and social welfare for three strategies, are presented in the following subsection.

7.3 Comparative analysis

7.3.1 Profit and consumer surplus analysis

Proposition 6 *For the non-blockchain traceability strategy, the relation of the optimal profits and consumer surplus under two subsidy policies are shown as follows:*

(1) *Profit of the EV maker: if* $\alpha > \beta, \pi_{NM}^{M*} > \pi_{NC}^{M*} > \pi_{NB}^{M*}$*; otherwise,* $\pi_{NC}^{M*} > \pi_{NM}^{M*} > \pi_{NB}^{M*}$*;*

(2) *Profit of the retailer: if* $\alpha > \alpha_{NB}^{R}, \pi_{NM}^{R*} > \pi_{NC}^{R*} > \pi_{NB}^{R*}$*; otherwise,* $\pi_{NC}^{R*} > \pi_{NM}^{R*} > \pi_{NB}^{R*}$.

(3) *Consumer surplus: if* $\alpha > \beta$, $CS_{NM} > CS_{NC} > CS_{NB}$*; otherwise,* $CS_{NC} > CS_{NM} > CS_{NB}$.

where $\alpha_{NB}^{R} = \frac{(4k-\theta^2(1-\tau))\sqrt{1-\beta}-\theta^2(1-\tau)-4k(1-\beta)}{4k(1-\beta+\sqrt{1-\beta})+\theta^2(1-\tau)}$.

Proposition 6 shows that, for the non-blockchain traceability strategy, the profit of both the EV maker and the supply chain and consumer surplus are always higher than those without subsidies, which is consistent with the findings by Gu et al., (2019 and Pi (2023). However, there are differences between the two subsidy policies. From Proposition 6-(i), we can see that when the subsidy proportion to the EV maker is higher than to the consumers, i.e., $\alpha > \beta$, the EV maker will gain higher profits from the EV maker subsidy scheme, but if the subsidy proportion to the consumer is greater than that to the EV maker, i.e., $\alpha < \beta$, the EV maker will gain more profit from the subsidy-to-consumer policy.

Proposition 6-(ii) implies that only a higher subsidy to the maker can ensure the highest profits for the retailer under the EV maker subsidy scheme. Proposition 6-(iii) shows that when the subsidy degree to the EV maker is greater than that to the consumers, i.e., $\alpha > \beta$, the consumer surplus will be higher in the subsidy-to-EV-maker scheme. Otherwise, the consumer surplus will benefit more from the subsidy-to-consumers program.

The findings reveal that the higher subsidy-to-EV-maker policy or lower subsidy-to-consumer policy always benefits the EV maker and consumers, but the retailer is better off only with the higher subsidy-to-EV-maker policy, which is different from the prior work. This interesting finding indicates that, under the non-blockchain traceability strategy, the higher subsidy-to-EV-maker policy is the better choice for the government because it motivates the EV maker, the retailer, and the consumers.

Proposition 7 *For the forward traceability strategy (under the Forward–reverse traceability strategy), the relation of optimal profits and consumer surplus with two subsidy policies is shown as follows:*

(1) *Profit of the EV maker: if* $\alpha > \frac{4\beta k}{4\beta k+\theta^2}$ *and* $q > q_{FB}^{M}(q > q_{FRB}^{M})$, $\pi_{FM}^{M*} > \pi_{FC}^{M*} > \pi_{FB}^{M*}$ $(\pi_{FRM}^{M*} > \pi_{FRC}^{M*} > \pi_{FRB}^{M*})$*; otherwise,* $\pi_{FC}^{M*} > \pi_{FM}^{M*} > \pi_{FB}^{M*}(\pi_{FRC}^{M*} > \pi_{FRM}^{M*} > \pi_{FRB}^{M*})$*;*

(2) *Profit of the retailer: if* $\alpha > \alpha_{FB}^{R}(\alpha > \alpha_{FRB}^{R})$, $\pi_{FM}^{R*} > \pi_{FC}^{R*} > \pi_{FB}^{R*}(\pi_{FRM}^{R*} > \pi_{FRC}^{R*} > \pi_{FRB}^{R*})$*; otherwise,* $\pi_{FC}^{R*} > \pi_{FM}^{R*} > \pi_{FB}^{R*}(\pi_{FRC}^{R*} > \pi_{FRM}^{R*} > \pi_{FRB}^{R*})$*;*

