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Chen, T., Zheng, X.-X., Jia, F. orcid.org/0000-0002-9830-121X et al. (1 more author) (2025) Toward mass adoption of electric vehicles: policy optimisation under different infrastructure investment scenarios. International Journal of Production Research. pp. 1-26. ISSN 0020-7543

https://doi.org/10.1080/00207543.2024.2446624

International Journal of Production Research

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Submission ID	233588696
Article Type	Research Article
Keywords	Supply chain management; subsidies;, Infrastructure investment, Electric vehicle adoption
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ABSTRACT

Mass adoption of electric vehicles (EVs) has been regarded as an effective solution to overcome environmental degradation and realize low-carbon economy globally. To stimulate the adoption of EVs, the government's operational decisions include selecting the most efficient subsidy scheme from three subsidy schemes: incentivizing EV adoption by providing a pure purchase subsidy for consumers, providing a pure infrastructure subsidy for EV automakers, and a combination of both subsidies. This study characterizes the interactions among the government, automakers, and consumers in a Stackelberg game and investigates the optimal subsidy scheme to promote the adoption of EVs, considering different supply chain structures and government infrastructure investments. First, we compare the cost-effectiveness of different subsidies (a pure purchase subsidy, a pure infrastructure subsidy or a combination of both subsidies) and find that providing a pure subsidy arises as the optimal subsidy structure only if the supplier invests in charging infrastructure. However, if the downstream manufacturer makes infrastructure investment, a combination of both subsidies becomes optimal. Second, the government subsidy selection strategy depends on the adoption target and infrastructure investment costs. In most cases, a combined policy is optimal only when both the target and costs are high. Otherwise, a pure subsidy is the most cost-effective solution. Third, our analysis further identifies a complementary relationship between government subsidies and competition. That is, competition in the end-market between members of the EV supply chain (i.e., the co-opetitive supply chain structure) would reduce the need for larger subsidies, enabling the government to effectively alleviate its financial pressure. Finally, further analysis suggests that the most cost-effective subsidy scheme may have a poor economic performance and lead to lower profits in some cases.

Keywords: Supply chain management; Subsidies; Infrastructure investment; Policy optimization; Electric vehicle adoption

1. Introduction

Mass adoption of electric vehicles (EVs) is seen as an effective way to alleviate environmental problems in the transportation industry. However, promoting the diffusion of EVs is a daunting task. There are two major factors that push consumers away from EVs. One is the higher purchase cost of EVs; the other is the lack of charging infrastructure. For instance, in 2019, the retail price of the Nissan Leaf (EV) was approximately $10000 more than the price of Nissan Versa (a combustion vehicle). Additionally, EV battery has limited endurance and requires a long recharge time. Therefore, the underdevelopment of charging infrastructure, together with the higher price of EVs, is a major concern of consumers when purchasing EVs. Consequently, the insufficient charging infrastructure restricts the mass adoption of EVs.

However, building charging infrastructure is capital-intensive. Thus, if the adoption level of EVs is low, firms lack infrastructure investment incentives, further blocking EV market penetration. This is a “chicken-and-egg” dilemma faced by the EV industry. To overcome this, governments attempt to develop different types of financial incentives to stimulate the diffusion of EVs. On one hand, by providing purchase subsidy for consumers, the government can entice EV purchases. On the other hand, offering infrastructure subsidy to firms reduces their investment costs so as to incentivize them to invest more in building charging infrastructure.

The subsidy schemes vary across countries. Although governments in China and the UK have eliminated purchase subsidies at the end of 2022 and have focused solely on financial support for automaker charging infrastructure construction, many countries are maintaining their subsidy policies. For instance, Germany and Singapore increased their purchase subsidies in 2022.[1] The Indonesian government plans to concentrate solely on subsidizing the purchases of EVs in the second half of 2023. It seems that government subsidy policies differ from country to country; however, it is unclear which subsidy scheme is the most effective solution for mass EV adoption, that is, providing a pure purchase subsidy, a pure infrastructure subsidy, or both.

In addition to providing financial incentives, governments often make direct investments in infrastructure construction. In China, the government commits substantial funds to construct charging infrastructure through state-owned companies such as the State Grid and Southern Power Grid. As of June 2019, the number of charging stations built by the State Grid of the Chinese government was 78,000 (Li, 2019). Following a statement issued by the Federal Highway Administration in 2022, the US government proposed investing $5 billion to install 500,000 EV charging stations across the country (Kullman et al., 2021).

The above observations indicate that many governments incorporate their infrastructure investment into their incentive policies to enhance the mass adoption of EVs. However, most extant literature focusing on government policy decision ignores the important component of the government’s infrastructure investment. Furthermore, there is a lack of studies comparing the effectiveness of these three subsidy schemes. It remains unknown which subsidy scheme is

1 https://www.ndrc.gov.cn/fggz/gjhz/zywj/202205/t20220518_1324756.html

most efficient solution for promoting EV adoption, particularly when considering government infrastructure investments, that is, a pure purchase subsidy, a pure infrastructure subsidy, or a combination of both? In fact, Forbes perceives the unexpected inefficiency caused by the improper selection of subsidy schemes as the main reason for the unsatisfactory adoption of EVs.[2] Hence, it is crucial to investigate how to select appropriate subsidy scheme for promoting the market penetration of EVs. In light of the above issues, we develop the following research questions:

RQ1. What is the most cost-efficient subsidy scheme considering different investment scenarios and supply chain structures?

RQ2. How do the target adoption level and investment costs influence the government's policy decisions?

RQ3. Which supply chain structure is optimal for minimizing the total expenditure of the government incentive program?

RQ4. Do the most cost-efficient policies perform better economically?

To answer these questions, we have adopted a modified Stackelberg game framework to examine the unique dynamics of the three-party interaction. The government, as the policymaker, acts as the leader and sets the incentive policy, including subsidy schemes and infrastructure investment levels, with the objective of minimizing total policy expenditure while achieving a predefined EV adoption target. The two firms in the EV supply chain, i.e., the battery suppliers and the manufacturers, act as followers and respond to the government's policy by making decisions on infrastructure investment and pricing strategies to maximize their profits. Two typical channel structures in the EV supply chain have been studied: the baseline structure and the co-opetitive structure. In the baseline structure, the upstream firm (e.g., CATL) is a pure battery supplier for the downstream automaker (e.g., Ford). In a co-opetitive structure (Niu et al., 2018), the upstream firm (e.g., BYD) acts as both a battery supplier and an end-market competitor for the downstream automaker (e.g., Tesla). Building charging infrastructure has drawn considerable attention from firms such as upstream battery suppliers and downstream automakers. In the EV supply chain, both the upstream battery

2 https://www.forbes.com/sites/dougyoung/2016/08/29/reports-point-to-failure-of-chinas-ev-green-power-policies/

supplier and downstream automaker are capable of building infrastructure. For example, in the example CATL, Ford, BYD, and Tesla, either of them is capable of investing in charging infrastructure. Thus, consistent with the prevailing practical observations, we consider four scenarios regarding the channel structure and which firm makes infrastructure investments: supplier investing in a baseline supply chain (BS scenario), manufacturer investing in a baseline supply chain (BM scenario), supplier investing in a co-opetitive supply chain (CS scenario), and manufacturer investing in a co-opetitive supply chain (CM scenario).

In our model, the government acts as the leader, minimizing its total expenditure by optimizing the policy, whereas the firms that act as followers that maximize their profits by determining the optimal investment and price. This study contributes to the existing literature in several ways. First, distinct from the extant literature assuming that automakers focus solely on EV production without building charging infrastructure, our theoretical model is aligned with the real practice by assuming the infrastructure is built either by the battery supplier or the downstream automaker. Second, we examine the influence of channel structures on incentive policy optimization and find that the government's subsidy selection varies under different scenarios depending on the channel structure and mode of infrastructure investment. Third, we present an interesting mode, in which the manufacturer making infrastructure investment is more beneficial from the government's perspective. We then examine the economic benefits of the whole supply chain and surprisingly find that the most cost-effective policy (i.e., enabling the government to achieve adoption target with minimal expenditure) may not perform well from an economic point of view. A combination of two subsidies, the most cost-effective solution in most cases, cannot lead to the highest profits for the entire supply chain. Particularly, offering a pure infrastructure subsidy has the best economic performance, as the supply chain achieves maximum profits under this subsidy.

Furthermore, this research provides valuable managerial implications to the operation managers of battery supplier and automakers, helping them make decisions on investment and production. Finally, our study reveals the bright side of competition in improving the cost-efficiency of government policies for EV adoption. In this sense, it may be in the government's interest to encourage upstream suppliers to enter the end market. This enables the government to effectively reduce its financial burden. In summary, this study derives several results that are theoretically interesting and practically relevant, providing policy strategies for governments and recommendations for firms' operation decisions.

The remainder of this paper is organized as follows: Section 2 reviews the related literature. Section 3 presents the basic model settings. Section 4 examines the government's optimal policy decisions. Section 5 compares the equilibrium outcomes of the different business models. Section 6 explores the effects of different cultures on policy decision. Section 7 provides concluding remarks.

2. Literature Review

This study is closely related to two streams of literature: sustainable operations in the EV supply chain, and the governmental policies for sustainable production considering different market characteristics.

2.1. Sustainable operations of EV supply chain

In the context of the bright sides of EV adoption, such as the reduction of carbon dioxide emission, it is necessary to note the findings of research on sustainable operations of EV supply chain. Environmental issues have received widespread attention, and the global consensus has been achieved regarding the reduction of greenhouse gas emissions. Based on this, Bao et al. (2020) examine the game behaviour and production decisions of two manufacturers in the EV industry. Many EV firms facing financial constraints, leading to the significance for the research on sustainable supply chain financing. Using the real data from a top-four EV manufacturer in the world, Ma et al. (2022) investigate operational decisions and sustainable finance strategies for the members in EV supply chain through a case study. The frequent occurrence of extreme weather events in recent years highlights the importance of applying new technology or financial incentives to reduce carbon dioxide emissions in the EV supply chain. Pi (2023) develops analytical model to examine the decarbonisation of gasoline vehicle (GV) automakers in both GV and EV production under different policies and compare three policies (subsidy, regulation, hybrid subsidy-regulation) and identify conditions for the optimality of each policy.

Some studies emphasize that insufficient infrastructure or technology investment is a significant constraint on the mass adoption of EVs and highlight the importance of sustainable investment for EV adoption (Lin and Wu, 2018; Yu et al., 2021). Feng et al. (2023) investigate the effect of sustainable investment in EV supply chain on environmental sustainability and describe the relationship between the investment in technology improvement (i.e., the blockchain application) and the adoption of EVs. Further, they analyze the interaction between firms' technology investment and government regulation. Their results show that carbon cap-and trade regulation stimulate the firms to make sustainable investment in technology improvement. Lieven (2015) investigates three policy instruments: financial support (subsidies), traffic regulation-related measures (free use of fast lanes), and charging infrastructure investments. Some studies focus on the interaction between the EV adoption and the associated charging infrastructure. Lim et al. (2015) consider different scenarios for charging station ownership and charging options. Yu et al. (2021) study the coordination problem between the government and EV manufacturers arising from the establishment of charging infrastructure. Mak et al. (2017) study an optimal infrastructure deployment strategy under demand uncertainty by developing a robust optimization model. Yoo et al. (2021) examine service providers' decisions regarding the number of charging stations while incorporating government purchase subsidies.

All the aforementioned papers have demonstrated the effect of charging infrastructure deployment on the EV adoption, emphasizing the effectiveness of infrastructure investment for demand increment. The work of Feng et al. (2023) is similar to ours and investigates the effect of sustainable investment in EV supply chain on environmental sustainability. While they mainly describe the relationship between the investment in technology improvement (i.e., the blockchain application) and the EV adoption, we demonstrate the effect of charging infrastructure deployment on the EV adoption, emphasizing the effectiveness of infrastructure investment for increasing demand. The most relevant paper to ours by Kumar et al. (2021) considers four different modes of charging infrastructure investment and studied the issue of whose investment in charging infrastructure is most efficient from a societal perspective. Our research differs from theirs in multiple respects, such as considering the government's subsidy scheme selection problem, considering a holistic approach to minimizing financial expenditure for the government, and bringing into the co-operative relationship of stakeholders in the EV supply chain.

2.2. Governmental policies for sustainable production

The second stream starts with the government intervention to improve the adoption of sustainable technology (Yang et al., 2019; Zhang et al., 2017). Yu et al. (2016) formulate a sequential game for a two-sided market and study the interaction between EV adoption and the investment in charging station construction. Ji and Huang (2018) establish a two-stage Stackelberg game and provide an overview of subsidy policies related to China's charging infrastructure construction targets. They develop a model wherein a policymaker aiming at EV adoption decides on consumer and production subsidies for charging station providers.

Moving one step further, some works explore the role of incentive instruments and their influence on the market decisions of stakeholders of EV supply chain. Various supply chain structures have been investigated under different subsidy schemes to characterize the process of EV diffusion. Lieven (2015) examines the effects of different government EV regulations across 20 countries and suggest that investing in charging facilities is more effective than providing consumer subsidies. Centobelli et al. (2020) reveal a positive relationship between government incentive policies supporting adopting new technology and achieving sustainable goals. Chen et al. (2022) develop a game-theoretic model to investigate the impact of investment subsidy and usage subsidy on adopting new technology. They examine an optimal government subsidy policy scheme, subject to budget constraints.

Among above-mentioned papers, two studies point out that one solution to overcome this “chicken-and-egg” dilemma that blocks the EV market penetration is to design effective incentive policies (Brozynski et al., 2022; Ma et al., 2019). The works of Ma et al. (2019) and Brozynski et al. (2022) are related to our work in spirit; each of their models considers a cost-benefit-focused decision-making scenario in which the government sought to maximize the social benefits of improving EV adoption and reducing subsidy expenditure. In contrast, in our model, the government is assumed to minimize total expenditure on the incentive policy, subject to a pre-defined adoption level.

Our study is related to Cohen et al. (2016) and Chemama et al. (2019), who also analyze government’s optimal subsidy policy for promoting EVs adoption. Cohen et al. (2016) establish analytical models to investigate a consumer subsidy scheme given a pre-defined adoption level in a market with uncertain demand. They point out that the optimal subsidy structure depends on the government's adoption target and the uncertainty level. Chemama et al. (2019) study the effects of two types of subsidies provided to suppliers: fixed and flexible. Similar to our approach, their model is a cost-effective one, in which the supplier seeks to determine the least-cost method to achieve a targeted adoption level. The differences between their work and ours can be divided into three aspects: setup, models and results. First, our paper incorporates the automakers' responsibility for building charging infrastructure in EV supply chain, whereas theirs assume the automakers focus solely on EVs production but not on infrastructure investment. Second, our model is more general in that both the government and firms in the EV supply chain can invest in infrastructure construction. Third, while they focus solely on purchase subsidies, we focus on the government's decision regarding subsidy scheme selection among three different subsidy schemes by comparing their effectiveness in promoting EV adoption.

Methodologically, the modified Stackelberg game framework in our study is consistent with the extended applications of Stackelberg game theory, which have been adapted to include more than two players in specific contexts. For example, existing literature on policy optimization have incorporated the government and multiple firms to analyze the interaction between government's policy decision and firms' pricing decisions (Chen et al., 2019; Yoo et al., 2021; Ma et al., 2019). This modified Stackelberg game model facilitates us to investigate the complicated interactions between the government, battery supplier and EV automaker in the promotion of EV adoption, which constitutes the primary focus of this study.

The differences between prior literature on government subsidies for EV supply chains and this study are presented in Table 1. In summary, our study contributes to the literature by revealing the government's subsidy selection strategy by identifying policy dominance conditions. Furthermore, to better reflect this practice, we incorporate different infrastructure investment scenarios and different supply chain structures into the incentive policy.

Table 1. Summary of literature.

Representative paper	Market competition	Different infrastructure	Different supply chain	Analysis of subsidy scheme selection

		investment	structure	strategy
Ma et al. (2021)	No	No	No	Yes
Chen et al. (2022)	No	No	No	Yes
Zhang et al. (2017)	No	No	No	No
Yang et al. (2019)	No	Yes	No	No
Cohen et al. (2016)	No	No	No	Yes
Shi et al. (2022)	No	No	No	Yes
Brozynski et al. (2022)	Yes	No	No	No
Ji et al. (2018)	No	No	No	Yes
Zhang et al. (2021)	Yes	No	No	Yes
This study	**Yes**	**Yes**	**Yes**	**Yes**

3. Problem description and model setup

We consider an EV supply chain consisting of one supplier (denoted by s and she) and one manufacturer (denoted by m and he) under government incentive policy. The government acts as the leader in implementing an incentive policy composed of a subsidy scheme (t,K) and its infrastructure investment level x_1 (representing the quantity of infrastructure, e.g., the number of charging stations to be established by the government) to stimulate EV adoption in the first stage, where t denotes the purchase subsidy offered to EV buyers and K represents the infrastructure subsidy granted to the firm upon its investment in infrastructure construction. Note that the government chooses an appropriate subsidy scheme from three options: a pure purchase subsidy, a pure installation subsidy, or a combination of the two. In the second stage, observing the set of government incentive policies (t,K,x_1), the firms act as followers, setting the quantity of the charging infrastructure to build and making price decisions. More specifically, the supplier/manufacturer decides on their infrastructure investment x_2, and then makes pricing decisions. In practice, it is often observed that the government tends to formulate a policy aimed at increasing the total sales of EVs. Governments are interested in assigning an adoption target to their subsidy schemes. For example, President Obama announced a goal that having one million EVs on the road by 2015 when developing an incentive policy. To conform to the practical observations, we assume the government's objective is to minimize the total policy expenditure, subject to an exogenously given adoption target τ, where τ represents the total sales of EVs in the market. The corresponding infrastructure investment cost is given by $f{x_i}^2$ (i=1,2), where $f > 0$ is the cost coefficient of infrastructure investment (Raz and Druehl, 2013; Yenipazarli, 2019). A recent report on charging infrastructure construction by the Boston Consulting Group suggested that infrastructure investment exhibits diseconomies of scale. A quadratic cost function is widely used and attributed to diseconomies of scale in infrastructure construction (Marette, 2007, Xiao & Xu, 2012). To simplify the model and obtain more managerial insights, the production cost of EVs is assumed to be negligible.

Market demand. Following the related paper in operations management (Feng et al. 2022), we use a utility of a representative consumer from the perspective of aggregate demand as follows:

$$U(q_s,q_m) = (a+\beta(x_1+x_2))(q_s+q_m) - \left(\frac{{q_s}^2}{2}+\frac{{q_m}^2}{2}+\delta q_s q_m\right) - (p_s - t)q_s - (p_m - t)q_m \qquad (1)$$

Since its introduction, this specific form of utility function has been widely adopted in the economics, marketing and operations management literature (Zhang et al., 2020; Zhen et al., 2022). a denotes the basic demand, and p_s (p_m) denotes the retail price of the EVs of the supplier (manufacturer); and q_s (q_m) denotes the sales of the EVs of the supplier (manufacturer). $0 < \delta < 1$ captures the competition intensity between the two products; $\beta > 0$ captures the positive effect of charging availability on EV adoption. $\beta(x_1+x_2)$ captures consumers' preferences for the quantity of charging infrastructure; that is, consumers are willing to pay more for EVs with larger quantity of charging infrastructure. Accordingly, consumers obtain a higher utility from buying an EV. t is the government purchase subsidy. Note that this form of utility function was first established by Spence (1976) and Levitan (1980) for two substitute products. The term "representative consumer" is drawn from the economic notion of "a fictional individual" and can be seen as "a theoretically average consumer" or "a continuum of consumers of the same type" (Ingene and Parry, 2004). Therefore, the utility of a representative consumer, which represents the consumer surplus, is also termed as "consumer surplus" in prior literature (Liu et al., 2014). This utility implies that the consumer utility/surplus from owing a product increases as the consumption of the product increases. The reason lies in the concept of consumer surplus. Consumer surplus refers to the additional value that consumers derive from purchasing a product at a lower price than their willingness to pay. As consumers buy more products, their overall satisfaction from the products increases. However, the price they pay remains constant. This leads to an increase in the difference between the price they are willing to pay and the actual price paid, thereby increasing the consumer utility/surplus.

One crucial factor affecting the consumer utility/surplus is competition. In most cases, there is usually more than one firm on the market. In the field of EVs, many companies are taking actions in this industry (e.g., Tesla and BYD) in the hope that reducing carbon emissions. In such a competitive market, consumer utility is determined by the total utility obtained from purchasing competing products, taking into account the principle of diminishing marginal utility. As consumers allocate their limited income across two competitive products, they weigh the additional satisfaction derived from consuming one more unit of each good relative to its price. When two firms compete within an industry, consumers have more options to choose from, allowing them to optimize their utility by selecting the combinations of products that provide the highest satisfaction relative to their prices. Therefore, in line with Feng et al. (2022), the demand for the two competitive products can be determined by maximizing the consumption utility function of the representative consumer $U(q_s, q_m)$:

$$q_s = \frac{1}{1-\delta^2}((1-\delta)(a+\beta(x_1+x_2)) - (p_s - t) + \delta(p_m - t) \quad (2)$$

$$q_m = \frac{1}{1-\delta^2}((1-\delta)(a+\beta(x_1+x_2)) - (p_m - t) + \delta(p_s - t) \quad (3)$$

In the base supply chain, the upstream firm acts as a pure battery supplier of the downstream firm. Distinct from base supply chain, in the co-opetitive supply chain, the upstream firm acts as both a battery supplier and an end-market competitor of the downstream automaker. An example of co-opetitive supply chain is between BYD and Tesla, where Tesla buys BYD's batteries and BYD also competes with Tesla directly in the EV market.

In particular, in the baseline supply chain, the demand function degenerates into a leaner downward-sloping demand function:

$$q_m = a + \beta(x_1 + x_2) - (p_m - t) \quad (4)$$

As a convenience, the parameters are summarized in Table 2.

Table 2. Notations and descriptions.

Exogenous variable	
a	basic demand
δ	the intensity of competition
β	the demand expansion effect of per unit of charging station
f	cost coefficient of charging infrastructure investment
τ	the preset target of EV adoption level
U_i	the utility of a representative consumer
Endogenous variable	
w	wholesale price
p_s	price of the supplier
p_m	price of the manufacturer
q_s	the sales quantity of the upstream supplier
q_m	the sales quantity of the downstream automaker
x_2	the firm's infrastructure investment
x_1	the government's infrastructure investment
t	the purchase subsidy for per unit of EV offered to consumers
K	the infrastructure subsidy for per charging station offered to the firm
Equilibrium outcomes	
π_g	the government policy expenditure
π_s	the profit of the upstream supplier
π_m	the profit of the downstream automaker
Different scenarios	
BS	the scenario where the supplier invests in infrastructure in the base supply chain
BM	the scenario where the automaker invests in infrastructure in the base supply chain
CS	the scenario where the supplier invests in infrastructure in the co-opetitive supply chain
CM	the scenario where the automaker invests in infrastructure in the co-opetitive supply chain

Decision sequence. The timeline is shown in Fig. 1. In the first stage, the government acts as the leader and announces its incentive policy (t, K, x_1), which includes the subsidy scheme and the level of infrastructure investment x_1. In the second stage, the battery supplier (in the BS scenario and CS scenario) or the manufacturer (in the BM scenario and CM scenario), observing the government's policy, sets the level of infrastructure investment x_2. In the third stage, for the BS and BM scenario, the battery supplier sets the wholesale price w and then, the manufacturer determines the retail price p_m. For the CS and CM scenario, after the battery supplier sets the wholesale price w, the manufacturer and supplier engage in price competition by simultaneously setting their prices p_m and p_s, respectively.

Based on the game sequence, the firm's infrastructure investment is made prior to the pricing decisions, as it is strategic choice that reshapes the firm's cost structure and market potential, thereby influencing the pricing strategy of firms.

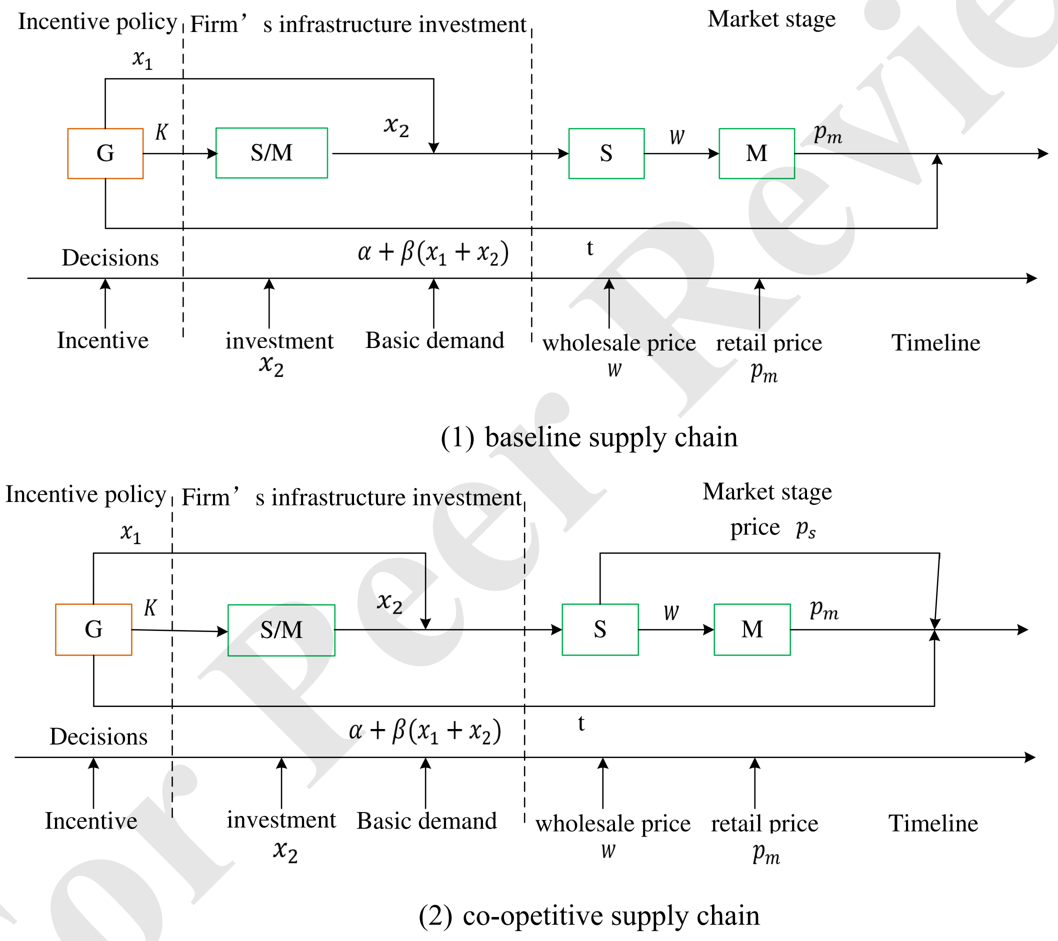


Fig. 1. Timeline of events

4. Equilibrium analysis

This section analyzes the optimal decisions of firms and the government under four scenarios illustrated earlier: the BS scenario, the BM scenario, the CS scenario, and the CM scenario. A backward induction approach is employed; that is, for each scenario, given the government's incentive policy, we first derive the firms' best responses and then formulate the government's decision model.

4.1. The supplier invests in infrastructure in a baseline supply chain (BS scenario)

This scenario reflects the practical observation that CATL supplies EV batteries to automakers (the baseline supply chain) and takes responsibility for infrastructure investment.

Firms' decision. Given the government's incentive policy, the decision problems of the suppliers and manufacturers are formulated as:

$$\max_{(x_2,w)} \pi_s^{BS} = \max_{(x_2,w)} (w(\alpha + \beta(x_1 + x_2) - (p_m - t)) - f{x_2}^2 + Kx_2) \tag{5}$$

$$\max_{(p_m)} \pi_m^{BS} = \max_{(p_m)} ((p_m - w)(\alpha + \beta(x_1 + x_2) - (p_m - t))) \tag{6}$$

Solving the firms' decision problems formulated in Eq. (5) and (6), we obtain the results summarized in Table 3 by considering the first-order condition. Corollary 1 shows how government incentive policies influence the market decisions of the firms. The superscript "*" represents the firms' best response given the government policy (*t, K,* x_1).

Corollary 1. *Given the government's incentive schemes* (t,K,x_1), $\frac{\partial x_2^*}{\partial x_1} > 0$, $\frac{\partial p_m^*}{\partial t} > 0$, $\frac{\partial p_m^*}{\partial K} > 0$, $\frac{\partial q_m^*}{\partial t} > 0$, $\frac{\partial q_m^*}{\partial K} > 0$, $\frac{\partial \pi_m^*}{\partial t} > 0$, $\frac{\partial \pi_m^*}{\partial K} > 0$, $\frac{\partial q_m^*}{\partial t} > \frac{\partial q_m^*}{\partial K}$ *holds if and only if* $f > \frac{\beta}{2}$.

Corollary 1 suggests that the supplier subsidized with infrastructure subsidy essentially transfers part of the subsidy to the manufacturer. The manufacturer's quantity and price simultaneously increase with the government's financial incentives. Corollary 1 shows that the government can enhance the base demand for EVs by either the purchase subsidy or infrastructure subsidy, which in turn facilitates the manufacturer to increase total sales while keeping the retail price high ($\frac{\partial p_m^*}{\partial t} > 0$, $\frac{\partial p_m^*}{\partial K} > 0$, $\frac{\partial q_m^*}{\partial t} > 0$, $\frac{\partial q_m^*}{\partial K} > 0$). This indicates that the government should be aware of the manufacturer taking advantage of the subsidy to increase his profit, as this free-riding incentive may undermine the efficiency of the subsidies and the government's heavy financial burden. Furthermore, from Corollary 1, we know that only if the investment cost is sufficiently large ($f > \frac{\beta}{2}$), the purchase subsidy is more effective in promoting the EV adoption than the infrastructure subsidy.

Table 3. The firms' best response under the four scenarios.[3]

	w	p_m	p_s	x_2
BS	$\frac{4af+4ft+4f\beta x_1}{8f-\beta^2}$	$\frac{2f(3a+3t)+3K\beta+6f\beta x_1}{8f-\beta^2}$	None	$\frac{4K+a\beta+\beta t+\beta^2 x_1}{8f-\beta^2}$
B M	$\frac{8f(a+t)+4K\beta+8f\beta x_1}{16f-\beta^2}$	$\frac{6(2f(a+t)+K\beta+2f\beta x_1)}{16f-\beta^2}$	None	$\frac{8K+a\beta+\beta t+\beta^2 x_1}{16f-\beta^2}$
CS	$\frac{\left\{\begin{matrix}(8+8\delta+\delta^3+\delta^4)\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}(1+\delta)(12-\delta(4-(2-\delta)\delta))\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}(4-\delta)(1+\delta)(2+\delta)\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}2K(1+\delta)(8+\delta^2)+(a+t)\beta\\(12+\delta(4+\delta+\delta^2))\\+\beta^2(12+\delta(4+\delta+\delta^2))x_1\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$
C M	$\frac{\left\{\begin{matrix}(1+\delta)(8+\delta^2)(8+\delta^3)\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4(f(1+\delta)(8+\delta^2)^2+\\\beta^2(1-\delta)(2+\delta^2)^2)\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}(4-\delta)(1+\delta)(2+\delta)(8+\delta^2)\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4(f(1+\delta)(8+\delta^2)^2+\\\beta^2(1-\delta)(2+\delta^2)^2)\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}(1+\delta)(8+\delta^2)(12-\delta(4-\\(2-\delta)\delta))(2f(a+t)\\+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4(f(1+\delta)(8+\delta^2)^2+\\\beta^2(1-\delta)(2+\delta^2)^2)\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}-2(a+t)\beta(-1+\delta)(2+\delta^2)^2+\\K(1+\delta)(8+\delta^2)^2-\\2\beta^2(-1+\delta)(2+\delta^2)^2x_1\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$

The government's decision. In the first stage, the government introduces the incentive policy (t,K,x_1) to spur EV sales and reach the targeted adoption level τ.

As mentioned previously, the government's objective is to minimize the total expenditure of the incentive policy. The government's decision problem is formulated as follows:

$$\begin{cases} \min_{(t,K,x_1)} \pi_g(t,K,x_1) = \min_{(K,s,x_1)} (f x_1^2 + t q_m + K x_2) \\ \text{Subject to:} \\ q_m \geq \tau, \\ q_m \in \max_{q_m} \pi_m^{BS}, \\ x_2 \in \max_{x_2} \pi_s^{BS}, \\ K,t \geq 0. \end{cases} \quad (7)$$

The objective function comprises the subsidy expenditure and infrastructure investment costs. The first constraint states that total sales of EVs must be at least equal to the pre-defined adoption level τ. By comparing the total expenditure under different subsidy schemes (i.e., providing either a pure purchase subsidy, pure infrastructure subsidy, or a combination of both subsidies), while considering the precondition of a positive subsidy, the government's optimal policy can be characterized by Proposition 1.

Proposition 1. *Under the BS scenario, the government's policy decision can be characterized as follows:*

[3] Note: For BS scenario, we assume $f > \frac{\beta^2}{8}$ to ensure the firm's demand is positive without government's incentives, i.e., $s = 0, K = 0, x_1 = 0$. That is, we restrict the analysis for BS scenario to $f > \frac{\beta^2}{8}$. Following the same logic, we add assumptions in other scenarios. See Appendix A for details.

(1) If $f > \frac{\beta^2}{4}$ *and* $\tau > \frac{\alpha f}{4f-\beta^2}$*, it is optimal for the government to provide a pure purchase subsidy policy, and* $(t,K,x_1) = (\frac{(4f-\beta^2)\tau-\alpha f}{f}, 0, \frac{\beta\tau}{2f})$*.*

(2) Otherwise, i.e., if $f < \frac{\beta^2}{4}$ *or* $f > \frac{\beta^2}{4}$ *and* $\tau < \frac{\alpha f}{4f-\beta^2}$*, it is optimal for the government to provide no subsidy, and* $x_1 = \frac{(8f-\beta^2)\tau-2\alpha f}{2f\beta}$*.*

The profits of the firms and the government's total expenditure are shown in the appendix.

From this proposition, the government chooses its subsidy policy based on the cost coefficient f and adoption level target τ. Cost coefficient f and adoption level target τ are indicators of the difficulty of promoting EV adoption through infrastructure construction. The higher the investment cost and adoption target are, the more challenging it is to promote EV adoption. Proposition 1 shows that, in the baseline supply chain, if the supplier makes infrastructure investment, the government does not provide an infrastructure subsidy. Intuitively, the government "directly" providing infrastructure subsidies can incentivize the supplier to invest more in infrastructure to increase consumer base demand. However, in the BS scenario, the increase in base demand induces the downstream manufacturer to free-ride on the enlarged market size by charging high retail prices, increasing the degree of inefficient double marginalization. In such a case, the government has no incentive to provide infrastructure subsidies because doing so will result in economic inefficiency. When stimulating EVs diffusion is not a challenging practice, the government eliminates subsidies and induces high adoption by building charging infrastructure.

4.2. The manufacturer invests in infrastructure in a baseline supply chain (BM scenario)

In real life, we observe a scenario in which the downstream automaker in the baseline supply chain (e.g., Tesla) installs charging facilities. In this scenario, the firms' decision-making problems are formulated as follows.

$$\max_{(w)} \pi_s^{BM} = \max_{(x_2,w)} (w(\alpha + \beta(x_1 + x_2) - (p_m - t)) \quad (8)$$

$$\max_{(x_2,p_m)} \pi_m^{BM} = \max_{(p_m)} ((p_m - w)(\alpha + \beta(x_1 + x_2) - (p_m - t)) - f{x_2}^2 + Kx_2) \quad (9)$$

Firms' decision. The optimal price decisions are summarized in Table 3.

