Two-Sided Subsidies for Complementary Products: The Case of Electric Vehicles

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Electric vehicles (EVs) are touted as the future of urban transportation and a solution to climate change. Despite their benefits, EV adoption has not met the expectations globally. This slow progress is attributed to high EV prices and inadequate charging station infrastructure, which creates "range anxiety" for EV drivers. To overcome these obstacles, many governments have introduced financial support policies for EVs. While some governments only subsidize EV purchasers, others resort to a hybrid policy that offers subsidies to both EV purchasers and charging station developers. In this paper, we analyze a government's problem of designing subsidy policy for EVs, and shed light on the benefits of implementing a hybrid policy. Our model captures the positive network effect of charging stations on consumers' utility for EVs and the competition between investors. We characterize the optimal subsidy mechanism for both sides of the market and specify conditions under which it suffices for the policymaker to only incentivize EV buyers. We further investigate the impact of different technology and market characteristics on the government's policy. Even though investor subsidy aims to reduce the cost of building infrastructure, we find that the government should actually subsidize purchasers more and subsidize investors less when the cost of infrastructure is relatively high. Furthermore, the two subsidy instruments can be either substitutes or complements following technological advancements that entail cost reductions. When EVs are more beneficial to society, the government increases the subsidy for investors but may reduce the subsidy to purchasers depending on the network effect of charging stations. We also find that the impact of consumers' environmental consciousness on the subsidies depends on the cost of building stations. Finally, we calibrate our model with data from the metropolis of Shenzhen and measure the benefits of subsidizing purchasers and investors simultaneously.

Key words: electric vehicles, charging stations, subsidy policy, complementary products

1. Introduction

Air pollution continues to be a significant environmental concern around the globe. The World Health Organization (WHO) highlights air pollution as the greatest environmental risk to human health, and it is estimated to be the cause of seven million premature deaths every year. 91% of the world's population lives in places where air quality exceeds WHO guideline limits (WHO 2018). According to the Environmental Protection Agency (EPA), motor vehicles collectively account for 75% of carbon monoxide pollution in the U.S. It is estimated that on-road vehicles contribute one-third of the air pollution emitted in the country, and transportation is responsible for 27% of its greenhouse gas emissions (EPA 2020, Howsuffworks 2012).

Electric vehicles (EVs) are postulated by policymakers and environmental leaders as a potential solution to reducing greenhouse gas emissions and their adverse consequences. It has been long recognized that extracting and processing minerals from the earth to manufacture EV batteries can contribute to emissions and entail other ecological harms. Nevertheless, recent studies have shown a significant difference in environmental footprint between electric and internal combustion vehicles throughout their lifetimes (Boureima et al. 2009, Kukreja 2018, Ma et al. 2012). The absence of combustion and tailpipe emissions give EVs a substantial advantage over petrol and diesel-powered cars. As more EVs are adopted and the technology for recycling batteries matures, the need for new battery cells reduces and EVs become even more beneficial to the environment (Ellsmoor 2019). Widespread adoption of EVs also helps countries reduce their dependence on domestic or foreign sources of oil, and safeguard them against fluctuations in oil prices.

However, promoting large-scale adoption of electric mobility has proven challenging due to economic and sentimental obstacles on the consumer side. Since EVs are high-tech and innovative products, consumers may have reservations about different aspects of EVs, including insufficient charging infrastructure, short cruise range, high purchase price, and potential battery problems (Zhang and Bai 2017). Without proper government intervention, the EV market would face a critical mass problem where the market diminishes in the long run because the rate of adoption fails to self-sustain and create further growth (Zhou and Li 2018). To overcome these concerns and harness the environmental benefits of EVs, many governments around the world have introduced policy measures to stimulate demand for EVs by increasing their appeal to potential buyers. The United States, Germany, Norway, and China, among other countries, have launched various support programs to encourage consumers to purchase EVs.

Despite the consensus on the need for government involvement in expediting EV adoption, countries differ significantly in their intervention strategies and where government resources are spent. On the one hand, some governments focus on offering subsidies and tax credits that directly support EV buyers, thereby alleviating their upfront financial barrier. For instance, the U.S. federal government, as well as some state governments, offer subsidies for the purchase of EVs.[1] The governments of Italy, Portugal, Slovenia, Slovakia, Estonia, and the United Kingdom offer subsidies

[1] https://www.fueleconomy.gov/feg/taxevb.shtml

to EV buyers but do not subsidize public charging stations (EAFO 2020).[2] On the other hand, an alternative approach involves addressing consumers' concern about limited charging infrastructure when driving EVs. For example, Germany launched a €1 billion EV subsidy program in 2016, providing tax exemption for EV purchases and a 30% subsidy for the cost of building charging stations (Zhang and Dou 2020). The Norwegian government offers generous subsidies both for purchasing EVs and investing in charging stations (Springel 2016). Austria, Finland, Spain, and Romania are among other countries that have adopted this hybrid subsidy policy (EAFO 2020). The motivation behind such initiatives is to mitigate consumers' *range anxiety*, which is the psychological concern that the driving range of EVs may not be sufficient to meet derivers' needs (Lim et al. 2015).

This contrast in government policies raises an important question about how subsidy mechanisms for EVs should be designed and the extent to which government efforts should be directed towards the deployment of charging infrastructure. The most salient feature of this problem, which makes it different from other government policy problems studied in the literature, is the complementarity between EVs and charging stations that creates an indirect network effect. While the value of owning EVs increases with the expansion of the charging infrastructure, investing in charging stations also becomes more profitable as the number of EV owners rises. This "two-sidedness" creates a situation in which two complementary products, whose diffusion trajectories are intertwined, compete for government support. The existing literature on green technology subsidies, albeit being very active in recent years, has generally overlooked such network effects and focused primarily on a single product.[3] The few exceptions include Springel (2016), which conducts an empirical analysis of the subsidies for EVs and charging stations in Norway, and Ma et al. (2019), which consider a single industry player with a binary decision for infrastructure deployment. We study this problem in an analytical framework and investigate how a support policy should strike the right balance between boosting consumers' purchasing power and fostering investments in infrastructure development. Moreover, we investigate how the government's policy depends on specific technology and market characteristics.

The motivation of our study is further strengthened by the unsatisfactory performance of subsidy policies currently in place, which suggests a lack of recognition of how EV markets evolve in response to government interventions. Overall, the diffusion rates of EVs have been inadequate

[2] In the United States, the federal government and some local counties offer incentives for the installation of individual home charing equipment and/or workplace charging points. Italy and the U.K. offer similar subsidies. Such charging points, however, are not publicly accessible.

[3] Recent studies in this domain have explored direct vs. indirect subsidies (e.g., subsidizing the end-consumer or the manufacturer (Yu et al. 2018)), and examined upfront payments vs. performance-based remunerations (e.g., comparing tax rebates and feed-in-tariffs for rooftop solar panels (Babich et al. 2020)). Nevertheless, the simultaneous offering of subsidies for two complementary products is absent in all these analyses.

under existing regulatory supports. For example, the number of EVs on U.S. roads reached one million at the end of 2018, which is a small fraction of the projected 18.7 million target by 2030.[4] China introduced its Electric Vehicle Subsidy Scheme in 2009, which was followed by an update in 2013 (Hao et al. 2014). Under this program, which is one of the world's most comprehensive incentive schemes for EVs, the Chinese government offers different types of support mechanisms: (i) the finance policy, (ii) the infrastructure expansion, and (iii) the research and development (R&D) investment (Zhang and Bai 2017, Zhang et al. 2017). Despite having the highest number of EVs globally, the share of EVs in the car industry across China is low. In November 2015, the cumulative production of Chinese EVs narrowly exceeded 1% of the vehicle market. The sales volume of EVs was 507,000 and 777,000 in 2016 and 2017, respectively, accounting for only 1.81% and 2.69% of the aggregate sales volume of vehicles (Zhang and Qin 2018).

While low adoption rates may be attributable to several reasons, both the existence and proper implementation of subsidy programs play a vital role in the diffusion of EVs. This is perhaps best exemplified by the evolution of EVs in Shenzhen – the city that ranks first in China in terms of EV adoption. The city authorities launched an EV subsidy program from 2009 to 2012, which allocated more than 2 billion Yuans to increase the number of EVs to 15,000 and the number of public charging stations to 200 by the end of 2012.[5] However, Shenzhen only accomplished 5,640 EVs and 81 charging stations by the beginning of 2013.[6] The Shenzhen government also stated in a report that the growth in charging stations could not satisfy the demand from EV owners, and it could adversely affect the adoption process.[7] This concern triggered a drastic revision in the Shenzhen government's approach; the lawmakers started offering financial support to charging stations in 2014. Figure 1 shows the total number of EVs (panel a) and charging stations (panel b) and the amount of subsidies per EV and charging station in Shenzhen (panel c). Even though the subsidy for EV buyers was reduced in 2014 and the subsequent years, a sharp growth in both the number of EVs and charging stations is apparent after the introduction of the hybrid policy. This suggests that leveraging the complementary role of charging stations may have substantially influenced the diffusion of EVs in Shenzhen.