(3) *Consumer surplus: if* $\alpha > \beta$ *and* $q > q_{FB}^{CS}(q > q_{FRB}^{CS})$, $CS_{FM} > CS_{FC} > CS_{FB}$ $(CS_{FRM} > CS_{FRC} > CS_{FRB})$*; otherwise,* $CS_{FC} > CS_{FM} > CS_{FB}$ $(CS_{FRC} > CS_{FRM} > CS_{FRB})$*;*

where

$$q_{FB}^{M} = \frac{1}{1-e^{-\lambda}}(\delta c_b - 1 + \frac{\beta\delta c_b\sqrt{4k(1-\alpha)-\theta^2}}{(1-\alpha)(4k(1-\beta)-\theta^2)-\sqrt{4k(1-\alpha)-\theta^2}}),$$

$$q^{M}_{FRB} = \delta c_b - 1 + \frac{\beta\delta c_b\sqrt{4k(1-\alpha)-\theta^2}}{\sqrt{(1-\alpha)(4k(1-\beta)-\theta^2)} - \sqrt{4k(1-\alpha)-\theta^2}},$$

$$\alpha^{M}_{FB} = 1 - \frac{\theta^2\sqrt{1-\beta}(1+q(1-e^{-\lambda})-(1-\beta)c_b)}{(1+q(1-e^{-\lambda})-c_b)(4k(\sqrt{1-\beta}-(1-\beta))+\theta^2)+4k\beta\sqrt{1-\beta}c_b},$$

$$\alpha^{R}_{FRB} = 1 - \frac{\theta^2\sqrt{1-\beta}(1+q-(1-\beta)\delta c_b)}{(1+q-\delta c_b)(4k(\sqrt{1-\beta}-(1-\beta))+\theta^2)+4k\beta\sqrt{1-\beta}\delta c_b},$$

$$q^{CS}_{FB} = \frac{\beta c_b(4k(1-\alpha)-\theta^2)(1-\beta)-\theta^2(1-c_b)(\alpha-\beta)}{\theta^2(1-e^{-\lambda})(\alpha-\beta)},$$

$$q^{CS}_{FRB} = \delta c_b - 1 + \frac{\beta\delta c_b(4k(1-\alpha)-\theta^2)(1-\beta)}{\theta^2(\alpha-\beta)}.$$

Proposition 7-(i) reveals that, with blockchain traceability adopted, when the subsidy proportion α and the reference quality of retired batteries q are greater than the threshold values, the EV makers' profit in the subsidy-to-EV maker policy is much higher than that in the subsidy-to-consumer policy. This means that if sufficient subsidies are offered and the higher reference quality level is reached, the subsidy-to-EV-maker policy is the optimal choice for the EV maker and vice versa.

From Proposition 7-(ii), we can infer that when the subsidy proportion to the EV maker exceeds a certain threshold value, the retailer can earn more profit with the subsidy-to-EV maker policy than in the subsidy-to-consumer policy, and vice versa.

Proposition 7-(iii) indicates that when the subsidy to the EV maker is greater than that to the consumers, i.e., $\alpha > \beta$, and the reference quality of retired batteries meets the condition of $q > q^{CS}_{FB}(q > q^{CS}_{FRB})$, consumer surplus is higher in the subsidy-to-EV-maker program. Otherwise, consumers will benefit more from the subsidy-to-consumers program.

The findings interestingly indicate that, for the two blockchain traceability strategies, the government should adequately determine the subsidy proportions based on the reference quality of retired batteries; that is to say, if the EV maker has a higher level of retired battery reference quality, the government should increase subsidies to the EV makers, vice versa. In this regard, the subsidy policies can be effective and efficient, which is aligned with the work by Gu et al. (2019), Pi (2023).

7.3.2 Social welfare analysis

Next, we investigate the social welfare (SW), which comprises the EV maker's profit (π^M), the retailer's profit (π^R), the consumer surplus (CS), the government subsidy (GS), and the environmental benefit (EB). The environmental benefit here mainly considers the reduction of carbon emission, i.e., $EB = d \times r$, where r is the carbon reduction benefits due to purchasing EVs. Therefore, the social welfare can be formulated as

$$SW_j = \pi^M_j + \pi^R_j + CS_j - GS_j + EB_j, \tag{19}$$

where $j = NM, FM, FRM, NC, FC\ or\ FRC$, denoted by two subsidy schemes under the three traceability strategies.