The government's decision. By substituting the responses $q_m(t,K,x_1)$ and $x_2(t,K,x_1)$ into the government's objective function, we formulate the government's decision problem:

$$\begin{cases} \min\limits_{(t,K,x_1)} \pi_g(t,K,x_1) = \min\limits_{(K,s,x_1)} (f x_1^{\ 2} + t q_m + K x_2) \\ \text{Subject to:} \\ q_m \geq \tau, \\ q_m \in \max\limits_{q_m} \pi_m^{BM}, \\ x_2 \in \max\limits_{x_2} \pi_s^{BM}, \\ K,t \geq 0. \end{cases} \quad (10)$$

Proposition 2. *Under the BM scenario, it is optimal for the government to set the incentive policy* (t,K,x_1) *as follows:*

(1) If $f > \frac{7\beta^2}{32}$ *and* $\tau > \frac{8af}{32f-7\beta^2}$*, the government provides both subsidies and* $(t,K,x_1) = (\frac{-8af+(32f-7\beta^2)\tau}{8f}, \frac{\beta\tau}{4}, \frac{\beta\tau}{2f})$.

(2) If $\frac{\beta^2}{8} < f < \frac{3\beta^2}{16}$ *and* $\tau > \frac{2af}{8f-\beta^2}$ *or* $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ *and* $\frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2}$ *or* $f > \frac{7\beta^2}{32}$ *and* $\frac{2af}{8f-\beta^2} < \tau < \frac{8af}{32f-7\beta^2}$*, the government provides a pure infrastructure subsidy and* $(t,K,x_1) = (0, \frac{2((4f-\beta^2)\tau-af)}{3\beta}, \frac{(16f-\beta^2)\tau-4af}{6f\beta})$.

(3) Otherwise, the government provides no subsidy, and $x_1 = \frac{(16f-\beta^2)\tau-4af}{4f\beta}$.

Proposition 2 (1) reveals that providing both subsidies simultaneously is the optimal choice if both the cost coefficient f and adoption target τ are high, in contrast to the BS scenario, where the government never provides infrastructure subsidies. Furthermore, different from Proposition 1, Proposition 2 (2) shows that when the automaker constructs infrastructure, providing a pure infrastructure subsidy is an optimal choice for the government when either f or τ is within a moderate range. The rationale behind this result is that, compared with the supplier, the manufacturer has less incentive to invest in infrastructure, increasing the necessity of providing infrastructure subsidies to encourage infrastructure construction. Proposition 2 shows that offering a pure purchase subsidy never arises as the government's optimal policy. This result can be attributed to the manufacturer taking advantage of purchase subsidies. In the BM scenario, the manufacturer has stronger incentive to free-ride, increasing the government's financial burden. Therefore, when either the adoption target or the cost coefficient is at a medium level, the government ceases to use an extra purchase subsidy as a supplementary incentive owing to its lower efficiency. When the task is challenging (f and τ are both high enough), the government must use the purchase subsidy as an extra incentive. Intuitively, when the task is not difficult, focusing solely on establishing infrastructure is the most cost-efficient solution instead of using subsidy incentives. This result suggests that to strike a better balance between the expenditure burden and the effectiveness in improving EV penetration. The government should also be aware of the manufacturer's free-riding practice, which enables the manufacturer to accrue more profit but results in negative consequences (i.e., lowered cost efficiency and aggravated expenditure burden of the policy).

4.3. The supplier invests in infrastructure in a co-opetitive supply chain (CS scenario)

A co-opetitive supply chain appears in the example of BYD, which launches its own EVs and focuses on supplying EV batteries to the automaker Tesla and other automakers. In the CS scenario, an upstream battery supplier (e.g., BYD) deploys the charging infrastructure, and the firms' decision problems are expressed as

$$\max_{(x_2,w)} \pi_s^{CS} = \max_{(x_2,w)} (p_s\left(\frac{1}{1-\delta^2}((1-\delta)(\alpha+\beta(x_1+x_2)) - (p_s - t)) + \delta(p_m - t)\right) + wq_m - f{x_2}^2 + Kx_2) \quad (11)$$

$$\max_{(p_m)} \pi_m^{CS} = \max_{(p_m)} ((p_m - w)(\frac{1}{1-\delta^2}((1-\delta)(\alpha+\beta(x_1+x_2)) - (p_m - t) + \delta(p_s - t))) \quad (12)$$

The firms' decision. Firms' best responses, given government incentives (t,K,x_1), are summarized in Table 3. It can be observed that the government's optimal subsidy level t^* and K^* increase in δ. Put another way, competition increases the government's incentive to offer a higher subsidy. This finding provides valuable management insights for the government, which should increase subsidies as the supply chain structure of the EV industry evolves due to intensified competition.

The government's decision. The government's decision problem is formulated as:

$$\begin{cases} \min_{(t,K,x_1)} \pi_g(t,K,x_1) = \min_{(s,K,x_1)} (f{x_1}^2 + t(q_s+q_m) + Kx_2) \\ \text{Subject to:} \\ q_s + q_m \geq \tau, \\ q_s \in \max_{q_s} \pi_s^{CS}, \\ q_m \in \max_{q_m} \pi_m^{CS}, \\ x_2 \in \max_{x_2} \pi_s^{CS}, \\ K,t \geq 0. \end{cases} \quad (13)$$

As mentioned earlier, the government determines the policy (t,K,x_1), and thereafter the firms make pricing decisions w, p_s and p_m. Based on firms' best responses summarized in Table 3, we solve the above optimization problem by backward induction and find that providing both subsidies never arises as an optional solution. Either a pure purchase subsidy or a pure infrastructure subsidy can be chosen. Table 4 characterizes the equilibrium solutions under the pure purchase subsidy and the pure infrastructure subsidy, respectively. The related policy expenditure is presented in the second row of Table 4. The third row of Table 4 presents the preconditions to ensure positive subsidies.

Table 4. Government policy design under each subsidy scheme of CS scenario.

Subsidy scheme	Pure purchase subsidy	Pure infrastructure subsidy
(t,K,x_1)	$\begin{cases} \frac{\left\{ \begin{array}{c} -af(12+\delta(1+\delta)(2+\delta))+2f(1+\delta) \\ (8+\delta^2)\tau-\beta^2(12+\delta(3+\delta(2+\delta)))\tau \end{array} \right\}}{4f(12+\delta(1+\delta)(2+\delta))} \\ 0 \\ \frac{\beta\tau}{2f} \end{cases}$	$\begin{cases} 0 \\ \frac{\left\{ \begin{array}{c} -2af(12+\delta(1+\delta)(2+\delta))+ \\ 4f(1+\delta)(8+\delta^2)\tau- \\ 2\beta^2(12+\delta(4+\delta+\delta^2))\tau \end{array} \right\}}{3\beta(12+\delta(1+\delta)(2+\delta))} \\ \frac{\beta\tau}{2f} \end{cases}$
Expenditure	$\frac{\left\{ \begin{array}{c} \tau(-4af(12+\delta(1+\delta)(2+\delta))+ \\ (8f(1+\delta)(8+\delta^2)-\beta^2(36+ \\ \delta(10+\delta(5+3\delta))))\tau) \end{array} \right\}}{4f(12+\delta(1+\delta)(2+\delta))}$	$\frac{\left\{ \begin{array}{c} (1+\delta)(4-(2-\delta)\delta)(20+\delta(2+5\delta))\tau \\ (4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))- \\ (8f(1+\delta)(8+\delta^2)^2+\beta^2(112+\delta(16+ \\ \delta(36+\delta(-4+(5-3\delta)\delta)))))\tau) \end{array} \right\}}{4f(12+\delta(1+\delta)(2+\delta))}$
Preconditions	$f>f_1$ *and* $\tau>\tau_1$	$f>f_2$ *and* $\tau>\tau_2$

Interestingly, by comparing the policy expenditures of the two candidate subsidy schemes, we identify that both the pure purchase subsidy and the pure infrastructure subsidy can be the optimal solution, depending on the cost coefficient f and the adoption target τ. The results are summarized in Proposition 3.

Proposition 3. *Under the CS scenario, the government's optimal incentive policy can be characterized as follows:*

(1) If $f>f_2$ *and* $\tau>\tau_2$, *it is optimal for the government to provide a pure infrastructure subsidy.*

(2) If $f_1<f<f_2$ *and* $\tau>\tau_1$ *or* $f>f_2$ *and* $\tau_1<\tau<\tau_2$, *it is optimal for the government to provide a pure purchase subsidy.*

(3) Otherwise, the government should provide no subsidy and

$$x_1=\frac{-2af(12+\delta(1+\delta)(2+\delta))+(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{2f\beta(12+\delta(1+\delta)(2+\delta))}$$

The value of (t, K, x_1) *is summarized in Table 4, and the value of these thresholds are specified in the appendix.*

Proposition 3 implies that subsidizing EV purchases or charging infrastructure can be optimal solutions. Similar to Propositions 1 and 2, the cost coefficient and targeted adoption level largely determine which side to subsidize. However, in contrast to the BS scenario, in which the government never selects an infrastructure subsidy, a feasible region exists where offering an infrastructure subsidy may be preferable. Intuitively, two effects occur when a purchase subsidy is provided. First, EV adoption of EVs is increased, benefitting governments. Second, recall from Proposition 1 that double marginalization in the supply chain intensifies, which reduces the supplier's profit and weakens the supplier's willingness to invest in infrastructure. The first effect is positive, but the second is negative for the cost efficiency of the purchase subsidy. In contrast to the baseline supply chain, market competition in a co-opetitive supply chain reduces the degree of inefficient double marginalization in the retail channel. The degree of the positive effect may dominate the negative one when either f or τ is medium. This finding provides an additional benefit to upstream firms' encroachment in the context of government subsidies for the EV industry. In other words, this interesting finding reveals the complementary relationship between the government's subsidy incentive and competition as competition may weaken double marginalization and raise the efficiency of the purchase subsidy. This finding may explain the government policy encouraging more firms to enter the EV industry. Combining Propositions 1 and 2, Proposition 3 indicates that policymaking, in practice, may proceed in the opposite direction. Evidence can be found in China, where purchase subsidies was terminated by the end of 2022. Similarly, in the United States, EV purchase subsidies have decreased. Additionally, for governments considering subsidizing infrastructure, subsidizing EV purchases is better than subsidizing infrastructure construction when promoting market diffusion of EVs is not too difficult. Our findings can provide valuable guidance for governments.

4.4. The manufacturer invests in infrastructure in a co-opetitive supply chain (CM scenario)

In this scenario, the downstream firm in the co-opetitive supply chain, instead of the upstream partner, is responsible for constructing the charging facilities. The firms' decision problems are formulated as follows:

$$\max_{(w)} \pi_s^{CM} = \max_{(x_2,w)} (p_s(\frac{1}{1-\delta^2}((1-\delta)(\alpha+\beta(x_1+x_2))-(p_s-t))+\delta(p_m-t))+wq_m) \quad (14)$$

$$\underset{(x_2,p_m)}{\text{Max}}\ \pi_m^{CM} = \max_{(p_m)}((p_m-w)(\frac{1}{1-\delta^2}((1-\delta)(\alpha+\beta(x_1+x_2))-(p_m-t)+\delta(p_s-t))-fx_2{}^2+Kx_2) \quad (15)$$

Firms' decision. Table 3 lists the firms' optimal decisions in Stage 2.

Government's decision. The government's decision problem is formulated as:

$$\begin{cases} \min\limits_{(t,K,x_1)} \pi_g(t,K,x_1) = \min\limits_{(t,K,x_1)} (fx_1^{\ 2} + \Lambda_1 t(q_s+q_m) + \Lambda_2 K x_2) \\ \text{Subject to:} \\ q_s + q_m \geq \tau, \\ q_s \in \max\limits_{q_s} \pi_s^{CM}, \\ q_m \in \max\limits_{q_m} \pi_m^{CM}, \\ x_2 \in \max\limits_{x_2} \pi_m^{CM}\ , \\ K,t \geq 0. \end{cases} \quad (16)$$

Consequently, we can derive the government's policy design for each subsidy scheme, as summarized in Table 5. Similar to Table 4, Table 5's first row characterizes the equilibrium outcomes of each candidate subsidy scheme. The second row summarizes the corresponding policy expenditure. The third row presents preconditions for providing positive subsidy is feasible.

Table 5. Government policy design under each subsidy scheme of CM scenario.

	Pure purchase subsidy	Pure infrastructure subsidy	Both subsidies
(t,K,x_1)	$\begin{cases} \frac{\left\{\begin{matrix} -2af(8+\delta^2)(12+\delta(1+\delta)(2 \\ (4f(1+\delta)(8+\delta^2)^2+\beta^2(- \\ \delta^2(-52+\delta(6+\delta(-7+3\delta \end{matrix}\right.}{2f(8+\delta^2)(12+\delta(1+\delta)(2} \\ 0 \\ \frac{\beta\tau}{2f} \end{cases}$	$\begin{cases} 0 \\ \frac{\left\{\begin{matrix} 4(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta) \\ (8+\delta^2)^2)\tau-2af(8+\delta^2) \\ (12+\delta(1+\delta)(2+\delta)) \end{matrix}\right\}}{3\beta(12+\delta(1+\delta)(2+\delta))} \\ \frac{\beta\tau}{2f} \end{cases}$	$\begin{cases} \frac{\left\{\begin{matrix} -4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) \\ +\beta^2(-304+\delta(-32+\delta(-124+ \\ (-14+\delta)\delta(1+\delta)))))\tau \end{matrix}\right\}}{4f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} \\ \frac{\left\{\begin{matrix} \beta(80+\delta(32+\delta(20+\delta(26+\delta(-1 \\ +5\delta)))))\tau \end{matrix}\right\}}{2(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} \\ \frac{\beta\tau}{2f} \end{cases}$
Expenditure	$\frac{\left\{\begin{matrix} \tau(-4af(8+\delta^2)(12+\delta(1+\delta)(\\ +(8f(1+\delta)(8+\delta^2)^2+\beta^2(- \\ \delta(16+\delta(-68+\delta(22+\delta(- \\ 7\delta))))))\tau) \end{matrix}\right.}{4f(8+\delta^2)(12+\delta(1+\delta)(2+}$	$\frac{\left(\begin{matrix} 2(a^2f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2 \\ -2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) \\ (2f(1+\delta)(8+\delta^2)^2-\beta^2(1+\delta)(2+\delta^2)^2)\tau \\ +2(-\beta^4(-1+\delta)^2(2+\delta^2)^4+2f\beta^2(-1+ \\ \delta^2)(2+\delta^2)^2(8+\delta^2)^2+2f^2(1+\delta)^2 \\ (8+\delta^2)^4)\tau^2)) \end{matrix}\right.}{3f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$	$\frac{\left(\begin{matrix} \tau(-8af(8+\delta^2)^2 \\ (12+\delta(1+\delta)(2+\delta))^2+(16f(1+\delta) \\ (8+\delta^2)^3(12+\delta(1+\delta)(2+\delta))- \\ \beta^2(30976+\delta(6144+\delta(25984+\delta \\ (4800+\delta(8656+\delta(720+\delta(1460+ \\ \delta(-132+\delta(143+\delta(-30+ \\ 11\delta)))))))))))\tau) \end{matrix}\right)}{8f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$

Precondition	$f > f_3$ *and* $\tau > \tau_3$	$f > f_4$ *and* $\tau > \tau_4$	$f > f_5$ *and* $\tau > \tau_5$

A comparison of expenditures under the three candidate subsidy schemes yields the government's optimal subsidy scheme selection.

Proposition 4. *Under the CM scenario, given the targeted adoption level* τ*, to minimize the total expenditure, it is optimal for the government to set the incentive policy* (t,K,x_1) *as follows:*

(1) If $f > f_5$ *and* $\tau > \tau_5$*, the government should provide both subsidies.*

(2) If $f_4 < f < f_5$ *and* $\tau > \tau_4$ *or* $f > f_5$ *and* $\tau_4 < \tau < \tau_5$*, the government should provide a pure infrastructure subsidy.*

(3) Otherwise, the government provides no subsidy, and

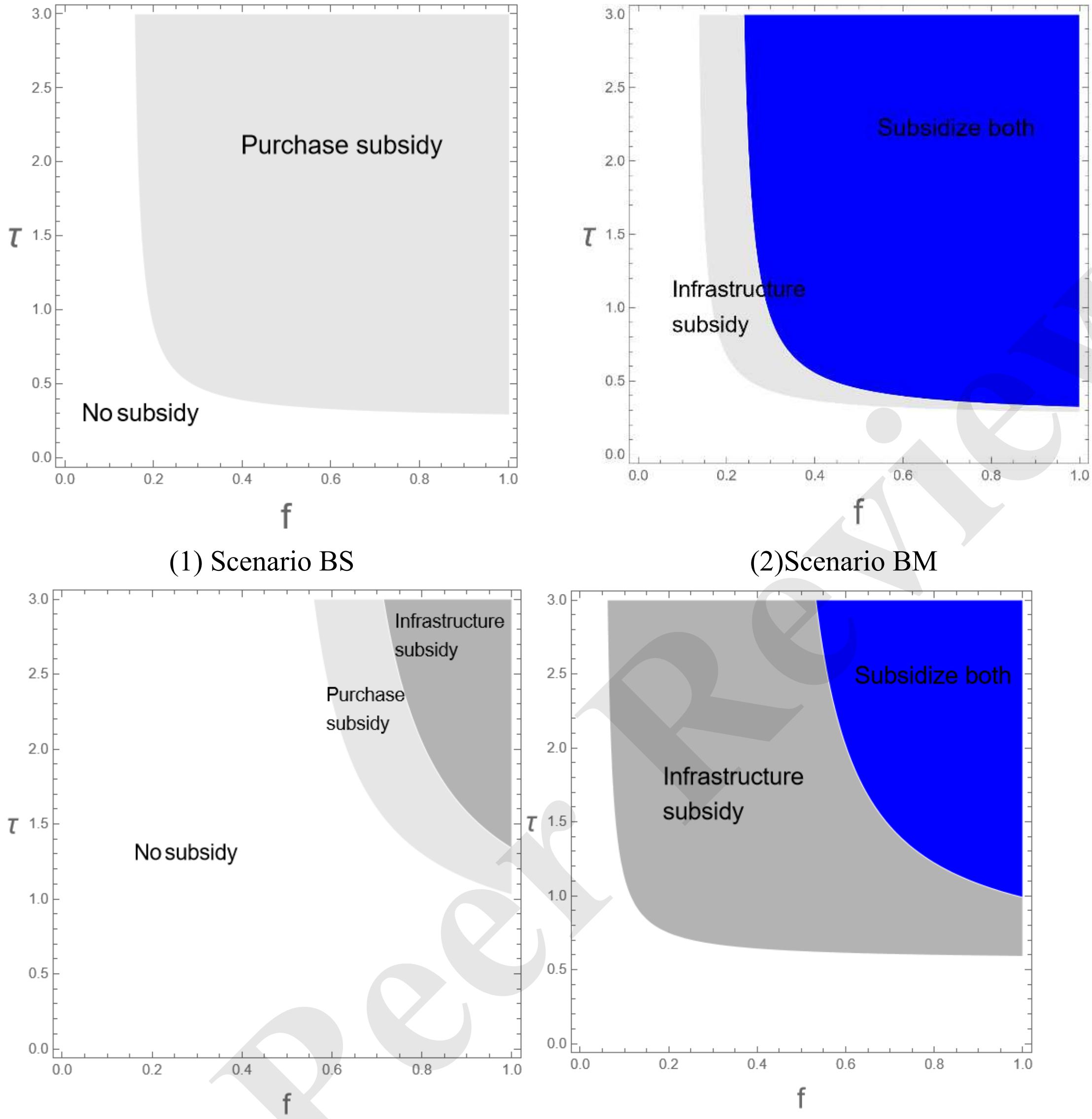
$$x_1 = \frac{-af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + 2(\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{f\beta(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}$$

The value of (t,K,x_1) *can be found in Table 5, and the value of the thresholds are provided in the Appendix.*

A careful comparison of the government's optimal incentive policy under the four scenarios reveals significant differences. First, together with the earlier findings, Proposition 4 suggests that both subsidies can become the most efficient choice under certain conditions only when the downstream automaker invests in infrastructure. Regardless of which firm constructs the infrastructure, increases in infrastructure investment and production quantity jointly contribute to increasing the government's financial burden. However, under scenarios where the supplier builds infrastructure, the supplier's infrastructure investment facilitates the manufacturer's free ride on the expanded basic demand, leading to a larger infrastructure subsidy expenditure. Therefore, when the supplier constructs charging infrastructure, the government no longer subsidizes both sides simultaneously. It should be noted that if the government decides to discontinue providing a purchase subsidy and switch to a pure infrastructure subsidy, this decision should depend on the cost coefficient and the targeted adoption level. This interesting finding makes policymakers' decision-making easier.

Fig. 2 illustrates the results in Proposition 3 and Proposition 4 with varying f and τ. The parameters are set similarly to those of Ma et al. (2019) and Shi et al. (2022) and are shown as $a = 1$, $\beta = 0.5$, $\delta = 0.6$. As shown in Fig. 2, the main findings are as follows: (i) These thresholds decrease with the coefficient of construction investment f, meaning that regardless of which firm builds infrastructure and whether the supplier has her own direct channel, the government is likely to provide a positive subsidy when building infrastructure is costly. (ii) Under the BS and CM scenarios, the shadow region consistently lies above the gray region, implying that for a small adoption target increase, the government is better off offering both subsidies. (iii) In the CS, the gray region consistently lies above the light gray region, indicating that the government is more likely to be better off when the targeted adoption level is higher. (iv) Compared to the CS scenario, the ranges of f and τ that induce the government's elimination of subsidies decrease under the CM scenario, indicating that in a co-opetitive supply chain, the government is more likely to provide a positive subsidy when the manufacturer is responsible for establishing infrastructure. (v) Under the CM scenario (Fig. 2(4)), when f is sufficiently large, the thresholds of the government's optimal subsidy selection strategy decrease with increasing f, meaning that the government is likely to provide both subsidies when the cost coefficient increases.

Consistent with Proposition 3 and Proposition 4, Fig. 2 reveals that if the manufacturer engages in infrastructure construction, the government's optimal incentive scheme follows a "sandwich rule" defined by the cost coefficient f and adoption target level τ: the government subsidizes only the infrastructure construction when the two parameters both fall in moderate range; however, if the two parameters are both sufficiently high, it is optimal to use a combination of both subsidies; otherwise, to provide no subsidy. Additionally, the blue region in Fig. 2 (2) and (4) suggests that if the supplier invests in infrastructure when infrastructure construction is costly (f is sufficiently large), the two subsidies are complementary from the government's perspective. The disincentive against building infrastructure stemming from the purchase subsidy can be effectively weakened by the simultaneous offering of the infrastructure subsidy. Under the two scenarios depicted in Fig. 2 (2) and (4), the purchase subsidy is efficient only when the infrastructure subsidy is concurrently offered but inefficient if offered alone for a sufficiently high cost coefficient.



(1) Scenario BS (2)Scenario BM

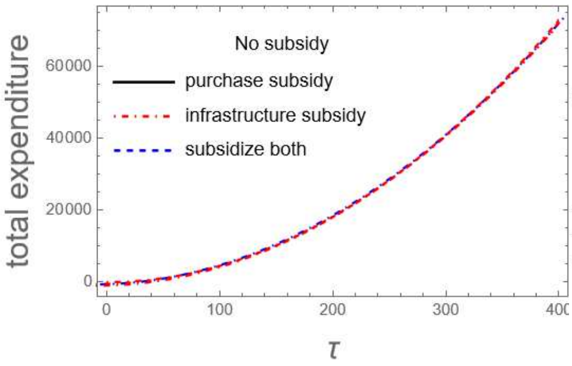
(3) Scenario CS (4) Scenario CM

Fig. 2. Optimal subsidy policy selection strategy under four scenarios[4]

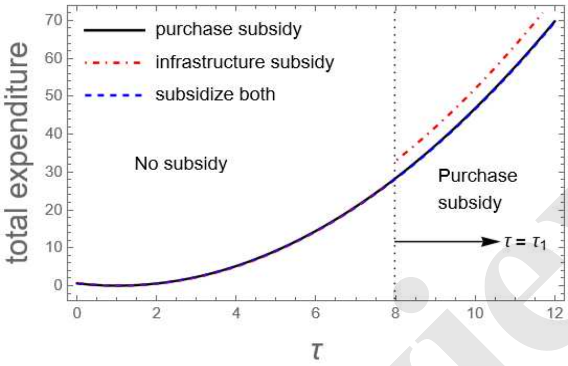
Fig. 3 provides a numerical example of Proposition 3 and Proposition 4. The parameters remain the same as in Fig. 2. Fig. 3 (1)-(3) demonstrates that the blue line coincides perfectly with the black line, which implies that a combination of both subsidies degenerates into a purchase subsidy under the CS scenario. In Fig. 3 (1), the three lines coincide perfectly, which indicates that regardless of the government's choice of subsidy scheme, it is optimal for the government to set $(t,K) = (0,0)$. Fig. 3 (2) illustrates that if $f_1 < f < f_2$ and $\tau > \tau_1$, the government should select the pure purchase subsidy scheme. Fig. 3 (2) illustrates that if $f > f_2$ and $\tau_1 < \tau < \tau_2$, the optimal subsidy scheme is a pure purchase subsidy; otherwise, if $\tau > \tau_2$, the pure

[4] Note that axis label f represents the cost coefficient and τ represents the preset adoption target.

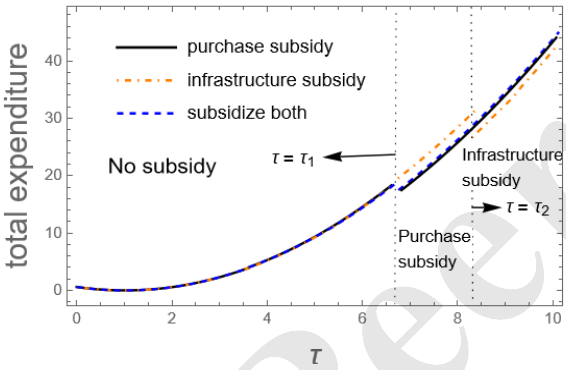
infrastructure is the optimal choice. Fig. 3 verifies the results of Proposition 3, demonstrating that as promoting EV penetration becomes more challenging, the government's optimal subsidy scheme shifts from providing no subsidy to providing a pure purchase subsidy and finally to providing both subsidies.



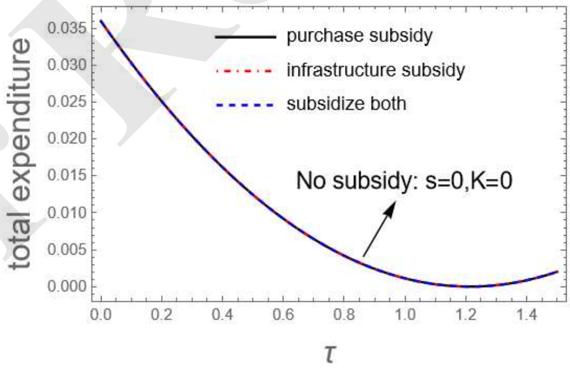
(1) CS scenario ($f = 0.12 < f_1$)



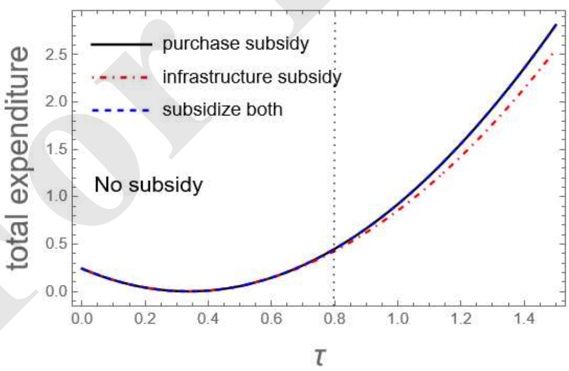
(2) CS scenario ($f_1 < f = 0.138 < f_2$)



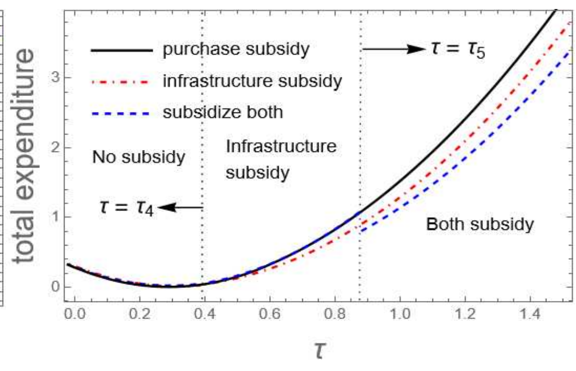
(3) CS scenario ($f = 0.15 > f_2$)



(4) CM scenario ($f = 0.009 < f_4$)



(5) CM scenario ($f_4 < f = 0.05 < f_5$)



(6) CM scenario ($f = 0.12 > f_5$)

Fig. 3. Total expenditure with respect to different f and τ [5]

From Fig. 3 (4)–(7), under the CM scenario, when f is sufficiently large ($f > f_5$), as τ increases, the government's equilibrium choice of subsidy changes from no subsidy to pure infrastructure subsidy, and finally to providing both subsidies. In the CS scenario, total government expenditure decreases when the government's choice shifts from a pure purchase subsidy to a pure infrastructure subsidy.

Due to the chicken-and-egg dilemma in the EV adoption process, the government must consider the balance between immediate EV adoption induced by the purchase subsidy and EV adoption induced indirectly by the infrastructure subsidy while selecting an appropriate subsidy. Fig. 3 indicates that under certain conditions, the government reduces the firm's burden via infrastructure subsidy rather than solely targeting immediate EV adoption via purchase subsidy. This underlying implication can be applied widely. Recently, evidence was found in China, where the central government advised local authorities to cease purchase subsidies, emphasizing the importance of financial support for charging infrastructure. These findings are valuable because governments often mistakenly prioritize these policies. For instance, many governments heavily subsidize EV purchases in the early stages when the charging network is immature. However, our findings imply that there are circumstances in which supporting EV purchases is more efficient in the long run.

For a more intuitive presentation, the government's optimal subsidy selection decision in four scenarios, and corresponding conditions for the optimality of each candidate subsidy scheme (subsidizing both sides, subsidizing the firm or subsidizing consumers) are shown in Table 6. Here, $\hat{\Omega}_i (i = 1\ldots,7)$ are shown in the Appendix.

Table 6. Preferred subsidy scheme in all scenarios. [6]

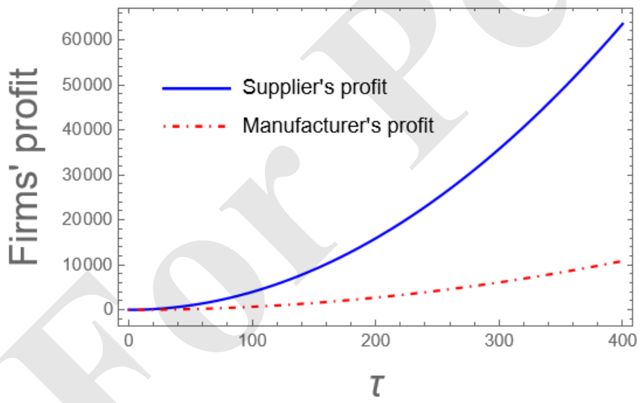
Scenario	BS	BM
condition	$\{f,\tau\} \in \hat{\Omega}_1$: subsidizing consumers Otherwise: providing no subsidy	$\{f,\tau\} \in \hat{\Omega}_2$: subsidizing both sides $\{f,\tau\} \in \hat{\Omega}_3$: subsidizing the manufacturer Otherwise: providing no subsidy

[5] Note that the value of the thresholds of τ, i.e., τ_1, τ_2, τ_4, τ_5, depend on the value of f. Thus, the values of thresholds of τ have different values. For example, in Fig. 3 (5), $\tau_4 = 0.8$, whereas in Fig. 3 (6), $\tau_4 = 0.43$. The value of the thresholds of f are listed as follows: $f_1 = 0.138$, $f_2 = 0.14$, $f_3 = 0.073$, $f_4 = 0.01$, $f_5 = 0.104$.

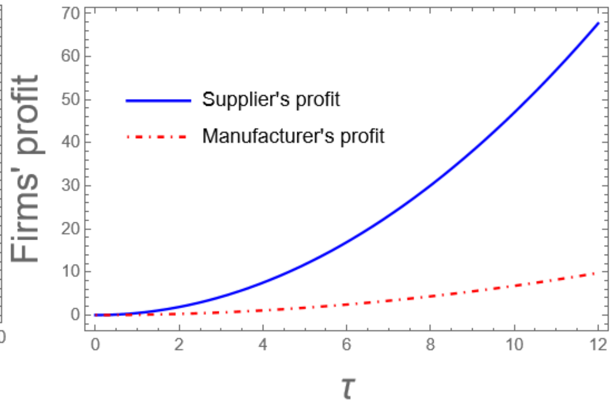
[6] Here, $\hat{\Omega}_1 - \hat{\Omega}_7$ are shown in the Appendix B.

Scenario	CS	CM
condition	$\{f,\tau\} \in \hat{\Omega}_4$: subsidizing the supplier $\{f,\tau\} \in \hat{\Omega}_5$: subsidizing consumers Otherwise: providing no subsidy	$\{f,\tau\} \in \hat{\Omega}_6$: subsidizing both sides $\{f,\tau\} \in \hat{\Omega}_7$: subsidizing the manufacture Otherwise: providing no subsidy

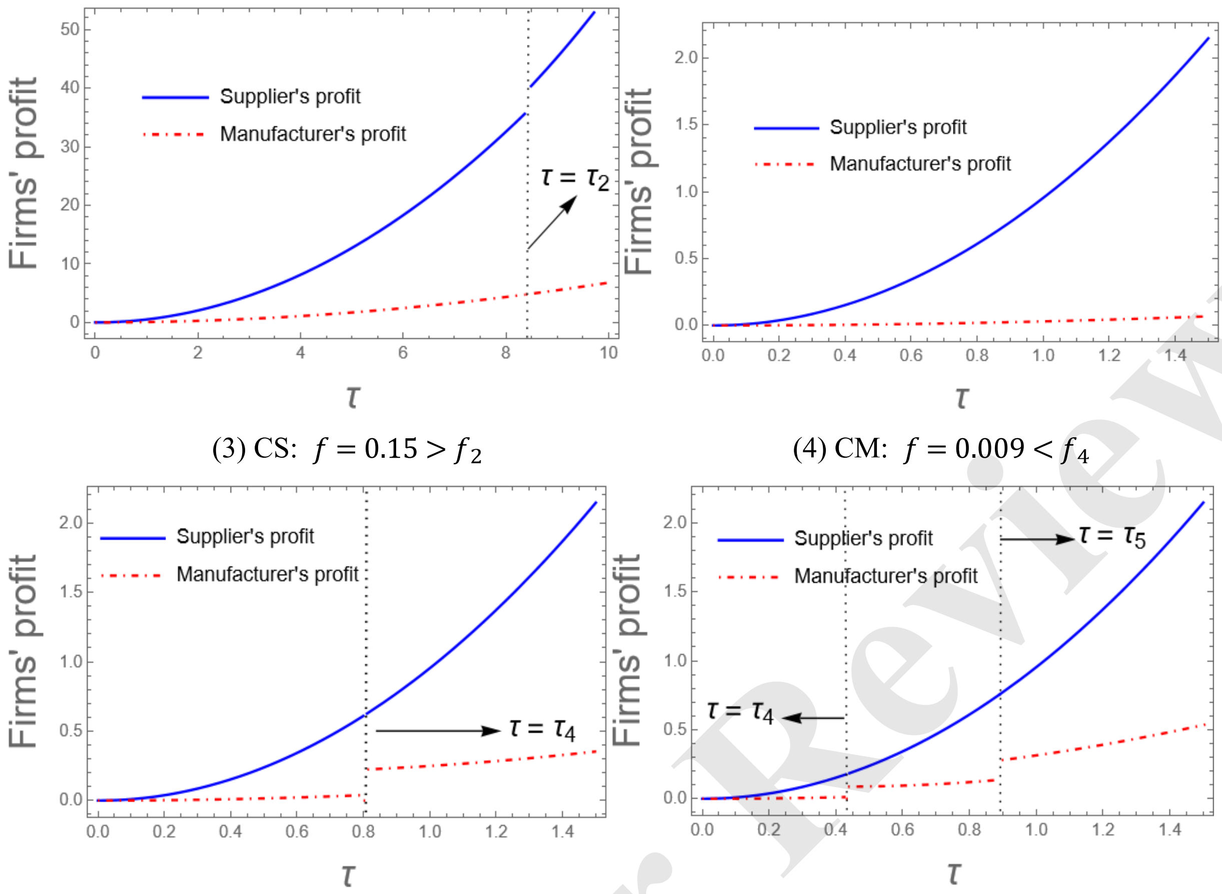
For intuitive presentation, we show how the firms' profit varies with different values of f and τ in Fig. 4. The parameter settings are the same as those in Fig. 3. Together with Fig. 3, Fig. 4 (3) reveals that under the CS scenario, when the cost coefficient f is sufficiently large, with the increase of τ, the government's optimal subsidy shifts from a pure purchase subsidy to a pure infrastructure subsidy, leading to an upside jump for the supplier's profit. Fig. 4 (5) shows that, under the CM scenario, when the cost coefficient is moderate, with the increase of τ, the government's optimal choice shifts from no subsidy to a pure infrastructure subsidy, causing an up-side jump in the manufacturer's profit. From Fig. 4 (6), when f is sufficiently large, with changes in the government's subsidy selection (i.e., from no subsidy to pure infrastructure subsidy, and finally to providing both subsidies), the manufacturer's profit encounters two upside jumps. Note that from Propositions 3 and 4, the thresholds of τ to characterize the government's subsidy selection vary with the value of f. Consequently, the x-axis range of τ in Fig. 4 changes based on the specific value of f. A similar approach involving the use of different axes can be observed in the study of Zhang et al. (2020).