In this paper, we incorporate the indirect network effect between EVs and charging infrastructure and investigate the optimal offering of government subsidies to achieve the highest net benefit to the society. We construct a game-theoretic model that consists of the government, a population

[4] `https://www.eei.org/resourcesandmedia/newsroom/Pages/Press%20Releases/EEI%20Celebrates%201%20Million%20Electric%20Vehicles%20on%20U-S-%20Roads.aspx`

[5] Ministry of Science and Technology of the People's Republic of China `http://www.sz.gov.cn/zfgb/content/post_6569009.html`

[6] `https://www.zhev.com.cn/news/show-1383638494.html`

[7] `http://www.sz.gov.cn/cn/xxgk/zfxxgj/bmdt/content/post_1620922.html`

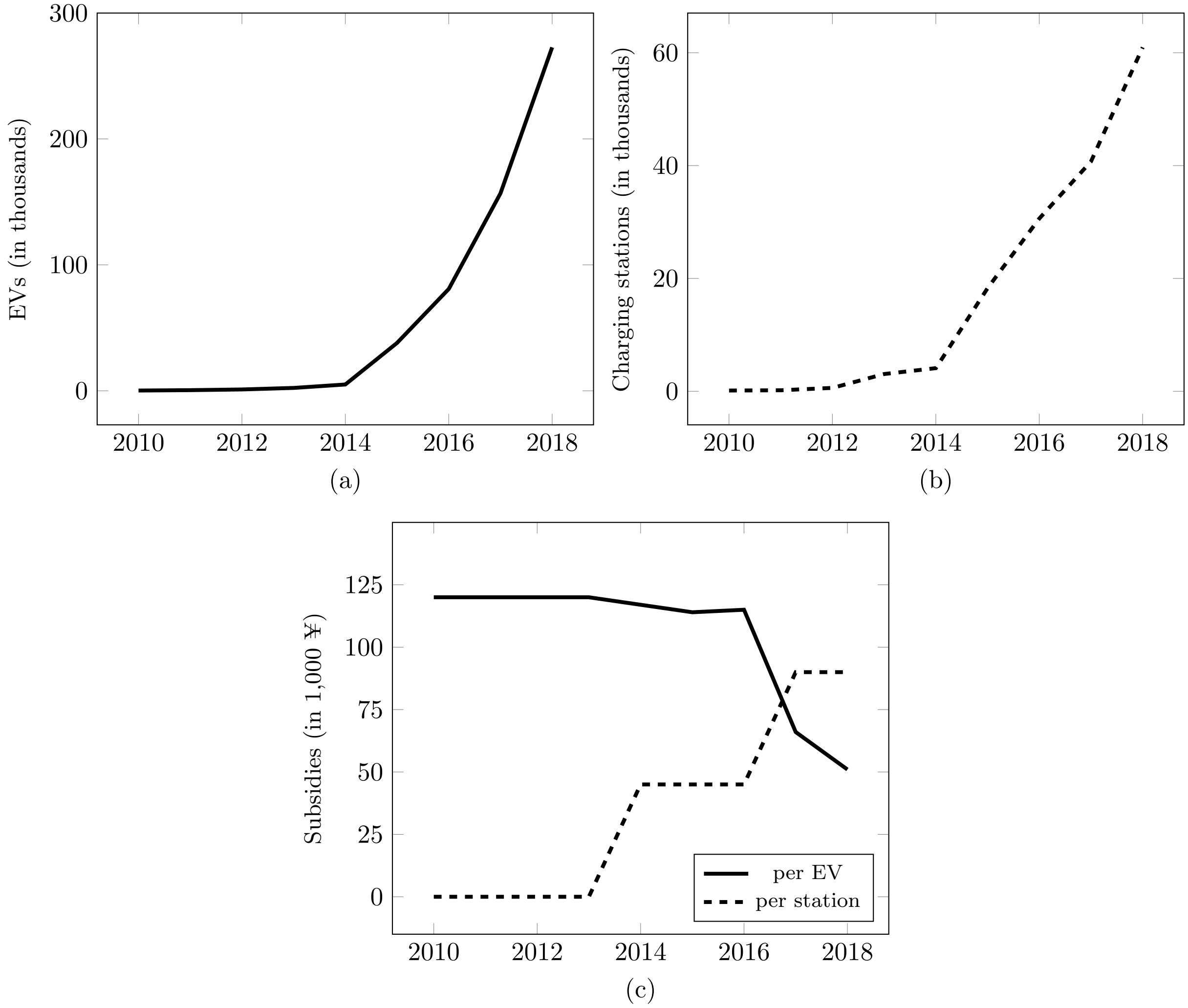

Figure 1 **Number of EVs and charging stations, and the amount of subsidies in Shenzhen, China**

of heterogenous infinitesimal consumers, and a collection of charging station investors. The government is the Stackelberg leader and announces the subsidy rates for EV buyers and investors at the beginning of the game. The consumers and the investors then engage in a simultaneous game to make their purchasing and investment decisions, respectively, while accounting for the best responses from all other players. In our model, higher availability of charging stations creates positive network externalities and increases the attractiveness of EVs through lessening consumers' range anxiety (Springel 2016). We represent the magnitude of this positive externality with a network effect parameter in the consumer utility model. A stronger network effect means consumers are more sensitive to the number of public charging stations. A larger population of EV drivers, on the other hand, creates more potential revenue for charging stations, and thus makes investing in the charging infrastructure more lucrative.

The government's objective in our model accounts for the environmental and health benefits of EVs to the society as well as the total subsidy expenditure. We derive the optimal solution to the government's problem and show how the policymaker should utilize the two subsidy levers in conjunction with one another to generate the highest value. This enables us to identify conditions under which the government should only subsidize the consumers, as opposed to offering a hybrid policy to both sides of the market. This contrast provides a plausible justification for the two distinct approaches currently observed in the practice of various legislators around the world. Our results further highlight the effects of key market characteristics in updating the subsidy rates. We provide guidelines about how the optimal policy should be adjusted in response to variations in technology and market conditions, such as technological improvements, the societal cost of greenhouse gas emissions, and consumers' eco-consciousness.

Our findings suggest that cost reduction trends, which occur due to technological breakthroughs and R&D advancements, impact the optimal subsidy rates in a non-trivial fashion. On the one hand, reduction in the price of EVs or the development cost of charging stations always leads to a lower subsidy for consumers. On the other hand, the same cost trends can generate an opposite effect on the subsidy for investors. This indicates that the two subsidy levers can be either substitutes or complements, depending on the extent of technological cost reductions and their interplay with other market realities. An important policy implication of this result is that when the EV market is still at its infancy and going through the early stages of development (which is the case in most of the jurisdictions around the world), any technological cost reduction must be accompanied with a decrease in the subsidy for EV buyers and an increase in the support for station developers.

We also investigate the impact of the infrastructure network effect on the model outcome. We find that when the network effect is stronger (e.g., in regions where driving distances are longer on average and hence, range anxiety is more pronounced), the government should ratchet up its support for station deployment, whereas the subsidy for EV purchasers should decrease.

Our analysis further explores how the attitude towards protecting the environment should be incorporated into the design of the subsidy programs. For consumers, this reflects the heterogeneity in their environmental consciousness and the utility premium they gain from using a green product. For policymakers, environmental consciousness is interpreted as the value they associate with the diffusion of an environmentally-friendly technology in society. We show that the government should always increase its support for building charging stations when EVs become more valuable to society. However, the same recommendation does not necessarily apply to the EV purchase subsidy, particularly when the network effect is sufficiently strong. Variations in the level of eco-consciousness among the consumer population, on the other hand, generate non-monotone behaviors in both subsidy instruments. Therefore, it is crucial that policymakers account for environmental preferences among different stakeholders when crafting incentive mechanisms for EVs.

Finally, we calibrate our model based on data from Shenzhen, China, to shed light on the potential advantages of offering a hybrid subsidy policy. Our numerical results reveal that subsidizing both EV buyers and station developers is significantly advantageous over only supporting the buyers. More specifically, we observe that the number of charging stations under the two-sided policy can reach, on average, more than 11 times the number under the single-sided policy. In the same vein, such policy change also improves the number of EVs and the government's net benefit by up to 30% and 26%, respectively.