To better illustrate the social welfare under three strategies in the presence of subsidy, we conduct numerical analysis to graph the trends of social welfare (Figs. 8, 9, and 10). Among which, k represents the cost coefficient of low-carbon level.

Observation 1 *For the three strategies, the subsidy policies always improve social welfare compared to the non-subsidy scheme.*

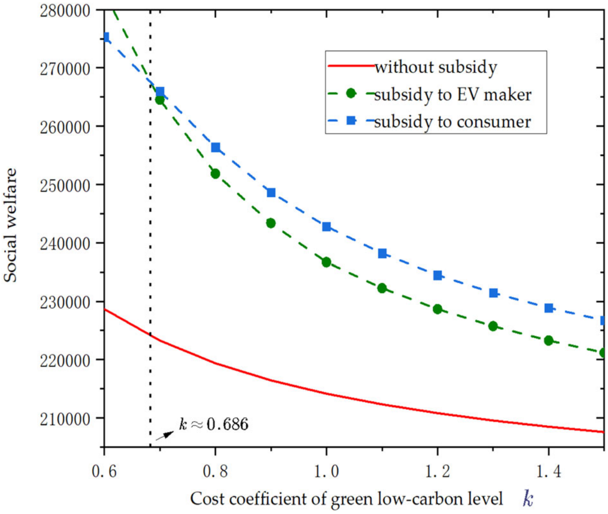


Fig. 8 The social welfare under the non-blockchain traceability ($q = 10$, $\eta = 5$, $\tau = 0.3$)

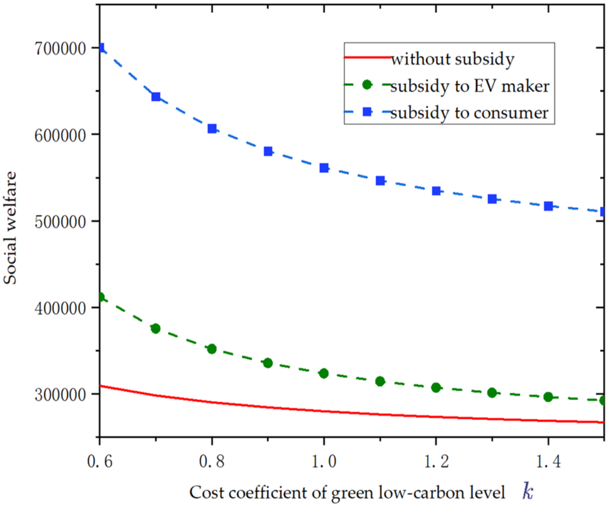


Fig. 9 The social welfare under the forward blockchain traceability ($q = 10$, $\eta = 5$, $\tau = 0.3$)

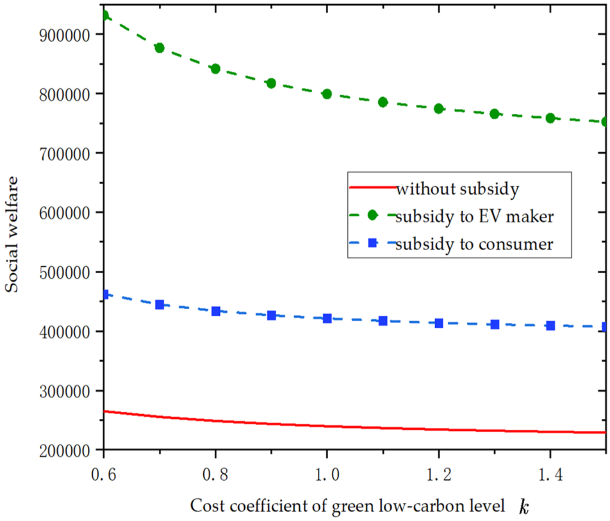


Fig. 10 The social welfare under the Forward–reverse blockchain traceability ($q = 10$, $\eta = 5$, $\tau = 0.3$)

Observation 2 *For the forward blockchain traceability strategy, the social welfare with the subsidy-to-consumer policy is greater than that with the subsidy-to-EV maker policy. However, under the Forward–reverse blockchain traceability strategy, the social welfare with the subsidy-to-consumer policy is less than that with the subsidy-to-EV maker policy.*