(1) CS: $f = 0.12 < f_1$



(2) CS: $f_1 < f = 0.138 < f_2$



(3) CS: $f = 0.15 > f_2$ (4) CM: $f = 0.009 < f_4$

(5) CM: $f_4 < f = 0.05 < f_5$ (6) CM: $f = 0.12 > f_5$

Fig. 4. The firms' profits with respect to different f and τ

In Appendix G, we use examples of CATL, BYD, Ford and Tesla to verify the conclusions put forward through the analysis of four scenarios.

4.5. Economic performance analysis

The above analysis focuses on how the government designs an appropriate policy by selecting one of the three subsidy schemes. However, a policy that minimizes the total financial expenditure of an incentive policy may not perform well economically. Therefore, we examined the economic performance under different subsidy schemes by comparing the equilibrium profits of the total supply chain. Note that we derive the comparison results under the precondition of a positive subsidy. For ease of exposition, we define system vy, where $v \in \{BS,BM,CS,CM\}$ represents four different scenarios, and $y \in \{B,P,I\}$ denotes the three subsidy schemes, that is, providing Both subsidies, a pure Purchase subsidy, and a pure

Infrastructure subsidy. To illustrate, the BSP system represents a case in which the government uses a pure purchase subsidy under the BS scenario.

Proposition 5. *Comparison results of firms' profits under different subsidy schemes can be summarized as follows:*

(1) under the BS scenario, it can obtain $\pi_s^{BSP} < \pi_s^{BSI}$ *and* $\pi_m^{BSP} = \pi_m^{BSI}$.

(2) under the BM scenario, it can obtain $\pi_s^{BMP} = \pi_s^{BMI} = \pi_s^{BMB}$ *and* $\pi_m^{BMP} < \pi_m^{BMB} < \pi_m^{BMI}$.

(3) under the CS scenario, it can obtain $\pi_s^{CSP} < \pi_s^{CSI}$ *and* $\pi_m^{CSP} = \pi_m^{CSI}$.

(4) under the CM scenario, it can obtain $\pi_s^{CMP} = \pi_s^{CMI} = \pi_s^{CMB}$ *and* $\pi_m^{CMP} < \pi_m^{CMB} < \pi_m^{CMI}$.

Proposition 5 states that infrastructure subsidy schemes generate the highest profits in the supply chain. Moreover, Proposition 5 highlights the firms' preferences among these three subsidy schemes. First, under the scenarios where the supplier sets up infrastructure, the supplier is always better off under a pure infrastructure subsidy scheme. Second, when the manufacturer undertakes infrastructure construction, his profit is the highest (lowest) under the infrastructure (purchase) subsidy. Third, when the manufacturer (supplier) establishes the infrastructure, the supplier (manufacturer) is indifferent to government subsidy policies. To understand these results, we first identify three factors that influence firms' profits: total sales of EVs, price of EVs, and infrastructure investment cost. Purchase subsidies may lead to greater total sales than do infrastructure subsidies. However, the government's increased financial burden, caused by the firm's free riding, discourages the government from offering higher purchase subsidy, thereby limiting total sales and price for the firm. Therefore, a limited purchase subsidy cannot generate greater profits for firms. To actively boost sales, a firm must play a more aggressive role in infrastructure investment, which can lead to lower profits. Proposition 5 implies that infrastructure subsidies are always superior to the other two forms of subsidy in terms of economic performance.

4.6. Environmental performance and social welfare analysis

Following Niu et al. (2019) and Zhang et al. (2021), we adopt the index of environmental impact (EI) to measure the environmental performance. The index is quantity-related and can be formulated as follows:

$$EI = \gamma(q_m + q_s)$$

γ represents the positive environmental benefit that per unit of EV brings to society and $(q_m + q_s)$ is the total consumption of EVs in the market. Clearly, the environmental performance of different subsidy schemes remains the same in each scenario.

Similar to Singh et al. (1984), we denote the social welfare function as follows:

$$SW = \pi_s + \pi_m + CS - \pi_g$$

where CS and π_g represent the consumer surplus and the total expenditure, respectively. Following Liu et al. (2014), the calculation of consumer surplus is based on the utility of the representative consumer in Equation (1). Proposition 6 compares different subsidy schemes in terms of social welfare.

Proposition 6. The comparison results of social welfare under different subsidies for each scenario is shown in Table 7. Here, $\Gamma_1 - \Gamma_{13}$ are shown in the Appendix.

Combined with Proposition 1 and Proposition 2, Proposition 6 indicates that the most cost-effective subsidy policy may not perform well from the perspective of social optimum. Proposition 6 also shows that the cost coefficient and adoption target affect the efficiency of the policy in improving social welfare. These subsidies directly or indirectly enhance the demand of consumers for EVs, and therefore increase the consumer surplus and firms' profits. However, from the perspective of social optimum, the policy expenditure needs to be considered. Providing a combined policy (i.e., providing both subsidies) for EVs is to the benefit of increasing the consumer surplus and firms' profits but to the detriment of reducing the policy expenditure (two conflicting effects on the social welfare). As shown in Table 7, only if the adoption target exceeds a threshold, would providing both subsidies arise as the most cost-effective policy. Under such case, the two conflicting effects are well balanced, enabling the government to achieve the highest social welfare under a combined policy. Otherwise, the low adoption target may discourage the government from providing both subsidies, to avoid any further economic burdens on the society. In this sense, Table 7 provides some thresholds for f and τ that reshape the efficiency of the three subsidy policies from the social welfare perspective.

Overall, Proposition 6 states that, the most cost-effective policy yields higher social welfare when adoption target is sufficiently high. Otherwise, a cost-effective policy yields lower consumer surplus, leading to lower social welfare. This fact suggests that the government should consider the performance of different subsidies from the social perspective when selecting which practical subsidy to offer. The comparison of social welfare provides a policy implication as to which side the government should subsidize, which depends on the government's situation. To be more specific, if the government is financially constrained, then the policy cost-effectiveness should be recommended as a criterion for subsidy selection, even if such decision-making often fails to yield social optimum. If the government cares more about social welfare, then it is better to adopt a pure subsidy as it yields social optimum in most cases. Only when the adoption target is high, would a combined policy bring a win-win outcome from the perspectives of policy cost-effectiveness and social optimum.

Table 7. The comparison results of social welfare under different subsidies. [7]

Scenario	Cost coefficient	Adoption target	Comparison results
BS	$f \in \Omega$	$\tau \in \Omega$	$SW^{BSP} > SW^{BSI}$
BM	$f < \frac{5\beta^2}{16}$	$\tau \in \Gamma_1$	$SW^{BMP} > SW^{BMB}$ and $SW^{BMP} > SW^{BMI}$
		$\tau \in \Gamma_2$	$SW^{BMB} > SW^{BMP} > SW^{BMI}$
		$\tau \in \Gamma_3$	$SW^{BMB} > SW^{BMI} > SW^{BMP}$
		$\tau \in \Gamma_4$	$SW^{BMI} > SW^{BMB} > SW^{BMP}$
	$\frac{5\beta^2}{16} < f < \frac{13\beta^2}{16}$	$\tau \in \Gamma_5$	$SW^{BMI} > SW^{BMP} > SW^{BMB}$
		$\tau \in \Gamma_6$	$SW^{BMI} > SW^{BMB} > SW^{BMP}$
		$\tau \in \Gamma_7$	$SW^{BMB} > SW^{BMI} > SW^{BMP}$
		$\tau \in \Gamma_8$	$SW^{BMB} > SW^{BMP} > SW^{BMI}$
	$f > \frac{13\beta^2}{16}$	$\tau \in \Gamma_9$	$SW^{BMI} > SW^{BMP} > SW^{BMB}$
		$\tau \in \Gamma_{10}$	$SW^{BMP} > SW^{BMB}$ and $SW^{BMP} > SW^{BMI}$
		$\tau \in \Gamma_{11}$	$SW^{BMB} > SW^{BMP} > SW^{BMI}$
CS	$f \in \Omega$	$\tau \in \Omega$	$SW^{CSP} > SW^{CSI}$
CM	$f \in \Omega$	$\tau \in \Gamma_{12}$	$SW^{CMI} > SW^{CMB} > SW^{CMP}$
		$\tau \in \Gamma_{13}$	$SW^{CMB} > SW^{CMP}$ and $SW^{CMB} > SW^{CMI}$

5. Results analysis and discussion

This section compares the decision variables for different channel structures and modes of infrastructure construction.

7 The proof for the derivation is summarized in Appendix E.

5.1. The impact of different firms responsible for infrastructure construction

Proposition 7. *The comparison results of players' decisions can be summarized as follows:*

(1) Under a pure purchase subsidy, it can obtain

(1a) $t^{BSP} < t^{BMP}$ *and* $t^{CSP} < t^{CMP}$.

(1b) $x_1^{BSP} = x_1^{BMP}$ *and* $x_1^{CSP} = x_1^{CMP}$.

(1c) $x_2^{BSP} > x_2^{BMP}$ *and* $x_2^{CSP} > x_2^{CMP}$.

(2) Under a pure infrastructure subsidy, it can obtain

(2a) $K^{BSI} < K^{BMI}$ *and* $K^{CSI} < K^{CMI}$.

(2b) $x_1^{BSI} < x_1^{BMI}$ *and* $x_1^{CSI} < x_1^{CMI}$.

(2c) $x_2^{BSI} > x_2^{BMI}$ *and* $x_2^{CSI} > x_2^{CMI}$.

Proposition 7 shows that, for any given subsidy policy, the government always sets a higher subsidy when the manufacturer engages in infrastructure construction ((1a) and (2a)) than when the supplier undertakes the construction task. The rationale for this result is as follows. The manufacturer's return on infrastructure investment (i.e., incremental consumption from constructing infrastructure) is lower than that of the supplier, which decreases the manufacturer's incentive to build infrastructure. As a result, the quantity of infrastructure built by the manufacturer was lower in the former scenario than in the latter scenarios ((1c) and (2c)). To actively enhance the manufacturer's infrastructure investment incentives, the government provides a higher subsidy under scenarios ((1a) and (2a)).

Interestingly, the government's infrastructure investment is the same regardless of which firm builds the infrastructure ((1b)). The reasons for this result are as follows: Different levels of purchase subsidies affect the construction plan of the firm (i.e., x_2). However, this effect is canceled out in the derivative of the total expenditure regarding the construction plan of the government (i.e., $\frac{\partial Expenditure}{\partial x_1}$) since every term in the expenditure has the same x_2 term. Therefore, the government construction plan x_1 is independent of the purchase subsidy level. However, Proposition 7 (2b) indicates this is not the case under infrastructure subsidy. Under infrastructure subsidy, the firm's infrastructure investment incentive is directly boosted by the government's infrastructure subsidy. The reason is similar to the illustration presented before; that is, the supplier's investment incentive is higher than that of the manufacturer because of their relatively higher return from investment, which in turn weakens the need for the government to establish more supplementary infrastructure in order to boost the consumption of EVs.

To reveal the effects of competition on government optimal incentives, Proposition 8 analytically compares the optimal incentives under different supply chain structures. To focus on the non-trivial region, for this part, we only consider optimal government subsidy scheme and omit the suboptimal subsidy scheme. For example, under BS scenario, the optimal subsidy scheme is a pure purchase subsidy (see Fig. 2), whereas under CS scenario, the optimal subsidy scheme is a pure infrastructure subsidy.

Proposition 8. If the supplier invests in infrastructure, the incentive policies under different scenarios are ranked as $x_1^{BSP} < x_1^{CSI}$; and if the manufacturer invests in infrastructure, we have $t^{BMB} > t^{CMB}$, $x_1^{BMB} = x_1^{CMB}$, $K^{BMB} < K^{CMB}$.

From Proposition 8, if the supplier makes infrastructure investment, the competition between two firms incentivizes the government to focus solely on offering a pure infrastructure subsidy and exert more effort in charging infrastructure construction ($x_1^{BSP} < x_1^{CSI}$). However, if the manufacturer invests in infrastructure, the government's incentive for constructing charging infrastructure remains the same. The rationale behind this is as follows: competition between the two firms weakens the demand-pull effect of government's infrastructure investment on the demand of EVs. To further entice the firms' infrastructure investment in the presence of competition, the government has to exert more efforts to build infrastructure. In correspondence with Proposition 3, it further reveals that, if the manufacturer builds infrastructure, there exists complementary relationship between subsidy and competition ($s^{BMB} > s^{CMB}$). In this regard, competition brings additional benefits to the government because the adoption target can be achieved with less expenditure.

In the following proposition, we characterize the effects of different modes of infrastructure investment on government optimal incentive design.

Proposition 9. *The comparison results of the government's total expenditure can be summarized as follows:*

(1) under a pure purchase subsidy, it can obtain $\pi_g^{BSP} < \pi_g^{BMP}$ *and* $\pi_g^{CSP} < \pi_g^{CMP}$.

(2) under a pure infrastructure subsidy, it can obtain $\pi_g^{BSI} < \pi_g^{BMI}$ *and* $\pi_g^{CSI} < \pi_g^{CMI}$.

Proposition 9 (1) suggests that under a purchase subsidy, the government is always better off when the manufacturer sets up the infrastructure. Recalling from Proposition 7 (1), the government is compelled to provide higher purchase subsidies to surge the manufacturer's infrastructure incentive, leading to a higher financial burden under the BM/CM (manufacturer's infrastructure construction) scenario than under the BS/CS (supplier's infrastructure construction) scenario. From Proposition 9 (2), under infrastructure subsidy, the supplier's infrastructure construction benefits the government if the targeted adoption level is low. To illustrate this finding, we first identify the three factors that influence comparisons: infrastructure subsidy level K, government infrastructure investment x_1 and firm infrastructure investment x_2. The government's total expenditures increase for these three factors. Recalling Proposition 7 (2), for the scenarios in which the supplier is responsible for infrastructure construction, lower K and x_1 result in lessened financial pressure, whereas a higher x_2 leads to a heavier financial burden. Proposition 9 (2) demonstrates that under the former scenario, the mitigated financial pressure generated by lower K and x_1 dominates the heavier financial burden stemming from higher x_2 ($\pi_g^{CSI} < \pi_g^{CMI}$) because the firm's reduced investment incentive induces the government's increased willingness to provide higher infrastructure subsidies, which in turn imposes a heavy financial burden on the government.

Proposition 9 explains why many governments have embraced suppliers' building infrastructure and has rapidly developed into a significant mode. In recent years, charging stations built by leading battery suppliers such as CATL and EVE Energy account for 60% of the total.

5.2. The impact of competition

To illustrate this, we compare the government's total expenditures under different supply chain structures.

Proposition 10. *The comparison results of the government's total expenditure can be summarized as follows:*

(1) Under purchase subsidy, it can obtain $\pi_g^{CSP} < \pi_g^{BSP}$ *and* $\pi_g^{CMP} < \pi_g^{BMP}$.

(2) Under infrastructure subsidy, it can obtain $\pi_g^{CSI} < \pi_g^{BSI}$ *and* $\pi_g^{CMI} < \pi_g^{BMI}$.

(3) Under both subsidies, it can obtain $\pi_g^{CMB} < \pi_g^{BMB}$.

Proposition 10 implies that the government always benefits from competition between the supplier and manufacturer in the end market, as competition relieves the government's financial pressure. In other words, competition and government subsidies may have a complementary effect. The rationale can be explained as follows: the enhanced consumption of EVs induced by competition weakens the need for higher subsidies, contributing to a reduced financial burden. These results highlight the bright side of competition and support the current government policy that induces end-market competition by encouraging more firms to enter the EV industry.

In the following proposition, we characterize the effects of different modes of infrastructure investment on government optimal incentive design.

Proposition 11. (1) The optimal incentives under the base supply chain have the following order: $t^{BSP} < t^{BMB}$, $x_1^{BSP} = x_1^{BMB}$. (2) The optimal incentives under the co-opetitive supply chain have the following orders: if $f < f_7$ and $\tau < \tau_6$ or $f > f_7$ and $\tau > \tau_6$, $K^{CSI} > K^{CMB}$, otherwise, $K^{CSI} < K^{CMB}$; $x_1^{CSI} = x_1^{CMB}$ always holds.

The thresholds f_7 and τ_6 are summarized in the Appendix.

An interesting finding of Proposition 11 is that under the base supply chain, the supplier taking responsibility of making infrastructure investment would effectively reduce the need of a higher purchase subsidy. This can be attributed to the fact that when the manufacturer invests in infrastructure, his free-riding over subsidies weakens the effectiveness of government subsidy.

The β captures the demand-pull effect of infrastructure investment. To further reveal the effects of some influencing factors on the equilibrium outcomes, we conduct sensitivity analysis for three important factors, i.e., β, τ and δ. Their influences on government optimal incentives are characterized in Table 8. The threshold f_8 is provided in the Appendix.

Proposition 12. As β, τ and δ increase, the changes in government policy expenditure and firms' profits are summarized in Table 8.

Table 8-1. Influence of β.

	Expenditure	π_s	π_m
BS scenario	↓	↓	—
BM scenario	↓	—	↓
CS scenario	↓	↓	—

CM scenario	↓	—	↑

Table 8-2. Influence of τ.

	Expenditure	π_s	π_m
BS scenario	↑	↑	↑
BM scenario	↑	↑	↑
CS scenario	↓	↑	↑
CM scenario	↑	↑	↑

Table 8-3. Influence of δ.

	Expenditure	π_s	π_m
BS scenario	—	—	—
BM scenario	—	—	—
CS scenario	↓	↑	↓
CM scenario	↓	↑	If $f < f_8$↑ If $f > f_8$↓

Table 8-1 reveals that the increase in demand-pull effect of infrastructure investment reduces the government policy expenditure and improves the effectiveness of incentive policy. However, from Table 8-2, the higher adoption target means a larger financial expenditure in most cases. Counterintuitively, under CS scenario, expenditure decreases when the adoption target becomes challenging. The intuition can be explained as follows. Under CS scenario, with the increase of adoption target, because of the existence of complementary effect we highlighted in Proposition 3, the government would increase its infrastructure investment but reduce the subsidy, leading to reduced total policy expenditure. Table 8-3 further confirms the bright side of competition on the government expenditure. Due to the complementary relationship between competition and government subsidy, the government policy expenditure decreases along with increasing competition intensity between two firms. Furthermore, Table 8-2 indicates that the challenging adoption target often benefits the firms. This is because that the higher adoption target forces the government to increase infrastructure investment or subsidies, leading to higher profits of firms.

6. Effects of different cultures on EV mass adoption

The results of model analysis indicate that consumer adoption intention, EV business, and the status of charging infrastructure construction have a significant impact on government policy decision. It is widely believed that national culture has a significant influence on consumers' EV adoption intention and EV business models. In this section, we extensively explore the impacts of cultural factors on promotion of EVs and the government's policy by global comparisons and systematic literature review (SLR). The purpose of the SLR is to clarify the opinions towards the effects of cultures on the EV adoption and government public policy. Together with the model analysis, this SLR would provide more specific policy implications for governments across different cultures. To save space, we refer interested readers to Appendix F for the formal SLR. Here, we only present the conceptual framework (Fig. 5) and summarize the results. This SLR helps us obtain the following results.

First, this SLR analysis highlights the numerous factors that impact consumers' inclination towards purchasing electric vehicles (EVs). These influences are evident in various contexts, including countries such as India, Indonesia, Malaysia, Thailand, China, and Germany. Key drivers such as performance expectations, facilitating conditions, and hedonic motivations consistently play significant roles across different regions. Additionally, social influence, environmental concerns, and personal norms consistently contribute positively to the intention to adopt EVs. Furthermore, government's financial supports emerge as a critical moderator, particularly notable in India and China. Conversely, safety concerns outweigh purchase costs and perceived benefits in shaping adoption intentions, highlighting consumers' prioritization of safety features. Technological knowledge and firsthand experience with EVs are also substantial influencers, indicating that increasing consumer awareness and offering practical experience could boost adoption rates. Notably, personal values, altruism, and identification with environmental consciousness also exert influence, reflecting a growing acknowledgment of the importance of environmental awareness in driving EV adoption. In summary, this study underscores the multifaceted nature of EV adoption intentions, emphasizing the interplay between individual beliefs, social influences, technological factors, and environmental considerations. These insights are invaluable for policymakers and industry stakeholders striving to advance sustainable transportation solutions.

Second, this SLR analysis found that cultural nuances shape stakeholder participation, including government entities, industries, and environmental groups. The cultural inclinations of these stakeholders shape their perceptions of EV adoption, thereby impact policy formulation and implementation strategies. For example, in societies with deep-rooted environmental consciousness, there is greater emphasis on EV incentives aligned with sustainability goals.

Additionally, cultural influences inform the customization of business models for specific markets. Research by Nian et al. (2019), Wesseling et al. (2020), Liao et al. (2019), and de Rubens et al. (2020) highlight how cultural norms and preferences influence the design of EV business models. Variations in consumer behavior, purchasing power, and attitudes towards innovation necessitate culturally sensitive approaches to business model innovation within the EV industry.

For instance, in countries deeply rooted in environmental consciousness like Norway or Germany, government policies may prioritize incentives aligned with sustainability goals, such as subsidies for EV purchases or the development of public EV charging infrastructure. Conversely, in nations with a stronger emphasis on individualism, like the United States, incentive policies might focus on catering to individual consumer preferences and economic benefits, such as tax rebates or incentives for private charging stations. Moreover, in countries with a collective mindset such as Japan or South Korea, policies may prioritize societal benefits and communal responsibility, leading to initiatives like promoting shared EV ownership schemes or supporting the integration of EVs into public transportation fleets. In essence, the cultural landscape of a nation significantly influences the direction and emphasis of government incentive policies aimed at driving EV adoption, reflecting varying societal values and attitudes towards sustainability, innovation, and governance.

In China, where collective interests and centralized planning are emphasized, the government may design policies that not only encourage individual EV ownership but also prioritize large-scale infrastructure projects like expanding EV charging networks and supporting domestic EV manufacturers. This approach reflects the cultural focus on collective progress and government-led initiatives.

In contrast, in the United States, where individual freedom and entrepreneurial spirit are valued, government policies might center on stimulating private investment in EV infrastructure through tax incentives for companies that develop charging stations or subsidies for individuals who purchase EVs. This cultural backdrop encourages government policies that favor market-driven growth and innovation.

This SLR analysis shows how cultural factors shape government policies that support EV adoption by shaping consumer behavior, stakeholder decisions, and business model development. Recognizing and accommodating these cultural intricacies is essential for governments seeking to devise effective incentive policies to drive EV adoption across diverse socio-cultural landscapes. In summary, the SLR suggests that consumers' consideration of charging convenience, stakeholders' infrastructure investment and the EV business models have significant influence on government policy formulation. This is also confirmed by our model analysis. Furthermore, this SLR analysis shows how cultural factors guide government policies that support EV adoption by shaping consumer behavior, stakeholder decisions, and business model development. Combining the results obtained by model analysis and SLR, our study identifies policy implications to assist governments across various countries in selecting the most appropriate policy from different subsidies.

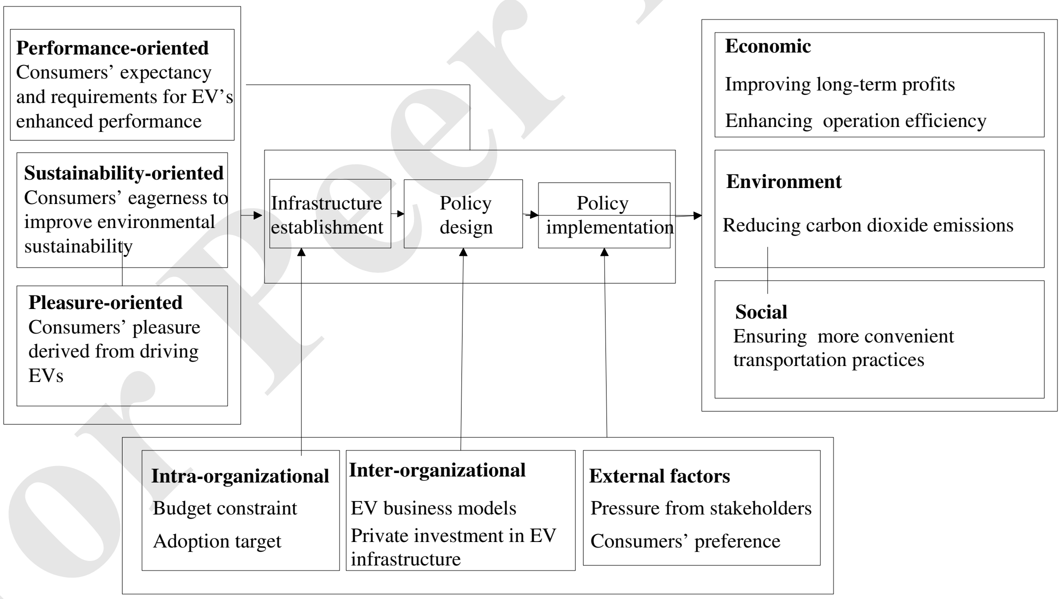


Fig. 5. Conceptual framework of EV adoption and policy decision[8]

7. Conclusion

7.1. Main findings

[8] Please refer to Appendix F for detailed explanation of the conceptual framework.

In this study, we investigate the government's policy decision for promoting mass adoption of EVs. The government selects the most cost-efficient among three candidate subsidy schemes, i.e., providing a pure purchase subsidy to consumers, providing a pure infrastructure subsidy to the firm or providing both. We consider four scenarios regarding the supply chain structure and the type of actors making EV charging infrastructure investment: (1) the battery suppliers invest in charging infrastructure in the baseline supply chain, (2) the manufacturers invest in charging infrastructure in the baseline supply chain, (3) the battery supplier invests in charging infrastructure in the co-opetitive supply chain, and (4) the manufacturer invests in charging infrastructure in the co-opetitive supply chain. We investigate the government's incentive policy optimization problem subject to satisfying a pre-defined EV adoption target. In each scenario, we characterize the government's policy decisions. Moreover, we compare the three subsidy schemes in terms of economic performance. The primary findings can be summarized as follows:

In the aforementioned four scenarios, any subsidy scheme can emerge as the optimal choice, and the rule of determining which side (firms versus consumers) to subsidize depends on the construction cost coefficient and pre-defined adoption level. Specifically, in the baseline supply chain, when the supplier engages in infrastructure construction, only subsidizing consumers guarantees superiority in balancing EV adoption and expenditures associated with the incentive policy. In contrast, under the BM scenario, subsidizing consumers fails to enable the government to use minimum expenditure and simultaneously achieve the targeted adoption level. Specifically, we find that subsidizing both is optimal if the construction cost and targeted adoption level are high. However, when either the construction cost or the target adoption is moderate, subsidizing firms proves to be the best option. In the CS scenario, providing pure infrastructure is preferred when construction costs and targeted adoption levels are high. When either of the two influencing factors is moderate, subsidizing only consumers is the least-cost subsidy scheme that enables the government to achieve its pre-defined adoption target. In this scenario, subsidizing both sides is not an effective solution. Under the CM scenario, the subsidy scheme that subsidizes both sides becomes the most effective when both influencing factors are high. If either of these is moderate, providing pure infrastructure is preferred.

7.2. Theoretical implications

Our work serves as the first step towards investigating government subsidy selection strategy considering the interaction of infrastructure investment and EVs adoption and contributes to the existing literature in the following ways.

First, this paper contributes to the literature on government policy decisions regarding EVs by examining the impacts of different infrastructure investment scenarios on government policy decision. We argue that a pure subsidy is optimal when the supplier invests in infrastructure, whereas a combination of both becomes optimal when the manufacturer makes infrastructure investment. Our study investigates which entity should be responsible for infrastructure investment to achieve a certain target of EVs adoption at the lowest cost, considering that multiple parties are capable of making such investments.

Second, we complement prior literature regarding relationship between supply chain structure and government policy decisions. An early study of Yoo et al. (2021) found that the government incentive policy is related to supply chain structure. In this work, we take a step further by revealing that the competition between the supplier and manufacturer in the end-market affects government subsidy selection strategy. Additionally, we also reveal that when the supply chain members have co-opetition relationship, there exists complementary effect between government subsidy and competition.

Third, while the previous works have considered maximization of social welfare for the government, our model studies a cost-effectiveness problem, in which the government aims to determine the most cost-efficient solution subject to a given adoption level of EVs. While existing studies have examined the chicken-and-egg dilemma in EV adoption, they tend to be either empirical studies using a particular historical case study, or structural equation models that are developed to analyze the diffusion process of a specific technology. However, these studies fail to capture the interactions of infrastructure investment and EV adoption. This research helps fill this research gap by incorporating both consumers' EV adoption and infrastructure investment, formulating a model across both the government investment stage and market stage.

7.3. Managerial and Policy implications

This research also offers practical implications for both entrepreneurs and policymakers when they formulate policies to promote EV adoption. Specifically, our study makes practical contributions in the following ways.

First, the findings aid firms to better understand the influences of supply chain structure and infrastructure investment on their profits in the presence of government subsidy. The results inform that the firms should consider the effects of infrastructure investment when deciding to take responsibility of constructing charging infrastructure. This is particularly significant if multiple parties are capable of taking responsibility for such investments. Furthermore, our analysis reveals that, for firms, a pure investment subsidy is favorable. In this regard, downstream automakers can induce the government to provide only infrastructure subsidy by taking responsibility for infrastructure investment. Under this investment scenario, the government is more likely to offer a pure investment subsidy.

Second, our research also provides guidance for governments when they select incentives to stimulate EVs diffusion. Although we confirm the effectiveness of subsidy programs in enticing EVs adoption, an appropriate subsidy, considering the supply chain structure and which entity makes infrastructure investment, is intensively suggested for policymakers. Importantly, since the government focuses on future benefits when formulating policies, we project our considerations into the future. The parameters in our study, the construction cost f and adoption target τ can be considered as two indicators to differentiate the future from the present. The construction cost f represents the current maturity level of the charging network in a country (if the charging network is mature, the construction cost becomes negligible accordingly). The second parameter represents the EVs adoption level in the future. Our findings show that the construction cost of charging infrastructure and the targeted adoption level play significant roles in government subsidy selection.

Third, our study conveys an important policy implication. That is, if the supplier in an EV supply chain invests in infrastructure, subsidizing the EV purchase is favorable for the government when the charging network is not mature (i.e., the construction cost of charging infrastructure is large) and the adoption target is high. However, subsidy scheme selection in practice often proceeds in the opposite direction than what our study suggests. Evidence can be found in China, where the government have ceased the subsidization of EV purchase and focused solely on subsidizing infrastructure investment. It is worth noting that the external environment varies across different countries. In this sense, our work facilitates the government in assessing the cost-efficiency of different subsidy schemes under present and future situations involving different conditions (e.g., current status of the charging infrastructure or the current adoption level of EVs). In some developed countries like the United Kingdom and the United States, where the charging network is mature (which is reflected by the relatively lower cost of building charging infrastructure, i.e., the efficiency of infrastructure investment is high), and the EV adoption target is not very challenging, switching to solely subsidizing infrastructure is more favorable. However, for most developing countries, where the charging network is not mature and the EV adoption target is high, subsidizing EV purchases should be more beneficial. Furthermore, this study also provides insights into how competition affects government policymaking. The finding reveals that, counterintuitively, competition brings additional benefits to the government, a fact that has been neglected in past research. In this sense, it may be in the government's interest to encourage upstream firms to enter the end market to relieve financial pressure when setting incentives to promote EV adoption.

7.4. Future work

There are several possible directions for future research in this field. First, we analyzed the government's policy optimization problem using a one-period model. This policy may differ in a multi-period setting. Therefore, the government must plan intertemporal policy optimization using a multi-period framework. Second, we focused on purchase and infrastructure subsidies to promote EV adoption. Investigating alternative subsidy formats to accelerate the penetration of EVs (e.g., the government may offer innovation subsidies to firms that decide to improve EV battery technology) would be an interesting topic. Finally, in addition to minimizing total expenditure, the government often tends to focus on maximizing social welfare in its policy formulation. The government's policy optimization problem under the social optimum objective is worth further discussion. Although this study investigates the government policy optimization problem based on the utility function of a representative consumer, it is a potential direction to discuss government policy decision by considering other reasonable forms of demand functions.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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Figure captions

Fig. 1. Timeline of events

Alter texts: Policy design decision at the first stage, infrastructure investment decision at the second stage and pricing decisions at the third stage.

Fig. 2. Optimal subsidy policy selection strategy under four scenarios

Alter texts: An intuitive presentation of decision regions for subsidy selection under different infrastructure investment scenarios.

Fig. 3. Total expenditure with respect to different f and τ

Alter texts: The comparison results of government's total policy expenditures under each infrastructure investment scenario, facilitating to derive the conditions for a dominating policy in the expenditure minimizing problem with a given target.

Fig. 4. The firms' profits with respect to different f and τ

Alter texts: The comparison results of firms' profits under each infrastructure investment scenario, facilitating the analysis of economic performance of the selected subsidy scheme.

Fig. 5. Conceptual framework of EV adoption and policy decision

Alter texts: The conceptual framework is proposed to facilitate the conceptual development of EV adoption and policy implementation.