The rest of this paper is organized as follows. The related literature is reviewed in Section 2. Section 3 introduces the notation and formulates the problem. We characterize the optimal subsidy design in Section 4, and compare the optimality of one-sided vs. hybrid policy. Section 5 examines the effects of different technology and market characteristics on the government subsidy. The model calibration using data from Shenzhen, China, is presented in Section 6, and we conclude the paper in Section 7.

2. Literature review

Our work contributes to the growing literature on electric vehicles in operations management. Some of the existing papers use empirical models to forecast the effectiveness of EV subsidies. Hao et al. (2014), Zhang and Bai (2017) and Zhang et al. (2017) review and summarize the Chinese EV policies and estimate the adoption rate at the end of the program horizon. Mueller and de Haan (2009) use an agent-based simulation model to forecast the outcome of EV incentives. Gnann et al. (2015) also use a similar simulation model to forecast EV market diffusion in Germany.

There are a number of papers that use analytical models to study EVs. Lim et al. (2015) explore the impacts of range and resale anxiety on mass adoption of electric mobility. They find that combinations of battery owning/leasing with enhanced charging service typically yield the best balance among the objectives of EV adoption when the degree of resale anxiety is low and high, respectively. Huang et al. (2013) analyze the competition between a fuel-automobile supply chain and an electric-and-fuel supply chain when the government subsidizes EV buyers. They find that a larger number of service and charging stations can increase the subsidy's positive impact on the EV market; however, the number of charging stations is a parameter in their model and they do not analyze subsidies for charging stations. Luo et al. (2014) consider a decentralized EV supply chain where the government offers a price discount rate and a subsidy ceiling for EVs. They show that the subsidy ceiling is more effective in influencing the manufacturer's optimal wholesale price when the unit production cost is high, but the discount rate is more effective when the production cost is low. Cohen et al. (2015) study a model where a government offers a subsidy for a green product to a decentralized supply chain in two periods under demand uncertainty. The government can commit to its subsidy or reserve the option to adjust the subsidy across the periods. They show that a flexible subsidy policy is, on average, more expensive, unless there is a significant negative demand correlation across the two periods. On the other hand, the government's additional spending in the flexible setting reduces the adoption level uncertainty. Shao et al. (2017) examine the electric-and-gasoline vehicle market under monopoly and duopoly, assuming the government either offers a fixed subsidy or a price discount to EV buyers. They show the two incentive schemes result in the same environmental impact and social welfare, but the government prefers the subsidy mechanism due to the lower expenditure.

Only a few papers have modeled the interaction between charging stations and EVs. Yu et al. (2016) formulate a sequential game for the two-sided market of EVs and charging stations, and characterize the equilibrium. They show that the socially-optimal solution requires more charging stations than the market outcome. Although the authors touch on the effect of subsidies in a sensitivity analysis, they do not analyze the government's optimal subsidy design. Springel (2016) uses a structural estimation model to investigate the two-sided market of EVs and charging stations. Using data from Norway, the paper presents descriptive evidence that EV purchases are positively related to both consumer price and charging station subsidies. Zhou and Li (2018) take into account the interdependence between charging station deployment and EV adoption. Using panel data from the U.S. Metropolitan Statistical Areas (MSA), they find that more than half of the MSA's face critical mass constraints and that a subsidy policy could be more effective in promoting EV adoption. Neither Springel (2016) nor Zhou and Li (2018) analyzes the optimal subsidy design by the government. Ma et al. (2019) examine simultaneous offering of both subsidies in the presence of an integrated monopoly firm. The firm simultaneously produces a clean technology product and makes a binary decision about whether or not to build infrastructure. In contrast, we model the competition between independent investors whose revenue depends on the adoption decision of a population of potential EV buyers.

Zhang and Dou (2020) is also closely related to our work. They consider an EV charging station investor (a service provider) that has to choose the locations for charging piles based on the following tradeoff: Building piles in urban areas is more expensive but may generate more revenue due to higher traffic, whereas piles built in suburban areas are less costly but will be used less frequently. The authors show that there could be a spatial mismatch between the demand and supply of charging piles, leading to weak EV adoptions in equilibrium. They study how the government should mitigate the mismatch using three subsidy policies: i) subsidizing the investor by the number of piles, ii) subsidizing the investor by the usage of piles, and iii) subsidizing EV buyers. The main findings are that subsidizing EV buyers or subsidizing the service provider by pile usage can be the best subsidy for the government, and that, in many cases, the government should not motivate the service provider to build the most piles in urban areas. Although Zhang and Dou (2020) analyze government subsidies, they focus on understanding how a single subsidy influences a single service provider's decision about building charging piles in two different locations (urban vs. suburban areas). We, on the other hand, focus on how the government should simultaneously offer subsidies to EV buyers and station developers, given the complementary interaction between EVs and charging stations.

Our paper is also related to the literature on complementary products and network effects, which dates back to Katz and Shapiro (1985), Farrell and Saloner (1985), Caillaud and Jullien (2003), Rochet and Tirole (2006) and Armstrong (2006). These papers focus on pricing and coordination in two-sided markets. In the operations management and marketing literature, Bhaskaran and Gilbert (2005) investigate how a durable goods manufacturer's choice between leasing and selling is affected by a complementary product produced by an independent firm. Gilbert and Jonnalagedda (2011) look at whether the manufacturer of a durable product (e.g., printer) should make its product incompatible with consumables (e.g., ink) that are produced by other firms. Yalcin et al. (2013) explore the pricing and quality decisions of two firms that produce complementary products. He et al. (2016) study how product and consumer characteristics affect the group selling decisions of complementary firms. He and Yin (2015) look at how competition in supply chains impacts joint selling partnerships among complementary suppliers. None of these papers considers a government's optimal design of subsidy policies for complementary products.

In summary, the existing literature mostly uses empirical models to estimate EV adoption rates. The analytical papers about EVs either treat subsidies as a model parameter and do not analyze the government's problem, or consider only one type of subsidy and ignore the complementarity effect. In contrast, we propose an analytical model that incorporates both subsidies for EV consumers and charging station investors. We characterize the government's optimal subsidy policy and examine how it depends on different technological and market characteristics.

3. Modeling Framework

We consider a government that seeks to promote the adoption of EVs in its jurisdiction. To achieve this goal, the government can utilize two distinct policy measures that are commonly used in practice and stimulate EV diffusion in different ways:

(i) Subsidizing EV buyers: Under this policy, a subsidy is offered to the pool of potential EV adopters, which is granted to each buyer upon the purchase of an EV. The goal of this policy instrument is to increase adoption by making EVs more affordable for consumers.

(ii) Subsidizing the public charging infrastructure: This is a subsidy that targets potential investors, and its objective is to reduce the upfront cost of investing in public charging stations. Through this mechanism, the government alleviates the range anxiety of EV drivers and enhances the attractiveness of EVs over conventional vehicles.

We model this problem as a Stackelberg game in which the government first announces the terms of its subsidy programs. Then, the consumers and investors simultaneously make their purchasing and investment decisions, respectively, while anticipating the best response from all other players. In designing the subsidy instruments, the government's objective is to maximize the net benefit of EV adoption to society, which accounts for the societal benefit of higher adoption and the subsidy expenditure. We next describe the decision making process for consumers and investors, and derive their best response decisions. Then, we formulate the government's optimization problem and characterize the optimal subsidy mechanism.

3.1. Consumer Utility Model and Adoption Decision

We model consumers as infinitesimal agents that make their purchasing decisions to maximize their individual utility. An EV consumer in our model is either a current EV driver, or one who can be potentially persuaded to purchase an EV. We denote the size of these two populations by λ_0 and Λ, respectively. Thus, λ_0 is the current size of the EV market before introducing the subsidy policy, whereas Λ is the population of the potential buyers targeted by the subsidies. To formalize a potential consumer's adoption decision, we next construct a utility function that captures the attractiveness of acquiring an EV.

The existing empirical literature on the dynamics of EV adoption (Degirmenci and Breitner 2017, Han et al. 2017, Lin and Wu 2018) suggests that consumers' decision about purchasing EVs depends on a combination of economic factors, usage convenience, and intrinsic environmental valuation. From an economic standpoint, consumers account for the EV retail price, the government's potential subsidy for buyers, and the cost of driving the EV (i.e., charging fee, which is a function of the price of electricity). The appeal of EVs to consumers further depends on inconveniences and obstacles they experience while using EVs, primarily due to the lack of charging station availability. Given the limited driving range of EVs (compared to traditional gas vehicles), widespread charging infrastructure is expected to alleviate consumers' range anxiety and make EVs a more viable option (Avci et al. 2014, Lim et al. 2015). Also, a consumer's decision to opt for an EV hinges on her attitude towards protecting the environment, which can vary across the consumer population.