Observation 3 *For the non-blockchain traceability strategy, when the cost coefficient of the low-carbon level is in the lower range, the social welfare with the subsidy-to-consumer policy is less than that with the subsidy-to-EV maker policy; when the cost coefficient of the low-carbon level is in the higher range, the social welfare with the subsidy-to-consumer policy is larger than that with the subsidy-to-EV maker policy.*

Observations 1–3 imply that the subsidy schemes always enhance social welfare for the three strategies. The outcomes are consistent with Propositions 6 and 7, which show that the subsidies expand EV sales and bring dividends to the EV maker, the retailer, and the consumers. This also verifies the robustness/validation of the blockchain traceability models. Therefore, it is wise for the governments to implement the subsidy policy.

Observations 2–3 interestingly reveal that the different subsidy policies situate the different blockchain traceability strategies. Specifically, for the forward blockchain traceability strategy, the government should adopt the subsidy-to-consumer policy, while for the Forward–reverse blockchain traceability strategy, the government should implement the subsidy-to-EV maker policy rather than the subsidy-to-consumer policy. The plausible explanation is that Forward–reverse blockchain traceability covers more stages than forward blockchain traceability, which reduces more carbon emissions of each EV by means of the secondary use of retired battery recycling. To this end, the government adopts the subsidy-to-EV maker policy to encourage the EV maker to decrease the per unit carbon emission, while the subsidy-to-consumer policy seems to stimulate the total EV sales. In this way, with the forward blockchain traceability, the subsidy-to-consumer policy reduces carbon emission in terms of the total amount of sales, thus yielding more social welfare.

8 Conclusions

Motivated by the growing EV consumers' awareness of the environment and the application of blockchain traceability, we analytically discuss the optimal blockchain traceability decisions of the EV maker and the retailer under three blockchain traceability strategies, i.e., the non-blockchain traceability strategy, the forward blockchain traceability strategy, and the Forward–reverse blockchain traceability strategy, and two government subsidy schemes (i.e., the subsidy-to-the EV maker scheme and the subsidy-to-consumer scheme), to explore their impacts on the EV supply chain members.

(1) Main contributions and managerial implications

  (i) Different from previous findings that blockchain technology yields more market demand (Niu et al., 2022; Xu & Choi, 2021), our results show that the adoption of blockchain traceability does not necessarily benefit the EV maker to promote EV sales and further identify the condition under which the typical blockchain traceability strategy the EV maker prefers to implement. We find that when the operational cost of blockchain falls in a moderately small range, the forward traceability strategy is the EV maker's best choice. If the blockchain's operational cost is even smaller, the Forward–reverse blockchain traceability strategy is the optimal strategy. It suggests that the EV maker could adopt the Forward–reverse blockchain traceability strategy when its sales volume is large or the EV marker is mature so the larger sales scale can effectively share the blockchain operational cost.

  (ii) Consistent with prior studies (Gu et al., 2019; Pi, 2023), our findings reveal that government subsidies increase consumer surplus and social welfare of the EV supply chain, but it is also observed that, in the setting of the forward blockchain traceability strategy, the social welfare under the subsidy-to-consumer policy is larger than that under the subsidy-to-EV maker policy. Conversely, for the Forward–reverse blockchain traceability strategy, the subsidy-to-EV maker policy is better than the subsidy-to-consumer policy. In this regard, policymakers should adequately adjust the subsidy policies based on blockchain technology and EV development; for example, at the infant stage of EV development and blockchain application, subsidy policy may focus on consumers instead of EV makers. Afterward, at the mature stage, the government should emphasize EV battery recycling and secondary use, and the related subsidy policy can be turned to focus on EV makers or both EV makers and consumers.

  (iii) The results also illustrate that if the manual assessment level surpasses a threshold value, the retail price under the forward traceability strategy is greater than that under the Forward–reverse traceability strategy, and vice versa. Additionally, the time cost coefficient and the degree of consumer uncertainty play a crucial role, but each can not alone determine the order in wholesale prices under the forward/Forward–reverse traceability strategy. It means that EV supply chain managers should pay attention to consumers' purchase psychology and behaviors and focus more on improving the EV makers' manual assessment level of retired batteries based on the different blockchain traceability strategies.