Toward mass adoption of electric vehicles: policy optimization under different infrastructure investment scenarios

Response Document

TPRS-2023-IJPR-1400.R2

Editor in Chief letter

29-Feb-2024

Dear Prof. Jia

Manuscript ID TPRS-2023-IJPR-1400.R2 entitled "Toward Mass Adoption of Electric Vehicles: Policy Optimization under Different Infrastructure Investment Scenarios" by Chen, Ting; Xiaoxue, Zheng; Jia, Fu; Koh, S C Lenny that you revised and re-submitted to the International Journal of Production Research, has been reviewed. The comments of the reviewer(s) are included at the bottom of this letter. Please note that fuller review reports may also be attached to this email.

You will see that, although the reviewer(s) found some merit in the paper, it is required that substantial additional revisions be done before we can consider it further. Nevertheless, we do hope you will be able to undertake the additional work on the paper and look forward to receiving re-submission of a revised manuscript in due course.

Dr. Alexandre Dolgui
Editor-in-Chief, International Journal of Production Research
alexandre.dolgui@mines-nantes.fr

Reply to Editor in Chief, Professor Alexandre Dolgui

We would like to sincerely thank the Editor-in-Chief Professor Alexandre Dolgui for offering us the opportunity to revise and resubmit our paper titled “Toward Mass Adoption of Electric Vehicles: Policy Optimization under Different Infrastructure Investment Scenarios”.

We are grateful to the entire review team, including the three reviewers, who offered invaluable, constructive guidance for developing the paper. We are indebted to their comments, which have helped us to develop a significantly improved manuscript.

We have made all the changes suggested by you and three reviewers and are here with resubmitting the paper for further evaluation. The changes are heighted in the manuscript with blue font.

We acknowledge the mandatory elements for IJPR papers and assure that we have made necessary revision of our paper accordingly. First, the revised paper has an exhaustive analysis of related production research publications, with a particular focus on IJPR. Second, we have provided a comprehensive explanation of our novel decision aid model, ensuring its accessibility to a wide audience in production research. Third, comparisons with the state of the art have been incorporated in the Literature Review Section in the revised manuscript to highlight the novelty and significance of our approach. Fourth, our revised manuscript has included managerial insights specifically aimed for decision-makers in the industry. Finally, we have provided research perspectives to further enrich the contribution of our work.

Response to Reviewer #1

Comment 1:

The order of the game is unclear. For example, what is the sequence of the game when the battery supplier decides on the wholesale price and the manufacturer determines the retail price? What is the sequence of the game concerning the firm's infrastructure investment as a decision variable, in relation to the battery supplier's wholesale price and the manufacturer's retail price? Additionally, the equilibrium solution about x_2 *is lacking. For instance, Table 3 contains only* $w\backslash p_m\backslash p_s$. *Regarding the CS scenario and CM scenario, is the battery supplier's decision on the wholesale price a decision variable? Why are only* $x_2\backslash p_m$ *marked as decision variables in the utility function?*

Response: Thank you for the time and effort you have invested in reviewing our manuscript. Your insightful comments and constructive suggestions have been invaluable in enhancing the quality of this paper. In response to your concerns, we have taken the following steps to address the specific points you have raised:

First, we would like to clarify that the battery supplier's decision on the wholesale price is defined as a decision variable, as it is a strategic choice that the supplier makes to maximize its profit. We have revised the manuscript to clearly outline the game sequence. Specifically, we have explained the sequence of the game with respect to the firm's infrastructure investment decision in relation to the battery supplier's wholesale price and the manufacturer's retail price. These revisions can be found in Page 13 of the revised manuscript, as shown below:

"In the first stage, the government acts as the leader and announces its incentive policy (t,K,x_1), which includes the subsidy scheme and the level of infrastructure investment x_1. In the second stage, the battery supplier (in the BS scenario and CS scenario) or the manufacturer (in the BM scenario and CM scenario), observing the government's policy, sets the level of infrastructure investment x_2. In the third stage, for the BS and BM scenario, the battery supplier sets the wholesale price w and then, the manufacturer determines the retail price p_m. For the CS and CM scenario, after the battery supplier sets the wholesale price w, the manufacturer and supplier engage in price competition by simultaneously setting their prices p_m and p_s, respectively.

Based on the game sequence, the firm's infrastructure investment is made prior to the pricing decisions, as it is strategic choice that reshapes the firm's cost structure and market potential, thereby influencing the pricing strategy of firms."

Second, we would like to clarify that Table 3, as presented, is not intended to represent equilibrium solutions but rather the best response functions of the firms. These functions are derived from the first-order conditions of the firms' optimization problems given government incentive policy (t, K,x_1) and describe each firm's optimal decisions in response to government's incentive policy. The firm's infrastructure investment x_2 is indeed derived from the firm's profit maximization problem and is a function of the government incentive policy. In response to your comment, we have incorporated the firm's optimal response regarding x_2 into Table 3 (Please refer to Page 15 for details).

Table 3. The firms' best response under the four scenarios.[1]

	w	p_m	p_s	x_2
BS	$\frac{4af+4ft+4f\beta x_1}{8f-\beta^2}$	$\frac{2f(3a+3t)+3K\beta+6f\beta x_1}{8f-\beta^2}$	None	$\frac{4K+a\beta+\beta t+\beta^2 x_1}{8f-\beta^2}$
BM	$\frac{8f(a+t)+4K\beta+8f\beta x_1}{16f-\beta^2}$	$\frac{6(2f(a+t)+K\beta+2f\beta x_1)}{16f-\beta^2}$	None	$\frac{8K+a\beta+\beta t+\beta^2 x_1}{16f-\beta^2}$
CS	$\frac{\left\{\begin{matrix}(8+8\delta+\delta^3+\delta^4)\\(2f(a+t)+K\beta+2f\beta x_1\end{matrix}\right.}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right.}$	$\frac{\left\{\begin{matrix}(1+\delta)(12-\delta(4-(2-\delta)\delta)\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right.}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}(4-\delta)(1+\delta)(2+\delta)\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}2K(1+\delta)(8+\delta^2)+(a+t)\beta\\(12+\delta(4+\delta+\delta^2))\\+\beta^2(12+\delta(4+\delta+\delta^2))x_1\end{matrix}\right\}}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$
CM	$\frac{\left\{\begin{matrix}(1+\delta)(8+\delta^2)(8+\delta^3)\\(2f(a+t)+K\beta+2f\beta x_1\end{matrix}\right.}{\left\{\begin{matrix}4(f(1+\delta)(8+\delta^2)^2+\\\beta^2(1-\delta)(2+\delta^2)^2)\end{matrix}\right.}$	$\frac{\left\{\begin{matrix}(4-\delta)(1+\delta)(2+\delta)(8+\delta^2\\(2f(a+t)+K\beta+2f\beta x_1)\end{matrix}\right.}{\left\{\begin{matrix}4(f(1+\delta)(8+\delta^2)^2+\\\beta^2(1-\delta)(2+\delta^2)^2)\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}(1+\delta)(8+\delta^2)(12-\delta(4-\\(2-\delta)\delta))(2f(a+t)\\+K\beta+2f\beta x_1)\end{matrix}\right.}{\left\{\begin{matrix}4(f(1+\delta)(8+\delta^2)^2+\\\beta^2(1-\delta)(2+\delta^2)^2)\end{matrix}\right\}}$	$\frac{\left\{\begin{matrix}-2(a+t)\beta(-1+\delta)(2+\delta^2)\\K(1+\delta)(8+\delta^2)^2-\\2\beta^2(-1+\delta)(2+\delta^2)^2 x_1\end{matrix}\right.}{\left\{\begin{matrix}4f(1+\delta)(8+\delta^2)-\\\beta^2(12+\delta(4+\delta+\delta^2))\end{matrix}\right\}}$

Third, we would like to clarify why the wholesale price w is not incorporated into the consumer utility function, even though it is a decision variable. The rationale for not including the supplier's wholesale price in the utility function is as follows. 1) the wholesale price determined by the supplier is considered as a cost component for the manufacturer and is embedded in the retail price he sets for consumers. It is the retail price that directly affects consumer purchasing decisions, reflecting the final cost borne by the consumer. 2) the utility function is designed to reflect the consumer's willingness to pay for EVs, which is influenced by the retail price (i.e., the price at which consumers actually purchase EVs) and the convenience and accessibility of charging infrastructure, represented by the infrastructure investment x_2. By focusing on the retail price and infrastructure investment, the utility function captures the essential elements that affect consumer surplus (i.e., the additional value consumers derive from purchasing a product at a price lower than their willingness to pay). 3) omitting the wholesale price from the utility function is in line with assumptions found in the economic and marketing literature. The utility function of a representative consumer modeled in existing literature abstracts from the underlying transfer price

[1] Note: For BS scenario, we assume $f > \frac{\beta^2}{8}$ to ensure the firm's demand is positive without government's incentives, i.e., $s = 0, K = 0, x_1 = 0$. That is, we restrict the analysis for BS scenario to $f > \frac{\beta^2}{8}$. Following the same logic, we add assumptions in other scenarios. See Appendix A for details.

between supply chain members and focuses on the final prices faced by consumers (Feng et al., 2022; Liu et al., 2014; Zhang et al., 2020; Zhen et al., 2022). In the equilibrium of the market modeled in our study, the wholesale price, being a transfer price between the supplier and manufacturer, does not directly influence the consumer utility. As such, retail prices p_m and p_s already incorporate the impact of all upstream costs, including the wholesale price, without the need to explicitly include it in the utility function.

Comment 2:

In the paper, the authors construct a Stackelberg game model involving the government and two heterogeneous firms (battery suppliers and electric vehicle manufacturers). However, I raise valid concerns about the model, the Stackelberg game is a model used to describe a two-party game in which one party (the leader) makes decisions first, and the other party (the follower) responds after knowing the leader's decisions. It is evident that this study is designed with a three-party game decision-making process.

Response: Thank you for your attentive comments. In response to your concerns, we have conducted a thorough review of the theoretical foundations of our model and identified that it aligns more closely with a variant of the Stackelberg game capable of accommodating multiple followers.

First, we have clarified this variant of the Stackelberg game in the Introduction section, providing a detailed explanation of how the adjusted Stackelberg framework aligns with our study involving three parties. The revisions are summarized as follows (see Page 3 in the revised manuscript for details):

"To answer these questions, we have adopted a modified Stackelberg game framework to examine the unique dynamics of the three-party interaction. The government, as the policymaker, acts as the leader and sets the incentive policy, including subsidy schemes and infrastructure investment levels, with the objective of minimizing total policy expenditure while achieving a predefined EV adoption target. The two firms in the EV supply chain, i.e., the battery suppliers and the manufacturers, act as followers and respond to the government's policy by making decisions on infrastructure investment and pricing strategies to maximize their profits."

Second, we have selected and cited new and relevant references in the Literature section to discuss similar studies that have applied multi-follower Stackelberg game model to government policy optimization problem, closely related to our study. The revisions are summarized as follows (see Page 8-9 in the revised manuscript for details):

"Methodologically, the modified Stackelberg game framework in our study is consistent with the extended applications of Stackelberg game theory, which have been adapted to include more than two players in specific contexts. For example, existing literature on policy optimization have incorporated the government and multiple firms to analyze the interaction between government's policy decision and firms' pricing decisions (Chen et al., 2019; Yoo et al., 2021; Ma et al., 2019). This modified Stackelberg game model facilitates us to investigate the complicated interactions between the government, battery supplier and EV automaker in the promotion of EV adoption, which constitutes the primary focus of this study."

Comment 3:

The author mentions specific cases of CATL, Ford, BYD, and Tesla. Why not conduct a concrete case analysis for the theoretical results? So, how to prove the application of theoretical results in real practice?

Response: Thank you for thoughtful comment. In response to your comment, we use a case study to validate the findings from the model analysis, enhancing the understanding of government incentive design under the context of enhancing EV adoption.

To reduce the length of the manuscript to meet the submission requirement of the journal, the case study is summarized in Appendix G, which is for review and for online publication. Here, to avoid redundancy and ensure clarity, we have not copied and pasted large chunks here, please see Page 50-57 in the appendix for details. In the manuscript, we refer readers to Appendix for the case study.

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Zhen, X., Xu, S., Li, Y., Shi, D., 2022. When and how should a retailer use third-party platform channels? The Impact of spillover effects. European Journal of Operational Research, 301(2), 624-637.

Response to Reviewer #2

No more comments. The paper can be accepted for publication.

Response: We are grateful for your overall endorsement of our research and recognition that "the paper can be accepted for publication". We are extremely grateful for the constructive comments that you have put forward to help us improve the quality and presentation of the paper.

Response to Reviewer #3

The authors revised their paper in response to the reviewers' reports. However, not all of my previous comments were addressed satisfactorily.

Response: We would like to extend my heartfelt thanks for your continued engagement and the valuable feedback you have provided on our manuscript. We have identified the specific areas that require further clarification and have made the necessary revisions to the manuscript. We appreciate the opportunity to refine our work based on your expert insights and are eager to hear your thoughts on the updated manuscript.

Comment 1:

The formatting of table 2 is still odd. Many lines are out of place. Please check again.

Response: Thank you for your insightful feedback. According to your comment, we have revised Table 2 to ensure that all lines are correctly placed and that the information is displayed in a coherent and organized manner. The revised table 2 is shown below (Please refer to Page 12 for details).

Table 2. Notations and descriptions.

	Exogenous variable
a	basic demand
δ	the intensity of competition
β	the demand expansion effect of per unit of charging station
f	cost coefficient of charging infrastructure investment
τ	the preset target of EV adoption level
U_i	the utility of a representative consumer
	Endogenous variable
w	wholesale price
p_s	price of the supplier
p_m	price of the manufacturer
q_s	the sales quantity of the upstream supplier
q_m	the sales quantity of the downstream automaker
x_2	the firm's infrastructure investment
x_1	the government's infrastructure investment
t	the purchase subsidy for per unit of EV offered to consumers
K	the infrastructure subsidy for per charging station offered to the firm
	Equilibrium outcomes
π_g	the government policy expenditure
π_s	the profit of the upstream supplier

π_m	the profit of the downstream automaker
	Different scenarios
BS	the scenario where the supplier invests in infrastructure in the base supply chain
BM	the scenario where the automaker invests in infrastructure in the base supply chain
CS	the scenario where the supplier invests in infrastructure in the co-opetitive supply chain
CM	the scenario where the automaker invests in infrastructure in the co-opetitive supply chain

Comment 2:

Unfortunately, the question regarding the utility function was inadequately addressed. I raised concerns about why the utility for an individual user should increase with the number of EVs they own. I understand the argumentation for other consumer goods that are lower in price, but not for EVs. This seems unrealistic, as most people are unlikely to purchase more than one car. The authors did not address this aspect. I believe that assuming a classic demand function would be more appropriate.

Response: Thank you for your insightful feedback and constructive criticism. In response to your concern regarding the utility function, we have conducted a thorough examination of the utility function within the context of EV subsidies. The utility function of a representative consumer is grounded in both theoretical rationale and practical evidence from the EV industry.

First, according to your comments regarding the consumer utility function and the assumption that a consumer's utility increases with the number of EVs owned, we have provided the following explanations. (1) (Rationale for the assumption that a consumer's utility increases with the number of EVs owned). Upon reviewing the related literature, particularly the work of Huang et al. (2021) published in Omega, we found that using a utility function of a representative consumer to characterize the market demands of EVs for both firms from an aggregate demand perspective is not uncommon. The representative consumer in our study is consistent with theirs and facilitates to capture the overall market dynamics and consumer behavior trends in the context of EV adoption. This form of consumer utility function allows us to analyze the market from an aggregate demand perspective, reflecting the average consumer's willingness to pay and the derived satisfaction from EV ownership. As pointed by

Ingene et al. (2004), this form of utility function reduces the computational complexity and allows for more tractable models. Accordingly, the rationale for the increase in utility with the number of EVs owned can be explained as follows. The utility function of a representative consumer simplifies the complex dynamics of consumer behavior by aggregating individual preferences into a single, representative consumer. Therefore, the increase in utility with more EVs owned, as depicted in the utility function, does not imply that an individual consumer would purchase multiple cars. Instead, it captures the cumulative impact of all consumers adopting EVs on the utility. The marginal utility of owning an EV increases with the overall number of EVs in the market can be attributed to the fact that from an aggregate perspective (i.e., aggregating individual preferences into a single, representative consumer), as all consumers (i.e., the representative consumer) purchase more EVs, their satisfaction and benefits derived from the consumption of EVs typically rise. This is under the assumption that the marginal utility, or the additional satisfaction gained from consuming one more unit, is positive. As long as the marginal utility is greater than zero, the total utility will increase with each additional unit consumed, reflecting a higher level of overall satisfaction and well-being. Along this line, Huang et al. (2021) also captures this feature (i.e., the utility of the representative consumer increases with the number of EVs owned) in the context of EVs adoption by introducing this form of consumer utility (i.e., the utility function of a representative consumer). The representative consumer (i.e., representing all consumers in the market) maximizes this utility by determining optimal quantities of EVs purchased from each firm. Consequently, solving the problem of utility maximization yields the demand function for each firm. (2) (Merits of this consumer utility function in analyzing policy optimization problem). Besides the aforementioned merits, the representative consumer surplus facilitates the comprehensive market analysis and policy formulation. In the EV context, the representative consumer utility function offers several distinct advantages. It facilitates an analysis that accounts for how the aggregate market responds to various stimuli, such as price changes, infrastructure development, and policy incentives. This is crucial because consumer attitudes and adoption rates can vary widely due to factors like environmental awareness, economic status, and access to charging infrastructure. As highlighted by Huang et al. (2021), this form of consumer utility is particularly advantageous when the focus is on the market's collective response to policy incentives rather than individual purchasing behaviors. In their study, they employ this form of consumer utility to characterize the EV's market demand and investigate the effectiveness of Zero Emission Vehicle (ZEV) credit regulation in reducing emissions. They propose a modified regulation to mitigate the adverse effects of stringent policies on EV production and market share. Given this characteristic, this form of consumer utility is widely used in prior literature focusing on policy formulation (Huang et al., 2021; Yu et al., 2018). (3) (Merits of this consumer utility function in analyzing consumer surplus and social welfare). This utility function is instrumental in welfare analysis, as it helps in quantifying consumer surplus and evaluating the welfare implications of market policies. By substituting the equilibrium outcomes of the decision variables (i.e., p_s, p_m, x_1 and x_2) into the consumer utility function formulated in Eq. 1, we obtain the consumer surplus. This view of consumer surplus is the standard approach for researchers using this form of consumer utility function to analyze the consumer surplus and social welfare (Liu et al., 2014). According to the social welfare function formulated in our study, we also obtain the social welfare. Along this line, this consumer utility to effectively examine the impact of incentive policy on consumer surplus and social welfare. This is essential for developing policies that not only enhance profitability in the EV industry but also maximize social welfare. Based on this merit, we have evaluated the effectiveness of different subsidies from the perspective of social welfare in Proposition 6.

Second, in response to your suggestion regarding assuming a classic demand function, we have conducted a thorough analysis and would like to clarify why demand functions formulated in our study is more appropriate for addressing our optimization problem. To summarize, the reasons can be divided into two parts: (1) our demand functions, although not presented in the classic form, is equivalent to those classic demand functions that widely used in prior studies (Huang et al., 2021; Niu et al., 2019). To be more specific, our study can also adopt the following classic demand functions:

$p_s = a + t + \beta(x_1 + x_2) - q_s - \delta q_m$ and $p_m = a + t + \beta(x_1 + x_2) - q_m - \delta q_s$, where $0 < \delta < 1$ captures the competition intensity between the two products. In fact, our demand functions derived from maximization of the consumer utility is equivalent to the above classic demand function. By solving the equations (i.e., $p_s = a + t + \beta$ $(x_1 + x_2) - q_s - \delta q_m$ and $p_m = a + t + \beta(x_1 + x_2) - q_m - \delta q_s)$, we can determine the values of q_s and q_m that are consistent with the demand functions formulated in our study (Eq.2 and Eq.3 on Page 12 of the manuscript). This ensures that our demand functions are grounded in the classic demand functions that are widely used in the literature. (2) the classic demand functions mentioned above are widely used to examine quantity competition between firms. However, in most cases, the automakers in EV supply chain compete on price. The practical observation indicates that price competition is a more accurate reflection of the EV market dynamics. Pricing strategy serves as a prevalent competitive tool among EV firms, and thus, incorporating this aspect into our model provides a more realistic representation of the industrial practices. In fact, most existing literature on the EV supply chain adopts price competition (Shi et al., 2022; Brozynski et al., 2022; Yoo et al., 2021). Furthermore, previous literature focusing on optimization problem of government policies subject to specified constraints often incorporates price competition because price is a key strategic variable for firms (Yu et al., 2018; Brozynski et al., 2022). When facing regulatory constraints, such as adoption targets or fixed budgets, firms have to balance their pricing strategies within these constraints imposed by the government to maintain competitiveness. As such, price competition becomes a primary strategy as it directly influences market share and profitability. Firms aim to maximize their profits by setting prices that attract consumers while considering the constraints imposed by the government. In the strategic interactions among firms under government policies, price competition emerges as a crucial element, as it is a direct and immediate way for firms to respond to market conditions and regulatory pressures. To model price competition, the classic demand functions $p_s = a + t + \beta(x_1 + x_2) - q_s - \delta q_m$ and $p_m = a + t + \beta(x_1 + x_2) - q_m - \delta q_s$ are solved to determine the values of q_s and q_m. Therefore, we obtain our demand functions and assume that the demand functions take the following specification: $q_s = \frac{1}{1-\delta^2}((1-\delta)(a+\beta(x_1+x_2)) - (p_s - t) + \delta(p_m - t)$ $\quad q_m = \frac{1}{1-\delta^2}((1-\delta)$ $(a+\beta(x_1+x_2)) - (p_m - t) + \delta(p_s - t)$.

Based on these aforementioned merits, we maintain that the use of this consumer utility and the corresponding demand functions derived from it are more appropriate to explore the policy optimization problem targeting EVs adoption promotion in our study.

Furthermore, your suggestion to assume a classic demand function would be helpful for us to open up a new and promising research opportunity in the future work. In our future work, we plan to extend our analysis to include a classic demand function. We will explore the optimal policy formulation for the government under this traditional framework and conduct empirical studies to compare the effectiveness and robustness of the conclusions drawn from both the classic and the current demand functions. Therefore, we have added new content in Sub-section 7.4 (Future work) to discuss the government policy decision under other forms of demand functions in the future work, as shown below (see the last paragraph on Page 44 in the revised manuscript):

"Although this study investigates the government policy optimization problem based on the utility function of a representative consumer, it is a potential direction to discuss government policy decision by considering other reasonable forms of demand functions."

References

Huang, W., Zhu, H., 2021. Performance evaluation and improvement for ZEV credit regulation in a competitive environment. Production and Operations Management 23 (11), 1845-1858.

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Niu, B., Xu, J., Lee, C., 2019. Order timing and tax planning when selling to a rival in a low-tax emerging market. Transportation Research Part E 123, 165-179.

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Yu, JJ., Tang, CS., 2018. Improving consumer welfare and manufacturer profit via government subsidy programs: subsidizing consumers or manufacturers? Manufacturing & Service Operations Management 20 (4), 752-766.

As defined in this paper, system vy, where $v \in \{BS,BM,CS,CM\}$ represents the business model, i.e., the four scenarios, and $y \in \{B,P,I\}$ denotes the three subsidy schemes, is used to denote the corresponding case where the government employs subsidy instrument y under v scenario. For example, **case BSP** represents the case where the government provides a pure purchase subsidy in BS scenario.

Appendix A. Derivation of equilibrium outcomes of each case.

BS scenario:

Recall that, as stated in Footnote 1 in subsection 4.1, to avoid the negative demand, we restrict our attention to $f > \frac{\beta^2}{8}$.

Case BSP: In this case, the government provides a pure purchase subsidy in BS scenario. To derive the government subsidy decision, we solve this two-stage game by backward induction method. Let us begin with Stage 2 of the game.

Firms' decisions (w,p_m,x_2): According to Eq. (6), we have $\frac{\partial^2 \pi_m^{BS}}{\partial {p_m}^2} < 0$. That is, π_m^{BS} is strictly concave in the price p_m. Thus, we can calculate the firm's best-response function p_m via the first-order condition $\frac{\partial \pi_m^{BS}}{\partial p_m} = 0$, that is, $p_m^*(w,t,x_1,x_2) = \frac{1}{2}(a + t + w + \beta x_1 + \beta x_2)$. Substituting this response function into the profit function π_s^{BS}, we have $\pi_s^{BS} = Kx_2 - fx_2^2 + \frac{1}{2}w(a + t - w + \beta(x_1 + x_2))$. Obviously, π_m^{BS} is strictly concave in the wholesale price w (i.e., $\frac{\partial^2 \pi_s^{BS}}{\partial w^2} < 0$). Solving the first-order condition, we have $w^*(t,x_1,x_2) = \frac{1}{2}(a + t + \beta x_1 + \beta x_2)$. It is worth noting that under the case BSP where the government only provides a pure purchase subsidy t without providing infrastructure K, the supplier's optimal response w is independent of the infrastructure subsidy K. For the ease of analysis and presentation, we sometimes solve same player's simultaneous decisions sequentially, e.g., solving w first than x_2 (two joint decisions). We do this to take advantage of some structural properties that facilitate the analysis but note that the final solutions are the same regardless of the order of how they are solved as long as it is the same decision maker. Substituting $w^*(t,x_1,x_2)$ into π_s^{BS}, we have $\pi_s^{BS} = Kx_2 - kx_2^2 + \frac{1}{8}(a + t + \beta(x_1 + x_2))^2$. $\frac{\partial^2 \pi_m^{BS}}{\partial {x_2}^2} = -2f + \frac{\beta^2}{4}$. Recall the condition $f > \frac{\beta^2}{8}$ we defined in subsection 4.1, we can derive that $\frac{\partial^2 \pi_m^{BS}}{\partial {x_2}^2} < 0$. Thus, π_s^{BS} is strictly concave in x_2. Using the first-order condition and solving $\frac{\partial \pi_s^{BS}}{\partial x_2} = 0$, we have $x_2 = \frac{4K+a\beta+t\beta+\beta^2 x_1}{8f-\beta^2}$. Consequently, $w^*(s,x_1) = \frac{4af+4ft+4f\beta x_1}{8f-\beta^2}$ and $p_m^*(t,x_1) = \frac{2f(3a+3t)+6f\beta x_1}{8f-\beta^2}$.

Government's decision (x_1,t): Substituting $w^*(t,x_1)$, ${x_2}^*(t,x_1)$ and $p_m^*(t,x_1)$ into π_g^{BSP} and taking the first-order derivative of $\pi_g^{BSP}(t,x_1)$, we can derive that $\frac{\partial \pi_g^{BSP}}{\partial x_1} = \frac{2ft\beta}{8f-\beta^2} + 2fx_1$ and $\frac{\partial \pi_g^{BSP}}{\partial t} = \frac{2f(a+2t+\beta x_1)}{8f-\beta^2}$. Under the condition $f > \frac{\beta^2}{8}$, we have $\frac{\partial \pi_g^{BSP}}{\partial x_1} > 0$ and $\frac{\partial \pi_g^{BSP}}{\partial t} > 0$ which indicate that π_g^{BSP} always increases in x_1 and t. As the total sales of EVs q_m increases in x_1 and t. Thus, it is obvious that the constraint $q_m^* \geq \tau$ in the government's decision problem will bind at the optimum $(x_1^*,\ t^*)$, i.e., $q_m^*(x_1^*,\ t^*) = \tau$. Setting $q_m^*(x_1^*,\ t^*) = \tau$, we have $x_1^* = -\frac{2af+2ft-8f\tau+\beta^2\tau}{2f\beta}$, which is a function of t so that we denote as $x_1^*(t)$. By substituting $x_1^*(t)$ into π_g^{BSP}, the government's decision problem becomes:

$$\begin{cases} \min\limits_{(t,x_1)} \pi_g(t) = \frac{4a^2f^2+4f^2(t-4\tau)^2+8f\beta^2(t-2\tau)\tau+\beta^4\tau^2+4af\left(2f(t-4\tau)+\beta^2\tau\right)}{4f\beta^2} \\ \text{Subject to:} \\ x_1^*(t) = -\frac{2af+2ft-8f\tau+\beta^2\tau}{2f\beta} \geq 0, \\ t \geq 0. \end{cases} \quad (A.1)$$

Taking the first-order and second-order derivative of $\pi_g(t,x_1)$ with respect to t, we have $\frac{\partial \pi_g(t,x_1)}{\partial t} = \frac{8af^2+8f^2(t-4\tau)+8f\beta^2\tau}{4f\beta^2}$ and $\frac{\partial^2 6K\beta^2}{\partial t^2} = \frac{2f}{\beta^2} > 0$. Thus, $\pi_g(t,x_1)$ is convex and we obtain an interior solution $t^* = \frac{-af+4f\tau-\beta^2\tau}{f}$. $t^* = \frac{-af+4f\tau-\beta^2\tau}{f}$ is optimal when it is feasible. Checking the constraint $x_1^*(t) = -\frac{2af+2ft-8f\tau+\beta^2\tau}{2f\beta} \geq 0$ and $t \geq 0$, we derive the conditions under which the optimal is the interior solution. Otherwise, we obtain the optimal solution at the boundary $(x_1^*, t^*) = \left(\frac{-2af+(8f-\beta^2)\tau}{2f\beta}, 0\right)$. Through substituting the optimal incentive solutions into the profit function and response function, we can obtain other optimal solutions:

(1) if $f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$, then

$$x_2^* = \frac{\beta\tau}{2f},\ \pi_s^{BSP} = \frac{1}{4}\left(8 - \frac{\beta^2}{f}\right)\tau^2,\ \pi_m^{BSP} = \frac{(8f\tau - \beta^2\tau)^2}{(8f - \beta^2)^2},$$
$$\pi_g^{BSP} = \frac{(2af + (-8f + \beta^2)\tau)^2}{4f\beta^2}.$$

(2) if $f < \frac{\beta^2}{4}$ or $f > \frac{\beta^2}{4}$ and $\tau < \frac{af}{4f - \beta^2}$, then

$$x_2^* = \frac{\beta\tau}{2f},\ \pi_s^{BSP} = \frac{1}{4}\left(8 - \frac{\beta^2}{f}\right)\tau^2,\ \pi_m^{BSP} = \tau^2,$$
$$\pi_g^{BSP} = \frac{1}{4}\tau\left(-4a + \left(16 - \frac{3\beta^2}{f}\right)\tau\right).$$

Case BSI: In this case, the government provides a pure infrastructure subsidy in BS scenario. The solving process under this case is similar with that of case BSP. Thus, we will not belabor it.

Firms' decisions (w,p_m,x_2): First, in stage 2 of the game, the solving process is similar with that in case BSP. Solving the FOC $\frac{\partial \pi_s^{BSI}}{\partial w} = 0$ and $\frac{\partial \pi_s^{BSI}}{\partial x_2} = 0$, we have $w^*(K,x_1) = \frac{4af + 2K\beta + 4f\beta x_1}{8f - \beta^2}$, ${x_2}^*(K,x_1) = \frac{4K + a\beta + \beta^2 x_1}{8f - \beta^2}$ and $p_m^*(K,x_1) = \frac{6af + 3K\beta + 6f\beta x_1}{8f - \beta^2}$.

Government's decision (K,x_1): Substituting $w^*(K,x_1)$, ${x_2}^*(K,x_1)$ and $p_m^*(K, x_1)$ into π_g^{BSI} and taking the first-order derivative of $\pi_g^{BSI}(K,x_1)$, we can derive that $\frac{\partial \pi_g^{BSI}}{\partial x_1} = \frac{K\beta^2}{8f - \beta^2} + 2fx_1$ and $\frac{\partial \pi_g^{BSI}}{\partial s} = \frac{8K + a\beta + \beta^2 x_1}{8f - \beta^2}$. Under the condition $f > \frac{\beta^2}{8}$, we have $\frac{\partial \pi_g^{BSI}}{\partial x_1} > 0$ and $\frac{\partial \pi_g^{BSI}}{\partial I} > 0$ which indicate that π_g^{BSI} increase in x_1 and K. As the total sales of EVs q_m increases in x_1 and K. Thus, it is obvious that the constraint $q_m^* \geq \tau$ in the government's decision problem will bind at the optimum $(x_1^*,\ K^*)$, i.e., $q_m^*(x_1^*, K^*) = \tau$. Setting $q_m^*(x_1^*,\ K^*) = \tau$, we have $x_1^* = \frac{-2af - K\beta + 8f\tau - \beta^2\tau}{2f\beta}$, which is a function of K so that we denote as $x_1^*(K)$. By substituting $x_1^*(K)$ into π_g^{BSI}, the government's decision problem becomes:

$$\begin{cases} \min\limits_{(K,x_1)} \pi_g(t) = \frac{4a^2f^2 + 3K^2\beta^2 + 4K\beta(-4f + \beta^2)\tau + (-8f + \beta^2)^2\tau^2 + 4af(-8f\tau + \beta(K + \beta\tau))}{4f\beta^2} \\ \text{Subject to:} \\ x_1^*(K) = \frac{-2af - K\beta + 8f\tau - \beta^2\tau}{2f\beta} \geq 0, \\ K \geq 0. \end{cases} \tag{A.2}$$

Taking the first-order and second-order derivative of $\pi_g(K,x_1)$ with respect to K, we have $\frac{\partial \pi_g(K,x_1)}{\partial K} = \frac{4af\beta + 6K\beta^2 + 4\beta(-4f + \beta^2)\tau}{4f\beta^2}$ and $\frac{\partial^2 \pi_g(K,x_1)}{\partial K^2} = \frac{3}{2f} > 0$. Thus, $\pi_g(K,x_1)$ is convex and we obtain an interior solution $K^* = \frac{2(4f\tau - af - \beta^2\tau)}{3\beta}$. $x_1{}^* = \frac{16f\tau - 4af - \beta^2\tau}{6f\beta}$ is optimal when it is feasible. Checking the constraint $x_1^*(K) = \frac{-2af - K\beta + 8f\tau - \beta^2\tau}{2f\beta} \geq 0$ and $K \geq 0$, we derive the conditions under which the optimal is the interior solution. Otherwise, we obtain the optimal solution at the boundary $(x_1^*, K^*) = \left(\frac{(8f-\beta^2)\tau - 2af}{2f\beta}, 0\right)$.

Through substituting the optimal incentive policy into the profit function and response function, we can obtain other optimal solutions:

(1) if $f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$, then

$$x_2^* = -\frac{16af^2 - 2af\beta^2 - 64f^2\tau + \beta^4\tau}{48f^2\beta - 6f\beta^3},$$

$$\pi_s^{BSP} = \frac{4a^2f^2 + 8af(-4f + \beta^2)\tau + (64f^2 + 40f\beta^2 - 5\beta^4)\tau^2}{36f\beta^2},$$

$$\pi_m^{BSP} = \tau^2,\ \pi_g^{BSP} = \frac{8a^2f^2 + 4af(-16f + \beta^2)\tau + (128f^2 - 16f\beta^2 - \beta^4)\tau^2}{12f\beta^2}.$$

(2) if $f < \frac{\beta^2}{4}$ or $f > \frac{\beta^2}{4}$ and $\tau < \frac{af}{4f-\beta^2}$, then

$$x_2^* = \frac{\beta\tau}{2f},\ \pi_s^{BSP} = \frac{1}{4}(8 - \frac{\beta^2}{f})\tau^2,\ \pi_m^{BSP} = \tau^2,$$

$$\pi_g^{BSP} = \frac{(2af + (-8f + \beta^2)\tau)^2}{4f\beta^2}.$$

Case BSB: Providing both subsidies in BS scenario

Firms' decisions (w,p_m,x_2): First, in stage 2 of the game, the solving process is similar with that in case BSP. Solving the FOC $\frac{\partial \pi_s^{BSB}}{\partial w} = 0$ and $\frac{\partial \pi_s^{BSB}}{\partial x_2} = 0$, we have $w^*(t,K,x_1) = \frac{4af + 4ft + 2K\beta + 4f\beta x_1}{8f - \beta^2}$, $x_2{}^*(t,K,x_1) = \frac{4K + a\beta + t\beta + \beta^2 x_1}{8f - \beta^2}$ and $p_m^*(t,K,x_1) = \frac{2f(3a+3t) + 3K\beta + 6f\beta x_1}{8f - \beta^2}$.