To account for these factors, we assume consumers are heterogeneous in their environmental preferences and define the utility function for a consumer of type θ as

$$u_\theta(m|s) = \theta v - \mu(m) - (p - s) - \phi\,. \tag{1}$$

In the above formulation, v represents the nominal value that a consumer gains from acquiring a new vehicle. To adjust this value for EVs, we multiply v by consumer type θ, to reflect consumers' idiosyncratic concerns about protecting the environment. We assume θ is uniformly distributed over $[0,\bar{\theta}]$, where $\bar{\theta}$ is associated with the most environmentally-conscious consumer. The variable m in (1) denotes the number of public charging stations available to EV drivers, and $\mu(m)$ captures the disutility corresponding to the drivers' range anxiety. We assume $\mu(m)$ is decreasing and convex in m, such that adding one more charging station reduces the disutility but at a diminishing marginal rate. Parameter ϕ represents the average present value of the charging fees incurred over the vehicle's lifetime. Finally, p and s are the retail price and purchase subsidy for EVs, respectively, so that $(p-s)$ is the effective price paid by consumers.

Given the purchase subsidy s from the government and the number of charging stations, m, a consumer of type θ compares $u_\theta(m|s)$ against her reservation utility of u_0 (e.g., purchasing a conventional vehicle or no purchase at all), and chooses the option that generates a higher utility. Thus, there exists a threshold $\theta_1(m|s) \in [0,\bar{\theta}]$ such that a consumer adopts EV if and only if her type satisfies $\theta \geq \theta_1(m|s)$. Therefore, the population size of EV owners after the introduction of subsidies is given by

$$\begin{aligned}\lambda(m|s) &= \lambda_0 + \Lambda \Pr\left(u_\theta(m|s) \geq u_0\right) = \lambda_0 + \Lambda \Pr\left(\theta \geq \theta_1(m|s)\right) \\ &= \lambda_0 + \max\left\{0\,,\left[\frac{v\bar{\theta} - u_0 - (p-s) - \phi - \mu(m)}{v\bar{\theta}}\right]\Lambda\right\}.\end{aligned} \tag{2}$$

3.2. Charging Infrastructure Development

Potential investors can be mobilized to invest in public charging station development if they find the opportunity profitable. We assume that charging stations are symmetric in that they receive an equal share of the total revenue generated from EV drivers, and that they engage in perfect competition. Hence, new investments take place as long as launching an additional station is deemed profitable. Specifically, a potential developer compares the profit of investing in a charging station, π, against a reservation profit, π_0, and enters the market if and only if $\pi \geq \pi_0$, where,

$$\pi(\lambda, m|\kappa) = \frac{\lambda\phi}{m+1} - (f-\kappa)\,. \tag{3}$$

The first term in (3) calculates the revenue of a new entrant conditional on the current number of EVs, λ, and stations, m. More precisely, since the total revenue collected from EV drivers equals $\lambda\phi$, this amount is split equally between all operating stations (Springel 2016).[8] Thus, this term

[8] Here we have assumed, without loss of generality, that the cost of electricity is zero so that charging fees paid by drivers are retrieved by the station operators. In reality, the operators should cover the electricity cost and thus their revenue is only proportional (but not equal) to the fees paid by the drivers. This simplification, however, does not have any impact on our results.

represents the expected revenue gained by the $(m+1)^{st}$ station if launched. Parameter f denotes the initial capital expenditure needed to deploy a new station, and κ is the investment subsidy offered by the government to reduce the barrier to entry for potential developers. It follows that when the size of the EV market is λ and the government investment subsidy is κ, the best response from the population of investors, denoted by $m(\lambda|\kappa)$, equals

$$m(\lambda|\kappa) = \max\left\{m_0, \frac{\lambda\phi}{\pi_0 + f - \kappa}\right\}, \tag{4}$$

where m_0 is the initial number of stations before the introduction of the subsidy policies.

3.3. Government's Problem

The government's objective is to maximize the net benefit of EV adoption to the society by striking the right balance between the two possible subsidy instruments. We use β to denote the total benefit that each adopted EV generates for society over its lifetime. β mainly represents the negative environmental and health externalities that are avoided when a consumer drives an EV instead of an internal combustion-engine vehicle. β can also reflect other advantages of having an extra EV on the roads, such as reducing reliance on foreign oil and job creation in the renewable energy sector.

Anticipating the best response of consumers and investors in (2) and (4), the government solves the following Two-Sided Subsidy Problem (TSSP):

$$\max_{s,\kappa} \quad \Pi(\lambda_0, m_0) = \beta\,\lambda - s\,(\lambda - \lambda_0) - \kappa\,(m - m_0) \tag{TSSP}$$

$$\text{s.t.} \quad \lambda = \lambda_0 + \max\left\{0\,, \left[\frac{v\bar{\theta} - u_0 - (p-s) - \phi - \mu(m)}{v\bar{\theta}}\right]\Lambda\right\} \tag{5}$$

$$m = \max\left\{m_0, \frac{\lambda\phi}{\pi_0 + f - \kappa}\right\} \tag{6}$$

$$0 \le s \le p \quad , \quad 0 \le \kappa \le \pi_0 + f\,. \tag{7}$$

The first term in the government's objective reflects the societal benefit generated from the total population of EV owners. The second and third terms represent the total subsidies paid to consumers and developers, respectively. The constraints of (TSSP) are the best responses from consumers and investors for any given subsidy policy. We analyze this problem in the next section and investigate the properties of the equilibrium to gain insights into the simultaneous offering of the two subsidies. For the ease of exposition, and without loss of generality, we define $\widehat{\theta} = v\bar{\theta}$ and $c = \pi_0 + f$, so that $\widehat{\theta}$ and c can be interpreted as the maximum consumer valuation for EVs, and investors' effective barrier to entry, respectively.

In order to enable analytical tractability and sharpen our insights, we focus our analysis on situations where the initial number of public charing stations, m_0, is negligible. Although this assumption helps us to obtain closed-form results, it is not restrictive at all as it reflects the reality that the public charging infrastructure is immature in most markets. This is true even in developed countries or after governments offer infrastructure subsidies for quite some time. According to the New York Times and the Forbes, EV charging stations are far from sufficient, and the lack of public and residential EV chargers across America is a major deterrent to the purchase of EVs (Crothers 2019, Lawrence 2020). When China started its EV subsidy programs in 2010, it only had 76 charging stations (Prnewswire 2018). Norway had less than 200 charging points in 2009 when it first launched the EV subsidy program (Kvisle 2012). A similar situation is observed in Australia, Russia, and India (Guthrie 2020, Nair et al. 2017, Rodova 2018). Our assumption represents the situation in which initial EV owners mostly rely on home and workplace chargers. For the sake of completeness, we characterize the optimal solution to (TSSP) with a general m_0 in Appendix B. Although the complex formulas do not allow for further analysis, our numerical experiments show that the qualitative nature of our findings continues to hold when the initial number of charging stations is non-zero.

The following table summarizes all notations used in this paper.

Table 1 Notations

v	Consumer's valuation for a new vehicle
p	EV retail price
ϕ	Present value of average total charging expenses
θ	Environmental consciousness of consumers, uniformly distribution over $[0, \bar{\theta}]$
u_0	Reservation utility for each consumer
Λ	Population size of potential EV adopters
λ_0	Population size of current EV drivers
f	Capital expenditure for a charging station
π_0	Reservation profit for investors
s	Purchase subsidy offered to each EV buyer
κ	Investment subsidy offered to each charging station developer
β	Societal benefit of one EV adoption to the government
λ	Population size of all EV drivers after policy implementation
m	Total number of charging stations after policy implementation
$\widehat{\theta} = v\bar{\theta}$, $c = \pi_0 + f$	

4. Optimal Subsidy Design

We start our analysis of the government's problem by characterizing the equilibrium induced by best response functions (2) and (4) given subsidy parameters (s, κ). We then plug in the equilibrium into the government's objective and derive the optimal solution to (TSSP). To that end, we first need to make the following assumption:

Assumption 1. *Throughout our analysis, we assume that:*

(i) $\widehat{\theta} > u_0 + p + \phi + \mu(0)$.

(ii) $c > \Lambda r^2 / 4\widehat{\theta}$.

The first part of the assumption ensures that the most environmentally-conscious consumer is willing to be an EV driver, even in the absence of any governmental support. The second inequality ensures the optimal subsidy values for EV purchase and station development do not exceed the EV price and investment cost, respectively (i.e., the upper bounds in constraints $0 \le s \le p$, $0 \le \kappa \le c$ are not binding). Both of these assumptions are made to avoid degenerate solutions and rule out trivial and unrealistic scenarios.