(2) Limitations and future directions

There are three main limitations. First, this study only examines an EV maker context, not considering the scenario where two EV makers compete and determine whether to adopt the blockchain traceability strategy. Second, the model merely addresses the EV maker's bearing the blockchain operational cost, not considering the blockchain cost allocation between EV supply chain members. Finally, this paper assumes the subsidy proportion as an exogenous rather than endogenous parameter. In reality, the subsidy proportion may be a decision variable.

Meanwhile, four potential future research directions are listed below. First, it is worth researching further the EV supply chain, which involves more carbon footprint echelons under blockchain traceability. Second, considering the existence of the subsidy-penalty policy in reality, further analysis of the impact of such a subsidy-penalty policy on blockchain traceability would be an interesting extension. Third, given the fuel vehicle domination in the current automobile market, the EV makers' adoption of blockchain traceability strategies in the competitive environment can also be a future research direction. Finally, because consumers are heterogeneous, some may be sensitive to privacy concerns, while others may not due to blockchain adoption. Thus, this factor can be incorporated into models for future research scope.

Appendix

Proof of Lemma 1 In stage 2, the retailer decides p_{NB}^* to optimize her profit function in Eq. (3). Since the profit function is concave in p_{NB}, we can obtain $p_{NB}^* = \frac{1-\tau+w-\eta c_t+l(1-\tau)\theta+q(1-e^{-\lambda})}{2}$ by the first-order condition. Substituting $p_{NB}^* = \frac{1-\tau+w-\eta c_t+l(1-\tau)\theta+q(1-e^{-\lambda})}{2}$ into Eq. (4), we can obtain the EV maker's transformed profit function.

In stage 1, the EV maker decides w_{NB} and l_{NB} concurrently. We use the Hessian matrix to solve the problem of simultaneous decision-making. For constructing the Hessian matrix of π_{NB}^M, the following calculations are carried out to acquire the first and second-order derivatives of π_{NB}^M to w_{NB} and l_{NB}.

$$H_M = \begin{bmatrix} -\frac{1}{1-\tau} & \frac{\theta}{2} \\ \frac{\theta}{2} & -k \end{bmatrix}$$

The principal minor sequences of this matrix are shown as follows.

$$|H_M|_1 = -\frac{1}{1-\tau} < 0$$

$|H_M|_2 = \frac{k}{1-\tau} - \frac{\theta^2}{4} > 0$ when $k > \frac{\theta^2(1-\tau)}{4}$.

Therefore, π_{NB}^M proves to be jointly concave to (w_{NB}, l_{NB}). And its first-order partial derivative characterizes the best-response function, which converges to unique Stackelberg equilibrium. By setting $\frac{\partial \pi_{NB}^M}{\partial w_{NB}}$ and $\frac{\partial \pi_{NB}^M}{\partial l_{NB}}$ to zero simultaneously, the optimal results can be obtained: $w_{NB}^* = \frac{2k(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{4k-\theta^2(1-\tau)}$ and $l_{NB}^* = \frac{\theta(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{4k-\theta^2(1-\tau)}$.

Substituting w_{NB}^* and l_{NB}^* into $p_{NB}^* = \frac{1-\tau+w-\eta c_t+l(1-\tau)\theta+q(1-e^{-\lambda})}{2}$, we can obtain the retail price $p_{NB}^* = \frac{3k(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{4k-\theta^2(1-\tau)}$. Then, by substituting w_{NB}^*, l_{NB}^* and p_{NB}^* into

Eqs. (2)–(4), we can obtain: $d_{NB}^{*} = \frac{k(1+q(1-e^{-\lambda})-\eta c_t-\tau)}{(1-\tau)(4k-\theta^2(1-\tau))}$, $\pi_{NB}^{M*} = \frac{k(1+q(1-e^{-\lambda})-\eta c_t-\tau)^2}{2(1-\tau)(4k-\theta^2(1-\tau))}$ and $\pi_{NB}^{R*} = \frac{k(1+q(1-e^{-\lambda})-\eta c_t-\tau)^2}{(1-\tau)(4k-\theta^2(1-\tau))^2}$.

Proof of Lemmas 2 and 3 The proof is similar to that of Lemma 1 and will not be repeated here.