Government's decision (t,K,x_1): In scenario BS, if the government provides both subsidies (i.e., the case BSB), the government's decision problem is formulated as follows:

$$\begin{cases} \min\limits_{(t,K,x_1)} \pi_g^{BSB}(t,K,x_1) = \min\limits_{(K,s,x_1)} (f x_1^{\ 2} + t q_m + K x_2) \\ \text{Subject to:} \\ q_m \geq \tau, \\ q_m \in \max\limits_{q_m} \pi_m^{BSB}, \\ x_2 \in \max\limits_{x_2} \pi_s^{BSB}, \\ K,t \geq 0. \end{cases} \quad (A.3)$$

Substituting $w^*(t,K,x_1)$, ${x_2}^*(t,K,x_1)$ and $p_m^*(t,K,x_1)$ into π_g^{BSB} , we have $\pi_g^{BSB} = f{x_1}^2 + t(\frac{2f(a+t)+K\beta+2f\beta x_1}{8f-\beta^2}) + K(-\frac{-4K-a\beta-t\beta-\beta^2 x_1}{8f-\beta^2})$. And the decision problem (A.3) can be reformulated as

$$\begin{cases} \min_{(K,s,x_1)} \pi_g^{BSB}(t,K,x_1) = \min_{(K,s,x_1)} \{f{x_1}^2 + t\left(\frac{2f(a+t)+K\beta+2f\beta x_1}{8f-\beta^2}\right) + K\left(-\frac{-4K-a\beta-t\beta-\beta^2 x_1}{8f-\beta^2}\right)\} \\ \text{Subject to:} \\ q_m \geq \tau, \\ q_m \in \max_{q_m} \pi_m^{BSB}, \\ x_2 \in \max_{x_2} \pi_s^{BSB}, \\ K,t \geq 0. \end{cases} \quad \text{(A.4)}$$

Taking the first-order derivative of $\pi_g^{BSB}(t,K,x_1)$ with respect to t, K and x_1, we obtain

$$\frac{\partial \pi_g^{BSB}}{\partial t} = \frac{2(af+2ft+K\beta+f\beta x_1)}{8f-\beta^2} > 0; \ \frac{\partial \pi_g^{BSB}}{\partial K} = \frac{8K+a\beta+2t\beta+\beta^2 x_1}{8f-\beta^2} > 0;$$

$$\frac{\partial \pi_g^{BSB}}{\partial x_1} = \frac{\beta(2ft+K\beta)}{8f-\beta^2} + 2fx_1 > 0$$

Taking the first-order derivative of q_m with respect to t, K and x_1, we obtain

$$\frac{\partial q_m}{\partial t} = \frac{2f}{8f-\beta^2} > 0; \ \frac{\partial q_m}{\partial K} = \frac{\beta}{8f-\beta^2} > 0; \ \frac{\partial q_m}{\partial x_1} = \frac{2f\beta}{8f-\beta^2} > 0.$$

According to these results, π_g^{BSB} and q_m are increasing in t, K and x_1. As both the objective and constraint functions (i.e., π_g and $q_m \geq \tau$) increase in t, K and x_1, the constraint in the decision problem (7) is binding at the optimal solution. That is, it is optimal to set $q_m^*(t,K,x_1) = \tau$ to minimize π_g. Setting ${q_m}^*(t, K, x_1) = \tau$, we have $t^*(K,x_1) = \frac{-2af-K\beta+8f\tau-\beta^2\tau-2f\beta x_1}{2f}$. That is, the equality constraint $q_m^*(t,K,x_1) = \tau$ is equivalent to $t^*(K,x_1) = \frac{-2af-K\beta+8f\tau-\beta^2\tau-2f\beta x_1}{2f}$. Substituting $t^*(K,x_1)$ into the objective function $\pi_g(t,K,x_1)$, we have $\pi_g(K,x_1) = \frac{K^2+\tau(-2af+8f\tau-\beta^2\tau)+2fx_1(-\beta\tau+fx_1)}{2f}$. Ensuring $t^*(K,x_1) \geq 0$, the government decision problem (7) can be reformulated as follows:

$$\begin{cases} \min_{(K,x_1)} \pi_g(K,x_1) = \dfrac{K^2 + \tau\big(-2af + 8f\tau - \beta^2\tau\big) + 2fx_1(-\beta\tau + fx_1)}{2f} \\ \text{Subject to:} \\ q_m \geq \tau, \\ q_m \in \max_{q_m} \pi_m^{BSB}, \\ x_2 \in \max_{x_2} \pi_s^{BSB}, \\ K,t \geq 0. \end{cases} \tag{A.5}$$

Based on $\pi_g(K,x_1) = \frac{K^2+\tau(-2af+8f\tau-\beta^2\tau)+2fx_1(-\beta\tau+fx_1)}{2f}$, we check the first-order derivative of $\pi_g(K,x_1)$ with respect to K. Obviously, it can be obtained that $\frac{\partial\pi_g^{BSB}}{\partial K} = \frac{K}{f} > 0$. $\boldsymbol{\frac{\partial\pi_g^{BSB}}{\partial K} > 0}$ **suggests that the objective function $\boldsymbol{\pi_g(K,x_1)}$ in problem (8) increase in $\boldsymbol{K}$. To minimize the policy expenditure $\boldsymbol{\pi_g(K,x_1)}$, it is optimal for the government to set the infrastructure subsidy $\boldsymbol{K=0}$. That is, the government would never provide infrastructure subsidy.** Resultantly, case BSB (the government provides both infrastructure subsidy and purchase subsidy) degenerates into case BSP (the government provides a pure purchase subsidy).

The solutions of other three cases in BM scenario (**case BMP, BMI, BMB**) can be obtained by following the same backward induction solution procedure and we will not belabor it.

BM scenario:

Recall that, as stated in Footnote 1 in subsection 4.1, to avoid negative demand, we restrict our attention to $f > \frac{\beta^2}{16}$.

Case BMP: the equilibrium outcomes are

(1) If $f > \frac{3\beta^2}{16}$ and $\tau > \frac{4af}{16f-3\beta^2}$:

$$t = -a + \left(4 - \frac{3\beta^2}{4f}\right)\tau,\ x_1^* = \frac{\beta\tau}{2f},$$

$$x_2^* = \frac{\beta\tau}{4f},$$

$$\pi_s^{CSP} = 2\tau^2,$$

$$\pi_m^{CSP} = (1 - \frac{\beta^2}{16f})\tau^2,$$

$$\pi_g^{CSP} = \frac{1}{2}\tau(-2a + (8 - \frac{\beta^2}{f})\tau).$$

(2) If $f < \frac{3\beta^2}{16}$ or $f > \frac{3\beta^2}{16}$ and $\tau < \frac{4af}{16f-3\beta^2}$:

$$t = 0,\ x_1^* = -\frac{a}{\beta} + \frac{4\tau}{\beta} - \frac{\beta\tau}{4f},$$

$$x_2^* = \frac{\beta\tau}{4f},$$

$$\pi_s^{CSP} = 2\tau^2,$$

$$\pi_m^{CSP} = (1 - \frac{\beta^2}{16f})\tau^2,$$

$$\pi_g^{CSP} = \frac{(4af - (16f - \beta^2)\tau)^2}{16f\beta^2}.$$

Case BMI: the equilibrium outcomes are

(1) If $f > \frac{\beta^2}{8}$ and $\tau > \frac{2af}{8f-\beta^2}$:

$$K = \frac{-2af + (8f - \beta^2)\tau}{3\beta}, x_1^* = \frac{-8af + (32f - \beta^2)\tau}{12f\beta}$$

$$x_2^* = \frac{-4af + (16f + \beta^2)\tau}{12f\beta},$$

$$\pi_s^{CSP} = 2\tau^2,$$

$$\pi_m^{CSP} = \frac{16a^2f^2 + 16af(-8f + \beta^2)\tau + (256f^2 + 80f\beta^2 - 5\beta^4)\tau^2}{144f\beta^2},$$

$$\pi_g^{CSP} = \frac{32a^2f^2 + 8af(-32f + \beta^2)\tau + (512f^2 - 32f\beta^2 - \beta^4)\tau^2}{48f\beta^2}.$$

(2) If $f < \frac{\beta^2}{8}$ or $f > \frac{\beta^2}{8}$ and $\tau < \frac{2af}{8f-\beta^2}$:

$$K = 0, x_1^* = -\frac{a}{\beta} + \frac{4\tau}{\beta} - \frac{\beta\tau}{4f}$$

$$x_2^* = \frac{\beta\tau}{4f}$$

$$\pi_s^{CSP} = 2\tau^2,$$

$$\pi_m^{CSP} = (1 - \frac{\beta^2}{16f})\tau^2,$$

$$\pi_g^{CSP} = \frac{(4af - (16f - \beta^2)\tau)^2}{16f\beta^2}.$$

Case BMB: the equilibrium outcomes are

(1) If $f > \frac{7\beta^2}{32}$ and $\tau > \frac{8af}{32f-7\beta^2}$:

$$t = -a + \left(4 - \frac{7\beta^2}{8f}\right)\tau, \qquad K = \frac{\beta\tau}{4},\ x_2^* = \frac{3\beta\tau}{8f},$$

$$\pi_s^{CSP} = 2\tau^2,$$

$$\pi_m^{CSP} = (1 - \frac{3\beta^2}{64f})\tau^2,$$

$\pi_g^{CSP} = \tau(-a + (4 - \frac{17\beta^2}{32f})\tau)$.

(3) If $f < \frac{7\beta^2}{32}$ or $f > \frac{7\beta^2}{32}$ and $\tau < \frac{8af}{32f-7\beta^2}$: Case BMB degenerates into case BMI.

CS scenario:

Recall that, as stated in Footnote 1 in subsection 4.1, to avoid negative demand, we restrict our attention to $f > \frac{\beta^2(12+\delta(4+\delta+\delta^2)}{4(1+\delta)(8+\delta^2)}$.

Case CSP: Providing a pure purchase subsidy in CS scenario.

Firms' decisions (w,p_m,p_s,x_2): Following backward induction solution procedure in stage 1, we have

$w^*(x_1,t) = \frac{(8+8\delta+\delta^3+\delta^4)(2f(a+t)+2f\beta x_1)}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$,

${x_2}^*(x_1,t) = \frac{(a+t)\beta(12+\delta(4+\delta+\delta^2))+\beta^2(12+\delta(4+\delta+\delta^2))x_1}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$,

$p_s^*(x_1,t) = \frac{(4-\delta)(1+\delta)(2+\delta)(2f(a+t)+2f\beta x_1)}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$,

$p_m^*(x_1,t) = \frac{(1+\delta)(12+\delta(4-(2-\delta)\delta))(2f(a+t)+2f\beta x_1)}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$.

Government's decision (t, x_1): Substitute $w^*(t,x_1)$, ${x_2}^*(t,x_1)$, $p_s^*(t, x_1)$ and $p_m^*(t, x_1)$ into π_g^{CSP}. As the total sales of EVs $q_m + q_s$ increases in x_1 and t. It is obvious that the constraint $q_m^* + q_s^* \geq \tau$ in the government's decision problem will bind at the optimum (t^*,x_1^*), i.e., $q_m^*(t^*,x_1^*) + q_s^*(t^*,x_1^*) = \tau$. Setting $q_m^*(t^*,x_1^*) + q_s^*(t^*,x_1^*) = \tau$, we have $t^*(x_1) = -a + \frac{(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{2f(12+\delta(1+\delta)(2+\delta))} - \beta x_1$. By substituting $t^*(x_1)$ into π_g^{CSP}, the government's decision problem becomes:

$$\begin{cases} \min_{(t,x_1)} \pi_g(x_1) = \frac{1}{2}\tau(-2a + \frac{(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{f(12+\delta(1+\delta)(2+\delta))}) - \beta\tau x_1 + f x_1^2 \\ \text{Subject to:} \\ t^*(x_1) = \frac{-2af-K\beta+8f\tau-\beta^2\tau}{2f\beta} \geq 0, \\ x_1 \geq 0. \end{cases} \quad (A.6)$$

Taking the first-order and second-order derivative of $\pi_g(x_1)$ with respect to x_1, we have $\frac{\partial \pi_g(x_1)}{\partial x_1} = -\beta\tau + 2fx_1$ and $\frac{\partial^2 \pi_g(x_1)}{\partial x_1} = 2f > 0$. Thus, $\pi_g(x_1)$ is convex and we obtain an interior solution ${x_1}^* = \frac{\beta\tau}{2f}$. Substituting ${x_1}^* = \frac{\beta\tau}{2f}$ into $t^*(x_1)$, we have $t^* = \frac{-af(12+\delta(1+\delta)(2+\delta))+2f(1+\delta)(8+\delta^2)\tau-\beta^2(12+\delta(3+\delta(2+\delta)))\tau}{f(12+2\delta+3\delta^2+\delta^3)}$. t^* is optimal when it is feasible. Checking the constraint $x_1{}^* \geq 0$ and $t^* \geq 0$, we derive the conditions under which the optimal is the interior solution. Otherwise, we obtain the optimal solution at the boundary$(x_1^*, t^*) = \left(\frac{-2af(12+\delta(1+\delta)(2+\delta))+4f(1+\delta)(8+\delta^2)\tau-\beta^2(12+\delta(4+\delta+\delta^2))\tau}{2f\beta(12+2\delta+3\delta^2+\delta^3)},0\right)$.

Through substituting the optimal incentive policy into the profit function and response function, we can obtain other optimal solutions:

(1) If $f > \frac{\beta^2(12+3\delta+2\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ and $\tau > \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(3+\delta(2+\delta)))}$,

$$x_2^* = \frac{\beta\left(12+\delta(4+\delta+\delta^2)\right)\tau}{2f(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(12+\delta(4+\delta+\delta^2))(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau^2}{4f(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(4-3\delta^4-\delta^6)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{1}{4}\tau(-4a+\frac{(8f(1+\delta)(8+\delta^2)-\beta^2(36+\delta(10+\delta(5+3\delta))))\tau}{f(12+\delta(1+\delta)(2+\delta))}).$$

(2) If $f < \frac{\beta^2(12+3\delta+2\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ or $f > \frac{\beta^2(12+3\delta+2\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ and $\tau > \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(3+\delta(2+\delta)))}$

$$x_2^* = \frac{\beta\left(12+\delta(4+\delta+\delta^2)\right)\tau}{2f(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(12+\delta(4+\delta+\delta^2))(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau^2}{4f(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(4-3\delta^4-\delta^6)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{(2af(12+\delta(1+\delta)(2+\delta))+(-4f(1+\delta)(8+\delta^2)+\beta^2(12+\delta(4+\delta+\delta^2)))\tau)^2}{4f\beta^2(12+\delta(1+\delta)(2+\delta))^2}.$$

Case CSI: Providing a pure infrastructure subsidy in CS scenario.

Firms' decisions (w,p_m,p_s,x_2): Following backward induction solution procedure in stage 1, we have

$$w^*(x_1,K) = \frac{(8+8\delta+\delta^3+\delta^4)(2af+K\beta+2f\beta x_1)}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))},$$

$$x_2{}^*(x_1,K) = \frac{2K(1+\delta)(8+\delta^2)+a\beta(12+\delta(4+\delta+\delta^2))+\beta^2(12+\delta(4+\delta+\delta^2))x_1}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$$

$$p_s^*(x_1,K) = \frac{(4-\delta)(1+\delta)(2+\delta)(2af+K\beta+2f\beta x_1)}{4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$$

$$p_m^*(x_1,K) = \frac{(1+\delta)(12-\delta(4-(2-\delta)\delta))(2af+K\beta+2f\beta x_1)}{4f(1+\delta)(8+\delta^2)\pm(12+\delta(4+\delta+\delta^2))}.$$

Government's decision (x_1,K): Substitute $w^*(x_1,K)$, $x_2{}^*(x_1,K)$, $p_s^*(x_1,K)$ and

$p_m^*(x_1,K)$ into π_g^{CSI}. As the total sales of EVs $q_m + q_s$ increases in x_1 and K. Thus, it is obvious that the constraint $q_m^* + q_s^* \geq \tau$ in the government's decision problem will bind at the optimum (x_1^*, K^*), i.e., $q_m^*(x_1^*,K^*) + q_s^*(x_1^*,K^*) = \tau$. Setting $q_m^*(x_1^*,K^*) + q_s^*(x_1^*,K^*) = \tau$, we have $x_1^* = \frac{-(2af+K\beta)(12+\delta(1+\delta)(2+\delta))+(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{2f\beta(12+\delta(1+\delta)(2+\delta))}$, which is a function of K so that we denote as $x_1^*(K)$. By substituting $x_1^*(K)$ into π_g^{CSI}, the government's decision problem becomes: $\min_{(K,x_1)} \pi_g^{CSI} = \frac{1}{4f\beta^2(12+\delta(1+\delta)(2+\delta))^2}(4a^2f^2$

$(12+\delta(1+\delta)(2+\delta))^2 + 3K^2\beta^2(12+\delta(1+\delta)(2+\delta))^2$

$+4K\beta(12+\delta(1+\delta)(2+\delta))(-2f(1+\delta)(8+\delta^2)+\beta^2(12+\delta(4+\delta+\delta^2)))\tau +$

$(-4f(1+\delta)(8+\delta^2)+\beta^2(12+\delta(4+\delta+\delta^2)))^2\tau^2$

$+4af(12+\delta(1+\delta)(2+\delta))(K\beta(12+\delta(1+\delta)(2+\delta))+(-4f(1+\delta)(8+\delta^2)+\beta^2$

$(12+\delta(4+\delta+\delta^2)))\tau))$

Subject to:

$$\begin{cases} x_1^*(K) = \frac{-(2af+K\beta)(12+\delta(1+\delta)(2+\delta))+(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{2f\beta(12+\delta(1+\delta)(2+\delta))} \geq 0 \\ K \geq 0. \end{cases}$$

(A.7)

Taking the first-order and second-order derivative of $\pi_g(K)$ with respect to K, we have $\frac{\partial \pi_g(K)}{\partial K} = \frac{(2af+3K\beta)(12+\delta(1+\delta)(2+\delta))+2(-2f(1+\delta)(8+\delta^2)+\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{2f\beta(12+\delta(1+\delta)(2+\delta))}$ and $\frac{\partial^2 \pi_g(x_1)}{\partial K^2} = \frac{3}{2f} > 0$. Thus, $\pi_g(K)$ is convex and we obtain an interior solution $K^* = \frac{-2af(12+\delta(1+\delta)(2+\delta))+4f(1+\delta)(8+\delta^2)\tau-2\beta^2(12+\delta(4+\delta+\delta^2))\tau}{3\beta(12+\delta(1+\delta)(2+\delta))}$. Substituting K^* into $x_1^*(K)$, we have $x_1^* = \frac{-4af(12+\delta(1+\delta)(2+\delta))+8f(1+\delta)(8+\delta^2)\tau-\beta^2(12+\delta(4+\delta+\delta^2))\tau}{6f\beta(12+2\delta+3\delta^2+\delta^3)}$. x_1^* is optimal when it is feasible. Checking the constraint ${x_1}^* \geq 0$ and $K^* \geq 0$, we derive the conditions under which the optimal is the interior solution. Otherwise, we obtain the optimal solution at the bound

$(x_1^*, K^*) = \left(\frac{-2af(12+\delta(1+\delta)(2+\delta))+4f(1+\delta)(8+\delta^2)\tau-\beta^2(12+\delta(4+\delta+\delta^2))\tau}{2f\beta(12+2\delta+3\delta^2+\delta^3)}, 0\right)$.

Through substituting the optimal incentive policy into the profit function and response function, we can obtain other optimal solutions:

(1) If $f > \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ and $\tau > \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$,

$$x_2^* = \frac{-2af(12+\delta(1+\delta)(2+\delta)) + (4f(1+\delta)(8+\delta^2) + \beta^2(12+\delta(4+\delta+\delta^2)))\tau}{6f\beta(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{\left\{\begin{matrix} 4a^2f^2(12+\delta(1+\delta)(2+\delta))^2 - 8af(12+\delta(1+\delta)(2+\delta))(2f(1+\delta)(8+\delta^2) - \beta^2(\\ 12+\delta(4+\delta+\delta^2)))\tau + (20f\beta^2(1+\delta)(2+\delta)(6+(-1+\delta)\delta)(8+\delta^2) + \\ 16f^2(1+\delta)^2(8+\delta^2)^2 - 5\beta^4(12+\delta(4+\delta+\delta^2))^2)\tau^2 \end{matrix}\right\}}{36f\beta^2(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(4-3\delta^4-\delta^6)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{\left\{\begin{matrix} (1+\delta)(4+(-2+\delta)\delta)(20+\delta(2+5\delta))\tau(4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) \\ -(8f(1+\delta)(8+\delta^2)^2 + \beta^2(112+\delta(16+\delta(36+\delta(-4+(5-3\delta)\delta)))))\tau) \end{matrix}\right\}}{12f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}.$$

(2) If $f < \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ or $f > \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ and $\tau < \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$

$$x_2^* = \frac{\beta(12+\delta(4+\delta+\delta^2))\tau}{2f(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(12+\delta(4+\delta+\delta^2))(4f(1+\delta)(8+\delta^2) - \beta^2(12+\delta(4+\delta+\delta^2)))\tau^2}{4f(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(4-3\delta^4-\delta^6)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{(2af(12+\delta(1+\delta)(2+\delta)) + (-4f(1+\delta)(8+\delta^2) + \beta^2(12+\delta(4+\delta+\delta^2)))\tau)^2}{4f\beta^2(12+\delta(1+\delta)(2+\delta))^2}.$$

Case CSB: Providing both subsidies in CS scenario

Firms' decisions (w,p_m,p_s,x_2): Following backward induction solution procedure in stage 1, we have

$$w^*(x_1,t,K) = \frac{(8+8\delta+\delta^3+\delta^4)(2f(a+t)+K\beta+2f\beta x_1)}{4f(1+\delta)(8+\delta^2) - \beta^2(12+\delta(4+\delta+\delta^2))}$$

$$x_2{}^*(x_1,t,K) = \frac{2K(1+\delta)(8+\delta^2) + (a+t)\beta(12+\delta(4+\delta+\delta^2)) + \beta^2(12+\delta(4+\delta+\delta^2))x_1}{4f(1+\delta)(8+\delta^2) - \beta^2(12+\delta(4+\delta+\delta^2))}$$

$$p_s^*(x_1,t,K) = \frac{(4-\delta)(1+\delta)(2+\delta)(2f(a+t)+K\beta+2f\beta x_1)}{4f(1+\delta)(8+\delta^2) - \beta^2(12+\delta(4+\delta+\delta^2))}$$

$$p_m^*(x_1,t,K) = \frac{(1+\delta)(12-\delta(4-(2-\delta)\delta))(2f(a+t)+K\beta+2f\beta x_1)}{4f(1+\delta)(8+\delta^2) - \beta^2(12+\delta(4+\delta+\delta^2))}$$

Government's decision(x_1,t,K): Substitute $w^*(x_1,t,K)$, $x_2{}^*(x_1,t,K)$, $p_s^*(x_1,t,K)$ and $p_m^*(x_1,t,K)$ into π_g^{CSB}. As the total sales of EVs $q_m + q_s$ increases in x_1,t and K. Thus, it is obvious that the constraint $q_m^* + q_s^* \geq \tau$ in the government's decision problem will bind at the optimum (x_1^*, t^*, K^*), i.e., $q_m^*(x_1^*, t^*, K^*) + q_s^*(x_1^*, t^*, K^*) = \tau$. Setting $q_m^*(x_1^*, t^*, K^*) + q_s^*(x_1^*, t^*, K^*) = \tau$, we have $t^*(x_1,K) =$

$$\frac{-(2af+K\beta)(12+\delta(1+\delta)(2+\delta))+(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau-2f\beta(12+\delta(1+\delta)(2+\delta))x_1}{2f(12+\delta(1+\delta)(2+\delta))}$$

By substituting $t^*(x_1,K)$ into π_g^{CSI}, the government's decision problem becomes:

$$\min_{(K,x_1)} \pi_g^{CSB} =$$

$$\frac{K^2(12+\delta(1+\delta)(2+\delta))-2(K\beta(-1+\delta)\delta+af(12+\delta(1+\delta)(2+\delta)))\tau+(4f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau^2+2f(12+\delta(1+\delta)(2+\delta))x_1(-\beta\tau+fx_1)}{2f(12+\delta(1+\delta)(2+\delta))}$$

.

Subject to:

$$\begin{cases} x_1^*(K) = \dfrac{-(2af+K\beta)(12+\delta(1+\delta)(2+\delta))+\left(4f(1+\delta)(8+\delta^2)-\beta^2\left(12+\delta(4+\delta+\delta^2)\right)\right)\tau}{2f\beta(12+\delta(1+\delta)(2+\delta))} \geq 0 \\ K \geq 0. \end{cases}$$

Taking the first-order derivative of $\pi_g^{CSB}(x_1,t,K)$, we can derive that $\frac{\partial \pi_g^{CSB}}{\partial K} = \frac{2K(12+\delta(1+\delta)(2+\delta))+2\beta(1-\delta)\delta\tau}{2f(12+\delta(1+\delta)(2+\delta))} > 0$. $\frac{\partial \pi_g^{CSB}}{\partial K} > 0$ suggests that the government's total expenditure increases in K, so that the optimal infrastructure subsidy is $K = 0$. That is, the government would never provide infrastructure subsidy and case CSB degenerates into case CSP.

The solutions of other three cases in base supply chain (**case CMP, CMI, CMB**) follow the same backward induction solution procedure and we will not belabor it.

CM scenario:

Recall that, as stated in Footnote 1 in subsection 4.1, to avoid negative demand, we restrict our attention to $f > \frac{\beta^2(1-\delta)(2+\delta^2)^2}{(1+\delta)(8+\delta^2)^2}$.

Case CMP: The equilibrium outcome of case CMP are summarized as follows:

(1) If $f > \frac{\beta^2(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))}{4(1+\delta)(8+\delta^2)^2}$ and $\tau > \frac{2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{4f(1+\delta)(8+\delta^2)^2+\beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta))))}$,

$$t = -a - \frac{\beta^2\tau}{2f} + \frac{2\left(\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2\right)\tau}{f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$x_1^* = \frac{\beta\tau}{2f},$$

$$x_2^* = \frac{2\beta(1-\delta)(2+\delta^2)^2\tau}{f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(1+\delta)(2+\delta)(6-(1-\delta)\delta)(8+\delta^2)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(1-\delta)(2+\delta^2)^2(-\beta^2(1-\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)\tau^2}{f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = -\frac{\beta^2\tau^2}{4f} + \tau(-a + \frac{2(\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}).$$

(2) If $f < \frac{\beta^2(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))}{4(1+\delta)(8+\delta^2)^2}$ or $f > \frac{\beta^2(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))}{4(1+\delta)(8+\delta^2)^2}$ and

$\tau < \frac{2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{4f(1+\delta)(8+\delta^2)^2+\beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta))))}$,

$t = 0$,

$$x_1^* = \frac{-af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + 2(-\beta^2(1-\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{f\beta(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$x_2^* = \frac{2\beta(1-\delta)(2+\delta^2)^2\tau}{f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(1+\delta)(2+\delta)(6+(-1+\delta)\delta)(8+\delta^2)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(1-\delta)(2+\delta^2)^2(\beta^2(1-\delta)(2+\delta^2)^2 - f(1+\delta)(8+\delta^2)^2)\tau^2}{f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{(2af(12+\delta(1+\delta)(2+\delta)) + (-4f(1+\delta)(8+\delta^2) + \beta^2(12+\delta(4+\delta+\delta^2)))\tau)^2}{4f\beta^2(12+\delta(1+\delta)(2+\delta))^2}.$$

Case CMI: The equilibrium outcome of case CMI are summarized as follows:

(1) If $f > \frac{2\beta^2(1-\delta)(2+\delta^2)^2}{(1+\delta)(8+\delta^2)^2}$ and $\tau > \frac{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{2(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)}$,

$$K = \frac{-2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + 4(2\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{3\beta(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$x_1^* = \frac{-af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + 2(\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{f\beta(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$x_2^* = \frac{-af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + 2(-\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{3f\beta(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(1+\delta)(2+\delta)(6+(-1+\delta)\delta)(8+\delta^2)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{\left\{\begin{matrix} a^2f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2 - 4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(2\beta^2(-1+\delta)(2+\delta^2)^2 \\ +f(1+\delta)(8+\delta^2)^2)\tau + 4(-5\beta^4(-1+\delta)^2(2+\delta^2)^4 - 5f\beta^2(-1+\delta^2)(2+\delta^2)^2(8+\delta^2)^2 + \\ f^2(1+\delta)^2(8+\delta^2)^4)\tau^2 \end{matrix}\right\}}{9f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

,

$$\pi_g^{CSP} = \frac{\left\{\begin{matrix} 2(a^2f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2 - 2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(\\ \beta^2(-1+\delta)(2+\delta^2)^2 + 2f(1+\delta)(8+\delta^2)^2)\tau + 2(-\beta^4(-1+\delta)^2(2+\delta^2)^4 + 2f\beta^2(-1+\delta^2)(2+\delta^2)^2 \\ (8+\delta^2)^2 + 2f^2(1+\delta)^2(8+\delta^2)^4)\tau^2) \end{matrix}\right\}}{3f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

.

(2) If $f < \frac{2\beta^2(1-\delta)(2+\delta^2)^2}{(1+\delta)(8+\delta^2)^2}$ or $f > \frac{2\beta^2(1-\delta)(2+\delta^2)^2}{(1+\delta)(8+\delta^2)^2}$ and $\tau <$ $\frac{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{2(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)}$,

$K = 0$,

$$x_1^* = \frac{-af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + 2(-\beta^2(1-\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau}{f\beta(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$x_2^* = \frac{2\beta(1-\delta)(2+\delta^2)^2\tau}{f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(1+\delta)(2+\delta)(6+(-1+\delta)\delta)(8+\delta^2)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{4(1-\delta)(2+\delta^2)^2(\beta^2(1-\delta)(2+\delta^2)^2 - f(1+\delta)(8+\delta^2)^2)\tau^2}{f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{(af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) - 2(\beta^2(-1+\delta)(2+\delta^2)^2 + f(1+\delta)(8+\delta^2)^2)\tau)^2}{f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}.$$

Case CMB: The equilibrium outcome of case CMB are summarized as follows:

(1) If $f > \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$ and $\tau > \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$,

$$t^* = \frac{\left\{ -4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + (8f(1+\delta)(8+\delta^2)^2 + \beta^2(-304+\delta(-32+\delta(-124+ (-14+\delta)\delta \right\}}{4f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}$$

$$K^* = \frac{\beta(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta)))))\tau}{2(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$x_1^* = \frac{\beta\tau}{2k},$$

$$x_2^* = \frac{\beta(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))\tau}{4f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))},$$

$$\pi_s^{CSP} = \frac{(1+\delta)(2+\delta)(6+(-1+\delta)\delta)(8+\delta^2)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_m^{CSP} = \frac{\left\{ (-64f(-1+\delta^2)(2+\delta^2)^2(8+\delta^2)^2 - \beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta))))(48+ \delta(64+\delta(-12+\delta(58+\delta(-9+13\delta))))))\tau^2 \right\}}{16f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2},$$

$$\pi_g^{CSP} = \frac{\left\{ \tau(-8af(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2 + (16f(1+\delta)(8+\delta^2)^3(12+\delta(1+\delta)(2+\delta)) - \beta^2(30976+\delta(6144+\delta(25984+\delta(4800+\delta(8656+\delta(720+\delta(1460+\delta(-132 +\delta(143+\delta(-30+11\delta))))))))))))\tau) \right\}}{8f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

(2) If $f < \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$ or $f > \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$ and $\tau < \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$, the case CMB degenerates into case CMI.

Appendix B. The threshold values for f and τ.

$$f_1 = \frac{\beta^2(12+3\delta+2\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$$

$$f_2 = \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$$

$$f_3 = \frac{\beta^2(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))}{4(1+\delta)(8+\delta^2)^2}$$

$$f_4 = \frac{2\beta^2(1-\delta)(2+\delta^2)^2}{(1+\delta)(8+\delta^2)^2}$$

$$f_5 = \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$$

$$f_6 = \frac{\beta^2(64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta)))))}{4(8+\delta^2)(16+\delta(-4+\delta(5+\delta)))}$$

$$f_7 = \frac{\beta^2(624+\delta(224+\delta(140+\delta(126+\delta+19\delta^2))))}{8(1+\delta)(8+\delta^2)^2}$$

$$f_8 = -\frac{\beta^2(-2+\delta)(72+\delta(20+\delta(52+\delta(7+11\delta))))(112+\delta(-120+\delta(210+\delta(-12+\delta(45+2\delta(3+\delta))))))}{(8(8+\delta^2)^3(4+\delta(12+\delta(4+\delta(30+\delta+3\delta^2)))))}$$

$$\tau_1 = \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(3+\delta(2+\delta)))}$$

$$\tau_2 = \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$$

$$\tau_3 = \frac{2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{4f(1+\delta)(8+\delta^2)^2+\beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta))))}$$

$$\tau_4 = \frac{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{2(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)}$$

$$\tau_5 = \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$$

$$\tau_6 = \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2-\beta^2(624+\delta(224+\delta(140+\delta(126+\delta+19\delta^2))))}$$

$$\hat{\Omega}_1 = \{f,\tau | f > \frac{\beta^2}{4} \text{ and } \tau > \frac{af}{4f-\beta^2}\}$$

$$\hat{\Omega}_2 = \{f,\tau | f > \frac{7\beta^2}{32} \text{ and } \tau > \frac{8af}{32f-7\beta^2}\}$$

$$\hat{\Omega}_3 = \{f,\tau | \frac{\beta^2}{8} < f < \frac{3\beta^2}{16} \text{ and } \tau > \frac{2af}{8f-\beta^2} \text{ or } \frac{3\beta^2}{16} < f < \frac{7\beta^2}{32} \text{ and } \frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2} \text{ or } f > \frac{7\beta^2}{32} \text{ and } \frac{2af}{8f-\beta^2} < \tau < \frac{8af}{32f-7\beta^2}\}$$

$$\hat{\Omega}_4 = \{f,\tau | f > f_2 \text{ and } \tau > \tau_2\}$$

$$\hat{\Omega}_5 = \{f,\tau | f_1 < f < f_2 \text{ and } \tau > \tau_1 \text{ or } f > f_2 \text{ and } \tau_1 < \tau < \tau_2\}$$

$$\hat{\Omega}_6 = \{f,\tau | f > f_5 \text{ and } \tau > \tau_5\}$$

$$\hat{\Omega}_7 = \{f,\tau | f_4 < f < f_5 \text{ and } \tau > \tau_4 \text{ or } f > f_5 \text{ and } \tau_4 < \tau < \tau_5\}$$

Appendix C. Proof of propositions

Proof of Corollary 1. $\frac{\partial x_2^*}{\partial x_1} = \frac{\beta^2}{8f-\beta^2}$, $\frac{\partial p_m^*}{\partial t} = \frac{6f}{8f-\beta^2}$, $\frac{\partial p_m^*}{\partial K} = \frac{3\beta}{8f-\beta^2}$, $\frac{\partial q_m^*}{\partial t} = \frac{2f}{8f-\beta^2}$, $\frac{\partial q_m^*}{\partial K} =$

$\frac{\beta}{8f-\beta^2}$, $\frac{\partial \pi_m^*}{\partial t} = \frac{4f(2f(a+t)+K\beta+2f\beta x_1)}{(-8f+\beta^2)^2}$. $\frac{\partial \pi_m^*}{\partial K} = \frac{2\beta(2f(a+t)+K\beta+2f\beta x_1)}{(-8f+\beta^2)^2}$.