LEMMA 1. *For any given subsidy policy (s, κ) and initial EV population λ_0, the market equilibrium achieved by consumers and investors is unique and can be characterized as,*

$$\widehat{\lambda} = F^{-1}\left(\lambda_0 + \left[\frac{\widehat{\theta} - u_0 - (p - s) - \phi}{\widehat{\theta}}\right]\Lambda\right),$$
$$\widehat{m} = \widehat{\lambda}\phi / (c - \kappa) \ ,$$

where function $F(\cdot)$ is defined as

$$F(x) = x + \frac{\Lambda}{\widehat{\theta}}\,\mu\left(\frac{x\phi}{c - \kappa}\right) \ ,$$

and is monotone increasing in x.

All proofs are provided in Appendix A. Lemma 1 characterizes the evolution of the EV market and charging infrastructure after the introduction of government subsidies. An immediate implication of this lemma is that both $\widehat{\lambda}$ and $\widehat{m}$ are increasing in s and κ, so that a larger subsidy on either side of the market leads to more entry on both sides due to the indirect network effect. Nevertheless, the specific nature of these relations is more intricate, and can be used by the government to achieve the highest benefit of EV adoption.

Hereafter, we adopt a specific functional form for $\mu(.)$:

ASSUMPTION 2. $\mu(m) = r_0 - r\sqrt{m}$.

The advantage of adopting the above functional form is twofold. First, it enables us to derive closed-form solutions while maintaining the essential features of the indirect network effect. Second, this function is characterized by readily interpretable parameters, so their impact on the equilibrium outcome entails unambiguous policy recommendations. More specifically, $\mu(m)$ is decreasing and convex in m, which is consistent with conventional wisdom about the impact of charging infrastructure: adding more stations reduces the disutility induced by range anxiety at a diminishing marginal rate. Further, one can interpret the driving range limit as the radius of the area that EVs can travel without requiring a recharge. Therefore, as the number of stations increases and each particular station's coverage area shrinks accordingly, it is natural to expect the driving range of EVs to extend proportional to the square root of the number of stations.[9]

In this formulation, r_0 is the maximum reduction in consumer utility due to driving range limitations when there are no public charging stations available (i.e., when consumers should rely entirely on home or workplace recharging). On the other hand, r captures the strength of the (positive) network externality generated by public charging stations. That is, it quantifies the rate at which the range anxiety is mitigated (and thus consumer utility improves) as more charging stations are launched. We note that $\mu(m)$ should be non-negative by definition, since it represents the drivers' disutility from lack of access to charging points. Hence, we require r_0 to be large enough compared to r such that $\mu(m)$ always remains non-negative. A sufficient condition for this to happen is $r_0/r \geq \sqrt{\Lambda(\beta+\phi)/c}$.

As the first step of characterizing the government's optimal policy, consider the following polynomial equation of z:

$$4c^2\widehat{\theta}z^3 - 3\Lambda rc\phi z^2 + \Big(2\Lambda\phi c(\phi-\beta+(p+u_0+r_0)-\widehat{\theta}) - 4c\phi\widehat{\theta}\lambda_0\Big)\, z + \Lambda r\phi^2\lambda_0 = 0\,.$$

Using Descartes' Rule of Signs, we can show that this equation has two positive roots. Let z_0 denote the larger of the two roots. The following result characterizes the optimal solution to (TSSP).

PROPOSITION 1. *Define*

$$\begin{aligned}\bar{s}_0 &= \beta+\phi-\frac{2c\widehat{\theta}(\beta+\widehat{\theta}-(p+u_0+r_0))}{4c\widehat{\theta}-\Lambda r^2},\\ \bar{\kappa}_0 &= c-\frac{2\phi c\,(4c\widehat{\theta}-\Lambda r^2)}{(\beta+\widehat{\theta}-(p+u_0+r_0))\Lambda r^2}-\frac{\phi(4c\widehat{\theta}-\Lambda r^2)^2}{\Big[(\beta+\widehat{\theta}-(p+u_0+r_0))\Lambda r\Big]^2}\lambda_0\,.\end{aligned} \tag{8}$$

If $\bar{s}_0, \bar{\kappa}_0 > 0$, then the optimal subsidy payments offered to consumers and investors are $s^* = \bar{s}_0$ and $\kappa^* = \bar{\kappa}_0$, respectively. Otherwise, we have

$$s^* = \begin{cases} \dfrac{cz_0^2\widehat{\theta} - \Lambda r\phi z_0 + \Lambda\phi((p+u_0+r_0)+\phi-\widehat{\theta}) - \lambda_0\widehat{\theta}\phi}{\Lambda\phi}, & \text{if } \bar{s}_0 \geq 0, \bar{\kappa}_0 < 0,\\ 0, & \text{if } \bar{s}_0 < 0, \end{cases}$$

$$\kappa^* = \begin{cases} \dfrac{c\Big[(\phi^2+\beta^2)\Lambda^2 r^2 + 4\Lambda c\phi\widehat{\theta}(\phi+(p+u_0+r_0)-\widehat{\theta}) - 4\phi\widehat{\theta}^2 c\lambda_0\Big]}{\big(\Lambda r(\phi+\beta)\big)^2}, & \text{if } \bar{s}_0 < 0, \bar{\kappa}_0 \geq 0,\\ 0, & \text{if } \bar{\kappa}_0 < 0. \end{cases}$$

[9] This interpretation assumes stations are uniformly spread across the jurisdiction.

Proposition 1 illustrates the complex dynamics between the two subsidy schemes, and highlights that these two policy measures must be examined in conjunction with one another. Any effort to solely support one side of the market in isolation without incorporating the other side into consideration is misguided and may lead to suboptimal outcomes. Specifically, this result also highlights situations where either of the two subsidies must be set equal to zero and the government's hybrid policy reduces to a one-sided one. When that is the case, all government incentives are directed to only one side of the market, as discussed in the next corollary.

COROLLARY 1. *The optimal solution to (TSSP) presented in Proposition 1 leads to the following statements:*

(a) There exist thresholds $r_\kappa, c_\kappa, p_\kappa, \bar{\theta}_\kappa$ *such that the subsidy to investors becomes zero if and only if, keeping everything else constant, one of the following conditions holds: i)* $r < r_\kappa$*, ii)* $c > c_\kappa$*, iii)* $p > p_\kappa$*, iv)* $\widehat{\theta} < \widehat{\theta}_\kappa$*.*

(b) There exist thresholds $r_s, c_s, p_s, \widehat{\theta}_s$ *such that the EV purchase subsidy becomes zero if and only if, keeping everything else constant, one of the following conditions holds: i)* $r > r_s$*, ii)* $c < c_s$*, iii)* $p < p_s$*, iv)* $\widehat{\theta} > \widehat{\theta}_s$*.*

For a simpler exposition, we have suppressed the dependence of the thresholds in the corollary on the model parameters. This corollary specifies conditions under which the optimal policy does not entail subsidizing both sides of the market. Comparing parts (a) and (b) of Corollary 1 leads to some valuable insights. In particular, it draws a sharp contrast between situations where the government should only resort to direct (i.e., subsidizing the EV buyers) vs. indirect (i.e., subsidizing infrastructure deployment) measures to accelerate the adoption process of EVs.

Perhaps the most surprising implication of Corollary 1 is the effect of the two cost parameters that capture the upfront financial barrier for the two sides of the market – namely, the retail price of EVs and development cost of stations. According to the corollary, these two parameters play similar roles in driving the structure of the optimal policy (i.e, one-sided vs. two-sided). This is contrary to the intuition because, in situations where a one-sided policy turns out to be optimal, one may expect the government's incentives to always target the market side for which the initial cost is high. Corollary 1 shows this is not the case. In particular, when either of the two costs exceeds its corresponding threshold, station developers are excluded from the government support, and a one-sided policy that only incentivizes consumers becomes optimal. On the flip side, when either of these parameters is sufficiently low, direct subsidy to EV buyers is ruled out, and government resources are better spent by fostering infrastructure development.

The effect of the range anxiety parameter on the structure of the optimal subsidy policy is more intuitive. When the range anxiety parameter is sufficiently low, charging stations do not create a strong enough network effect for consumers. As a result, providing financial incentives to station developers is not as advantageous as directly subsidizing potential purchases. However, the opposite is true when the network effect becomes sufficiently strong, in which case EV buyers should not receive any incentives. A similar argument holds with respect to the consumers' environmental preferences. That is, when the consumer valuation for an environmentally-friendly vehicle is low enough, it is in the policymaker's interest to allocate all of its resources to purchase subsidy, thereby directly boosting consumers' utility for EVs. On the other hand, stopping direct purchase subsidies and focusing entirely on charging infrastructure becomes optimal when consumers' valuation for EVs exceeds a threshold.