Proof of Proposition 1 We prove Proposition 1 by comparing the profits of the EV maker in three models. By calculating the optimal results in Lemmas 1–3, the analysis results shown in Proposition 1 can be easily derived by introducing three intermediate variables $\overline{c}_b = 1 + q(1 - e^{-\lambda}) - \sqrt{\frac{4k-\theta^2}{(1-\tau)(4k-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau)$, $\hat{c}_b = \frac{qe^{-\lambda}}{\delta-1}$ and $\tilde{c}_b = \frac{1}{\delta}(1 + q - \sqrt{\frac{4k-\theta^2}{(1-\tau)(4k-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau))$.

Proof of Proposition 2 We prove Proposition 2 by comparing the retailer's profits and consumer surplus in three models. Similar to the proof of Proposition 1, we can easily obtain the intermediate variables $\overline{c}_b$, $\tilde{c}_b$ as well as the restriction $k < \frac{\theta^2(2-\tau)}{4}$.

Proof of Proposition 3 We prove Proposition 3 by comparing the retail prices in three models. By calculating, we have $p_{FB}^{*} - p_{NB}^{*} > 0$ when $\tau > \hat{\tau}^p = \frac{(4k-\theta^2)((3\eta c_t+c_b)k-c_b\theta^2)}{\theta^2(k-\theta^2)c_b+3(1+q(1-e^{-\lambda}))k+3(4k-\theta^2)k}$, otherwise, $p_{FB}^{*} - p_{NB}^{*} < 0$; $p_{FRB}^{*} - p_{NB}^{*} > 0$ when $\tau > \overline{\tau}^p = \frac{(4k-\theta^2)((k-\theta^2)\delta c_b+3k(\eta c_t+qe^{-\lambda}))}{\theta^2(k-\theta^2)c_b+3(1+q)k+3(4k-\theta^2)k}$, otherwise, $p_{FRB}^{*} - p_{NB}^{*} < 0$; $p_{FRB}^{*} - p_{FB}^{*} > 0$ when $\lambda < \hat{\lambda}^p = \ln(\frac{3kq}{c_b(\delta-1)(\theta^2-k)})$; otherwise, $p_{FRB}^{*} - p_{FB}^{*} < 0$. Combining the above analysis, we can obtain the conclusion of Proposition 3.

Proof of Proposition 4 We prove Proposition 3 by comparing the retail prices in three models. By calculating, we have $w_{FB}^{*} - w_{NB}^{*} > 0$ when $\eta > \hat{\eta}^w = \frac{\theta^2(2k(\tau(q(e^{-\lambda}-1)-c_b)+3c_b)-c_b\theta^2(1-\tau))-8k^2(c_b+\tau)}{2kc_t(4k-\theta^2)}$; otherwise, $w_{FB}^{*} - w_{NB}^{*} < 0$; $w_{FRB}^{*} - w_{NB}^{*} > 0$ when $\eta > \overline{\eta}^w = \frac{2k(1+q(1-e^{-\lambda})-\tau)(4k-\theta^2)-(4k-\theta^2(1-\tau))((2k-\theta^2)\delta c_b+2(1+q)k)}{2kc_t(4k-\theta^2)}$, otherwise, $w_{FRB}^{*} - w_{NB}^{*} < 0$; $w_{FRB}^{*} - w_{FB}^{*} > 0$ when $q > \hat{q}^w = \frac{(\delta-1)(\theta^2-2k)}{2e^{-\lambda}k}$; otherwise, $w_{FRB}^{*} - w_{FB}^{*} < 0$. Combining the above analysis, we can obtain the conclusion of Proposition 4.

Proof of Proposition 5

(1) For the EV demand, by calculating, we have $d_{FB}^{*} - d_{NB}^{*} > 0$ when $\eta > \hat{\eta}^d = \frac{1+q(1-e^{-\lambda})-\tau}{c_t} - \frac{(1+q(1-e^{-\lambda})-c_b)(4k-\theta^2(1-\tau))(1-\tau)}{(4k-\theta^2)c_t}$, otherwise, $d_{FB}^{*} - d_{NB}^{*} < 0$; $d_{FRB}^{*} - d_{NB}^{*} > 0$ when $\eta > \overline{\eta}^d = \frac{1+q(1-e^{-\lambda})-\tau}{c_t} - \frac{(1+q-\delta c_b)(4k-\theta^2(1-\tau))(1-\tau)}{(4k-\theta^2)c_t}$, otherwise, $d_{FRB}^{*} - d_{NB}^{*} < 0$; $d_{FRB}^{*} - d_{FB}^{*} > 0$ when $c_b < \hat{c}_b = \frac{qe^{-\lambda}}{\delta-1}$, otherwise, $d_{FRB}^{*} - d_{FB}^{*} < 0$. Combining the above analysis, we can obtain the conclusion of Proposition 5-(1).