Under the precondition $f > \frac{\beta^2}{8}$, it can obtain the results in Corollary 1.

The derivations concerning the governments incentives

To investigate the government's subsidy selection decision under each scenario, we characterize the decision regions by comparing the thresholds of the government's optimal policy design decisions for the optional subsidy schemes.

Taking the analysis in BS scenario and BM scenario as an example, the decision regions can be characterized as follows:

(1) For the BS scenario:

Under BS scenario, providing either a pure purchase subsidy or infrastructure subsidy is optional. To investigate the government's subsidy selection decision under BS scenario, we characterize the decision regions by comparing the thresholds of the government's optimal policy design decisions for the optional subsidy schemes. Then, based on the characterization for the decision regions, we provide derivation of optimal subsidy selection strategy under BS. Under BS scenario, the decisions regions can be divided into three parts, namely, *zero-option, single-option, and dual-option* regions. These regions can be characterized by two parameters, i.e., f and τ.

(1a) dual-option region: in the dual-option region, both a pure purchase subsidy and a pure infrastructure subsidy are optional for the government and it should select the subsidy scheme that leads to the least policy expenditure. Comparing the thresholds in preconditions of positive purchase subsidy ($f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$) and positive infrastructure subsidy ($f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$), we can identify the conditions that characterize the dual-option region. That is, when $f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$, both a pure purchase subsidy and a pure infrastructure subsidy are optional. We define the optimality un the following way: the optimal policy achieves the same adoption level at the least cost. Thus, in the dual-option region (i.e., $f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$) the optimal policy is identified by comparing the policy expenditure under two subsidy schemes (a pure purchase subsidy and a pure infrastructure subsidy).

(1b) In the single-option region, only the pure purchase subsidy or the pure infrastructure subsidy is optional. According to (1a), the single-option region does not exist.

(1c) Otherwise, in the zero-option region, i.e., when $f < \frac{\beta^2}{4}$ or $f > \frac{\beta^2}{4}$ and $\tau < \frac{\alpha f}{4f - \beta^2}$, the government provides no subsidy.

(2) For the BM scenario:

(2a) triple-option region: comparing the thresholds in preconditions of positive subsidies under three subsidy schemes ($\{f > \frac{7\beta^2}{32}$ and $\tau > \frac{8\alpha f}{32f - 7\beta^2}\}$ and $\{f > \frac{3\beta^2}{16}$ and $\tau > \frac{4\alpha f}{16f - 3\beta^2}\}$ and $\{f > \frac{\beta^2}{8}$ and $\tau > \frac{2\alpha f}{8f - \beta^2}\}$), we can identify the conditions that characterize the triple-option region. That is, if $f > \frac{7\beta^2}{32}$ and $\tau > \frac{8\alpha f}{32f - 7\beta^2}$, the three subsidy schemes (a pure purchase subsidy, a pure infrastructure subsidy, a combination of both) are all selectable options, and the government would choose the most cost-efficient subsidy scheme in the region.

(2b) dual-option region: comparing the thresholds in preconditions of three subsidy schemes, we can identify the conditions that characterize the dual-option region where both a pure subsidy and a pure infrastructure subsidy are selectable. However, in the dual-option region, the combined subsidy policy (i.e., a combination of both) is not optional. Therefore, the dual-option region can be characterized by the following conditions: $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ and $\tau > \frac{4\alpha f}{16f - 3\beta^2}$ or $f > \frac{7\beta^2}{32}$ and $\frac{4\alpha f}{16f - 3\beta^2} < \tau < \frac{8\alpha f}{32f - 7\beta^2}$.

(2c) single-option region: in the single-option region, only the pure purchase subsidy or the pure infrastructure subsidy is optional. If $\frac{\beta^2}{8} < f < \frac{3\beta^2}{16}$ and $\tau > \frac{2\alpha f}{8f - \beta^2}$ or $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ and $\frac{2\alpha f}{8f - \beta^2} < \tau < \frac{4\alpha f}{16f - 3\beta^2}$ or $f > \frac{7\beta^2}{32}$ and $\frac{2\alpha f}{8f - \beta^2} < \tau < \frac{4\alpha f}{16f - 3\beta^2}$, only the infrastructure subsidy policy is optional.

(2d) zero-option region: otherwise, the government provides no subsidy.

Based on the above analysis, the government's decision regions can be characterized as the following.

Theorem 1 (regions characterization). In the two scenarios of base supply chain, the government's policy selection decision can be characterized as follows:

(1) **For the BS scenario:**

(1a) dual-option region: if $f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$, the purchase subsidy policy and infrastructure subsidy policy are both selectable options, and the government would choose the policy which is more cost-efficient.

(1b) zero-option region: if $f < \frac{\beta^2}{4}$ or $f > \frac{\beta^2}{4}$ and $\tau < \frac{af}{4f-\beta^2}$, the government provides no subsidy.

(2) **For the BM scenario:**

(2a) triple-option region: if $f > \frac{7\beta^2}{32}$ and $\tau > \frac{8af}{32f-7\beta^2}$, the three subsidy policies are all selectable options, and the government would choose the most cost-efficient policy.

(2b) dual-option region: if $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ and $\tau > \frac{4af}{16f-3\beta^2}$ or $f > \frac{7\beta^2}{32}$ and $\frac{4af}{16f-3\beta^2} < \tau < \frac{8af}{32f-7\beta^2}$, the purchase subsidy and infrastructure subsidy are both selectable options, and the government would choose the policy which is more cost-efficient.

(2c) single-option region: if $\frac{\beta^2}{8} < f < \frac{3\beta^2}{16}$ and $\tau > \frac{2af}{8f-\beta^2}$ or $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ and $\frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2}$ or $f > \frac{7\beta^2}{32}$ and $\frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2}$, only the infrastructure subsidy policy is optional.

(2d) zero-option region: otherwise, the government provides no subsidy.

Based on the characterization for the decision regions in Theorem 1, we provide the derivation of optimal policy under BS and BM scenarios in the following proofs for Proposition 1 and Proposition 2.

Proof of Proposition 1. Recall from Theorem 1 that, we define the optimality un the following way: the optimal policy achieves the same adoption level at the least cost. Accordingly, we derive the optimal government subsidy scheme by comparing the policy expenditure of different subsidy schemes for each decision region. Under BS scenario, (1) in the dual-option region, comparing the government's expenditure under purchase subsidy (case BSP) and infrastructure subsidy (case BSI), we obtain $\pi_g^{BSP} - \pi_g^{BSI} = -\frac{2(af-(4f-\beta^2)\tau)^2}{3f\beta^2} < 0$. Thus, in the dual-option region ($f > \frac{\beta^2}{4}$ and $\tau > \frac{af}{4f-\beta^2}$), the government prefers to provide purchase subsidy. Otherwise, the government provides no subsidy. (2) Otherwise, in the zero-option region, the government provides no subsidy.

Proof of Proposition 2. Similar with Proposition 1, under BM scenario, we need to compare the policy expenditure of different subsidy schemes for each decision region.

(1) For the **triple-option region in BM scenario**, comparing the government's total expenditure, we obtain

$$\pi_g^{BMB} - \pi_g^{BMI} = -\frac{(8af-32f\tau+7\beta^2\tau)^2}{96f\beta^2} < 0$$

$$\pi_g^{BMB} - \pi_g^{BMP} = -\frac{\beta^2\tau^2}{32f} < 0$$

Thus, we can conclude that in the triple-option region ($f > \frac{7\beta^2}{32}$ and $\tau > \frac{8af}{32f-7\beta^2}$), the government prefers to provide both subsidies.

(2) For the **dual-option region in BM scenario**, comparing government's total expenditure, we have $\pi_g^{BMP} - \pi_g^{BMI} = \frac{g(\tau)}{48f\beta^2}$, where $g(\tau) = -32a^2f^2 + 8af(32f - 7\beta^2)\tau + (-512f^2 + 224f\beta^2 - 23\beta^4)\tau^2$. Since sgn $(\pi_g^{BMP} - \pi_g^{BMI})$ = sgn $(g(\tau))$, we only need to analyze sgn $(g(\tau))$ below.

Solving $g(\tau) = 0$, we obtain two real roots, τ_{A1} and τ_{A2}, as follows:

$\tau_{A1} = \frac{4(7+\sqrt{3})af}{16(7+\sqrt{3})f-23\beta^2}$, $\tau_{A2} = \frac{4(7-\sqrt{3})af}{16(7-\sqrt{3})f-23\beta^2}$, and $\tau_{A2} - \tau_{A1} = \frac{8\sqrt{3}af\beta^2}{512f^2-224f\beta^2+23\beta^4}$.

(i) Since $\frac{(7-\sqrt{3})\beta^2}{32} < \frac{3\beta^2}{16} < \frac{7\beta^2}{32} < \frac{(7+\sqrt{3})\beta^2}{32}$, it is obvious that if $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$, the coefficient of quadratic term of $g(\tau)$, i.e., $(-512f^2 + 224f\beta^2 - 23\beta^4)$ is positive and $g(\tau)$ is a quadratic function of τ graphed by a parabola opening upward with $\tau_{A2} < \tau_{A1}$. Since $\tau_{A2} < \tau_{A1} < \frac{4af}{16f-3\beta^2}$, $g(\tau) > 0$ holds when $\tau > \frac{4af}{16f-3\beta^2}$. **That is,** $\boldsymbol{\pi_g^{BMP} > \pi_g^{BMI}}$ **if** $\boldsymbol{\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}}$ **and** $\boldsymbol{\tau > \frac{4af}{16f-3\beta^2}}$**.**

(ii) The coefficient of quadratic term of $g(\tau)$ is positive with $\frac{7\beta^2}{32} < f < \frac{(7+\sqrt{3})\beta^2}{32}$ and

$g(\tau)$ is a quadratic function of τ graphed by a parabola opening upward with $\tau_{A2} < \tau_{A1}$. Since $\tau_{A2} < \tau_{A1} < \frac{4af}{16f-3\beta^2}$, $g(\tau) > 0$ holds when $\tau > \frac{4af}{16f-3\beta^2}$. **That is,** $\boldsymbol{\pi_g^{BMP} > \pi_g^{BMI}}$ **if** $\boldsymbol{\frac{7\beta^2}{32} < f < \frac{(7+\sqrt{3})\beta^2}{32}}$ **and** $\boldsymbol{\frac{4af}{16f-3\beta^2} < \tau < \frac{8af}{32f-7\beta^2}}$**.**

(iii) If $f > \frac{(7+\sqrt{3})\beta^2}{32}$, the coefficient of quadratic term of $g(\tau)$, i.e., $(-512f^2 + 224f\beta^2 - 23\beta^4)$ is negative and $g(\tau)$ is a quadratic function of τ graphed by a parabola opening downward with $\tau_{A2} > \tau_{A1}$. Since $\tau_{A1} < \frac{4af}{16f-3\beta^2} < \frac{8af}{32f-7\beta^2} < \tau_{A2}$, $g(\tau) > 0$ holds when $\frac{4af}{16f-3\beta^2} < \tau < \frac{8af}{32f-7\beta^2}$. **That is,** $\boldsymbol{\pi_g^{BMP} > \pi_g^{BMI}}$ **if** $\boldsymbol{f > \frac{(7+\sqrt{3})\beta^2}{32}}$ **and** $\boldsymbol{\frac{4af}{16f-3\beta^2} < \tau < \frac{8af}{32f-7\beta^2}}$**.**

Based on analysis above, we obtain that in the dual-option region the infrastructure subsidy policy is more cost-efficient than the purchase subsidy. Taken these conditions together with that presented in the single-option region where the infrastructure subsidy is optional (if $\frac{\beta^2}{8} < f < \frac{3\beta^2}{16}$ and $\tau > \frac{2af}{8f-\beta^2}$ or $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ and $\frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2}$ or $f > \frac{7\beta^2}{32}$ and $\frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2}$), we derive the conditions under which the government prefers infrastructure subsidy and summarize the conditions as follows: If $\frac{\beta^2}{8} < f < \frac{3\beta^2}{16}$ and $\tau > \frac{2af}{8f-\beta^2}$ or $\frac{3\beta^2}{16} < f < \frac{7\beta^2}{32}$ and $\frac{2af}{8f-\beta^2} < \tau < \frac{4af}{16f-3\beta^2}$ or $f > \frac{7\beta^2}{32}$ and $\frac{2af}{8f-\beta^2} < \tau < \frac{8af}{32f-7\beta^2}$, the government should provide infrastructure subsidy, and $(K, x_1) = (\frac{2((4f-\beta^2)\tau-af)}{3\beta}, \frac{(16f-\beta^2)\tau-4af}{6f\beta})$.

(3) Otherwise, the government should provide no subsidy.

For CS and CM scenarios, we start by charactering the decision regions and then derive the optimal policy by comparing the government policy expenditure of different subsidy schemes in each region. The derivation of optimal policy for CS and CM scenarios are similar with that for BS and BM scenarios, and we will not belabor it, and the characterization of decision regions and derivation of optimal policy are summarized in Theorem 2, Proposition 3 and Proposition 4.

Theorem 2 (regions characterization). In the co-opetitive supply chain, the government's policy selection decision can be characterized as follows:

(1) For the CS scenario:

(1a) dual-option region: if $f > f_2$ and $\tau > \tau_2$, the purchase subsidy policy and infrastructure subsidy policy are both selectable options, and the government would choose the policy which is more cost-efficient.

(1b) single-option region: if $f_1 < f < f_2$ and $\tau > \tau_1$ or $f > f_2$ and $\tau_1 < \tau < \tau_2$, only the purchase subsidy policy is optional.

(1c) zero-option region: otherwise, neither of the two policies is optional, and the government provides no subsidy.

(2) For the CM scenario:

(2a) triple-option region: if $f > f_5$ and $\tau > \tau_5$, the three subsidy policies are all selectable options, and the government would choose the most cost-efficient policy.

(2b) dual-option region: if $f_3 < f < f_5$ and $\tau > \tau_3$ or $f > f_5$ and $\tau_3 < \tau < \tau_5$, the purchase subsidy and infrastructure subsidy are both selectable options, and the government would choose the policy which is more cost-efficient.

(2c) single-option region: if $f_4 < f < f_3$ and $\tau > \tau_4$ or $f_3 < f < f_5$ and $\tau_4 < \tau < \tau_3$ or $f > f_5$ and $\tau_4 < \tau < \tau_3$, only the infrastructure subsidy policy is optional.

(2d) zero-option region: otherwise, neither of the two policies is optional, and the government provides no subsidy.

Proof of Theorem 2. Similar with Theorem 1, we first compare the theorems for three policies to investigate the government's policy selection decisions. Based on the equilibrium outcomes under each given subsidy scheme, it can obtain

$f_1 = \frac{\beta^2(12+3\delta+2\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$,

$\tau_1 = \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(3+\delta(2+\delta)))}$,

$f_2 = \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$,

$\tau_2 = \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$. Obviously, $f_1 < f_2$ and $\tau_1 < \tau_2$. Taken these together, we have that under CS scenario, when $f > f_2$ and $\tau > \tau_2$, the purchase subsidy policy and infrastructure subsidy policy are both selectable options. Under CM scenario, it can obtain

$f_3 = \frac{\beta^2(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))}{4(1+\delta)(8+\delta^2)^2}$,

$f_4 = \frac{2\beta^2(1-\delta)(2+\delta^2)^2}{(1+\delta)(8+\delta^2)^2}$,

$f_5 = \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$,

$\tau_3 = \frac{2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{4f(1+\delta)(8+\delta^2)^2+\beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta))))}$,

$\tau_4 = \frac{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{2(f(1+\delta)(8+\delta^2)^2-2\beta^2(1-\delta)(2+\delta^2)^2)}$,

$\tau_5 = \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$. Comparing these thresholds, we have $f_4 < f_4 < f_5$ and $\tau_4 < \tau_3 < \tau_5$. Based on the comparing results of the thresholds and the equilibrium outcomes under each given subsidy scheme, we can derive the decision regions characterized in Theorem 2.

Proof of Proposition 3. (1) Under the CS scenario, we compare the government's total expenditure in each region characterized in Theorem 2 (1). (1a) For the dual-option region, comparing the government's total expenditure yields

$\pi_g^{CSP} - \pi_g^{CSI} = \frac{g_1(\tau)}{3f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$, where $g_1(\tau) = -2af(2+\delta)(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(92+\delta(-22+\delta(39+\delta(-5+4\delta))))\tau + (4f(1+\delta)(2+\delta)(8+\delta^2)^2(92+\delta(-22+\delta(39+\delta(-5+4\delta)))) - \beta^2(18496+\delta(7552+\delta(13184+\delta(6528+\delta(3952+\delta(1784+\delta(723+\delta(172+\delta(89+2\delta+6\delta^2))))))))))\tau^2$. Obviously, $g_1(\tau)$ is quadratic function of τ. Solving $g_1(\tau) = 0$, we obtain two real roots, τ_{A3} and τ_{A4}, as follows:

$\tau_{A3} = 0$

$$\tau_{A4} = \frac{\{2af(2+\delta)(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(92+\delta(-22+\delta(39+\delta(-5+4\delta))))}{\{4f(1+\delta)(2+\delta)(8+\delta^2)^2(92+\delta(-22+\delta(39+\delta(-5+4\delta)))) - \beta^2(18496+\delta(7552+\delta(13184+\delta(6528+\delta(3952+\delta(1784+\delta(723+\delta(172+\delta(89+2\delta+6\delta^2)))))))))\}}\}$$

If $f > f_{A2} = \frac{\beta^2(18496+\delta(7552+\delta(13184+\delta(6528+\delta(3952+\delta(1784+\delta(723+\delta(172+\delta(89+2\delta+6\delta^2)))))))))}{4(1+\delta)(2+\delta)(8+\delta^2)^2(92+\delta(-22+\delta(39+\delta(-5+4\delta))))}$, the coefficient of $g_1(\tau)$ is positive. Since $f_2 = \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)} > f_{A2}$, the coefficient of $g_1(\tau)$ is positive if $f > f_2$ and $g_1(\tau)$ is a quadratic function graphed by a parabola opening upward, with $\tau_{A4} > \tau_{A3}$. In this case, comparing τ_{A4} and τ_2 yields

$$\tau_2 - \tau_{A4} =$$

$$\frac{\{(af\beta^2(12+\delta(1+\delta)(2+\delta))(16832+\delta(13440+\delta(8000+\delta(8960+\delta(2240+\delta(2144+\delta(557+\delta(230+\delta(71+2\delta(6+\delta))))))))))\}}{\{(2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))(4f(1+\delta)(2+\delta)(8+\delta^2)^2(92+\delta(-22+\delta(39+\delta(-5+4\delta))))-\beta^2(18496+\delta(7552+\delta(13184+\delta(6528+\delta(3952+\delta(1784+\delta(723+\delta(172+\delta(89+2\delta+6\delta^2))))))))))\}}$$

Obviously, the denominator is positive and the numerator is positive, thus, the sign of ($\tau_2 - \tau_{A4}$) is positive, i.e., $\tau_2 > \tau_{A4}$. In this case, $g_1(\tau) > 0$ holds if $\tau > \tau_2$. Thus, we obtain the result that $\pi_g^{CSP} - \pi_g^{CSI} > 0$ in the dual-option region ($f > f_2$ and $\tau > \tau_2$).

(1b) For the single-option region, i.e., if $f_1 < f < f_2$ and $\tau > \tau_1$ or $f > f_2$ and $\tau_1 < \tau < \tau_2$, only the purchase subsidy is optional.

(1c) Otherwise, the government provides no subsidy.

Proof of Proposition 4. Under the CM scenario, we compare the government's total expenditure in each region characterized in Theorem 2 (2). **(1)** For the triple-option region, comparing the government's total expenditure yields

$$\pi_g^{CMB} - \pi_g^{CMI} = -\frac{\{(-4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)) + (8f(1+\delta)(8+\delta^2)^2 + \beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))))\tau)^2\}}{24f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2} < 0$$

$$\pi_g^{CMB} - \pi_g^{CMP} = -\frac{\beta^2(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta)))))^2\tau^2}{8f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2} < 0$$

Thus, $\pi_g^{CMB} < \pi_g^{CMI}$ and $\pi_g^{CMB} < \pi_g^{CMP}$ hold in the triple-option region ($f > f_5$ and $\tau > \tau_5$). **(2)** For the dual-option region, comparing the government's total expenditure yields

$\pi_g^{CMI} - \pi_g^{CMP} = \frac{g_2(\tau)}{12f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$, where $g_2(\tau) = (8a^2f^2(8+\delta^2)^2 (12+\delta(1+\delta)(2+\delta))^2 - 4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(8f(1+\delta)(8+\delta^2)^2 + \beta^2 (-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))))\tau + (32f^2(1+\delta)^2(8+\delta^2)^4 + 8f\beta^2(1+\delta)(8+\delta^2)^2 (-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))) + \beta^4 (36608+\delta(2048+\delta(31872+\delta(64+\delta(9232-\delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta))))))))))\tau^2)$

Obviously, $g_2(\tau)$ is quadratic function of τ. **If** $\boldsymbol{f_3 < f < f_5}$**,** the coefficient of quadratic term is negative and $\boldsymbol{g_2(\tau)}$ **is a quadratic function graphed by a parabola opening downward.**

Solving $g_2(\tau) = 0$, we obtain two real roots, τ_{A5} and τ_{A6}, as follows:

$\tau_{A5} =$

$$\frac{\{(2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\sqrt{3}\beta^2(80+\delta(32+\delta(20 \; \delta(26+\delta(-1+5\delta)))))))}{\{(32f^2(1+\delta)^2(8+\delta^2)^4+8f\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\beta^4(36608+\delta(2048+\delta(31872+\delta(6 \; \delta(9232-\delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta)))))))))))}$$

$\tau_{A6} =$

$$\frac{\{(2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\sqrt{3}\beta^2(80+\delta(32+\delta(20 \; \delta(26+\delta(-1+5\delta)))))))}{\{(32f^2(1+\delta)^2(8+\delta^2)^4+8f\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\beta^4(36608+\delta(2048+\delta(31872+\delta(6 \; \delta(9232-\delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta)))))))))))}$$

$\tau_{A6} - \tau_{A5} =$

$$\frac{(4\sqrt{3}af\beta^2(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta))))))}{\{(32f^2(1+\delta)^2(8+\delta^2)^4+8f\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\beta^4(36608+\delta(2048+\delta(31872+\delta(6 \; \delta(9232-\delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta)))))))))))}$$

Obviously, since the denominator is positive, $\tau_{A6} > \tau_{A5}$ holds. Comparing thresholds τ_3 and τ_5 with these two real roots (τ_{A5} and τ_{A6}) yields

$\tau_{A5} - \tau_3 = -$

$$\frac{\{(2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta)))(\beta^2(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta)))))(4(-1+\sqrt{3})f(1+\delta)(8+\delta^2)^2+\beta^2(32-112\sqrt{3}+ \; \delta(-32+\delta(32-52\sqrt{3}+\delta(-32+6\sqrt{3}+\delta(8-7\sqrt{3}+(-8+3\sqrt{3})\delta)))))))}{\{(32f^2(1+\delta)^2(8+\delta^2)^4+8f\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\beta^4(36608+\delta(2048+\delta(31872+\delta(6 \; \delta(9232-\delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta)))))))))))}$$

The sign of the numerator is determined by the factor $(4(-1+\sqrt{3})f(1+\delta)(8+\delta^2)^2+\beta^2$ $(32-112\sqrt{3}+\delta(-32+\delta(32-52\sqrt{3}+\delta(-32+6\sqrt{3}+\delta(8-7\sqrt{3}+(-8+3\sqrt{3})\delta))))))$, whose sign is positive if and only if

$$f > \frac{\beta^2(304+80\sqrt{3}+\delta(32(1+\sqrt{3})+\delta(4(31+5\sqrt{3})+\delta(14+26\sqrt{3}+\delta(13-\sqrt{3}+(-1+5\sqrt{3})\delta)))))}{8(1+\delta)(8+\delta^2)^2}$$

The sign of the denominator is determined by the factor $(32f^2(1+\delta)^2(8+\delta^2)^4+8f\beta^2(1+\delta)$ $(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\beta^4$ $(36608+\delta(2048+\delta(31872+\delta(64+\delta(9232-\delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta)))))))))))$, which is a quadratic function of f graphed by a parabola opening upward. Thus, the denominator is positive if and only if

$$f < -\frac{\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))+\sqrt{3}(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta))))))}{8(1+\delta)(8+\delta^2)^2} \text{ or}$$

$$f > \frac{\beta^2(304+80\sqrt{3}+\delta(32(1+\sqrt{3})+\delta(4(31+5\sqrt{3})+\delta(14+26\sqrt{3}+\delta(13-\sqrt{3}+(-1+5\sqrt{3})\delta)))))}{8(1+\delta)(8+\delta^2)^2}$$

Comparing these thresholds with f_3 and f_5, we have

$$-\frac{\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))+\sqrt{3}(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta))))))}{8(1+\delta)(8+\delta^2)^2} < f_3 < f_5 <$$

$$\frac{\beta^2(304+80\sqrt{3}+\delta(32(1+\sqrt{3})+\delta(4(31+5\sqrt{3})+\delta(14+26\sqrt{3}+\delta(13-\sqrt{3}+(-1+5\sqrt{3})\delta)))))}{8(1+\delta)(8+\delta^2)^2}$$

Thus, for the dual-option region, i.e., if $f_3 < f < f_5$, both the denominator and the numerator are negative and we have $\tau_{A5} < \tau_3$.

Similarly, comparing τ_{A6} and τ_3, we summarize the comparing results as follows:

$$\tau_{A6} - \tau_3 = \frac{\left\{ \begin{array}{c} (2af\beta^2(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta)))))(4(1+\sqrt{3})f(1+\delta)(8+\delta^2)^2 \\ +\beta^2(-16(2+7\sqrt{3})+\delta(32+\delta(-4(8+13\sqrt{3})+\delta(32+6\sqrt{3}+\delta(-8-7\sqrt{3}+(8+3\sqrt{3})\delta)))))) \end{array} \right\}}{\left\{ \begin{array}{c} ((4f(1+\delta)(8+\delta^2)^2+\beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta)))))(32f^2(1+\delta)^2(8+\delta^2)^4+8f\beta^2(1+\delta)(8+\delta^2)^2 \\ (-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\beta^4(36608+\delta(2048+\delta(31872+\delta(64+\delta(9232- \\ \delta(816+\delta(-244+\delta(164+\delta(321+\delta(-2+37\delta))))))))))) \end{array} \right\}}$$

If $f > \frac{\beta^2(16(2+7\sqrt{3})+\delta(-32+\delta(32+52\sqrt{3}-\delta(32+6\sqrt{3}+\delta(-8-7\sqrt{3}+(8+3\sqrt{3})\delta)))))}{4(1+\sqrt{3})(1+\delta)(8+\delta^2)^2}$, the numerator is positive.

If $f < -\frac{\left\{ \begin{array}{c} (\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\sqrt{3}\beta^2(1+\delta)(8+\delta^2)^2(80 \\ +\delta(32+\delta(20+\delta(26+\delta(-1+5\delta)))))) \end{array} \right\}}{8(1+\delta)^2(8+\delta^2)^4}$

or

$f > \frac{\left\{ \begin{array}{c} -\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\sqrt{3}\beta^2(1+\delta)(8+\delta^2)^2(80+ \\ \delta(32+\delta(20+\delta(26+\delta(-1+5\delta))))) \end{array} \right\}}{8(1+\delta)^2(8+\delta^2)^4}$,

the denominator is positive.

Comparing these three thresholds with f_3 and f_5, we have

$$\frac{\beta^2(16(2+7\sqrt{3})+\delta(-32+\delta(32+52\sqrt{3}-\delta(32+6\sqrt{3}+\delta(-8-7\sqrt{3}+(8+3\sqrt{3})\delta)))))}{4(1+\sqrt{3})(1+\delta)(8+\delta^2)^2} < f_3 < f_5$$

$$-\frac{\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))+\sqrt{3}(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta))))))}{8(1+\delta)(8+\delta^2)^2} < f_3$$

$$< f_5 < \frac{\left\{ \begin{array}{c} -\beta^2(1+\delta)(8+\delta^2)^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))+\sqrt{3}\beta^2(1+\delta)(8+\delta^2)^2(80+ \\ \delta(32+\delta(20+\delta(26+\delta(-1+5\delta))))) \end{array} \right\}}{8(1+\delta)^2(8+\delta^2)^4}$$

.

Thus, under condition $f_3 < f < f_5$, the numerator is positive and the denominator is negative. Thus, $\tau_{A6} < \tau_3$ holds if $f_3 < f < f_5$. We have $\tau_{A5} < \tau_{A6} < \tau_3 < \tau_5$. Since $\boldsymbol{g_2(\tau)}$ **is a quadratic function graphed by a parabola opening downward with** $\tau_{A5} < \tau_{A6} < \tau_3 < \tau_5$ under the condition $f_3 < f < f_5$, $\boldsymbol{g_2(\tau) < 0}$ holds if $\tau_3 < \tau < \tau_5$. That is, if $f_3 < f < f_5$ and $\tau_3 < \tau < \tau_5$, $\pi_g^{CMI} < \pi_g^{CMP}$ holds.

Similarly, we can obtain the same comparing result, i.e., $\pi_g^{CMI} < \pi_g^{CMP}$ holds under the condition $f > f_5$ and $\tau_3 < \tau < \tau_5$.

That is, $\pi_g^{CMI} < \pi_g^{CMP}$ always holds in the dual-option region. Taken the dual-option region together with the single-option region where only the infrastructure subsidy is optional characterized in Theorem 2 (2c), we obtain the conditions under which $\pi_g^{CMI} < \pi_g^{CMP}$ holds. That is, if $f_3 < f < f_5$ and $\tau > \tau_3$ or $f > f_5$ and $\tau_3 < \tau < \tau_5$ or $f_4 < f < f_3$ and $\tau > \tau_4$ or $f > f_3$ and $\tau_4 < \tau < \tau_3$, the government prefers to provide infrastructure subsidy.

Otherwise, the government provides no subsidy.

Thus, the proof is completed.

Proof of Proposition 5. (1) Comparing the two firms' profits under the BS scenario, we obtain

$$\pi_s^{BSP} - \pi_s^{BSI} = -\frac{\left(af+(4f-\beta^2)\tau\right)^2}{9f\beta^2} < 0$$

$$\pi_m^{BSP} - \pi_m^{BSI} = 0$$

(2) Comparing firms' profits under the BM scenario, we obtain

$$\pi_s^{BMP} - \pi_s^{BMI} = \pi_s^{BMI} - \pi_s^{BMB} = 0$$

$$\pi_m^{BMB} - \pi_m^{BMP} = \frac{\beta^2\tau^2}{64f} > 0$$

$$\pi_m^{BMB} - \pi_m^{BMI} = -\frac{(8af-32f\tau+7\beta^2\tau)(8af-(32f-\beta^2)\tau)}{576f\beta^2}$$

$$\pi_m^{BMP} - \pi_m^{BMI} = -\frac{\left(2af-(8f-\beta^2)\tau\right)^2}{36f\beta^2} < 0.$$

Under the condition of positive subsidy (i.e., $f > \frac{7\beta^2}{32}$ and $\tau > \frac{8af}{32f-7\beta^2}$ and $f > \frac{\beta^2}{8}$ and $\tau > \frac{2af}{8f-\beta^2}$), $(8af - 32f\tau + 7\beta^2\tau) < 0$ and $8af - (32f - \beta^2)\tau < 0$ hold. Thus, $\pi_m^{BMB} < \pi_m^{BMI}$. That is, $\pi_m^{BMP} < \pi_m^{BMB} < \pi_m^{BMI}$.

(3) Comparing firms' profits under the CS scenario, we obtain

$$\pi_s^{CSP} - \pi_s^{CSI} = -\frac{(af(12+\delta(1+\delta)(2+\delta)) + (-2f(1+\delta)(8+\delta^2) + \beta^2(12+\delta(4+\delta+\delta^2)))\tau)^2}{9f\beta^2(12+\delta(1+\delta)(2+\delta))^2} < 0$$

$$\pi_m^{CSP} - \pi_m^{CSI} = 0$$

Thus, $\pi_s^{CSP} < \pi_s^{CSI}$ and $\pi_m^{CSP} = \pi_m^{CSI}$.

(4) Comparing firms' profits under the CM scenario, we obtain

$$\pi_s^{CMP} - \pi_s^{CMI} = \pi_s^{CMI} - \pi_s^{CMB} = 0$$

$$\pi_m^{CMB} - \pi_m^{CMP} = \frac{\beta^2(80 + \delta(32 + \delta(20 + \delta(26 + \delta(-1 + 5\delta)))))^2\tau^2}{16f(8 + \delta^2)^2(12 + \delta(1 + \delta)(2 + \delta))^2} > 0$$

$$\pi_m^{CMB} - \pi_m^{CMI} = -\frac{\left\{\begin{array}{l}\left(4af(8 + \delta^2)(12 + \delta(1 + \delta)(2 + \delta)) - \left(8f(1 + \delta)(8 + \delta^2)^2 + \beta^2(-304 + \delta(-32 + \delta(-124 + (-14 + \delta)\delta(1 + \delta))))\right)\tau\right)\\ \left((4af(8 + \delta^2)(12 + \delta(1 + \delta)(2 + \delta)) - (8f(1 + \delta)(8 + \delta^2)^2 + \beta^2(176 + \delta(160 + \delta(-4 + \delta(142 + \delta(-19 + 31\delta))))))\tau\right)\end{array}\right\}}{144f\beta^2(8 + \delta^2)^2(12 + \delta(1 + \delta)(2 + \delta))^2}$$

$(4af(8 + \delta^2)(12 + \delta(1 + \delta)(2 + \delta)) - (8f(1 + \delta)(8 + \delta^2)^2 + \beta^2 (-304 + \delta(-32 + \delta(-124 + (-14 + \delta)\delta(1 + \delta)))))\tau) < 0$ and $(4af(8 + \delta^2)(12 + \delta(1 + \delta)(2 + \delta)) - (8f(1 + \delta)(8 + \delta^2)^2 + \beta^2 (176 + \delta(160 + \delta(-4 + \delta(142 + \delta(-19 + 31\delta))))))\tau) < 0$ under the condition for positive subsidy. Thus, $\pi_m^{CMB} < \pi_m^{CMI}$ and we have $\pi_m^{CMP} < \pi_m^{CMB} < \pi_m^{CMI}$.

Proof of Proposition 7. (1) (a) $t^{BSP} - t^{BMP} = -\frac{\beta^2\tau}{4f} < 0$;

$t^{CSP} - t^{CMP} = -\frac{\beta^2(1+\delta)(4-(2-\delta)\delta)(20+\delta(2+5\delta))\tau}{2f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} < 0.$

(b) $x_1^{BSP} - x_1^{BMP} = 0$ and $x_1^{CSP} - x_1^{CMP} = 0.$

(c) $x_2^{BSP} - x_2^{BMP} = \frac{\beta\tau}{4f} > 0$ $x_2^{CSP} - x_2^{CMP} = \frac{\beta(1+\delta)(4-(2-\delta)\delta)(20+\delta(2+5\delta))\tau}{2f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} > 0$

(2) (a) $K^{BSI} - K^{BMI} = -\frac{\beta\tau}{3} < 0$ and

$K^{CSI} - K^{CMI} = -\frac{2\beta(1+\delta)(4+(-2+\delta)\delta)(20+\delta(2+5\delta))\tau}{3(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} < 0$

(b) $x_1^{BSI} - x_1^{BMI} = -\frac{\beta\tau}{12f} < 0$

$x_1^{CSI} - x_1^{CMI} = -\frac{\beta(1+\delta)(4+(-2+\delta)\delta)(20+\delta(2+5\delta))\tau}{6f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} < 0$

(c) $x_2^{BSI} - x_2^{BMI} = \frac{\beta\tau}{12f}$

$x_2^{CSI} - x_2^{CMI} = \frac{\beta(1+\delta)(4+(-2+\delta)\delta)(20+\delta(2+5\delta))\tau}{6f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}$.