5. Policy Implications

Proposition 1 enables us to explore how the equilibrium subsidy rates depend on specific technology and market characteristics, and how they should be adjusted in response to evolving trends observed in practice. This section examines these questions in situations where a hybrid policy (i.e., subsidizing both EV buyers and investors) is optimal for the government.

5.1. Technological Cost Reductions

As EVs grow in popularity worldwide and electric mobility expands in size and scope, the research and development undertaken by EV manufacturers accomplish technological breakthroughs and drive down the costs. For instance, the price of EVs compared to their fossil-fuel counterparts has demonstrated a declining trend in the U.S. over the last few years (Car and Driver 2020). The same pattern also applies to the cost of launching charging stations, which has been dropping due to technological improvements (Nicholas 2019). Thus, it is important to understand how such trends should be incorporated into government subsidy mechanisms. The next proposition addresses this question.

Proposition 2. *The effects of technological cost reductions on optimal subsidies and market outcome are as follows:*

i) The market outcomes λ^* and m^* are both decreasing in p and c.

ii) Purchase subsidy s^* is increasing in both p and c.

iii) Investment subsidy κ^* decreases in p, and is unimodal in c.

Part (i) of the proposition suggests that any cost reduction that happens on either side of the market as a result of technological advancements positively impacts the adoption process as it increases the ultimate number of EVs and charging stations. This is intuitive because a lower EV price or a lower upfront cost of station development attracts more buyers and investors, respectively, thereby expediting growth on both sides.

More interestingly, parts (ii) and (iii) of Proposition 2 reveal that technological cost reductions affect the two subsidy instruments in drastically different ways. As the retail price of EVs or the construction cost of stations declines, the government should reduce the subsidy offered to EV buyers. This is expected because a lower price makes EVs more competitive in the market and facilitates their diffusion without requiring much government support. Similarly, a lower construction cost expedites the expansion of charging stations, increases EVs' attractiveness and lessens the need for policy intervention.

Even though one might expect the same intuition to hold for the investment subsidy κ^*, part (iii) shows that the opposite can be true. That is, the subsidy for charging stations should *increase* as EVs become cheaper. The reason behind this result lies in the perfect competition between the station operators. More precisely, as EVs become more affordable (even without subsidies) and the population of EV owners grows, a higher total revenue is generated for the stations to collect. Subsequently, assuming that the investment subsidy κ^* remains constant, more developers decide to launch stations until the investment is no longer profitable. At this point, however, it becomes optimal for the government to increase κ^* because the rate of growth in the number of stations is higher when there are more EVs in the market. In other words, the additional number of stations that will be launched for one extra dollar spent on the investment subsidy is increasing in the population size of EVs. This induces the government to offer a more generous infrastructure support since it leads to a faster proliferation of stations.

Further, the infrastructure subsidy varies with the development cost of stations in a non-monotone fashion, exhibiting an inverse U-shape behavior that is the result of two competing forces. First, a higher cost drives the government to increase its support for the investors to offset the higher barrier to entry. Second, due to the marginal effect described in the paragraph above, there is less to be gained for the government from a higher investment subsidy when the population of EVs (and stations) is smaller. Thus, when the development cost is still high – and therefore, the number of EVs and stations is low – the second effect prevails and κ^* increases as c decreases. However, when c drops below a threshold, the population of EVs and stations grows to a level that the second effect diminishes and the first effect prevails. At this point, it becomes optimal for the government to scale up its infrastructure deployment incentives.

Therefore, the two subsidies can be either *substitutes* or *complements*, depending on the stage of technological improvements and their impact on market realities. Specifically, s^* and κ^* move in opposite directions and become substitutes when EV price declines or the cost of building stations drops moderately. On the other hand, when the cost of building stations reduces substantially, s^* and κ^* move in the same direction and act as complements.

Moreover, Proposition 2 leads to an important policy recommendation that is often overlooked in practice, specially by the countries that only subsidize EV buyers. When the EV market is still at its infancy and going through early stages of technological developments – which is the case in the majority of jurisdictions around the world – any technological cost reduction should entail a lower subsidy for EV buyers and a *higher* subsidy for station developers. That is, when the EV market is still immature and far from being competitive, the EV subsidies should go down whereas infrastructure subsidies should actually increase as time progresses. This recommendation reverses for the infrastructure subsidy only when the station development cost drops sufficiently.

5.2. Network Effect

The attractiveness of electric vehicles heavily depends on the availability of public charging stations. As the charging infrastructure expands and more stations become available, consumers are empowered to access charging points more easily and drive EVs for longer distances. This positive network effect mitigates range anxiety and enhances consumers' EV driving experience. However, the magnitude of this effect may vary for different consumer populations due to factors such as driving habits, urban characteristics, and trip distances. Therefore, legislators need to consider the strength of network effects when designing incentive policies and fine-tune their subsidies accordingly. In our model, the network effect is captured through parameter r, which reflects the rate at which consumers' disutility is mitigated as the number of stations increases.

PROPOSITION 3. *A higher r leads to a lower purchase subsidy s^* and a higher investment subsidy κ^*. Furthermore, a higher r makes the government better off so that Π^*, λ^*, and m^* all increase with r.*

This result suggests that, in jurisdictions where range anxiety is more intense and consumers are more sensitive to charging station availability, the government should increase the subsidy for infrastructure development and reduce the subsidy for EV buyers. To understand this result, note that a higher r increases the appeal of EVs to potential buyers and induces more EV purchases. While this justifies reducing s^*, it also increases the total revenue for stations and incentivizes more investors to enter the market. One may expect κ^* to go down in parallel with s^* as the network effect becomes stronger. However, Proposition 3 shows the opposite holds, and the subsidy for investors should increase in r. This finding, for instance, pertains to regions where average trips are usually longer, and commuting long distances is part of people's daily lives (e.g., Southern California, Texas). In these situations, our result calls on policymakers to take advantage of the stronger network effect and offer more generous subsidies to charging stations as this strategy would ultimately boost the adoption of EVs and benefit the government.

It is worth adding that r can also represent a proxy for the degree of improvements in the EV battery technology, which dictates the total distance that EVs can travel without recharging. As technology advances and EV batteries become capable of holding up more energy, consumers' sensitivity to the density of stations declines, and the network effect weakens. Subsequently, Proposition 3 recommends shifting the policy focus away from stations and reinforcing EV purchase subsidies. This recommendation goes against conventional wisdom because advancements in battery capabilities and life-spans are often associated with lower subsidies for EVs in practice.

5.3. Attitude Toward the Environment

Environmental preferences and the attitude toward combating climate change varies widely among consumers and policymakers alike. This reflects the extent to which a particular region holds a progressive stance concerning the environment, and manifests in consumers' environmental consciousness and the government's valuation of green technologies. For example, in the U.S., there is a high level of heterogeneity across different states when it comes to how environmentally-progressive their residents are. Similarly, governments in places with higher air pollution and smog may attribute a higher value to environmentally-friendly products such as EVs due to the urgency of the problem they face. This variability raises the question of how different stakeholders' environmental preferences should be incorporated into government incentive policies for EVs.

In the next two propositions, we address this question by examining the role of the corresponding parameters in our model. Recall that β captures the environmental and health benefits to the society from having one more EV on the roads. Parameter $\widehat{\theta}$, on the other hand, is a measure of the consumers' utility premium for using an environmentally-friendly vehicle. As $\widehat{\theta}$ increases, consumers become "greener" on average, while their disparity along this attribute also expands.

PROPOSITION 4. *κ^* always goes up in β. There exists a threshold $\widehat{r}$ on the magnitude of the network effect such that s^* increases in β if and only if $r \le \widehat{r}$.*

This result indicates that the government should always boost its support for charging stations as EVs' benefits to society increase. The same conclusion, however, is not necessarily true for supporting EV buyers. In particular, higher societal benefits of EVs translate into a lower subsidy for EV purchases when the network effect is sufficiently strong. In this situation, providing a more generous subsidy to charging stations is more effective in increasing EV adoption than subsidizing EV buyers. As a result, the government finds it optimal to scale back the incentives for potential adopters in response to a higher β. This implies that legislators should carefully adjust their subsidy programs based on their assessment of EVs' health and environmental implications in their jurisdictions.