(2) For the green low-carbon level, by calculating, we have $l_{FB}^{*} - l_{NB}^{*} > 0$ when $\eta > \hat{\eta}^l = \frac{(\eta c_t-(1-\tau)c_b)\theta^2+4k(c_b-\tau-\eta c_t)}{\theta^2\tau(1-e^{-\lambda})}$, otherwise, $l_{FB}^{*} - l_{NB}^{*} < 0$; $l_{FRB}^{*} - l_{NB}^{*} > 0$ when $\eta > \overline{\eta}^l = \frac{4k(\delta c_b-\tau)-(\delta c_b(1-\tau)+q\tau)\theta^2-(4k-\theta^2)qe^{-\lambda}}{(4k-\theta^2)c_t}$, otherwise, $l_{FRB}^{*} - l_{NB}^{*} < 0$;

$l_{FRB}^{*} - l_{FB}^{*} > 0$ when $c_b < \hat{c}_b = \frac{qe^{-\lambda}}{\delta-1}$; otherwise, $l_{FRB}^{*} - l_{FB}^{*} < 0$. Combining the above analysis, we can obtain the conclusion of Proposition 5-(2).

Proof of Lemma 5 The proof is similar to that of Proposition 1. We prove Lemma 5 by comparing the profits of the EV maker in three models under the subsidies to the EV maker. By calculating, the analysis results shown in Lemma 5 can be easily derived by introducing three intermediate variables $\bar{c}_b^{StoM} = 1 + q(1 - e^{-\lambda}) - \sqrt{\frac{4k(1-\alpha)-\theta^2}{(1-\tau)(4k(1-\alpha)-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau)$, $\hat{c}_b^{StoM} = \frac{qe^{-\lambda}}{\delta-1}$ and $\tilde{c}_b^{StoM} = \frac{1}{\delta}(1 + q - \sqrt{\frac{4k(1-\alpha)-\theta^2}{(1-\tau)(4k(1-\alpha)-\theta^2(1-\tau))}}(1 + q(1 - e^{-\lambda}) - \eta c_t - \tau))$.

Proof of Lemma 6 The proof is similar to that of Lemma 5 and will not be repeated here.

Proof of Proposition 6

(1) For the profit of EV maker, by comparing π_{NM}^{M*}, π_{NC}^{M*} and π_{NB}^{M*}, we can deduce that $\pi_{NM}^{M*} > \pi_{NB}^{M*}$ and $\pi_{NC}^{M*} > \pi_{NB}^{M*}$ are always hold; and $\pi_{NM}^{M*} > \pi_{NC}^{M*}$ when $\alpha > \beta$, otherwise, $\pi_{NM}^{M*} < \pi_{NC}^{M*}$.

(2) For the profit of retailer, by comparing π_{NM}^{R*}, π_{NC}^{R*} and π_{NB}^{R*}, we can deduce that $\pi_{NM}^{R*} > \pi_{NB}^{R*}$ and $\pi_{NM}^{R*} < \pi_{NB}^{R*}$ are always hold; and $\pi_{NM}^{R*} > \pi_{NC}^{R*}$ when $\alpha > \alpha_{NB}^{R} = \frac{(4k-\theta^2(1-\tau))\sqrt{1-\beta}-\theta^2(1-\tau)-4k(1-\beta)}{4k(1-\beta+\sqrt{1-\beta})+\theta^2(1-\tau)}$, otherwise, $\pi_{NM}^{R*} < \pi_{NC}^{R*}$.

(3) For the consumer surplus, by comparing CS_{NM}, CS_{NC} and CS_{NB}, we can deduce that $CS_{NM} > CS_{NB}$ and $CS_{NC} > CS_{NB}$ are always hold; and $CS_{NM} > CS_{NC}$ when $\alpha > \beta$, otherwise, $CS_{NM} < CS_{NC}$.

Proof of Proposition 7 The proof is similar to that of Proposition 6 and will not be repeated here.

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