Proof of Proposition 8.

$$x_1^{BSP} - x_1^{CSI} = \frac{2af(12 + 2\delta + 3\delta^2 + \delta^3) - 4f(8 + 8\delta + \delta^2 + \delta^3)\tau + \beta^2(24 + 5\delta + 5\delta^2 + 2\delta^3)\tau}{3f\beta(12 + 2\delta + 3\delta^2 + \delta^3)}$$

Under the preconditions of positive subsidies ($f > \frac{\beta^2(12+4\delta+\delta^2+\delta^3)}{2(1+\delta)(8+\delta^2)}$ and $\tau > \frac{af(12+\delta(1+\delta)(2+\delta))}{2f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2))}$), the sign of the numerator is negative. That is, $x_1^{BSP} - x_1^{CSI} < 0$ holds.

$$t^{BMB} - t^{CMB} = \frac{(16f(128 - 32\delta + 56\delta^2 + 4\delta^3 + 5\delta^4 + \delta^5) - \beta^2(64 + 48\delta + 4\delta^2 + 42\delta^3 - 5\delta^4 + 9\delta^5))\tau}{8f(8 + \delta^2)(12 + 2\delta + 3\delta^2 + \delta^3)}$$

Under the preconditions of positive subsidies ($f > \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$

and $\tau > \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$), the sign of the numerator is positive. That is, $t^{BMB} - t^{CMB} > 0$ holds.

Obviously, we have $x_1^{BMB} = x_1^{CMB}$.

$$K^{BMB} - K^{CMB} = -\frac{\beta(64 + 48\delta + 4\delta^2 + 42\delta^3 - 5\delta^4 + 9\delta^5)\tau}{4(8 + \delta^2)(12 + 2\delta + 3\delta^2 + \delta^3)} < 0$$

Proof of Proposition 9. (1) $\pi_g^{BSP} - \pi_g^{BMP} = -\frac{\beta^2\tau^2}{4f} < 0$

$$\pi_g^{CSP} - \pi_g^{CMP} = -\frac{\beta^2(1+\delta)(4+(-2+\delta)\delta)(20+\delta(2+5\delta))\tau^2}{2f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))} < 0.$$

(2) $\pi_g^{BSI} - \pi_g^{BMI} = \frac{8af-(32f+3\beta^2)\tau}{48f}$

Under the condition of positive subsidy, i.e., $f > \frac{\beta^2}{8}$ and $\tau > \frac{2af}{8f-\beta^2}$, $\pi_g^{BSI} < \pi_g^{BMI}$ holds.

$$\pi_g^{CSI} - \pi_g^{CMI} = -\frac{(-4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))+(8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta)))))\tau)^2}{12f\beta^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2} < 0.$$

Proof of Proposition 10. (1) $\pi_g^{CSP} - \pi_g^{BSP} = -\frac{(\beta^2(1-\delta)\delta+2f(16+\delta(-4+\delta(5+\delta))))\tau^2}{f(12+\delta(1+\delta)(2+\delta))} < 0.$

$$\pi_g^{CMP} - \pi_g^{BMP} = \frac{(-8f(8+\delta^2)(16+\delta(-4+\delta(5+\delta)))+\beta^2(64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta))))))\tau^2}{4f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}$$

Under the condition of positive subsidy, i.e., $f > \frac{\beta^2(112+\delta^2(52+\delta(-6+(7-3\delta)\delta)))}{4(1+\delta)(8+\delta^2)^2}$, the factor $(-8f(8 + \delta^2)(16 + \delta(-4 + \delta(5 + \delta))) + \beta^2(64 + \delta(48 + \delta(4 + \delta(42 + \delta(-5 + 9\delta))))))$ is negative. Thus, $\pi_g^{CMP} - \pi_g^{BMP} < 0$.

(2) $\pi_g^{BSI} - \pi_g^{CSI} =$

$$\frac{\left\{\begin{array}{c}2a^2f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2-2af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(8f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))+\beta^2(-1+\delta)\\(8+\delta(-8+\delta(8+\delta(-1+2\delta)))))\tau+(32f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2+2f\beta^2(8+\delta^2)^2(-208+\delta(32+\delta(-100+\\\delta(-40+\delta(-1+\delta(-10+3\delta))))))-\beta^4(-1+\delta)(-64+\delta(832+\delta(64+\delta(448+\delta(16+\delta(140+\delta(-13+\delta(34+\delta(-3+4\delta)))))))))\tau^2\end{array}\right\}}{\{3f\beta^2(8+\delta^2)^2(12+2\delta+3\delta^2+\delta^3)^2\}}$$

Then, we focus on the numerator of $(\pi_g^{BSI} - \pi_g^{CSI})$, i.e., $N =$

$$2a^2f^2(8 + \delta^2)^2(12 + \delta(1 + \delta)(2 + \delta))^2 - 2af(8 + \delta^2)(12 + \delta(1 + \delta)(2 + \delta))(8f(8 + \delta^2)(12 + \delta(1 + \delta)(2 + \delta)) + \beta^2(-1 + \delta)(8 + \delta(-8 + \delta(8 + \delta(-1 + 2\delta)))))\tau + (32f^2(8 + \delta^2)^2(12 + \delta(1 + \delta)(2 + \delta))^2 + 2f\beta^2(8 + \delta^2)^2(-208 + \delta(32 + \delta(-100 + \delta(-40 + \delta(-1 + \delta(-10 + 3\delta)))))) - \beta^4(-1 + \delta)(-64 + \delta(832 + \delta(64 + \delta(448 + \delta(16 + \delta(140 + \delta(-13 + \delta(34 + \delta(-3 + 4\delta)))))))))\tau^2.$$

Under the condition of positive subsidy ($f > \frac{\beta^2}{4}$), the coefficient of τ^2 is positive and the axis of symmetry of N is

$$\tau = \tau_{as} = \frac{\{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(8f(8+\delta^2)(12+\delta(1+\delta)(2+\delta))+\beta^2(-1+\delta)(8+\delta(-8+\delta(8+\delta(-1+2\delta)))))\}}{\left\{\begin{matrix}32f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2+2f\beta^2(8+\delta^2)^2(-208+\delta(32+\delta(-100+\delta(-40+\delta(-1+\delta(-10+3\delta))))))\\ -\beta^4(-1+\delta)(-64+\delta(832+\delta(64+\delta(448+\delta(16+\delta(140+\delta(-13+\delta(34+\delta(-3+4\delta)))))))))\end{matrix}\right\}}$$

Since τ_{as} is larger then $\frac{af}{4f-\beta^2}$, under the condition of positive subsidy ($\tau > \frac{af}{4f-\beta^2}$), the minimum value of N is obtained when $\tau = \tau_{as}$, i.e.,

$$N|_{\tau=\tau_{as}} = \frac{\left\{\begin{matrix}\beta^2(4f(1+\delta)(4+(-2+\delta)\delta)(8+\delta^2)(20+\delta(2+5\delta))(16+\delta(-4+\delta(5+\delta)))+\beta^2(-1+\delta)(-192+\\ \delta(1856+\delta(-192+\delta(1232+\delta(-224+\delta(440+\delta(-107+\delta(105+2\delta(-7+6\delta))))))))))\end{matrix}\right\}}{\left\{\begin{matrix}32f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2+2f\beta^2(8+\delta^2)^2(-208+\delta(32+\delta(-100\\ +\delta(-40+\delta(-1+\delta(-10+3\delta))))))-\beta^4(-1+\delta)(-64+\delta(832+\delta(64+\delta(448+\delta(16+\delta(140+\delta(-13+\\ \delta(34+\delta(-3+4\delta)))))))))\end{matrix}\right\}} > 0$$

Thus, $\pi_g^{BSI} > \pi_g^{CSI}$.

$$\pi_g^{BMI} - \pi_g^{CMI} = \frac{\left\{\begin{matrix}-8af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(16f(8+\delta^2)(16+\delta(-4+\delta(5+\delta)))-\beta^2(64+\delta(48+\delta(4+\\ \delta(42+\delta(-5+9\delta))))))+(128f^2(8+\delta^2)^2(16+\delta(-4+\delta(5+\delta)))(32+\delta(12+\delta(7+3\delta)))+\beta^4(-128\\ +\delta(16+\delta(-68+\delta(22+\delta(-11+7\delta)))))(64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta)))))-32f\beta^2(8+\delta^2)^2(128+\\ \delta(48+\delta(76+\delta(36+\delta(25+\delta(6+5\delta)))))))\tau\end{matrix}\right\}}{48f\beta^2(8+\delta^2)^2(12+2\delta+3\delta^2+\delta^3)^2}$$

Then, we focus on the numerator of $(\pi_g^{CMI} - \pi_g^{BMI})$, i.e., $N_1 = -8af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(16f(8+\delta^2)(16+\delta(-4+\delta(5+\delta)))-\beta^2(64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta))))))+(128f^2(8+\delta^2)^2(16+\delta(-4+\delta(5+\delta)))(32+\delta(12+\delta(7+3\delta)))+\beta^4(-128+\delta(16+\delta(-68+\delta(22+\delta(-11+7\delta)))))(64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta)))))-32f\beta^2(8+\delta^2)^2(128+\delta(48+\delta(76+\delta(36+\delta(25+\delta(6+5\delta)))))))\tau$, which is linear function of τ. Under the condition of positive subsidy, i.e., $f > \frac{\beta^2}{8}$, the coefficient of τ is positive. Solving $N_1 = 0$, we obtain the unique root

$$\tau = \frac{\{8af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(16f(8+\delta^2)(16+\delta(-4+\delta(5+\delta)))-\beta^2(64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta))))))\}}{\left\{\begin{matrix}128f^2(8+\delta^2)^2(16+\delta(-4+\delta(5+\delta)))(32+\delta(12+\delta(7+3\delta)))+\beta^4(-128+\delta(16+\delta(-68+\delta(22+\delta(-11+7\delta)))))\\ (64+\delta(48+\delta(4+\delta(42+\delta(-5+9\delta)))))-32f\beta^2(8+\delta^2)^2(128+\delta(48+\delta(76+\delta(36+\delta(25+\delta(6+5\delta))))))\end{matrix}\right\}}$$

which is lower than $\frac{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{2(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)}$. Thus, under the condition of positive subsidy, i.e., $f > \frac{\beta^2}{8}$ and $\tau > \frac{af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{2(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)}$, $\pi_g^{BMI} - \pi_g^{CMI} > 0$.

(3) $\pi_g^{BMB} - \pi_g^{CMB} =$

$$\frac{\left\{\begin{matrix}-64af(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2+64f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))(32+\delta(12+\delta(7+\\ 3\delta)))\tau-\beta^2(280576+\delta(76800+\delta(225792+\delta(71424+\delta(71888+\delta(20016+\delta(11756+\delta(1716+\delta(1065+\delta(-18+61\delta))))))))))\end{matrix}\right.}{32f(8+\delta^2)^2(12+2\delta+3\delta^2+\delta^3)^2}$$

Then, we focus on the numerator of $(\pi_g^{BMB} - \pi_g^{CMB})$, i.e., $N_2 = -64af(8+\delta^2)^2 (12+\delta(1+\delta)(2+\delta))^2 + (64f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))(32+\delta(12+\delta(7+3\delta))) - \beta^2(280576 + \delta(76800+\delta(225792+\delta(71424+\delta(71888+\delta(20016+\delta(11756+\delta(1716+\delta(1065+\delta(-18+61\delta))))))))))\tau$. N_2 is linear function of τ and under the condition of positive subsidy, i.e., $f > \frac{7\beta^2}{32}$, the coefficient of τ is positive. Solving $N_2 = 0$, we obtain the unique root

$$\tau = \frac{64af(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}{\left\{\begin{array}{c}64f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))(32+\delta(12+\delta(7+3\delta))) - \beta^2(280576+\delta(76800\\ +\delta(225792+\delta(71424+\delta(71888+\delta(20016+\delta(11756+\delta(1716+\delta(1065+\delta(-18+61\delta)))))))))\end{array}\right\}} < \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$$

Thus, under the condition of positive subsidy, i.e., $\tau > \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2+\beta^2(-304+\delta(-32+\delta(-124+(-14+\delta)\delta(1+\delta))))}$, $N_2 > 0$ holds and $\pi_g^{BMB} - \pi_g^{CMB} > 0$.

Proof of Proposition 11. $t^{BSP} - t^{BMB} = -\frac{\beta^2\tau}{8f} < 0$.

$$K^{CSI} - K^{CMB} = -\frac{4af(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5) + (-8f(1+\delta)(8+\delta^2)^2+\beta^2(624+224\delta+140\delta^2+126\delta^3+\delta^4+19\delta^5))\tau}{6\beta(8+\delta^2)(12+2\delta+3\delta^2+\delta^3)}$$

Solving $-8f(1+\delta)(8+\delta^2)^2+\beta^2(624+224\delta+140\delta^2+126\delta^3+\delta^4+19\delta^5) = 0$ yields $f = f_7 = \frac{\beta^2(624+\delta(224+\delta(140+\delta(126+\delta+19\delta^2))))}{8(1+\delta)(8+\delta^2)^2}$, solving $4af(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5) + \left(-8f(1+\delta)(8+\delta^2)^2+\beta^2(624+224\delta+140\delta^2+126\delta^3+\delta^4+19\delta^5)\right)\tau = 0$ yields $\tau = \tau_6 = \frac{4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{8f(1+\delta)(8+\delta^2)^2-\beta^2(624+\delta(224+\delta(140+\delta(126+\delta+19\delta^2))))}$

Obviously, if $f < f_7$ and $\tau < \tau_6$ or $f > f_7$ and $\tau > \tau_6$, $K^{CSI} > K^{CMB}$ holds, otherwise, $K^{CSI} < K^{CMB}$.

Proof of Proposition 12. The equilibrium outcomes of the four scenarios can be summarized in the Table A1.

Table A1. The equilibrium outcomes under four scenarios.

Scenarios	Expenditure	π_s	π_m
BS	$\frac{1}{4}\tau(-4a+(16-$	$\frac{1}{4}(8-\frac{\beta^2}{f})\tau^2$	τ^2

BM	$\tau(-a+(4-\frac{17\beta}{32f}$	$2\tau^2$	$(1-\frac{3\beta^2}{64f})\tau^2$
CS			$\frac{4(4-3\delta^4-\delta^6)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2}$
CM		$\frac{(1+\delta)(2+\delta)(6+(-1+\delta)\delta)(8+\delta^2)\tau^2}{(12+\delta(1+\delta)(2+\delta))^2}$	

$$\pi_s^{CS}=\frac{\left\{\begin{matrix}(1+\delta)(80+\delta(16+\delta(6+5\delta)(6+(-1+\delta)\delta)))\\(4f(1+\delta)(8+\delta^2)\tau-\beta^2(12+\delta(4+\delta+\delta^2))\tau)^2\end{matrix}\right\}}{2(12+\delta(1+\delta)(2+\delta))^2(-4f(1+\delta)(8+\delta^2)+\beta^2(12+\delta(4+\delta+\delta^2)))^2}$$

$$\pi_s^{CS}=\frac{\left\{\begin{matrix}(1+\delta)(80+\delta(16+\delta(6+5\delta)(6+(-1+\delta)\delta)))\\(4f(1+\delta)(8+\delta^2)\tau-\beta^2(12+\delta(4+\delta+\delta^2))\tau)^2\end{matrix}\right\}}{2(12+\delta(1+\delta)(2+\delta))^2(-4f(1+\delta)(8+\delta^2)+\beta^2(12+\delta(4+\delta+\delta^2)))^2}$$

$$\pi_g^{CS}=\frac{\left\{\begin{matrix}(1+\delta)(4+(-2+\delta)\delta)(20+\delta(2+5\delta))\tau(-4af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))+\\(8f(1+\delta)(8+\delta^2)^2+\beta^2(112+\delta(16+\delta(36+\delta(-4+(5-3\delta)\delta)))))\tau)\end{matrix}\right\}}{12f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

$$\pi_s^{CM}=\frac{\left\{\begin{matrix}(-64f(-1+\delta^2)(2+\delta^2)^2(8+\delta^2)^2-\beta^2(-112+\delta^2(-52+\delta(6+\delta(-7+3\delta))))\\(48+\delta(64+\delta(-12+\delta(58+\delta(-9+13\delta))))))\tau^2\end{matrix}\right\}}{12f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

$$\pi_g^{CM}=\frac{\left\{\begin{matrix}2a^2f^2(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5)^2-4af(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5)\\\left(\beta^2(-1+\delta)(2+\delta^2)^2+2f(1+\delta)(8+\delta^2)^2\right)\tau+4(-\beta^4(-1+\delta)^2(2+\delta^2)^4\\+2f^2(1+\delta)^2(8+\delta^2)^4+2f\beta^2(-1+\delta^2)(16+10\delta^2+\delta^4)^2)\tau^2\end{matrix}\right\}}{9f\beta^2(8+\delta^2)^2(12+2\delta+3\delta^2+\delta^3)^2}$$

$$\pi_m^{CM}=\frac{\left\{\begin{matrix}a^2f^2(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5)^2-4af(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5)\\(2\beta^2(-1+\delta)(2+\delta^2)^2+f(1+\delta)(8+\delta^2)^2)\tau+4(-5\beta^4(-1+\delta)^2(2+\delta^2)^4\\+f^2(1+\delta)^2(8+\delta^2)^4-5f\beta^2(-1+\delta^2)(16+10\delta^2+\delta^4)^2)\tau^2\end{matrix}\right\}}{12f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

Taking the derivative of the above equilibrium outcomes with respect to the three parameters, respectively, we obtain the results summarized in Proposition 12.

Appendix D: The formulation of alternative government objective and the proof for the equivalence.

Taking the BS scenario as an example, we show that this decision problem is equivalent to the decision-making scenario where the government seeks to achieve a predetermined adoption target at a minimum cost. Facing a fixed budget for the total policy expenditure, the government's decision problem can be formulated as follows:

$$\begin{cases}\max\limits_{(t,K,x_1)} D(t,K,x_1)=\max\limits_{(K,s,x_1)}\left(\dfrac{2f(a+t)+\beta K+2f\beta x_1}{8f-\beta^2}\right)\\ \text{Subject to:}\\ \pi_g(t,K,x_1)\le B,\\ q_m\in\max\limits_{q_m}\pi_m^{BS},\\ x_2\in\max\limits_{x_2}\pi_s^{BS},\\ K,t\ge 0.\end{cases}\qquad(ED.1)$$

Recall that in the derivation of the decision problem where the government seeks the most cost-effective solution subject to a given adoption target (as shown in the following), we have demonstrated that both $D(t,K,x_1)$ and $\pi_g(t,K,x_1)$ given in the following decision problem increase with x_1 and K. Thus, it is optimal for the government to set the least-cost solution so that $\pi_g = B$.

$$\begin{cases} \min\limits_{(t,K,x_1)} \pi_g(t,K,x_1) = \min\limits_{(K,s,x_1)} (fx_1^{\ 2} + tq_m + Kx_2) \\ \text{Subject to:} \\ q_m \geq \tau, \\ q_m \in \max\limits_{q_m} \pi_m^{BS}, \\ x_2 \in \max\limits_{x_2} \pi_s^{BS}, \\ K,t \geq 0. \end{cases} \qquad (ED.2)$$

The achieved optimal demand $D^*(t,K,x_1)$ is equivalent to $\tau = D^*(t,K,x_1)$. We now present the proof for the equivalence of these two decision problems by contradiction. Assume that $(t^*,{x_1}^*,K^*)$ is a feasible solution of (ED.1) with $D^*(t^*,{x_1}^*, K^*) = \tau$, but not the optimal solution. This suggests the existence of another solution $(t^{*1},{x_1}^{*1}, K^{*1})$ of (ED.1) satisfying $D^*(t^{*1},{x_1}^{*1}, K^{*1}) \geq \tau$ and $\pi_g(t^{*1},{x_1}^{*1}, K^{*1}) < \pi_g(t^*,{x_1}^*,K^*) = B$. Since $(t^{*1},{x_1}^{*1})$ is also feasible for (ED.1) with $D^*(t^{*1},{x_1}^{*1}, K^{*1}) \geq \tau = D^*(t^*,{x_1}^*, K^*)$, we find a solution $(t^{*1},{x_1}^{*1}, K^{*1})$ that is at least as good as $(t^*,{x_1}^*, K^*)$. The next step is to find a solution $(t^{*2},{x_1}^{*2}, K^{*2})$ that meets the budget constraint $\pi_g(t^{*2},{x_1}^{*2}, K^{*2}) = B$ and has a higher $D^*(t^{*2},{x_1}^{*2}, K^{*2})$ than $D^*(t^{*1},{x_1}^{*1}, K^{*1})$, contracting the original assumption. Therefore, we conclude that (ED.1) and (ED.2) have the same solution, with the solution given in Proposition 1. Overall, the government's optimization problem to maximize the adoption level subject to a policy budget constraint, is equivalent to the problem where the government aims to minimize the policy expenditure given a predetermined EV adoption level.

Appendix E: The Proof of Proposition 6.

Proof of Proposition 6. (1) Under BS scenario, either a pure purchase subsidy or infrastructure subsidy is optional. The social welfare under two forms of subsidies is given as

$$SW^{BSP} = a\tau + \frac{\tau^2}{2} + \frac{1}{2}\left(-2 + \frac{\beta^2}{f}\right)\tau^2$$

$$SW^{BSI} = \frac{\tau^2}{2} - \frac{10a^2f^2 + 2af(-40f + \beta^2)\tau + (160f^2 - 62f\beta^2 + \beta^4)\tau^2}{18f\beta^2}$$

Comparing the social welfare values under the purchase subsidy and infrastructure subsidy yields

$$SW^{BSP}-SW^{BSI}=\frac{5\left(8f-\beta^{2}\right)^{2}\left(af-4f\tau+\beta^{2}\tau\right)^{2}}{9f(-8f\beta+\beta^{3})^{2}}>0$$

(2) Under BM scenario, all the three policies (a pure purchase subsidy, a pure infrastructure subsidy and both subsidies) are optional. The social welfare under each policy is given as

$$SW^{BMP}=a\tau+\frac{1}{16}\left(-\frac{31}{2}+\frac{7\beta^{2}}{f}\right)\tau^{2}$$

$$SW^{BMI}=-\frac{40a^{2}f^{2}+4af(-80f+\beta^{2})\tau+(640f^{2}-268f\beta^{2}+\beta^{4})\tau^{2}}{72f\beta^{2}}$$

$$SW^{BMB}=\frac{5}{2}\tau^{2}$$

Comparing the social welfare values under different policies yields

$$SW^{BMB}-SW^{BMP}=\frac{-16af\tau+48f\tau^{2}-7\beta^{2}\tau^{2}}{16f}$$

$$SW^{BMB}-SW^{BMI}=\frac{40a^{2}f^{2}+4af(-80f+\beta^{2})\tau+(640f^{2}-88f\beta^{2}+\beta^{4})\tau^{2}}{72f\beta^{2}}$$

$$SW^{BMP}-SW^{BMI}=\frac{(4af-16f\tau+5\beta^{2}\tau)(20af-80f\tau+13\beta^{2}\tau)}{144f\beta^{2}}$$

It is worth noting that the social welfare is compared under the preconditions under which all the policies are optional (i.e., conditions to ensure positive subsidies).

Recall from the derivation of BM scenario (Page 17-21 of the appendix), the preconditions of positive subsidies is $\{f>\frac{7\beta^{2}}{32}$ and $\tau>\frac{8af}{32f-7\beta^{2}}\}$. Under this precondition, we obtain the following results:

(2a) if $\tau<\frac{16af}{48f-7\beta^{2}}$, $SW^{BMB}<SW^{BMP}$; otherwise, $SW^{BMB}>SW^{BMP}$.

(2b) if $\tau<-\frac{2(af(-80f+\beta^{2})+3\sqrt{a^{2}f^{2}(80f\beta^{2}-\beta^{4})})}{640f^{2}-88f\beta^{2}+\beta^{4}}$ or $\tau>\frac{2(af(80f-\beta^{2})+6\sqrt{a^{2}f^{2}(80f\beta^{2}-\beta^{4})})}{640f^{2}-88f\beta^{2}+\beta^{4}}$ $SW^{BMB}>SW^{BMI}$; otherwise, $SW^{BMB}<SW^{BMI}$.

(2c) if $f<\frac{13\beta^{2}}{80}$ or $f>\frac{5\beta^{2}}{16}$, when $\tau<\frac{4af}{16f-5\beta^{2}}$, $SW^{BMP}<SW^{BMI}$; otherwise $SW^{BMP}>SW^{BMI}$.

(2d) if $\frac{13\beta^{2}}{80}<f<\frac{5\beta^{2}}{16}$, when $\tau<\frac{4af}{16f-5\beta^{2}}$, $SW^{BMP}>SW^{BMI}$; otherwise $SW^{BMP}<SW^{BMI}$.

Combining all the comparison results, we obtain the results under BM scenario in Table

1.

(3) Under CS scenario, either a pure purchase subsidy or infrastructure subsidy is optional. The social welfare under two forms of subsidies is given as

$$
\begin{aligned}
SW^{CSP} = a\tau + \frac{1}{2f(-16f+\beta^2)^2(-4+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}(\beta^6(-4+\delta^2)^2(144+\delta(48+\delta(74 \\
+\delta(40+\delta(11+\delta(6+\delta))))))-256f^3(1+\delta)(1280+256\delta+\delta^3(384+\delta(-292+\delta(\\
-212+\delta(63+\delta(-33+2\delta(1+5\delta)))))))+64f^2\beta^2(2+\delta)(5248+\delta(320+\delta(624 \\
+\delta(360+\delta(-570+\delta(-189+\delta(50+\delta(-4+3\delta)(8+3\delta))))))))-2f\beta^4(2+\delta)^2 \\
(8896+\delta(-4928+\delta(2368+\delta(-544+\delta(-1212+\delta(396+\delta(-155+3\delta(6 \\
+7\delta)))))))))\tau^2
\end{aligned}
$$

$$
\begin{aligned}
SW^{CSI} = \frac{1}{18\beta^2}(-10a^2f+\frac{2a(20f(1+\delta)(8+\delta^2)-\beta^2(12+\delta(4+\delta+\delta^2)))\tau}{12+\delta(1+\delta)(2+\delta)} \\
+\frac{1}{f(-16f+\beta^2)^2(-4+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}(-\beta^8(-2+\delta)^2(2+\delta)^4(6+(-1 \\
+\delta)\delta)^2-10240f^4(-2+\delta)^2(1+\delta)^2(2+\delta)^2(8+\delta^2)^2-2f\beta^6(2+\delta)^2(-19776 \\
+\delta(12608+\delta(-10112+\delta(5072+\delta(-2540+\delta(464+\delta(-215+9(-10 \\
+\delta)\delta)))))))-256f^3\beta^2(1+\delta)(-55040+\delta(-14080+\delta(9984+\delta(3840+\delta(2988 \\
+\delta(252+\delta(47+\delta(-425+9\delta(-11+5\delta)))))))))+8f^2\beta^4(2+\delta)(-116224+\delta(\\
-15616+\delta(60800+\delta(2112+\delta(20264+\delta(-2036+\delta(762+\delta(-1165+\delta(-576 \\
+163\delta))))))))))\tau^2)
\end{aligned}
$$

Comparing the social welfare values under different policies yields

$$
SW^{CSP}-SW^{CSI} = \frac{\left\{\begin{array}{c}(af(12+\delta(1+\delta)(2+\delta))+(-2f(1+\delta)(8+\delta^2)+\beta^2(12+\delta+4\delta^2+\delta^3))\tau)(5af(12+\delta(1+\delta)) \\ (2+\delta))+(-10f(1+\delta)(8+\delta^2)+\beta^2(60+\delta(17+\delta(8+5\delta))))\tau)\end{array}\right\}}{9f\beta^2(12+\delta(1+\delta)(2+\delta))^2}
$$

Recall from the derivation of CS scenario (Page 21-23 of the appendix), the preconditions of positive subsidies is $\{f > f_2$ and $\tau > \tau_2\}$. Under this precondition, we obtain the following results: $SW^{CSP} > SW^{CSI}$.

(4) Under CM scenario, all the three policies (a pure purchase subsidy, a pure infrastructure subsidy and both subsidies) are optional. The social welfare under each policy is given as

$$
\begin{aligned}
SW^{CMP} \\
= a\tau - \frac{1}{4f(-16f+\beta^2)^2(-4+\delta^2)^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}(512f^3(1+\delta)(8+\delta^2)^2 \\
(1280+256\delta+\delta^3(384+\delta(-292+\delta(-212+\delta(63+\delta(-33+2\delta(1+5\delta)))))))+\beta^6(\\
-4+\delta^2)^2(-12032+\delta(-1024+\delta(-10112+\delta(-704+\delta(-2480+\delta(-240 \\
+\delta(260+\delta(-116+\delta(203+\delta(-22+23\delta))))))))))+4f\beta^4(1581056+\delta(147456 \\
+\delta(423936+\delta(40960+\delta(-353536+\delta(1024+\delta(-195008+\delta(23488+\delta(-23248 \\
+\delta(6272+\delta(952+\delta(776+\delta(-759+(182-179\delta)\delta)))))))))))))+128f^2\beta^2(\\
-425984+\delta(-65536+\delta(-106496+\delta(-14336+\delta(72320+\delta(30976+\delta(31008 \\
+\delta(9408+\delta(-2868+\delta(1556+\delta(-2453+\delta(74+\delta(-52+\delta(-50 \\
+41\delta)))))))))))))))\tau^2
\end{aligned}
$$

$$SW^{CMI} = -\frac{1}{9\beta^2(8+\delta^2)^2}(5a^2f(8+\delta^2)^2 - \frac{4a(8+\delta^2)(\beta^2(-1+\delta)(2+\delta^2)^2+5f(1+\delta)(8+\delta^2)^2)\tau}{12+\delta(1+\delta)(2+\delta)} \\ + \frac{1}{f(-16f+\beta^2)^2(-2+\delta)^2(2+\delta)^2(12+\delta(1+\delta)(2+\delta))^2}(8\beta^8(-2+\delta)^2(-1+\delta)^2(2 \\ +\delta)^2(2+\delta^2)^4 + 5120f^4(8+\delta^2)^4(-4-4\delta+\delta^2+\delta^3)^2 + 128f^3\beta^2(1+\delta)(8+\delta^2)^2(\\ -49920+\delta(-11008+\delta(7680+\delta(4096+\delta(2988+\delta(-132+\delta(159+\delta(-473+\delta(\\ -111+65\delta))))))))) - f\beta^6(1499136+\delta(1785856+\delta(1574912+\delta(-12288 \\ +\delta(1106688+\delta(-373248+\delta(709440+\delta(-190976+\delta(285968+\delta(-63168 \\ +\delta(59136+\delta(-9900+\delta(6009+13\delta(-38+17\delta)))))))))))))) + 4f^2\beta^4(11927552 \\ +\delta(14548992+\delta(6488064+\delta(1671168+\delta(371712+\delta(30720+\delta(-338176 \\ +\delta(460800+\delta(-75216+\delta(131136+\delta(-27552+\delta(8160+\delta(-3523+3\delta(-290 \\ +79\delta))))))))))))))))\tau^2)$$

$$SW^{CMB} = a\tau \\ + \frac{\left\{\begin{array}{c}(-2048f^3(1+\delta)(8+\delta^2)^2(1280+256\delta+\delta^3(384+\delta(-292+\delta(-212+\delta(63+\delta(-33+2\delta(1 \\ +5\delta))))))) - \beta^6(-4+\delta^2)^2(-67328+\delta(-19456+\delta(-53120+\delta(-19136+\delta(-15632+ \\ \delta(-6288+\delta(-1828+\delta(-908+\delta(29+\delta(-58+17\delta)))))))))) + 16f\beta^4(8+\delta^2)(-274432+ \\ \delta(-79872+\delta(-30976+\delta(-29696+\delta(45760+\delta(11072+\delta(15440+\delta(480+\delta(2152+\delta(-1168 \\ +\delta(161+\delta(-122+29\delta))))))))))) - 256f^2\beta^2(-1159168+\delta(-376832+\delta(-262144+\delta(-166912+\delta \\ (135424+\delta(91904+\delta(49152+\delta(38016+\delta(-1032+\delta(1816+\delta(-2710+\delta(-536+7\delta(-41+(-10+ \\ \delta)\delta)))))))))))))\tau^2\end{array}\right\}}{16f(-16f+\beta^2)^2(-4+\delta^2)^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2}$$

Comparing the social welfare values under different policies yields

$$SW^{CMB} - SW^{CMP} = \frac{3\beta^2(80+\delta(32+\delta(20+\delta(26+\delta(-1+5\delta)))))^2\tau^2}{16f(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2} > 0$$

$$SW^{CMB} - SW^{CMI} \\ = \frac{\left\{\begin{array}{c}80a^2f^2(8+\delta^2)^2(12+\delta(1+\delta)(2+\delta))^2 - 16af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))(20f(1+\delta)(8+\delta^2)^2 - \beta^2(880+ \\ +\delta(128+\delta(340+\delta(74+\delta(31+5\delta))))))\tau + (8f(1+\delta)(8+\delta^2)^2 + \beta^2(-304+\delta(-32+\delta(-124+ \\ (-14+\delta)\delta(1+\delta)))))(40f(1+\delta)(8+\delta^2)^2 - \beta^2(2000+\delta(352+\delta(740+\delta(226+ \\ \delta(59+25\delta))))))\tau^2\end{array}\right\}}{144f\beta^2(8+\delta^2)^2(12+2\delta+3\delta^2+\delta^3)^2}$$

$$SW^{CMP} - SW^{CMI} \\ = \frac{\left\{\begin{array}{c}20a^2f^2(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5)^2 - 4af(96+16\delta+36\delta^2+10\delta^3+3\delta^4+\delta^5)(20f(1+ \\ \delta)(8+\delta^2)^2 - \beta^2(880+128\delta+340\delta^2+74\delta^3+31\delta^4+5\delta^5))\tau + (80f^2(1+\delta)^2(8+\delta^2)^4 \\ -8f\beta^2(8+\delta^2)^2(880+1008\delta+468\delta^2+414\delta^3+105\delta^4+36\delta^5+5\delta^6) + \beta^4(108800+8192\delta+92544\delta^2+ \\ 4288\delta^3+24112\delta^4+624\delta^5-1316\delta^6+532\delta^7-1539\delta^8+134\delta^9-175\delta^{10}))\tau^2\end{array}\right\}}{36f\beta^2(8+\delta^2)^2(12+2\delta+3\delta^2+\delta^3)^2}$$

It is worth noting that the social welfare is compared under the preconditions under which all the policies are optional (i.e., conditions to ensure positive subsidies). Recall from the derivation of CM scenario (Page 21-26 of the appendix), the preconditions of positive subsidies is $\{f > f_5$ and $\tau > \tau_5\}$. Under this precondition, we obtain the following results:

(2a) $SW^{CMB} > SW^{CMP}$.

(2b) if $f < \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$, when $\tau < \frac{20af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{40f(1+\delta)(8+\delta^2)^2-\beta^2(2000+\delta(352+\delta(740+\delta(226+\delta(59+25\delta)))))}$, $SW^{BMB} > SW^{BMI}$; otherwise $SW^{BMB} < SW^{BMI}$.