Proposition 5. *There exists a threshold $\widehat{c}$ on the construction cost of stations so that*
(i) if $c > \widehat{c}$, then s^* decreases while κ^* increases in $\widehat{\theta}$.
(ii) if $c \le \widehat{c}$, then s^* is unimodal and κ^* is decreasing in $\widehat{\theta}$.

Proposition 5 shows that variations in consumers' environmental preferences may lead to opposing effects on the subsidy instruments depending on the development cost of charging stations. To understand this result, note that a higher value of $\widehat{\theta}$ can be utilized by the government in two distinct ways. On the one hand, a greener population increases the consumers' utility for EVs and entails the number of EV owners to grow. This enables the policymaker to reduce the subsidy to EV buyers and instead ratchet up the support for station development to further induce adoption. In this case, the government's total spending actually goes up, but this increase is more than offset by the value gained from the spike in adoption.

Alternatively, the government can use a higher $\widehat{\theta}$ as a way to save on its expenditure. To that end, the government reduces its infrastructure subsidy since the savings from this subsidy reduction outweighs the loss from a smaller pool of adopters. According to Proposition 5, the first approach is optimal when the construction cost of stations is sufficiently high, whereas the second approach is preferred when this cost is low. Therefore, a more environmentally conscious consumer population may trigger upward or downward adjustments in either of the two subsidy levels.

6. Model Calibration

Despite the lower-than-expected adoption rate, China is one of the largest EV markets globally. The metropolis of Shenzhen has the highest number of EVs in China.[10] The Shenzhen government was one of the first authorities that implemented a subsidy program for EVs. The program started in 2009 when there were very few EV owners and the number of charging stations was extremely low[11]. The program continued until 2014. (After 2014, Shenzhen launched a vehicle plate limit program, under which the city issues only 100,000 registrations per year for gas vehicles, but there is no limit on EVs.) We have collected data for EV sales and charging stations in Shenzhen for the program's duration, from 2014 to 2018, to calibrate our model and perform numerical experiments.

We have used various sources to collect all the data we need for our calibration exercise.[12][13][14] The base parameter estimates are listed in Table 6. We normalize u_0 to zero. There are several popular models of EVs in Shenzhen, so we use the average price of these models to estimate p.

[10] https://www.tyncar.com/schq/0327-8298.html

[11] http://www.sz.gov.cn/cn/xxgk/zfxxgj/zwdt/content/post_1565756.html

[12] http://www.xinhuanet.com/fortune/2018-07/22/c_1123160496.htm

[13] https://tech.sina.com.cn/i/2018-09-16/doc-ifxeuwwr4866727.shtml

[14] http://sz.people.com.cn/n/2014/0114/c202846-20379736.html

The values for c come from Hove and Sandalow (2019). Although some parameters in our model can be readily estimated from the available data (e.g., the subsidy values, price of EVs, and cost of station development), some others have to be inferred based on the market outcome. For instance, we use the total sales volume of all vehicles (both conventional and EV) each year as a proxy to estimate Λ, the population size of potential buyers. Not surprisingly, network effect parameters (r_0 and r) and also parameters related to environmental preferences of consumers and the government ($\widehat{\theta}$ and β) are the hardest to estimate because their values are implicit in how the EV market has evolved in Shenzhen.

In order to estimate r_0, r, and $\widehat{\theta}$, we have used the following approach: We first assume our model of Section 3 applies to the EV market in Shenzhen every year. That is, for every year during the 2014-2018 period, we obtain the data on:

(i) the initial number of EVs, λ_0, and stations, m_0, at the beginning of the year,

(ii) the EV subsidy, s, and the station development subsidy, κ, and

(iii) the final number of EVs, λ, and stations, m.

Then, using the data in items (i) and (ii) above, we run our model of Section 3 with unknown values of r_0, r, and $\widehat{\theta}$. This gives us predictions for EV adoption and station development in each year as functions of these unknown parameters. We then compare these predictions with their corresponding actual values given in item (iii) above. Finally, we run an optimization model to find values of r_0, r, and $\widehat{\theta}$ for which the total error of our predictions is minimized. We use the outcome of our optimization model as our estimates for these parameters, as reported in Table 6.

Since the network parameter r is one of the most important parameters in our model – capturing the magnitude of the consumers' range anxiety – we try different values for this parameter in the vicinity of our estimate. That is, we allow r to vary in $r = \{50, 60, \ldots, 200\}$ subject to the inequalities in Assumption 1. The only parameter for which we were not able to find any estimate is parameter β, which measures the government's estimate for the societal value of one EV unit. This is expected given the nature of this parameter, which makes it very difficult to estimate in the absence of a thorough empirical analysis. Thus, we allow β to vary according to $\beta \in \{200{,}000,\ 300{,}000,\ 400{,}000,\ 500{,}000\}$. This range is obtained by envisioning values of β that go from slightly below p, the retail price of EV, to twice the value of p. To check the robustness of our results while keeping the number of experiments manageable, we consider any possible combination of β, c, and r based on the estimates described above.

For each possible combination of model parameters, we consider two possible scenarios: implementing a hybrid policy that subsidizes both EVs and stations, and implementing a one-sided policy that only subsidizes EVs. We find the optimal subsidy policy for both scenarios and compare

variable	value	source
p	250,000	EV price
ϕ	1800	average charging fee
c	$\{40{,}000, 50{,}000, 60{,}000\}$	charging station cost
Λ	487,354	potential market size
r_0	96444.96	maximum range anxiety
r	70.16	network effect
$\widehat{\theta}$	366,583.65	consumers' environmental attitude

Table 2 **The default value for parameters. Monetary values are in RMB.**

their corresponding outcomes. Specifically, we measure the ratio of the number of EVs, charging stations, and the government's objective under the hybrid subsidy policy to those under the one-sided subsidy program. Across our experiments, the number of charging stations under the hybrid policy was, on average, 11.26 times the number of charging stations when only buyers are subsidized. The maximum ratio of stations was 33.96. The number of EVs in the hybrid policy increased by 6.82%, on average, and up to 30%. The government's benefit increased by 5.68% on average, with a maximum increase of 26%.

Figures 2 and 3 are two examples of our experiments. Figure 2 illustrates the three ratios as the benefits of EVs to society (parameter β) changes. We observe that, when both EV buyers and investors are subsidized, the number of charging stations can be 4 to 10 times the number of stations when only EV purchasers are supported. This improvement in the infrastructure increases the number of EVs by 2.7 to 4.1 percent, and the government's benefit by 1.8 to 3.3 percent.

Figure 3 illustrates the ratios when the infrastructure cost is set to 60,000 and the network effect r varies. Recall that a higher value of r indicates a high level of range anxiety, so that increasing the number of charging stations has a stronger network effect on consumers' utility. When consumers are not anxious about EVs' driving range (low r), the government's optimal policy is to only subsidize EV purchases. On the other hand, as consumers get more anxious about the driving range, the government switches its policy to subsidizing both EV buyers and investors. In fact, the government reduces the subsidy to buyers and increases the subsidy to investors as r increases. This adjustment of the support policy increases the number of charging stations drastically. As a result, the number of EVs increases by up to 20%, and the government's benefit increases by up to 17%. This example highlights the importance of implementing an appropriate subsidy policy that accounts for the infrastructure's positive network effect on consumers' EV utility.

7. Conclusion

The dire consequences of climate change have pressured policymakers to expedite the adoption of environmentally-friendly technologies. Electric vehicles can play a significant role in reducing