(2c) if $f > \frac{\beta^2(304+\delta(32+\delta(124-(-14+\delta)\delta(1+\delta))))}{8(1+\delta)(8+\delta^2)^2}$, when $\tau < \frac{20af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{40f(1+\delta)(8+\delta^2)^2-\beta^2(2000+\delta(352+\delta(740+\delta(226+\delta(59+25\delta)))))}$, $SW^{BMB} < SW^{BMI}$; otherwise $SW^{BMB} > SW^{BMI}$.

Combining all the comparison results, we obtain the results under CM scenario in Table 1.

The threshold values for τ.

Γ_1:$\{\tau|\tau < \frac{16af}{48f-7\beta^2}\}$

Γ_2:$\{\tau|\frac{16af}{48f-7\beta^2} < \tau < \frac{4af}{16f-5\beta^2}\}$

Γ_3:$\{\tau|\tau > \frac{4af}{16f-5\beta^2}\ and\ \{\tau < -\frac{2(af(-80f+\beta^2)+3\sqrt{a^2f^2(80f\beta^2-\beta^4)})}{640f^2-88f\beta^2+\beta^4}$ or $\tau > \frac{2af(80f-\beta^2)+6\sqrt{a^2f^2(80f\beta^2-\beta^4)}}{640f^2-88f\beta^2+\beta^4}$

Γ_4:$\{\tau|\tau > \frac{4af}{16f-5\beta^2}\ and\ \{-\frac{2(af(-80f+\beta^2)+3\sqrt{a^2f^2(80f\beta^2-\beta^4)})}{640f^2-88f\beta^2+\beta^4} < \tau < \frac{2af(80f-\beta^2)+6\sqrt{a^2f^2(80f\beta^2-\beta^4)}}{640f^2-88f\beta^2+\beta^4}$

}

Γ_5:$\{\tau|\tau < \frac{16af}{48f-7\beta^2}\}$

Γ_6:$\{\tau|\frac{16af}{48f-7\beta^2} < \tau < \frac{4af}{16f-5\beta^2}\ and\ \{\tau < -\frac{2(af(-80f+\beta^2)+3\sqrt{a^2f^2(80f\beta^2-\beta^4)})}{640f^2-88f\beta^2+\beta^4}$ or $\tau > \frac{2af(80f-\beta^2)+6\sqrt{a^2f^2(80f\beta^2-\beta^4)}}{640f^2-88f\beta^2+\beta^4}\}\}$

Γ_7:$\{\tau|\frac{16af}{48f-7\beta^2} < \tau < \frac{4af}{16f-5\beta^2}\ and\ \{-\frac{2(af(-80f+\beta^2)+3\sqrt{a^2f^2(80f\beta^2-\beta^4)})}{640f^2-88f\beta^2+\beta^4} < \tau < \frac{2af(80f-\beta^2)+6\sqrt{a^2f^2(80f\beta^2-\beta^4)}}{640f^2-88f\beta^2+\beta^4}\}$

Γ_8:$\{\tau|\tau > \frac{4af}{16f-5\beta^2}\}$

Γ_9:$\{\tau|\tau < \frac{4af}{16f-5\beta^2}\}$

Γ_{10}:$\{\tau|\frac{4af}{16f-5\beta^2} < \tau < \frac{16af}{48f-7\beta^2}\}$

Γ_{11}:$\{\tau|\tau > \frac{16af}{48f-7\beta^2}\}$

Γ_{12}:$\{\tau|\tau < \frac{20af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{40f(1+\delta)(8+\delta^2)^2-\beta^2(2000+\delta(352+\delta(740+\delta(226+\delta(59+25\delta)))))}\}$

Γ_{13}:$\{\tau|\tau > \frac{20af(8+\delta^2)(12+\delta(1+\delta)(2+\delta))}{40f(1+\delta)(8+\delta^2)^2-\beta^2(2000+\delta(352+\delta(740+\delta(226+\delta(59+25\delta)))))}\}$

Appendix F: The SLR

6. Effects of different cultures on EV mass adoption

The results of model analysis indicate that consumer adoption intention, EV business, and the status of charging infrastructure construction have a significant impact on government policy decision. It is widely believed that national culture has a significant influence on consumers' EV adoption intention and EV business models. In this section, we extensively explore the impacts of cultural factors on promotion of EVs and the government's policy by global comparisons and systematical literature review (SLR). The purpose of the SLR is to clarify the opinions towards the effects of cultures on the EV adoption and government public policy. Together with the model analysis, this SLR would provide more specific policy implications for governments across different cultures.

6.1. Research methodology

Inspired by Tranfield et al. (2003), the SLR has been widely employed to comprehensively analyze different streams of literature. Following the guidance of Sauer and Seuring (2023), the SLR process entails six steps and 14 decisions, with the optional step of conducting subsequent statistical analysis. This review strictly adheres to these guidelines, ensuring a comprehensive and rigorous analysis.

The SLR process is divided into three stages: planning, conducting, and composing. In the planning stage, the review's necessity is justified, research questions are formulated, and the scope is determined. An inductive approach is adopted, drawing upon the theoretical framework provided by Vu et al. (2021), which identifies stages and influential factors in technology adoption within sustainable agriculture supply chain management (SCM). This framework provides the theoretical foundation for the review, encompassing antecedents, outcomes, implementation phases, and pertinent influencing factors. By meticulously following the SLR process, this review aims to delineate the current research landscape, key themes, and future research directions regarding the influence of cultural factors on EV subsidy policies globally. Through this systematic approach, the review contributes to the development of theoretical and conceptual content in the field, facilitating a better understanding of the complex interaction between culture and policy in sustainable transportation.

6.1.1. SLR planning

The SLR planning stage encompasses several key steps. Initially, it involves justifying the review's necessity and formulating specific research questions. Following this, the scope of the SLR is delineated, and a review protocol is established. In our case, we adopted an inductive approach and utilized a theoretical framework proposed by Vu et al. (2021) as the foundation. The framework, derived from their SLR on sustainable technology implementation in sustainable agriculture SCM, outlines three implementation stages and associated influential factors.

Additionally, we referenced Xu et al. (2023) to solidify theoretical constructs, encompassing antecedents, outcomes, implementation stages, and influential factors. Subsequently, inclusion criteria were set, comprising both broad and detailed criteria for paper selection. These meticulous steps ensure the systematic selection of literature and lay the groundwork for a comprehensive SLR analysis.

6.1.2. SLR conducting

The SLR conducting stage involves crucial steps outlined in phases 3, 4, and 5. During this phase, the selected papers are finalized, and their findings are amalgamated. We opted to utilize the Scopus database, renowned for its extensive literature coverage, and supplemented our search with the WOS research database to ensure a comprehensive retrieval. Omitting sustainability-related keywords, we aimed to extract sustainability aspects across all EV adoption studies in SCM. EV-related keywords were derived from prior literature reviews, while SCM-related terms were based on existing research.

Initial searches were conducted in Scopus and WOS using specific search fields. We refined our search criteria, limiting the language to English and the study period from January 2008 to June 2023. Further constraints were applied, including source type and journal selection based on AJG rankings.

Following these restrictions, 1032 and 823 papers were identified from Scopus and WOS respectively. After eliminating duplicates, 523 papers remained for the first-round selection. Subsequent screening based on broad criteria yielded 237 papers for the second round. Applying consistent inclusion and exclusion criteria, 29 papers were eventually selected for content analysis, with two authors independently conducting the screening process to maintain accuracy and relevance.

Then, we followed a pre-defined theoretical construct in the coding process, categorizing the papers into antecedents, outcomes, policy implementation stages, and influential factors. Three subthemes under antecedents were identified, describing factors motivating EV adoption along the supply chain, i.e., the internal requirements.

Next, we classified the stages of policy implementation as initiation, pilot adoption, and full implementation, aligning with the framework introduced by Vu et al. (2021). Additionally, we analyzed the key factors impacting each stage of EV adoption, categorizing them into intra-organizational, inter-organizational, and external factors for a comprehensive understanding.

Finally, the main themes influencing EV adoption in diverse cultural settings were identified, with additional subthemes discovered. To enhance validity and reliability and minimize research bias, two authors independently conducted the coding process.

6.1.3. SLR composing

In this final stage, step 6 is carried out, culminating in the development of the SLR. Initially, we verified the review's structure, following Sauer and Seuring's guidelines (2023). Subsequently, findings were synthesized, confirming both descriptive and thematic contents.

6.2. Descriptive findings

Seventeen articles focus on North America, fifteen on Asia, thirteen on Europe, two on Oceania, and one on South America. The majority of Asian articles concentrate on China (Feng et al., 2019; Li et al., 2020; Jin et al., 2020; Huimin and Tengyu, 2011), particularly Beijing (Tal et al., 2018; Liu et al., 2019; Yoon et al., 2019; Zhuge et al., 2020), likely due to its well-documented pollution issues. For instance, Liu et al. (2019) centered their model on Beijing to evaluate the impact of the city's smog crisis on EV adoption behavior. Shankar and Kumari (2019), Prakash et al. (2018), and Kaur et al. (2021) focused on India, where eleven of the twelve most polluted cities were located in 2018, investigating barriers to EV adoption. Nian et al. (2019) and Huang et al. (2012)

studied Singapore, with the former labeling it as the worst-case market for EV adoption due to lack of incentives. Khazaei (2019) focused on Malaysia, while Cen et al. (2018) targeted Hong Kong.

In Europe, Pasaoglu et al. (2016) modeled the EU as a whole, with other studies having more specific focuses. The Nordic countries were highlighted, with articles modeling Norway (Harbo et al., 2018), Iceland (Shafiei et al., 2017), and describing the entire Nordic region. Mulholland et al. (2018) examined Ireland and Denmark to analyze the long-term effects of reducing EV subsidies. Various articles focused on the UK (Tiwari et al., 2020; Brand et al., 2017), the Netherlands (Wesseling et al., 2020).

Most North American studies centered on the US, with exceptions such as Khan et al. (2021), which focused on Canada. Some studies had broader focuses within the US (Kim and Choi, 2019), while others targeted specific regions like California (Ruan et al., 2021) and Oregon (Cho and Blommestein, 2015).

6.2. Thematic findings

Based on the sampled papers, this analysis identifies three themes in the research regarding the factors influencing the market penetration of EVs: (1) the factors influencing the EV business models; (2) the differences in adoption intention across cultures; (3) factors affecting the supportive policy design. Following sections will delve into each of these themes extensively.

6.2.1. The factors influencing EV business models

Understanding consumer attitudes is crucial for developing successful business models aimed at increasing the adoption of electric vehicles (EVs). Four articles examined consumer attitudes toward EV adoption. Some research explored public attitudes toward EV adoption, linking these attitudes to socio-demographic profiles through a model incorporating 10 socio-demographic and 24 attitudinal variables. Jin et al. (2020) focused on consumer behavior regarding battery electric vehicle (BEV) carsharing in China, analyzing how attitudes influence BEV sharing. Kaur et al. (2021) studied the impact of consumer knowledge on EV adoption in India, considering perceived risk, perceived usefulness, and financial incentives.

The absence of successful business models is seen as a barrier to widespread EV adoption, prompting investigation into five EV business models. Nian et al. (2019) proposed a model to reduce EV capital costs without policy support. Wesseling et al. (2020) extended the concept of a business model to encompass the socio-technical transition to EVs. Some works compared consumer preferences for battery/vehicle leasing and mobility guarantee models, considering various attributes across different vehicle types. Kim et al. (2019) assessed the impact of leasing models on EV adoption, considering socio-demographics and mobility behaviors. Some researchers interviewed experts to identify shortcomings in EV business models, highlighting the suitability of mobility guarantee models.

6.2.2. Differences in adoption intention across cultures

The literature on factors influencing EV adoption intentions highlights various factors, including environmental concerns, financial incentives, range anxiety, charging infrastructure, and sociodemographic factors, as key determinants. These factors are analyzed through different theories and models, such as attribution theory, innovation diffusion theory (IDT), norm activation model (NAM), risk–benefit model (RBM), self-determination theory (SDT), self-image congruence theory (SICT), technology acceptance model (TAM), theory of planned behavior (TPB), theory of reasoned action (TRA), uses and gratifications theory (UGT), unified theory of acceptance and use of technology (UTAUT), and values–beliefs–norms (VBN). The review also includes country-specific studies, significant findings, and research gaps.

Integrating the UTAUT2 and VBN models represents a novel approach to understanding the cultural differences in EV adoption intentions. While the UTAUT2 model has been extensively applied in various contexts, including EV adoption in India and Spain, it must consider how cultural values, beliefs, and norms influence individuals' intentions to adopt new technologies. Conversely, the VBN model offers a framework for comprehending the fundamental values, beliefs, and norms that shape behavior, including pro-environmental behavior.

6.2.3. Policy design across cultures

In exploring factors influencing electric vehicle (EV) adoption, various models have been developed to aid policy planning aimed at addressing concerns surrounding

EV uptake. These models encompass diverse perspectives and considerations across different studies. Barter et al. (2015) focused on non-cost barriers to battery electric vehicle (BEV) adoption, incorporating factors such as range and recharging infrastructure limitations. Zhuge et al. (2020) examined cost-related factors affecting plug-in hybrid electric vehicle (PHEV) adoption, distinguishing between upfront costs (e.g., purchase price) and usage-related costs (e.g., fuel expenses). Liu et al. (2019) delved into the effects of city smog crises on personal vehicle adoption, integrating hazard-related, resource-related, and socio-demographic variables. Brand et al. (2017) evaluated the potential impacts of investment pathways and policy interventions on plug-in electric vehicle (PEV) adoption in the UK.

Furthermore, stakeholders' perspectives play a crucial role in shaping EV adoption dynamics. Tiwari (2020) explored enablers and inhibitors of EV adoption from sellers' viewpoints, considering factors like corporate social responsibility and environmental concerns. Pasaoglu et al. (2016) adopted a holistic approach, examining interactions among various stakeholders under different scenarios, including oil prices, GDP growth rates, and subsidy schemes.

Government policies emerge as pivotal in incentivizing EV adoption, prompting extensive research on their effectiveness. These interventions ranged from subsidies and tax incentives to infrastructure development and technology policies, showcasing the multifaceted nature of policy design in shaping EV adoption trajectories.

Overall, the synthesis of these studies underscores the importance of considering cultural contexts, stakeholder perspectives, and multifaceted policy interventions in fostering sustainable EV adoption globally.

6.3. Conclusion of SLR

6.3.1. Conceptual framework of enhancing EV market penetration

As depicted in Figure 7, this paper provides an integrated framework of EV market penetration, drawing upon thematic findings. The framework delineates the consumers' EV adoption intention across cultures on the left, categorized by the different influencing factors. Consumers' expectancy for EV's enhanced performance is identified as performance-oriented motive, while the intention to improve environmental sustainability is denoted as sustainability-oriented motives. Another noteworthy difference lies in hedonic motivations, i.e., the emotions, sensations, enjoyment, and pleasure derived from driving EVs, categorized as pleasure-oriented motive.

In the center of the framework, government's supportive policy formulation process is outlined, highlighting three stages: infrastructure establishment, policy design and policy implementation. Three groups of influential factors on policy design are detailed, encompassing intra-organizational, inter-organizational, and external factors. On the right side of the framework, the benefits of effective incentive policy for EV market penetration are enumerated, including economic, social, and environmental aspects.

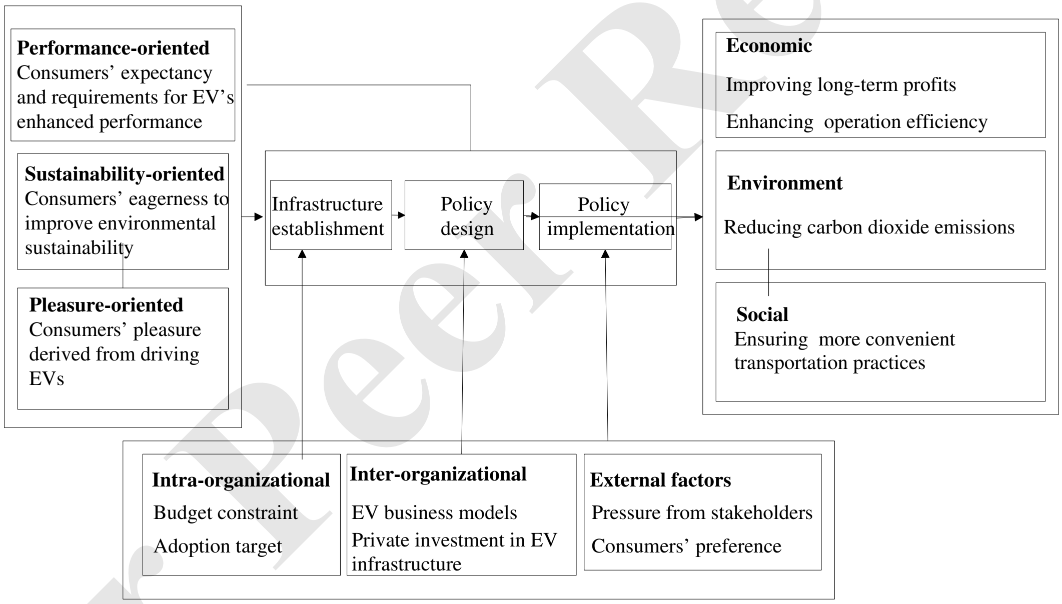

Fig. 7. Conceptual framework of EV adoption and policy decision

Compared to prior frameworks (Kaur et al., 2021; Nian et al., 2019; Tiwari et al., 2020), this new model comprehensively integrates consumers' adoption intention, government policy, the benefits of effective policy, and influential factors for each stage. Unlike the previous review, our model clearly identifies factors influencing EV adoption in different cultural contexts, further categorizing them based on attributes. Moreover, while outcomes were overlooked in prior reviews, this study explicitly illustrates how effective policy contributes to comprehensive sustainable SCM across environmental, social, and economic dimensions.

Regarding influential factors, while Vu et al. (2021) identified several groups, this review redefines factors based on existing studies and establishes connections between each group and the policy design process. Intra-organizational and actor-related factors influence the infrastructure investment, whereas both intra- and inter-organizational factors affect the policy design stage, and all three groups influence the implementation stage.

This framework has the potential to advance the exploration of factors influencing EV market penetration. The delineated consumers' adoption intention illustrates driving forces for governments to initiate and implement incentive policy, while the policy formulation process and related factors offer guidance for financial incentive policy design and implementation. The outcomes facilitate the evaluation of policy implementation results in SCs.

6.3.2. Results of SLR

First, this SLR analysis highlights the numerous factors that impact consumers' inclination towards purchasing electric vehicles (EVs). These influences are evident in various contexts, including countries such as India, Indonesia, Malaysia, Thailand, China, and Germany. Key drivers such as performance expectations, facilitating conditions, and hedonic motivations consistently play significant roles across different regions. Additionally, social influence, environmental concerns, and personal norms consistently contribute positively to the intention to adopt EVs. Furthermore, government's financial supports emerge as a critical moderator, particularly notable in India and China. Conversely, safety concerns outweigh purchase costs and perceived benefits in shaping adoption intentions, highlighting consumers' prioritization of safety features. Technological knowledge and firsthand experience with EVs are also substantial influencers, indicating that increasing consumer awareness and offering practical experience could boost adoption rates. Notably, personal values, altruism, and identification with environmental consciousness also exert influence, reflecting a growing acknowledgment of the importance of environmental awareness in driving EV adoption. In summary, this study underscores the multifaceted nature of EV adoption intentions, emphasizing the interplay between individual beliefs, social influences, technological factors, and environmental considerations. These insights are invaluable for policymakers and industry stakeholders striving to advance sustainable transportation solutions.

Second, this SLR analysis found that cultural nuances shape stakeholder participation, including government entities, industries, and environmental groups. The cultural inclinations of these stakeholders shape their perceptions of EV adoption, thereby impact policy formulation and implementation strategies. For example, in societies with deep-rooted environmental consciousness, there is greater emphasis on EV incentives aligned with sustainability goals.

Additionally, cultural influences inform the customization of business models for specific markets. Research by Nian et al. (2019), Wesseling et al. (2020), Liao et al. (2019), and de Rubens et al. (2020) highlight how cultural norms and preferences influence the design of EV business models. Variations in consumer behavior, purchasing power, and attitudes towards innovation necessitate culturally sensitive approaches to business model innovation within the EV industry.

For instance, in countries deeply rooted in environmental consciousness like Norway or Germany, government policies may prioritize incentives aligned with sustainability goals, such as subsidies for EV purchases or the development of public EV charging infrastructure. Conversely, in nations with a stronger emphasis on individualism, like the United States, incentive policies might focus on catering to individual consumer preferences and economic benefits, such as tax rebates or incentives for private charging stations. Moreover, in countries with a collective mindset such as Japan or South Korea, policies may prioritize societal benefits and communal responsibility, leading to initiatives like promoting shared EV ownership schemes or supporting the integration of EVs into public transportation fleets. In essence, the cultural landscape of a nation significantly influences the direction and emphasis of government incentive policies aimed at driving EV adoption, reflecting varying societal values and attitudes towards sustainability, innovation, and governance.

In China, where collective interests and centralized planning are emphasized, the government may design policies that not only encourage individual EV ownership but also prioritize large-scale infrastructure projects like expanding EV charging networks and supporting domestic EV manufacturers. This approach reflects the cultural focus on collective progress and government-led initiatives.

In contrast, in the United States, where individual freedom and entrepreneurial spirit are valued, government policies might center on stimulating private investment in EV infrastructure through tax incentives for companies that develop charging stations or subsidies for individuals who purchase EVs. This cultural backdrop encourages government policies that favor market-driven growth and innovation.

This SLR analysis shows how cultural factors shape government policies that support EV adoption by shaping consumer behavior, stakeholder decisions, and business model development. Recognizing and accommodating these cultural intricacies is essential for governments seeking to devise effective incentive policies to drive EV adoption across diverse socio-cultural landscapes. In summary, the SLR suggests that consumers' consideration of charging convenience, stakeholders' infrastructure investment and the EV business models have significant influence on government policy formulation. This is also confirmed by our model analysis. Furthermore, this SLR analysis shows how cultural factors guide government policies that support EV adoption by shaping consumer behavior, stakeholder decisions, and business model development. Combining the results obtained by model analysis and SLR, our study identifies policy implications to assist governments across various countries in selecting the most appropriate policy from different subsidies.

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Appendix G: A case study

G1. Model application

In this section, we use a case study to analyze and verify the findings put forward through model analysis. This case study applies these theoretical results to real-world practice, focusing on companies like CATL, Ford, BYD, and Tesla, and explores how government subsidies and infrastructure investments have influenced their strategies and market performance.

G1.1. BS scenario

BS scenario is characterized by a traditional supply chain structure where a battery supplier is responsible for providing essential components to an automaker. In our specific example, we examine the roles of Contemporary Amperex Technology Co. Limited (CATL), a leading battery supplier, and BYD Company Ltd., a prominent EV manufacturer. CATL, famous for its advanced lithium-ion battery technology, acts as the upstream firm, supplying batteries to the automaker BYD. In this scenario, CATL also takes the responsibility of investing in charging infrastructure, aligning with the BS scenario described in the model setup. This investment is crucial for overcoming the "chicken-and-egg" dilemma faced by the EV industry, where the charging infrastructure is essential to stimulate EV adoption but is hindered by the initial lack of widespread EV usage. On the other hand, BYD, as the downstream automaker, focuses on the production and sale of EVs. The company benefits from CATL's investment in charging infrastructure, which enhances the attractiveness of its EV to consumers by improving the charging convenience.

The Chinese government has been using a combination of purchase and infrastructure subsidies to enhance the EV adoption. During the initial stage of the EV penetration, the Chinese government offered substantial purchase subsidies to consumers. This pure consumer subsidy effectively improves the EV sales of BYD. However, as the market matured and the charging infrastructure expanded, the government has gradually shifted its focus towards subsidizing CATL's infrastructure investment, indicating a move towards a pure infrastructure subsidy policy.

G1.2. BM scenario

In the BM scenario, the roles are somewhat reversed, with the downstream manufacturer, such as Ford, taking on the mantle of investing in the charging infrastructure. This scenario is emblematic of the strategic moves seen in the real world, where major automakers recognize the pivotal role of charging infrastructure in the mass adoption of EVs and take proactive steps to develop it. CATL, while being a leading battery supplier, focuses on its core competency, providing the essential energy storage solutions that power these vehicles.

Governments around the world are keenly aware of the need to support this kind of investment. For example, in the United States, where Ford has been expanding its charging network, the government has implemented subsidy policies that are designed to encourage further investment in infrastructure by manufacturers. These policies align with Proposition 2, which suggests that when the manufacturer is responsible for infrastructure investment, a combination of subsidies can be optimal, particularly when both the infrastructure investment costs and the adoption targets are high. The U.S. government's approach to subsidies under the BM scenario is twofold: firstly, by offering financial incentives that offset a portion of Ford's investment costs in building out the Supercharger network, and secondly, by maintaining a consumer-focused subsidy that reduces the purchase price of EVs, making them more accessible to a broader market. This dual subsidy approach is particularly effective in the early stages of EV market penetration when the charging infrastructure is still developing, and consumer adoption is influenced by both the availability of charging stations and the initial purchase cost of the vehicle.

As the market matures and the charging infrastructure becomes more widespread, the government can adjust its subsidy strategy accordingly. If the cost of infrastructure investment remains high but the adoption target is moderate, the government may decide to shift towards a pure infrastructure subsidy, as stated in Proposition 2. This shift acknowledges the reduced need for consumer subsidies as the market becomes more self-sustaining and recognizes the ongoing need to support the expansion of the charging network. In countries where the charging infrastructure is less developed and the adoption targets are ambitious, governments may find it beneficial to maintain a combination of both subsidies. This approach is particularly relevant in emerging markets where EV penetration is still in its infancy, and the support from both consumer and infrastructure subsidies is crucial to stimulate growth and meet the adoption goals. These industrial practices highlight the importance of a flexible and adaptive government subsidy policy that responds to the evolving needs of the EV market. By considering the specific actions of key players in the supply chain, such as Ford's investment in charging infrastructure, governments can design policies that are not only cost-effective but also supportive of the broader goal of mass EV adoption.

G1.3. CS scenario

In the CS scenario, where we observe a co-opetitive structure exemplified by companies like BYD supplying batteries to automakers such as Tesla, the dynamics of government subsidy policies are intricately linked to the competitive nature of the supply chain. This scenario is particularly relevant as it reflects the real-world competitive and collaborative relationships between different players in the electric vehicle (EV) industry.

Governments worldwide, when crafting policies for a CS-structured supply chain, must consider the delicate balance of competition and the unique position of firms like BYD. For instance, a government might provide subsidies that specifically target the expansion of fast-charging networks in urban areas where Tesla has a strong market presence, thereby supporting BYD's infrastructure efforts and promoting a competitive EV market. Taking a real-world example, the Chinese government has historically offered substantial subsidies to both EV manufacturers and consumers. However, as the market matures, the focus has shifted more towards infrastructure development, reflecting a strategic move that aligns with Proposition 3's insights. This shift acknowledges the changing needs of the industry and the evolving roles of companies like BYD and Tesla within it. In another example, the U.S. government's approach to subsidy policy, with its focus on tax credits for EV purchases and grants for charging station development, exemplifies a balanced approach that considers both consumer adoption and infrastructure growth. For a CS-structured supply chain like that involving

BYD and Tesla, government subsidy policies should be specifically tailored to the competitive and cooperative nature of the industry.

G1.4. CM scenario

In the CM scenario, characterized by a co-opetitive supply chain structure where an upstream firm like BYD supplies batteries to a downstream automaker like Tesla, and Tesla is responsible for the construction of charging infrastructure, governments worldwide face the challenge of designing subsidy policies that will effectively promote the mass adoption of electric vehicles (EVs). The findings from the study, as encapsulated in Proposition 4, provide valuable insights for policymakers in various countries as they navigate the complexities of the EV market.

Governments must consider the delicate balance between incentivizing consumer adoption and supporting the necessary infrastructure development. When the targeted adoption level and infrastructure investment costs are both high, Proposition 4 suggests that the optimal policy is to provide both subsidies—a strategy that recognizes the dual importance of consumer demand and infrastructure support in facilitating EV adoption. This approach acknowledges that while consumer purchase subsidies can immediately boost market penetration, infrastructure subsidies are equally vital for long-term growth and sustainability of the EV market.

In countries where the cost of infrastructure investment is moderate, Proposition 4 indicates that a pure infrastructure subsidy is preferable. This policy choice reflects an understanding that while the market is not yet mature, the focus should be on building a robust charging network that can support future growth. It also implies that the government believes the market dynamics are sufficient to drive consumer adoption without additional purchase subsidies.

Conversely, when faced with a less challenging adoption target or lower infrastructure costs, the government's optimal policy may be to provide no subsidy at all. This decision points to a market that is either self-sustaining or where the government deems the current level of adoption and infrastructure maturity sufficient for the time being.

These findings are consistent with the diverse approaches taken by governments around the world. For instance, in countries with a well-established charging infrastructure and a lower adoption target, such as some regions in Western Europe, governments may opt for a reduced role, focusing on maintaining the existing network rather than aggressive subsidy programs. On the other hand, in nations where the EV market is nascent and the infrastructure is underdeveloped, such as in parts of Asia and South America, governments may find it more cost-effective to implement both subsidies to accelerate market growth and infrastructure development.

Furthermore, the co-opetitive nature of the supply chain in the CM scenario, with firms like BYD and Tesla both competing and cooperating in the market, adds a layer of complexity to policy design. Governments must consider not only the direct benefits of subsidies to consumers and manufacturers but also the indirect effects on competition and innovation. The presence of competition can, in some cases, reduce the need for larger subsidies, as the market forces drive down costs and encourage technological advancements. The government's subsidy policy under the CM scenario should be tailored to the specific conditions of the country, taking into account the maturity of the EV market, the state of charging infrastructure, and the broader socio-economic objectives.

G2. Theoretic verification

Many challenges encountered in the process towards mass EV adoption serve to validate the conclusions drawn from the model analysis.

First, Proposition 1 indicates that providing a pure subsidy for infrastructure investment is optimal when the supplier is responsible for building the charging infrastructure. This is exemplified by the strategic approach taken by CATL, a leading battery supplier in China. CATL's investment in charging infrastructure has been significant, and it has benefited from government subsidies designed to encourage the expansion of charging networks. This aligns with the proposition's logic that when the supplier takes on the infrastructure development, government subsidies are more effectively targeted, leading to a more robust and widespread adoption of EVs. The case of CATL also highlights the government's strategic decision to support the growth of the EV industry by optimizing financial incentives. As the supplier, CATL's investment in infrastructure has been instrumental in addressing the "chicken-and-egg" dilemma often associated with EV adoption—the lack of charging stations can deter consumers from buying EVs, and low consumer demand can discourage investment in charging infrastructure. By subsidizing the supplier's infrastructure efforts, the government has effectively stimulated the market, leading to increased EV adoption and a more developed charging network. Furthermore, the government's decision to focus on subsidizing infrastructure rather than providing direct purchase subsidies to consumers reflects a deeper understanding of the market dynamics and the recognition that a well-established charging infrastructure is crucial for the long-term success of the EV industry. This strategic shift in subsidy policy is a practical validation of Proposition 1's conclusion, demonstrating that when the supplier is the primary investor in infrastructure, a pure infrastructure subsidy can be the most cost-effective solution for the government while also promoting the mass adoption of EVs.

Second, the theoretical result suggests that when the downstream manufacturer invests in infrastructure, a combination of both subsidies becomes the optimal policy. This is well illustrated by Tesla's strategy and the corresponding government policy in the United States. Tesla, a prominent EV manufacturer, has made significant investments in building its Supercharger network. Recognizing the importance of a robust charging infrastructure for widespread EV adoption, the U.S. government, through various state and federal programs, has provided a combination of subsidies that not only support the purchase of EVs but also incentivize the development of charging infrastructure. For instance, the U.S. Department of Energy has allocated funds to support the deployment of EV charging stations, particularly along highways and in communities, complementing the purchase subsidies offered to consumers. This reality aligns with Proposition 2's conclusion that when manufacturers like Tesla undertake infrastructure investments, a combined policy of purchase and infrastructure subsidies is most effective. It addresses the financial barriers for both consumers and manufacturers, encouraging the adoption of EVs and the expansion of necessary charging networks. Tesla's proactive stance in building out its charging infrastructure has been instrumental in mitigating range anxiety among consumers, a significant factor hindering EV adoption. The government's supportive policies, including subsidies, have further lowered the costs for Tesla to invest in this infrastructure, creating a synergistic effect that propels the EV market forward. This case validates the proposition that a combined subsidy approach is not only cost-effective for the government but also beneficial in accelerating the diffusion of EVs and the establishment of a comprehensive charging network by manufacturers like Tesla.

Third, Proposition 3 states that under a co-opetitive supply chain structure where the supplier invests in infrastructure, the government's optimal subsidy policy can vary, with both pure purchase subsidies and pure infrastructure subsidies being potentially optimal depending on the cost coefficient and adoption target. A real-world example of this can be seen in the case of BYD, a Chinese company that operates both as an EV battery supplier and an EV manufacturer. BYD's strategic investment in charging infrastructure has been complemented by the Chinese government's subsidy policies. Initially, the government provided subsidies to encourage the purchase of EVs, which helped BYD and other manufacturers to increase their sales. However, as the market matured and the need for a more extensive charging network became apparent, the government shifted its focus towards subsidizing the construction of charging infrastructure. This policy change was instrumental in supporting BYD's continued investment in infrastructure, thereby enhancing the EV adoption level. The government's subsidy strategy in this scenario has been to adjust the levels of support based on the evolving market dynamics. When the cost of building charging infrastructure was high and the adoption target was ambitious, the government opted for a combination of subsidies to ensure both the growth of the EV market and the development of necessary infrastructure. As the market became more competitive and the cost of infrastructure investment decreased, the government was able to reduce the intensity of subsidies, sometimes favoring pure purchase subsidies to directly stimulate consumer demand. This case illustrates the dynamic interplay between government policy and corporate strategy in the co-opetitive supply chain. BYD's dual role as a supplier and manufacturer, combined with the government's flexible subsidy approach, demonstrates the validity of Proposition 3. It shows that the government's subsidy policy can effectively respond to the competitive nature of the supply chain and the investment decisions of firms, leading to an optimal balance between market stimulation and infrastructure development.

Finally, Tesla, recognizing the importance of a robust charging network for its EVs, has actively invested in building charging stations across the country. This strategic move aligns with the Chinese government's push for EV adoption and the subsequent phasing out of purchase subsidies in favor of infrastructure support. The government's policy shift from offering direct purchase incentives to focusing on charging infrastructure development has complemented Tesla's investment, facilitating a more rapid adoption of its EVs. In this scenario, the Chinese government's decision to prioritize subsidies for charging infrastructure over pure purchase subsidies reflects the proposition's insights. The government's policy aims to achieve a higher adoption target with a significant investment in infrastructure, understanding that a mature charging network is crucial for the long-term success of the EV market. Tesla's investment in infrastructure, coupled with the government's strategic subsidies, has created a synergistic effect that accelerates EV adoption while minimizing the financial burden on the government. This case illustrates the effectiveness of a combined subsidy approach when the manufacturer takes on the responsibility of infrastructure development. It highlights the importance of aligning government policy with the strategic initiatives of market leaders like Tesla to optimize the overall effectiveness of subsidy programs in promoting EV adoption and achieving environmental goals. Therefore, this case confirms the conclusion that when the downstream manufacturer invests in infrastructure within a co-opetitive supply chain, a combination of subsidies becomes the most effective strategy under certain conditions.