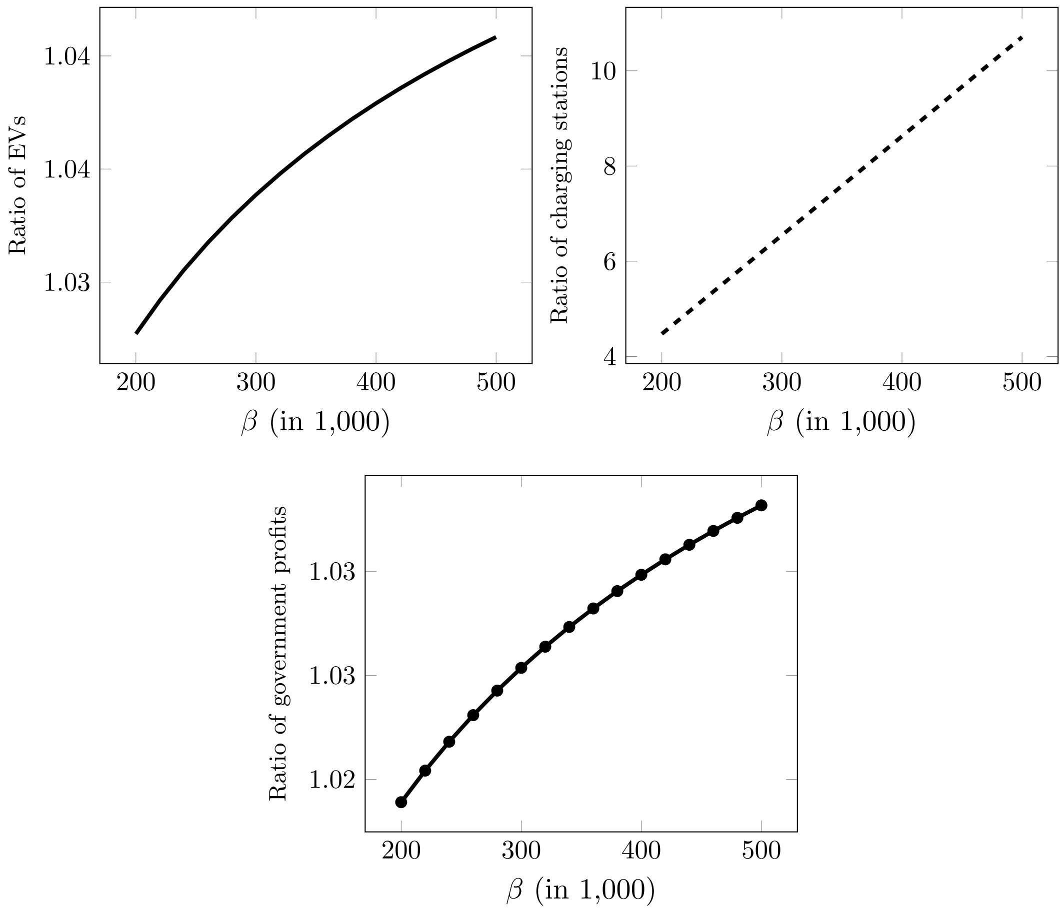

Figure 2 Comparison between hybrid policy and one-sided buyer subsidy ($c = 50{,}000$, $r = 100$)

greenhouse gas emissions and protecting the environment. However, the global adoption of EVs has not met the targets. Two major impediments to EV adoption are the high prices of EVs and the lack of public charging stations that causes range anxiety among EV drivers. To overcome these barriers, many governments have introduced incentive programs that aim to increase EVs' attractiveness and stimulate their adoption. These governments, nevertheless, have taken different approaches to support EVs. On the one hand, some legislators only rely on subsidizing EVs to make them more affordable for buyers. On the other hand, some others use a hybrid policy that simultaneously subsidizes buyers and provides an infrastructure subsidy to investors interested in building public charging stations.

Motivated by these different practices, we studied a government's optimal design of EV support policy. Our model considers the competition between investors and the two-sided nature of the EV market that follows from the complementarity between EVs and charging stations. EV drivers generate revenue for charging stations and charging stations create a positive network effect on consumers' utility of driving EVs. We characterized the government's optimal subsidy policy and specified conditions under which the government should resort to a hybrid policy instead of only

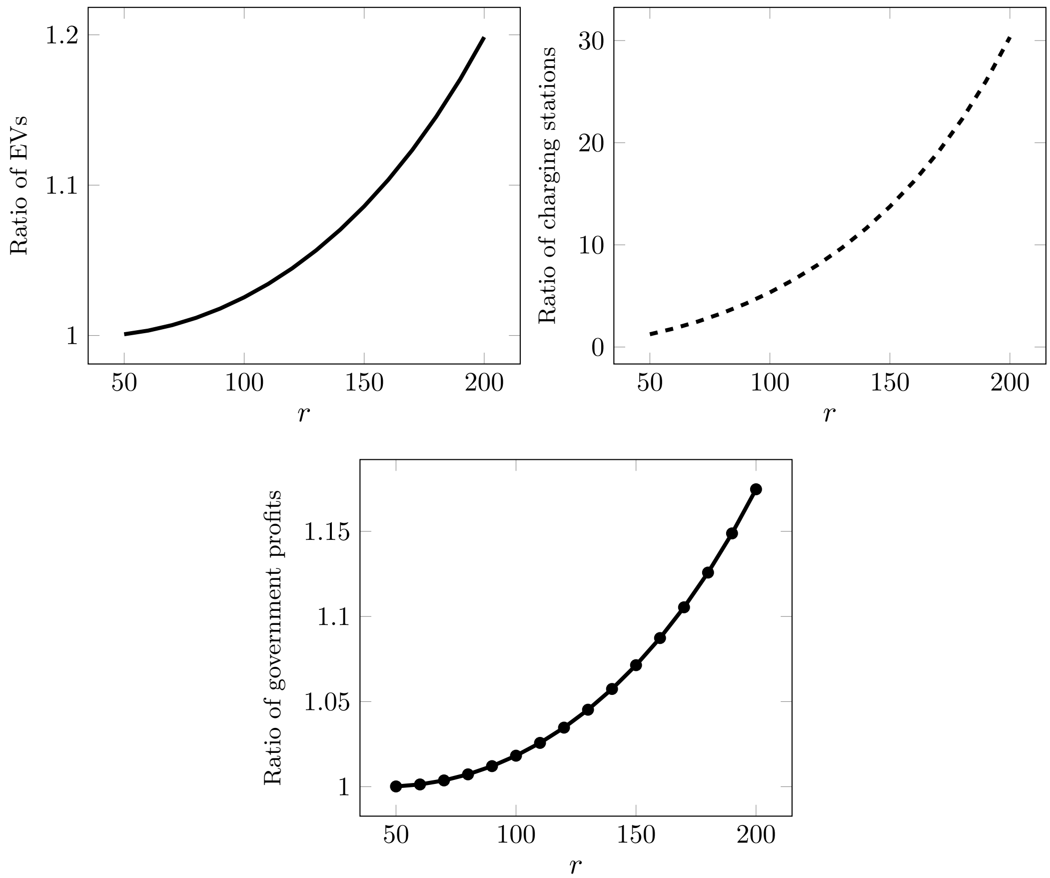

Figure 3 Comparison between hybrid policy and one-sided buyer subsidy ($\beta = 300{,}000$, $c = 60{,}000$)

subsidizing EV buyers. The conditions indicate that offering only purchase subsidies is the right policy when one of the following conditions holds: the network effect is weak, the infrastructure cost and/or the EV price is high, or consumers' attitude toward protecting the environment is not very strong. This provides a normative guideline for policymakers to assess whether or not employing a hybrid policy in their jurisdiction is advisable.

We also offered policy recommendations on how legislators should adjust the subsidy rates when various technology and market characteristics change. We explored the role of technological cost reductions, network effect, and the government's and consumers' environmental awareness in designing the optimal subsidy mechanisms. Our results show that the two subsidies can be either substitutes or complements depending on the level of technological improvement. In particular, when the EV market is still in its infancy, the government should gradually reduce the subsidy for EV buyers and increase the infrastructure subsidy as technology cost goes down. The same recommendation also applies when the network effect becomes stronger and consumers become more sensitive to charging station availability. When the benefit of EVs to society increases, the government should subsidize investors more, but the direction of change in the purchase subsidy depends on the network effect's strength. If the network effect is strong, the government should reduce the subsidy to buyers and indirectly promote EVs by expanding the infrastructure. Also, the change in subsidies when consumers' environmental consciousness varies depends on the infrastructure cost.

We calibrated our model with data from the metropolis of Shenzhen, China. We found that, when the hybrid policy is optimal, it increases the number of EVs and government's profit by 6.82%, and 5.68%, on average, and as much as 30% and 26%, respectively. Also, the number of charging stations under the hybrid policy is on average 11.26 times that of a one-sided policy that only supports buyers. This ratio can even reach 34 in some cases. These observations underscore the substantial gains that can be achieved by implementing a hybrid policy and indicate that solely focusing on EV purchase subsidies – which is the current practice of many countries around the world – can be misguided.

Our paper provides directions for future research. Due to analytical complexity, we did not consider strategic waiting by consumers or dynamic subsidy optimization by the government. Our analysis is focused on isolating the network effect and the complementarity between the two subsidy instruments. It would be interesting to incorporate strategic behavior by consumers, investors, and the government in a multiple period model. However, one would need to make simplifying assumptions in order to enable tractability in a dynamic game setting.

Second, it would be interesting to study the interactions between government subsidies and decisions made within the EV supply chain. These decisions include innovation and R&D investments in the battery technology, suppliers' capacity decisions, and pricing of EVs by the manufacturers.

Finally, our theoretical framework lends itself to a full-fledged empirical study that utilizes more detailed data on the micro-foundation of consumers' and investors' decision-making process and verifies the robustness of our analytical results. We hope our work spurs more research on EVs in the operations management community.

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